COMPUTER SIMULATION AS A DECISION-SUPPORT TOOL FOR SELECTING CO_2 EMISSION REDUCTION STRATEGIES IN THE CEMENT INDUSTRY

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ABSTRACT

Climate change is one of the most pressing concerns in the world today, with UN and 196 member countries pledging to limit the rise in average global temperatures to 2 °C when compared to pre-industrial levels. With CO2 emissions being the most significant contributor to climate change, there is an increasing need for adoption of mitigation strategies in the cement domain, which accounts for about a quarter of all industrial CO2 emissions in the world. Despite the availability of several potent mitigation strategies, the adoption rates in the cement domain have remained relatively low when compared to other domains. For fostering faster adoption rates of CO2 mitigation in the cement domain and improve their compliance in the global fight against climate-change, this study develops a decision support tool using system dynamics, which is a simulation modelling approach characterised by its emphasis on cause-and-effect relationships and feedback loops. The model constructed during this study bridges the gaps in existing studies in the cement domain by emphasising on individual cement plants and integration of multiple interacting mitigation strategies relevant to the cement domain such as clinker substitution, green captive power generation, alternative fuels, carbon capture and efficiency improvements. Unlike the previous studies which emphasised on modelling the cement industry as a whole, the model developed in this study assists in identifying the optimal combinations of mitigation strategies relevant to a specific cement plant under the regional market conditions. This would not only allow the cement plant stakeholders to identify the financially sustainable mitigation strategies for their specific plant, but would also enable policymakers to investigate and experiment the impact of policy on specific cement plants. The model allows the cement plant stakeholders to strategize their approach for compliance in CO2 emission reduction requirements. For demonstrating the utility of the model, real world data collected from a reference cement plant in India is used for running experiments for various combination of CO2 mitigation strategies under different policy scenarios. The results are then analysed to identify the most suitable approach under each strategy, and their respective payback periods are calculated. Additionally, experimental policies are drafted and tested for optimal utilisation of collected carbon tax for subsidies related to emission reduction.

INDEX

1. INTRODUCTION

1.1 Background

Climate change is considered as one of the most important issues in the world today, with an increasing amount of evidence blaming human activity as its leading cause (Myles Allen et al., 2019). It is estimated that the human activity alone has led to an increase of 1 °C in average global temperatures compared to pre-industrial era. At the beginning of the current century, it was estimated that the global average temperatures would increase by 1.5 °C by the year 2046. However, due to exponential industrial growth in the developing world in the last 2 decades, the increase in average global temperatures is estimated to reach 1.5 °C by the year 2035 under the most recent estimates in 2022, as illustrated in Fig. 1.

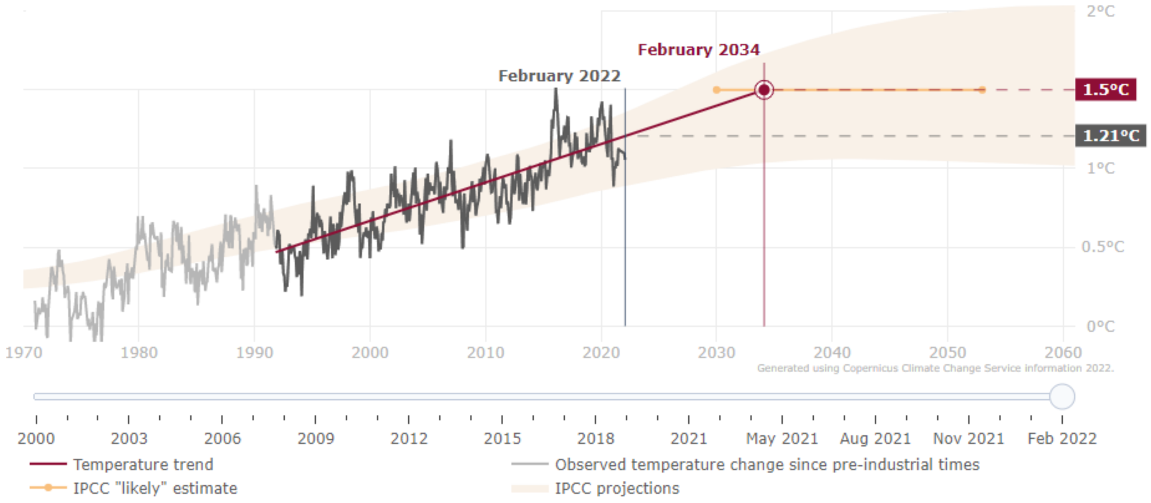

Fig. 1. Estimated average global temperature under the current trend (Copernicus Programme, 2021)

The climate situation is expected to rapidly deteriorate beyond the increase in temperature of 1.5 °C, with increased incidents of temperature extremes, droughts, freshwater availability, intense precipitation in few regions, mass extinction of wildlife species and irreversible damage to ecosystems, and increase in sea levels (Alan Buis, 2019). Under the current trajectory, the average global temperature is estimated to increase by 2 °C by the end of this century, which would have a catastrophic impact on the ability of human beings and ecosystems to survive (Masson-Delmotte et al., 2021).

The greenhouse effect is the primary cause of climate change, which is a phenomenon where certain gases in the atmosphere trap the heat energy from the sun and prevent it from escaping the earth, similar to a greenhouse. The most notorious greenhouse gases include carbon-di-oxide (CO2), methane, nitrous oxide, and fluorinated gases. The lifetime of the aforementioned gases is depicted in Table 1.

Table 1. Lifetime of greenhouse gases, adapted from (Han et al., 2009)

Greenhouse gas	**Atmospheric lifetime (years)**
Carbon-di-oxide	50-200
Methane	12
Nitrous Oxide	120
Carbon tetrafluoride	100000

Sulphur Hexafluoride	3200
Nitrogen Trifluoride	50-740

Among the greenhouse gases, CO2 has the highest concentration in the atmosphere, about 416 ppm in the northern hemisphere in 2020, followed by methane at 1850 ppb. Furthermore, at the end of its lifespan, methane disintegrates into CO2 (“Greenhouse gas concentrations,” 2022). Considering CO2 accounts for approximately 76% of all greenhouse gas emissions through human activities, it is currently the most potent enabler of greenhouse effect on Earth. In comparison, methane accounts for 16% of all emissions, followed by nitrous oxide at 6%, and fluorinated gases at 2%.

In order to tackle climate change, 196 countries in the world have signed the Paris Agreement, a legally binding international treaty, on 12 December 2015. The primary goal of the agreement is to limit the increase in average global temperatures to below 2 °C compared to pre-industrial levels (The Paris Agreement, 2015). For achieving this goal, the signed parties would reduce their greenhouse gas emissions to achieve carbon neutrality by the year 2050. For tracking the progress of the various parties to the agreement, every country was asked to submit their long-term climate actions as Nationally Determined Contribution[1] (NDC). The climate pledges of the top 4 largest emitters of Greenhouse Gases (GHG) are depicted in Table 2.

Table 2. Climate pledges of top GHG emitters, adapted from Intended Nationally Determined Contributions database (“NDC Registry,” n.d.)

Region	Share of GHG (2012)	NDC Pledge	Target year to complete pledge
China	23.75%	Reduce CO2 emissions per-capita by 60-65% of 2005 levels	2030
United States of America (USA)	12.10%	Reduce GHG emissions by 26-28% of 2005 levels	2025
European Union (EU)	8.97%	Reduce GHG emissions by 40% of 1990 levels	2030
India	5.73%	Reduce GHG emissions by 33-35% of 2005 levels	2030

As a means to reduce GHG emissions, the signed parties are in the process of introducing new laws and policies to promote mitigation in different GHG emission domains such as, energy sector, transportation, reforestation, and manufacturing. As per Intergovernmental Panel on Climate Change[2] (IPCC), 25% of the GHG emissions are from the energy sector which includes electricity and heat production, 24% from agriculture and livestock farming, 21% from industrial processes and energy use (excluding electricity), 14% from transportation sector, and 6% from buildings through on-site energy generation for air-conditioning (Edenhofer et al., 2014). The share of GHG emissions among the various sectors is illustrated in Fig. 2.

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[1] Nationally determined contribution is a non-binding national plan highlighting climate change mitigation, including climate-related targets for greenhouse gas emission reductions

[2] The Intergovernmental Panel on Climate Change is an intergovernmental body of the United Nations responsible for advancing knowledge on human-induced climate change

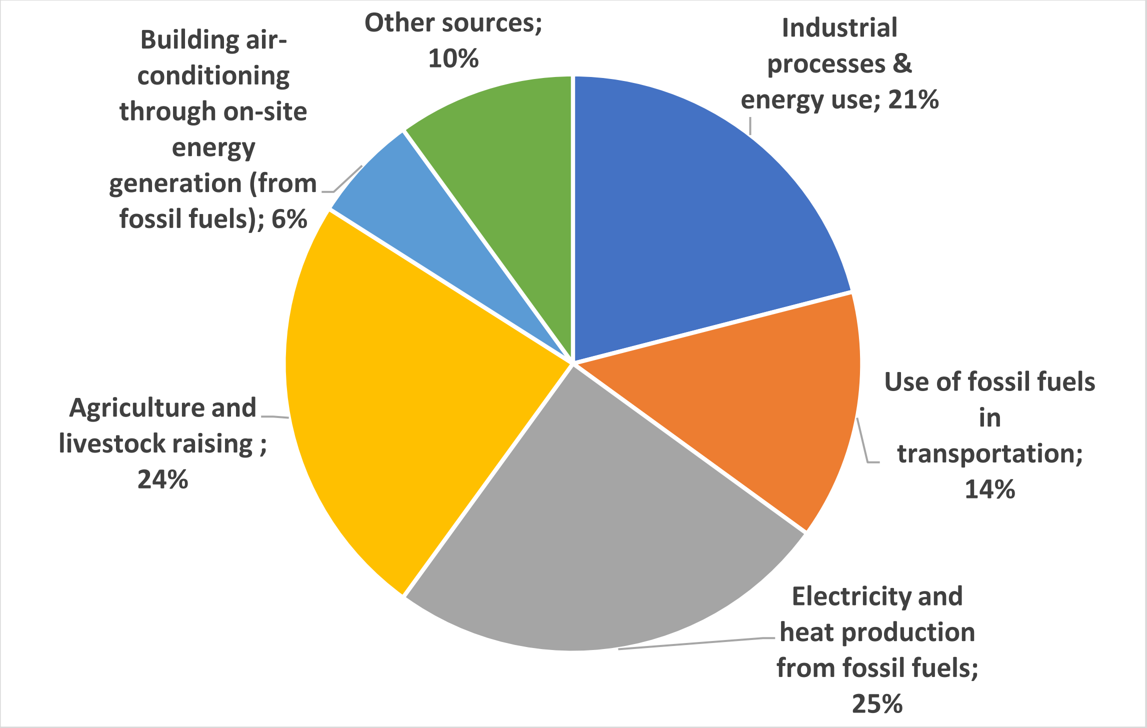

Fig. 2. Share of GHG emissions among the various emission sectors, adapted from (Edenhofer et al., 2014)

Among the industrial sources, steel and cement production are largest sources of emissions, each contributing 7% (2.6 billion tons) and 6.5% (2.3 billion tons) of the global CO2 emissions respectively (Caroline Brogan, 2022). Concrete, whose major component is cement, is the second most consumed resource globally, after water. The production of cement is an emission intensive process, resulting in CO2 emissions from both energy use and as well as through the release of carbon from the raw material. The use of concrete and cement is tied to the overall infrastructure growth of the region, which in turn influences the amount of clinker production (the major component of cement). The historical cement demand across various geographical regions and as well as the forecasted value until 2030 under the net zero scenario is depicted in Fig. 3. In the net zero scenario, it is assumed that the net CO2 emissions would reach 0 by 2050, and thereby limiting the global temperature rise by 1.5 °C. As the demand for cement increases, more plants would be set up and would eventually lead to more CO2 emissions unless it is kept in check through CO2 mitigation strategies.

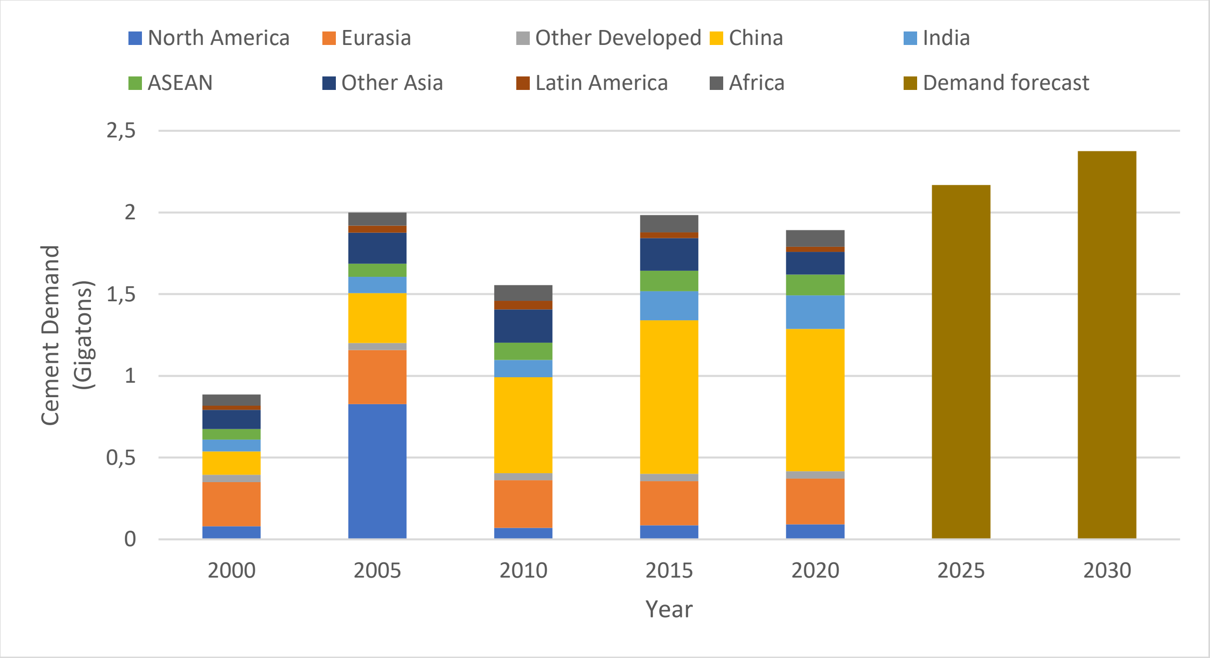

Fig. 3. Cement demand for construction projects across various geographical regions, between 2000 to 2020, with forecast until 2030. Adapted from International Energy Agency (IEA) dataset ("Global cement demand for building construction, 2000-2020, and in the Net Zero Scenario, 2025-2030," 2021).

The cement demand in developing countries like India, as visualised in Fig. 4, is set to increase by 8.5% in the current fiscal year (2022) and would likely continue to grow, highlighting the need for penetration of mitigation strategies in the cement industry. In the current forecast trajectories, the CO2 emissions from the cement industry are set to grow by 27% in 2050 if no checks are implemented for regulating the CO2 emissions from the industry.

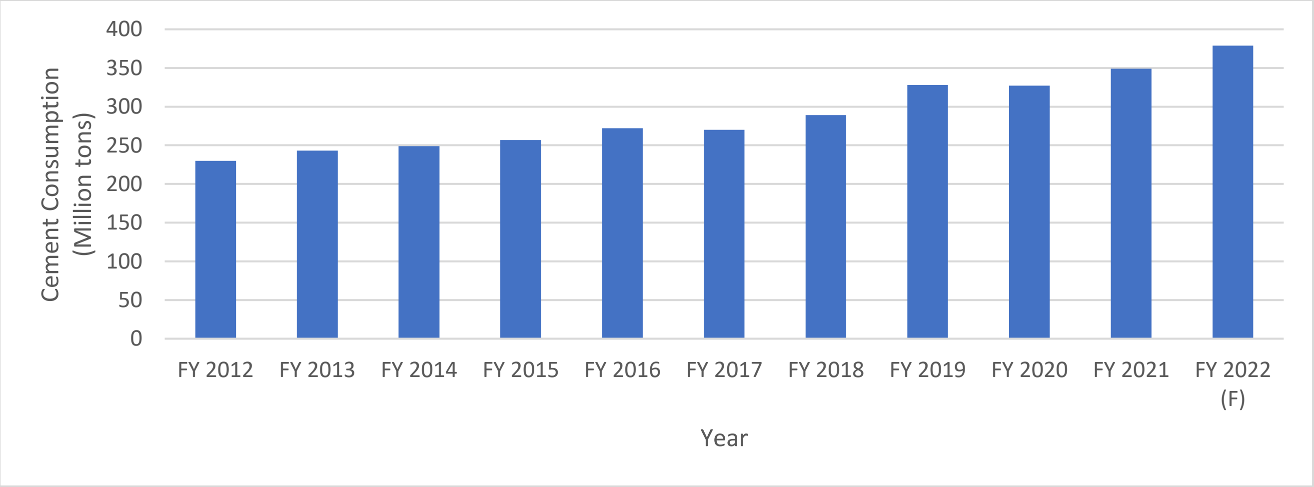

Fig. 4. Cement Consumption in India, between the Fiscal Years[3] (FY) 2012-2022. Adapted from (Shangliao Sun, 2022)

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[3] India's fiscal year begins in April and ends in March

As a measure to encourage CO2 mitigation, about 42 countries (as of 2019) have implemented schemes such as carbon tax and emissions trading systems, with more countries to follow suit (World Bank Group, 2019). Carbon tax would drive up the production costs of high CO2 emitting industries, prompting them to implement measures to reduce the emissions.

Considering cement industry is a major source of CO2 emissions as discussed in this section, CO2 abatement policies could motivate the industry stakeholders to take up more efforts in reducing CO2 emissions. The cement industry currently generates the most CO2 emissions per unit of revenue as tabulated in Table 3. There are several options to reduce emission intensity of cement production, which are further discussed in Chapter 2. The costs of mitigation vary depending on the strategy chosen, the local market conditions, and the existing policies/regulations.

Table 3. CO2 emissions per a USD of revenue, adapted from (Thomas Czigler et al., 2020).

Industrial product/activity	Emissions per unit of revenue (kgCO2/USD)
Cement	6.9
Steel	1.4
Oil and gas	0.8
Mining	0.4
Chemicals	0.3

Despite the availability of numerous mitigation strategies, which are described in Section 2.5, and the highest CO2 emissions per unit of revenue, the adoption of these strategies within the cement industry has been slow. Depending on the individual parameters of each cement plant and region, there is an immense potential for carbon mitigation in the cement industry through methods such as Waste Heat Recovery (WHR), carbon capture, alternative low-carbon fuels, and clinker substitution. Given the capital-intensive nature of these methods, the existing policies have not been ineffective in propelling the cement industries to adopt the available mitigation methods. However, through improved decision support tools, it is possible to design balanced policies that would enable the implementation of mitigation strategies that are economically feasible.

While there are several mitigation strategies available for implementation, each of them leads to varying results in terms of CO2 emissions reduced and changes to the plant expenditure, depending on various conditions. For example, implementing a captive power plant for harnessing solar energy would lead to no benefits if the existing local grid at the location of the cement plant is already utilising 100% renewable energy and supplies it to the cement plant at competitive tariffs. Similarly, changing market conditions over time would result in changing a mitigation strategy that may be suitable today into an expensive ordeal in the future. In order to assist the industry stakeholders, different types of decision-support tools exist, with specific use-cases such as life-cycle analysis, cost-benefit analysis, and multi-criteria decision analysis (Puig, Daniel et al., 2016). In the context of climate-change, life-cycle analysis is used to determine the financial and environmental impact of a product, from raw material sourcing to its end of life. Multi-criteria analysis allows for evaluation of various strategies on the basis of pre-established criteria. In cost-benefit analysis, the benefits and expense of each strategy are quantified over a period of time in order to determine if a particular strategy is viable. Cost-benefit analysis is especially suitable for CO2 mitigation projects that has an impact on existing goods and production processes. System Dynamic modelling is considered as an appropriate tool for decision support, by “simplifying reality into a comprehensible form that can variously employed to provide exploratory decision support” (Clifford-Holmes, 2018). The methodology is further discussed in Section 2.1.

1.2 Scope for implementation of mitigation strategies in the cement industry

The production of cement is one of the most significant sources of CO2 emissions in the industrial domain. Despite the existence of numerous mitigation strategies to reduce emissions from the cement manufacturing process, their adoption rate has been largely inadequate to meet the existing pathways for reducing CO2 emissions for meeting the 1.5 °C target.

The changes in specific electrical energy consumption per ton of cement produced between 1990 and 2019 is visualised in Fig. 5. There has been steady decrease in specific electricity consumption from 1990 to 2011, but has remained stable since then, indicating the scope for using captive power generation through green energy sources such as solar or WHR. Despite the active participation and support of various climate change protocols such as “Paris Agreement 2015”, regions such as North America, European Union, and Commonwealth of Independent States have a comparatively less efficient production of cement, as seen in Fig. 6 and Fig. 7, highlighting the potential of implementing mitigation strategies in this region.

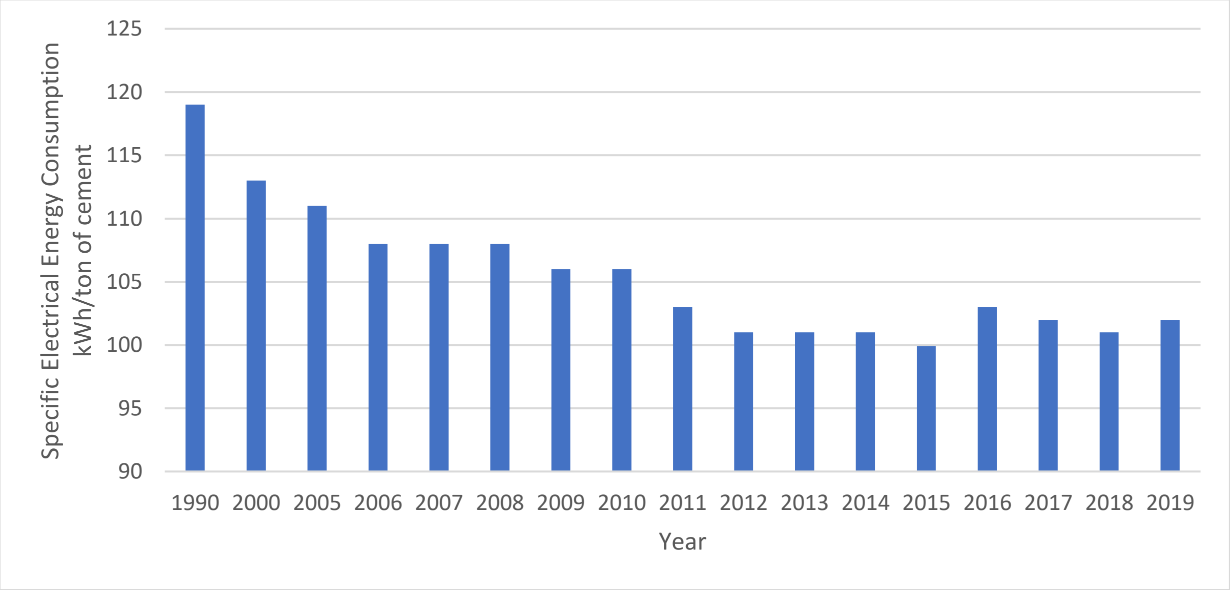

Fig. 5. Global average specific electrical energy consumption per ton of cement produced, sourced from (GNR Project, n.d.).

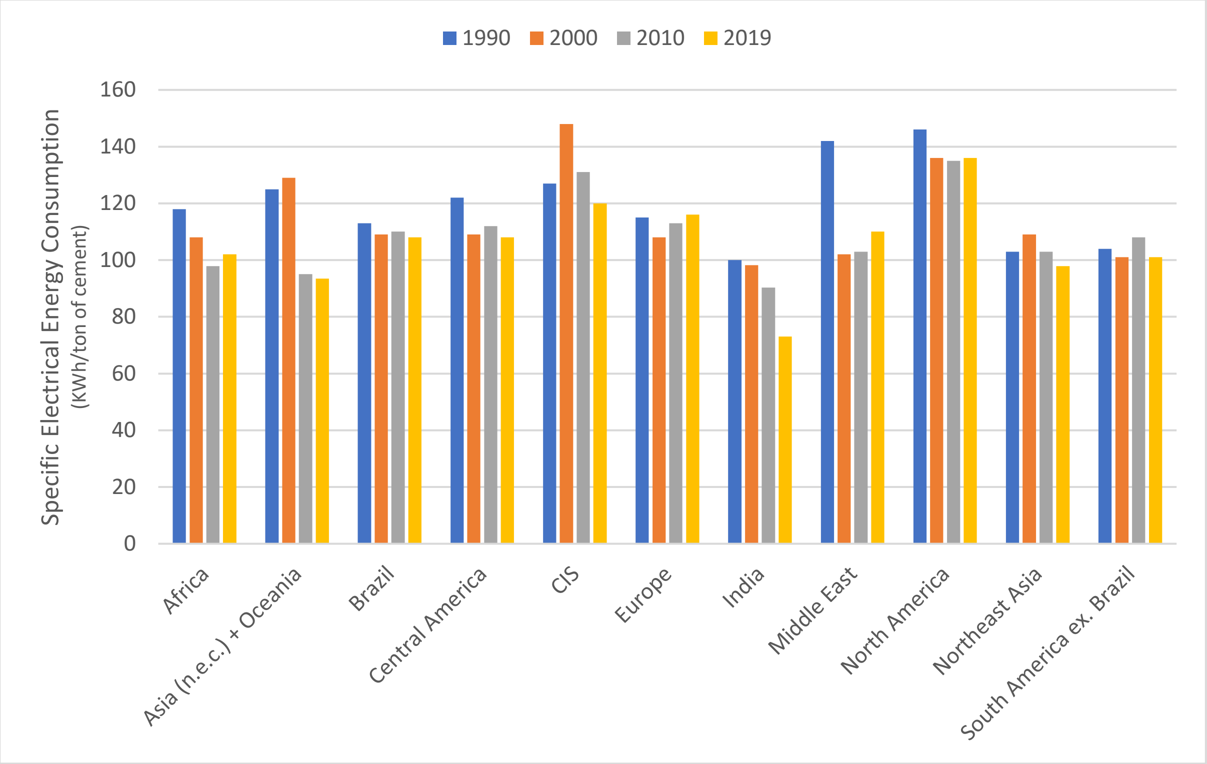

Fig. 6. Average specific electrical energy consumption per ton of cement produced in various regions, sourced from (GNR Project, n.d.).

There has been only marginal improvement in the efficiency of thermal energy use in the production of clinker across the world, with the exception of regions such as Commonwealth of Independent States (CIS), as depicted in Fig. 8 and Fig. 9. Similarly, the cement plants in regions such as North America, CIS, and Europe have highest consumption of electrical energy per ton of cement produced. They have only shown modest improvement in the last decade, indicating the scope for further improvement, as tabulated in Table 4.

Table 4. % Improvement in efficiency related to electricity consumption in production of Cement in various regions from 2010 to 2019. The negative value indicates drop in efficiency. Adapted from (GNR Project, n.d.)

Region	% Improvement
Africa	-4.19
Asia (excluding China and India) + Oceania	1.58
Brazil	1.82
Central America	3.57
CIS	8.40
Europe	-2.65
India	19.05
Middle East	-6.80
North America	-0.74
Northeast Asia	4.95
South America ex. Brazil	6.48

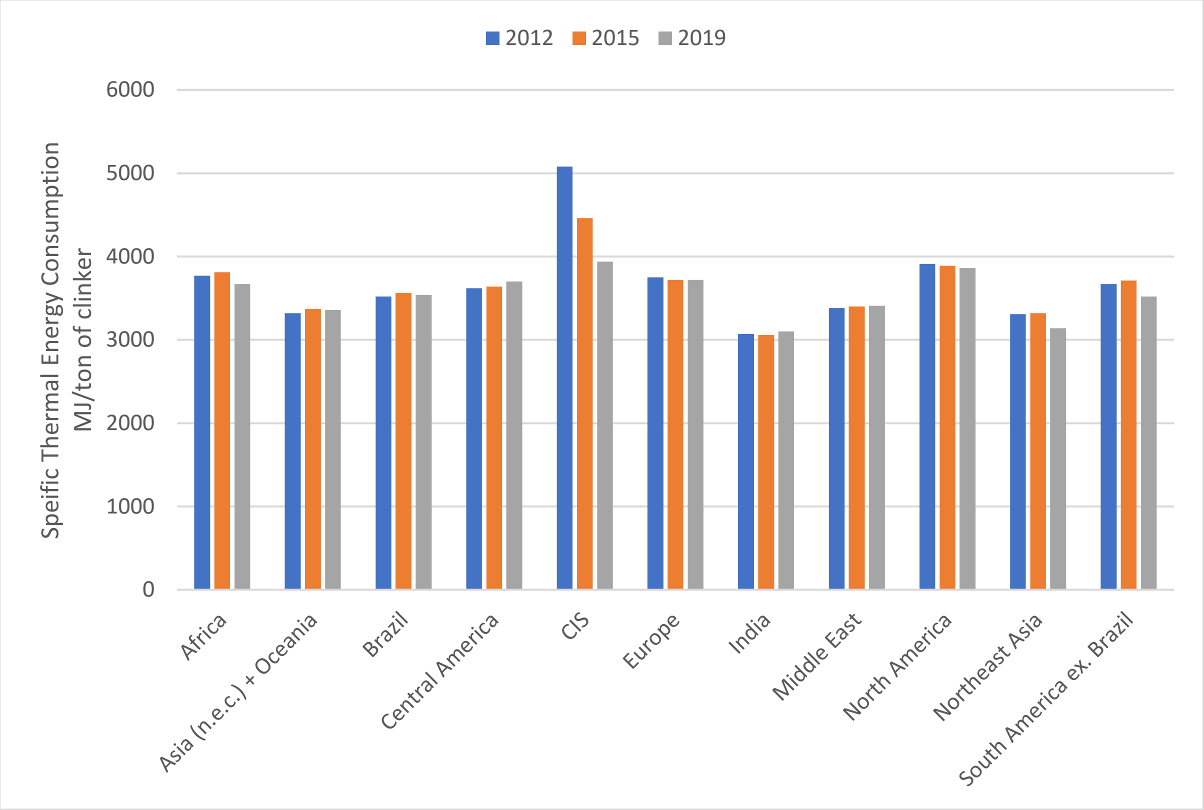

Fig. 7. Average specific thermal energy consumption per ton of clinker produced in various regions, sourced from (GNR Project, n.d.)

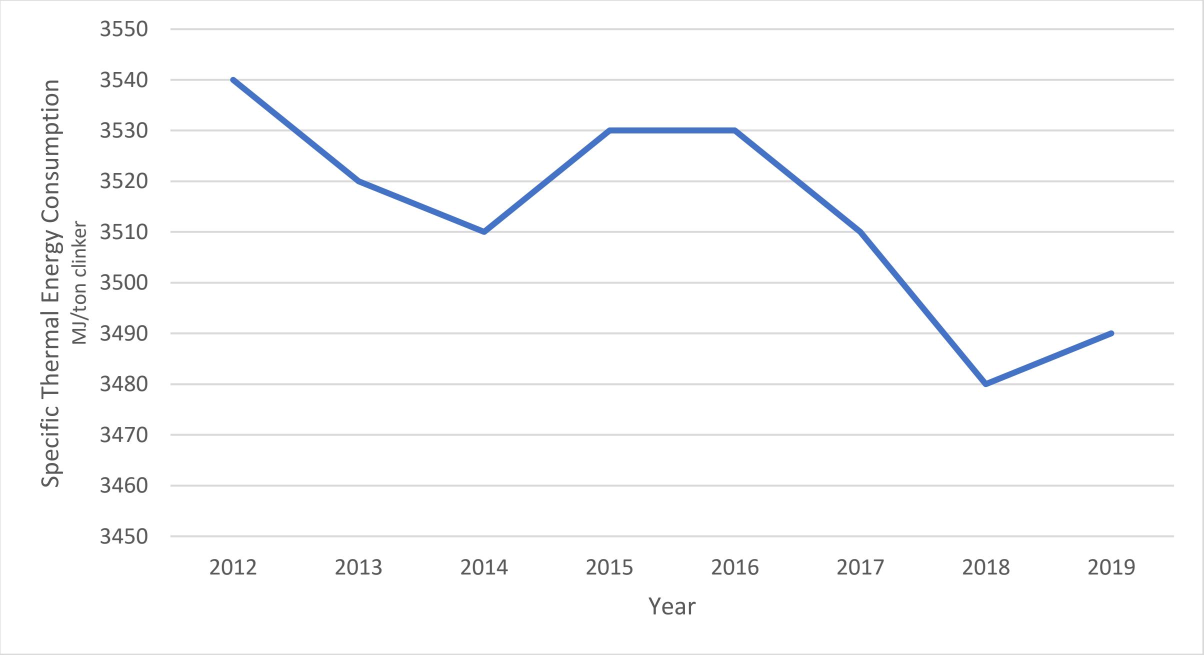

Fig. 8. Change in global average of Specific Thermal Energy consumption in the cement industry, between the years 2012 to 2019, based on(GNR Project, n.d.).

The average clinker-to-cement ratio is depicted in Fig. 10 and Fig. 12, indicating the propagation of clinker substitution strategy across various geographical regions. The global average in 2019 is currently at 76.3% as compared to 66.8% in India, the region with the lowest clinker-to-cement ratio, indicating an opportunity to reduce CO2 emissions through this strategy, especially in regions such as North America (85.5%) and CIS (82.7%).

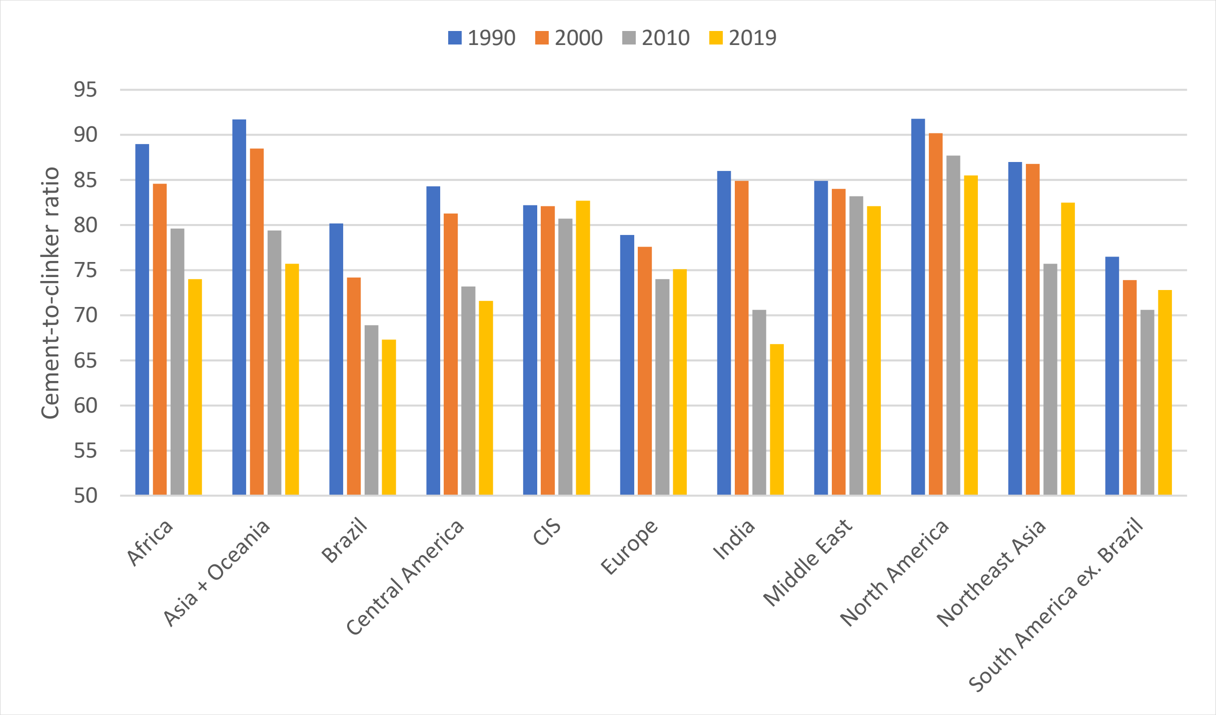

Fig. 9. Average clinker-to-cement ratio across various regions in the years 1990, 2000, 2010, and 2019, based on (GNR Project, n.d.).

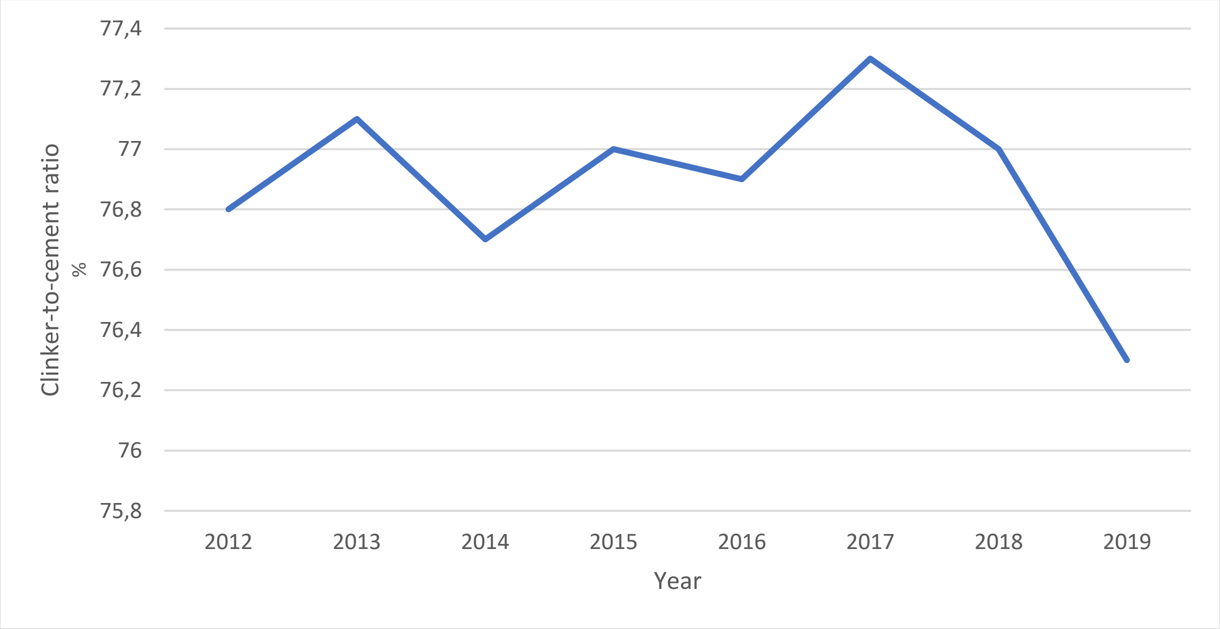

Fig. 10. Change in global average of clinker-to-cement ratio in the cement industry, between the years 2012 to 2019, based on (GNR Project, n.d.).

The average amount of CO2 emissions released per unit of energy generated through fuels is depicted in Fig. 11, indicating the relevance of fuel substitution strategy. Utilisation of coal as the primary kiln fuel leads to high carbon emission intensity as seen in regions such as India and other Asian regions. There has minimal changes in replacing coal as the fuel between the years 1990 and 2019 in majority of the regions, indicating the scope for implementing fuel substitution strategies to reduce CO2 emissions in the cement industry.

One of the most important factors influencing the adoption of mitigation strategies within the cement industry is the "payback period" of the capital investment. Majority of the mitigation strategies require a large initial capital investment to set up the plant and the time it takes for the plant to recover the cost is defined as the payback period. For a mitigation strategy to be deemed financially sustainable, it needs to recover the capital invested into the mitigation strategy either from either savings through reduced energy requirement or savings through reduced carbon tax.

While there has been a steady modernisation of cement kiln types between the years 1990 to 2010, the improvement has largely stalled since then, as depicted in Fig. 13. There are still a significant number of cement plants that operate on inefficient kilns, thereby presenting an opportunity to upgrade the older kilns with newer, more efficient equipment. The old, inefficient kilns currently contribute 34% of the total CO2 emissions from the cement industry. As discussed in the previous section, upgradation or modernisation of kiln is a financially intensive endeavour which requires a significant amount of downtime. Therefore, it might require policies that either incentivises upgradation or penalises inefficient kilns to bolster this approach as a CO2 mitigation strategy.

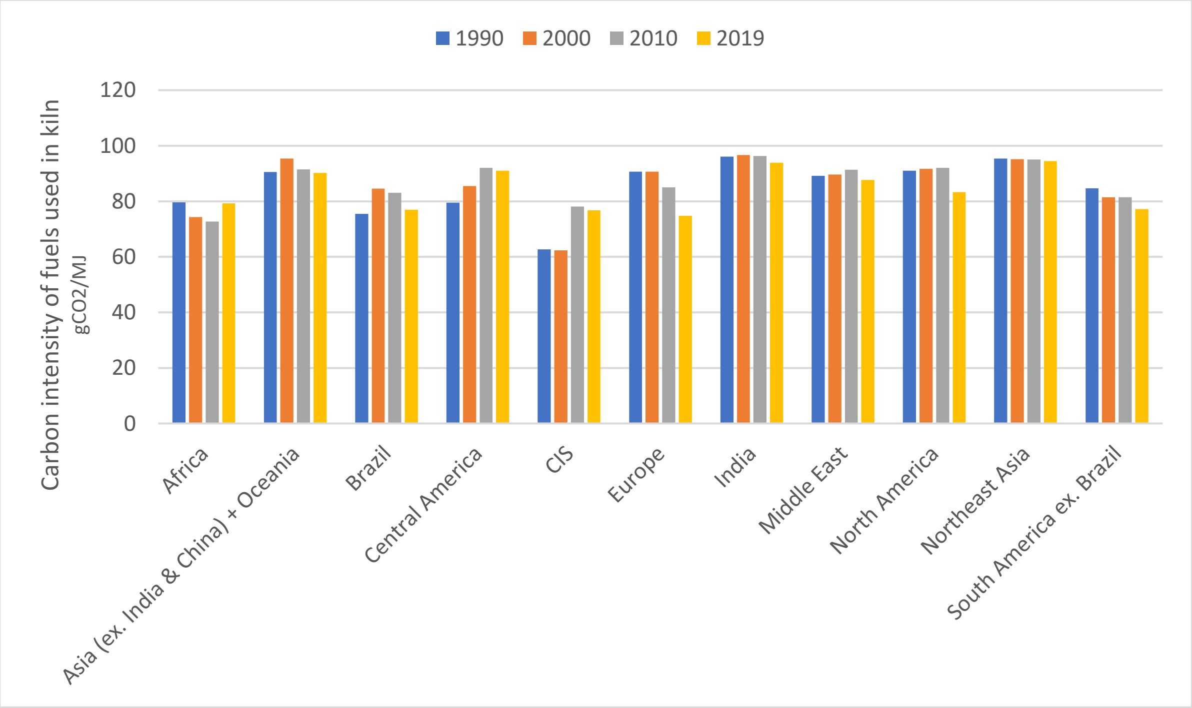

Fig. 11. Average amount of CO2 emissions per unit of energy derived from fuels in the kilns used in cement industry, by region, between the years 1990 to 2019, based on (GNR Project, n.d.).

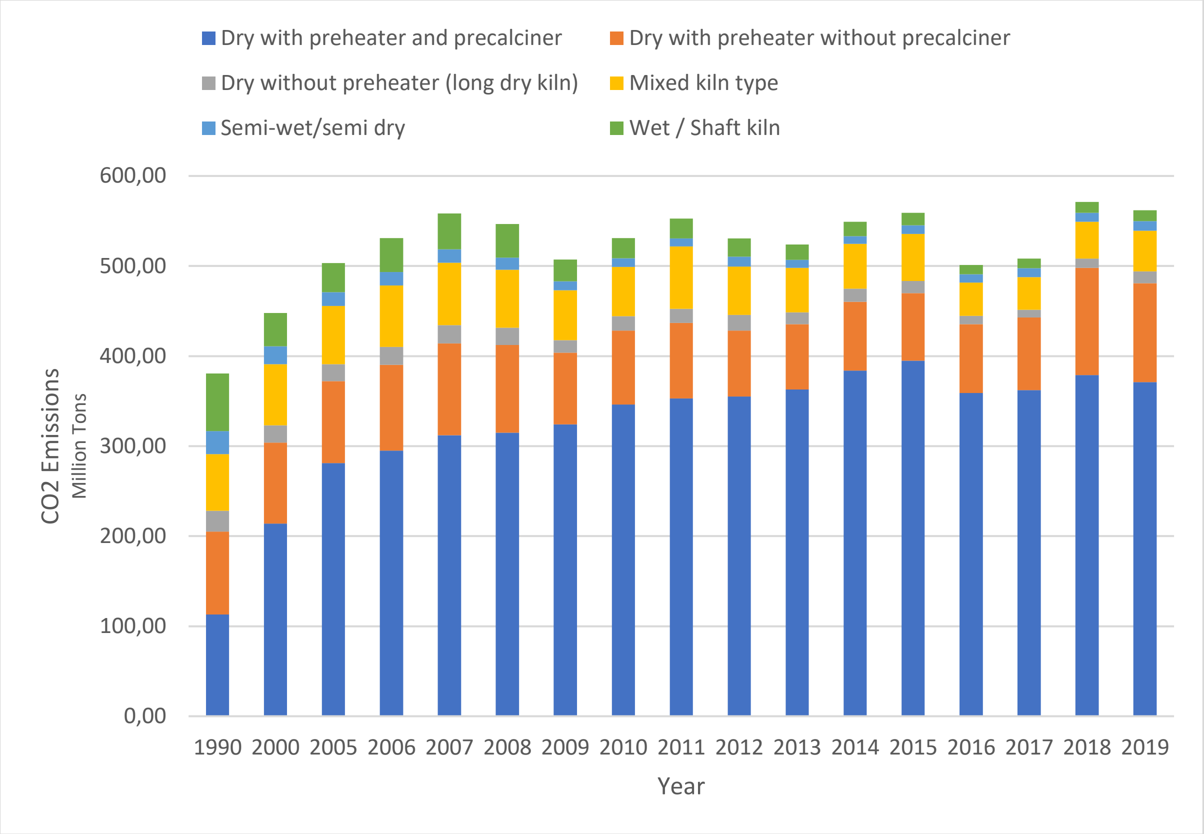

Fig. 12. CO2 emissions from global cement industry between the years 1990 to 2019, by kiln type, based on (GNR Project, n.d.).

For achieving the 1.5 °C target, many CO2 reduction pathways recommend that the specific CO2 emissions need to reduce to 350 to 410 kg CO2/ton of cement (Diczfalusy, B et al., 2012; Elzinga, D. et al., 2015). The average global CO2 emission factor is depicted in Figure 21, which shows a steady decrease in emission intensity between the years 1990 to 2010, but however has slowed down since then. In 2019, production of clinker on average releases 798 kgCO2 for every ton, excluding any emissions from on-site power generation (captive). For achieving the desired targets in the pathway for limiting global average temperature increase by 1.5 °C, significant mitigative steps need to be adapted in the cement industry in its current state.

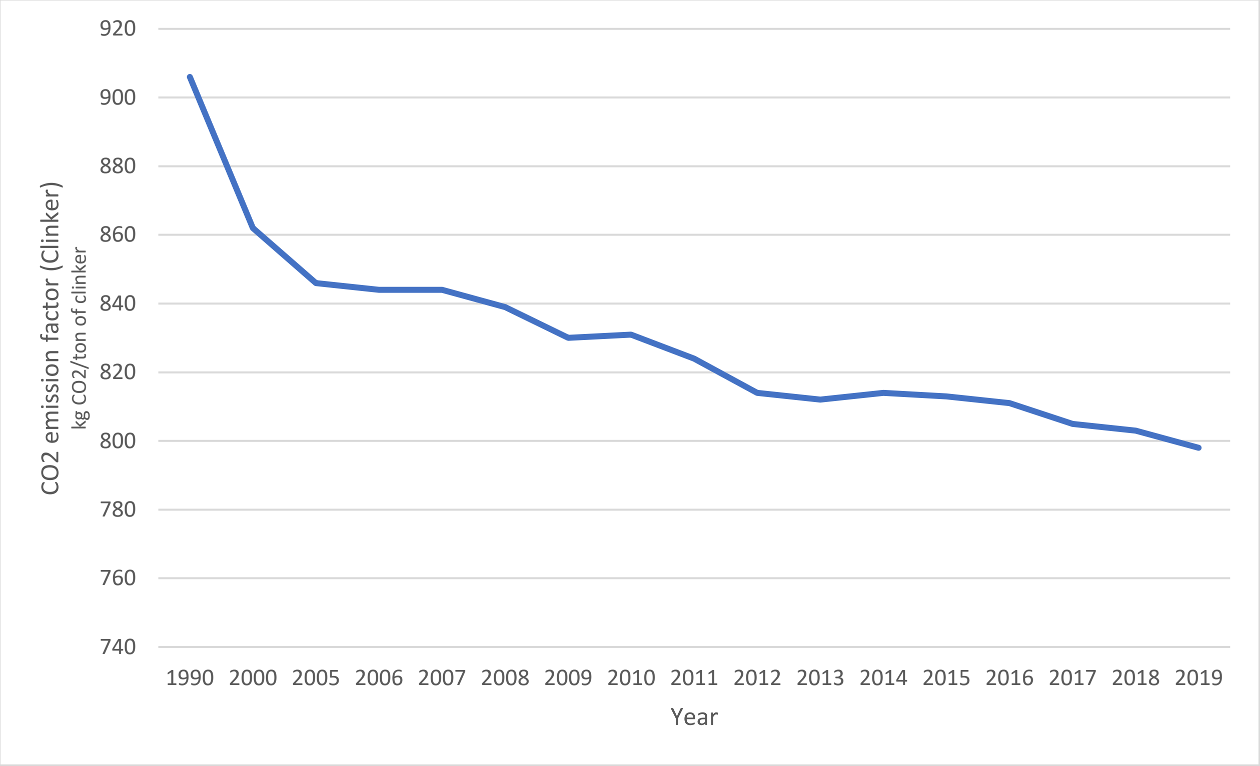

Fig. 13. Global average CO2 emission factor for clinker production (excluding emissions from electricity generation) between the years 1990 to 2019, based on (GNR Project, n.d.).

1.3 Research Objectives

The primary goal of this research is to identify and assess the impact of various CO2 mitigation strategies applicable for specific cement plant configurations under varying market conditions using System Dynamic (SD) simulation modelling approach. The simulation model developed in this study can be utilised as a decision support tool for the stakeholders in the cement industry domain as well as policymakers. Such a tool would enable the decisionmakers among the high-level management to evaluate the performance of different combinations of mitigation options under different scenarios to determine the most effective strategy for minimising both emissions and expenditure simultaneously.

For realising the primary goal, a SD model is developed to represent a typical cement plant with all the significant processes that contribute towards the CO2 emissions through electricity utilisation, fuel consumption and raw material decarbonisation. The model can be tweaked and adopted to represent various cement plant configurations currently in existence, whether they are the old installations relying on wet processes for clinker production, or the newest plants that utilise 6-stage preheating system with pre-calciners. Furthermore, the model would facilitate the interactions between various functions in the cement manufacturing process, subject to different mitigation strategies. It would allow the stakeholders to observe the decisions related to one aspect of the plant would influence the other processes.

The secondary goal of this research is to investigate the potential for using the chosen simulation method and subsequently demonstrate the utility of the model by comparing the impact of chosen mitigation strategies using real world data collected from a reference cement plant. The existing configuration of the plant will be compared with different CO2 mitigation strategies to identify potentially better approaches that would both minimise emissions and plant expenditure.

The tertiary goal of this research is to assess the various combinations of mitigation strategies under different policy scenarios and market conditions to identify the most appropriate schemes that would encourage the stakeholders of the cement plant to implement CO2 mitigation strategies.

1.4 Novelty and significance of the research

Despite the growing need for CO2 mitigation in the cement industry to achieve global climate targets, and the availability of proven mitigation strategies, their adoption rates across the world is relatively low, especially in the developing countries where the growing infrastructure demand is leading to an increase in cement manufacturing plants. Choosing and implementing appropriate mitigation strategies involves significant capital investment and would have a bearing over plant operations for the foreseeable future, as such, the decision-making process typically involves top-level management. With various governmental bodies, especially in the developing countries, are expected to impose taxation or ramp up existing penalties on the carbon emissions from the cement industry, there is a need for a decision support system which the top-level management could utilise for conforming to any upcoming policies while minimising the impact on bottom-line profits. Considering the complexity of the cement production process with several interacting processes that drive the energy consumption in the plant, System Dynamics (SD) modelling approach is chosen in this study. The utilisation of SD, a simulation approach characterised by its emphasis on cause-and-effect relationships and feedback loops, is still in its emergence in the cement domain. Additionally, existing studies prioritise modelling and simulating the cement industry as a whole, instead of individual installation, which limits their application as a decision support tool for the stakeholders in the cement domain. The model would allow management and decision-making stakeholders in the cement domain to effectively strategize their approach for compliance with the upcoming CO2 emission reduction requirements as the countries aim to limit the average global temperature by 2 °C when compared to pre-industrial levels.

The current study bridges the gaps in existing studies in this domain through construction of a model that can be adapted to individual cement plants (including facilities that exclusively partake in either production of clinker or the grinding process) and can be utilised to study the economical and mitigative impact of various combinations of mitigation strategies on the plant. For the policymakers, the model would provide a different perspective in the domain, i.e., investigating the consequences of carbon tax and subsidy policies in fostering the implementation of mitigation strategies in individual reference cement plants, as opposed to existing studies emphasising on the entire cement industry in a region. The model enclosed in this study can be adapted to any cement plant in the world by feeding in appropriate input datasets relevant to the plant and the regional market. As a result, it would reduce the existing friction among the cement holders in identifying the most relevant CO2 mitigation strategies for their cement plant. Furthermore, as newer mitigation strategies emerge in the cement domain, especially in carbon capture, they can be accordingly integrated in the current model. The model would henceforth continue to remain relevant as a decision support tool encompassing all the mitigation strategies that could be applied on a cement plant.

1.5 Limitations

The limitation of this study lies with the boundary chosen for the model, which encompasses the expenditure and emissions accounting from raw material sourcing until the production of cement (i.e., until the grinding of clinker and substitutes into cement ready to be packed and sold). It omits the processes beyond the production of cement such as packing, warehousing, marketing, etc., which would enable calculation of costs associated with the final finished product (as opposed to calculation of costs related to only energy consumption and raw material procurement, as featured in this model). Moreover, the selling price of cement is also not considered (which includes manufacturer margins), therefore plant incomes and expenditure are not considered in their entirety for this model. This model only aims to evaluate the expenditure and emissions related to energy use, i.e., through electricity utilisation and fuel consumption, and as well as raw material procurement, logistical (transportation) costs, and operational and maintenance costs of equipment related to mitigation strategies. Furthermore, the exogenous datasets used in the simulation are prepared either as per published forecast data or linearly extrapolated historic trends, thereby the accuracy of the quantitative results is directly influenced by the accuracy of the forecasted data. As such, the quantitative data in this study are only considered as an approximation of future trends.

1.6 Thesis Organisation

Chapter 1 is an introduction to the problem, describing the global consensus on reducing CO2 emissions to limit the increase of global average temperature rise by 1.5 °C compared to pre-industrial age. It also discusses on the importance of decision support tools in encouraging the stakeholders into implementing CO2 mitigation strategies. It also additionally highlights the scope for implementation of mitigation strategies in the cement domain, justifying the need for further research. Chapter 2 reports the cement manufacturing process and terminology relevant to the development of the model featured in this study. Chapter 3 is a literature review highlighting the previously published research on utilising system dynamics approach in the climate change domain. It further emphasises on the use of System Dynamics for CO2 mitigation in the cement industry. Chapter 4 goes through model construction process, with relevant causal loop diagrams and descriptions of each variable used in the model. Chapter 5 describes the experiments and scenario design, along with the relevant parameters chosen for each scenario as well as for the cement plant. Chapter 5 presents the results obtained from the experiments described in Chapter 6 and compares the results for each policy scenario. Chapter 7 concludes the dissertation and discusses on the objectives achieved with this study and recommendations for further research and improvements.

2. CEMENT PRODUCTION AND CO2 EMISSIONS

2.1 Emission sources in the cement production process

As discussed in the previous section, cement production is an emission and energy intensive process with the cost of energy amounting to approximately 60% of the total production cost. There are primarily two different processes that are currently utilised for cement production:

i. Wet Process
ii. Dry Process

The process is typically chosen based on the nature of the raw materials, i.e., if the raw materials are hard and dry, then the dry production process is chosen, but if the raw materials are soft (moisture content >20%), then the wet production process is chosen (Cochez and Nijs, 2010). The type of process also has different economic implications, with wet process requiring lower capital cost for the plant than dry process. However, the cost of production (operational expenditure) when producing the cement through wet process is significantly higher than dry process, as it requires more energy input in form of fuel in order to compensate for the added moisture in the production process. The global share of cement plants using wet process has significantly reduced in recent times, with all of the newer cement plants adopting the more energy efficient dry process.

The primary components of cement include clinker, gypsum, and other additives, which are mixed in selected proportions and ground to a size of 7-200 microns. A typical cement production using consists of the steps:

- Procurement of raw materials: In Ordinary Portland Cement (OPC), clinker typically accounts for 95% of the finished product, unless it is substituted by a suitable alternative such as fly ash or blast furnace slag. For production of clinker, limestone (Calcium Carbonate - $CaCO_3$) and clay need to be either procured from the local market or quarried from captive mine. Not all limestones are suitable for production of clinker, it is imperative that the raw material should contain more than 5% of Magnesium Carbonates ($MgCO_3$), 3% of Iron Sulphides, and free Silica.
- Processing of raw materials: Once the raw material is procured or mined from captive quarries, it is crushed, dried, and ground before being sent into the rotary kiln. In case of wet process, the raw material is mixed with water during the grinding process and the resultant slurry contains upto 36% water ("Cement Manufacturing Process," 2017). In the dry process, the raw material goes through two stages of grinding, with it being ground to 50 mesh using ball mills in the first stage, and then 200 mesh using tube mills.
- Production of clinker through calcination: The processed raw material is then transported to rotary kilns, where it is heated to a temperature of 1400-1500 °C. The length of the rotary kiln depends on the process used, i.e., dry process utilises shorter rotary kilns compared to wet process plants. As illustrated in Fig. 14, the rotary kiln is at an inclination of 15° and it rotates along its horizontal axis.

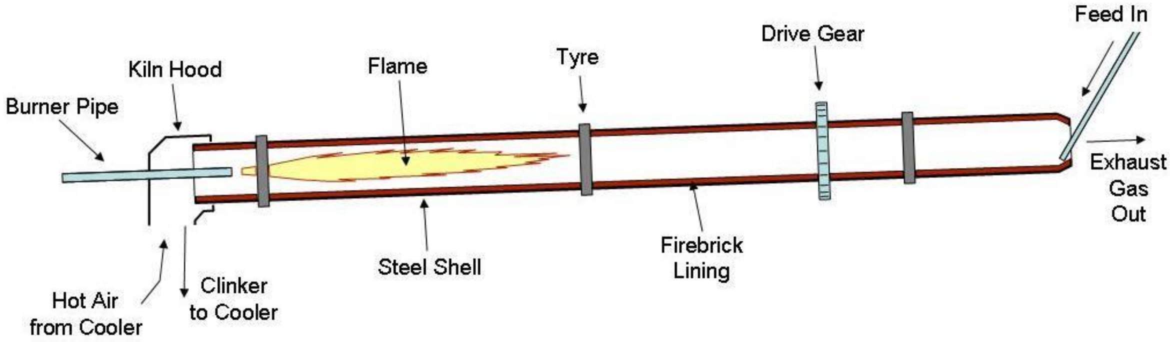

Fig. 14. Schematic illustration of a typical rotary kiln used in a cement plant, copied from (LinguisticDemographer, 2006), with necessary permissions.

The processed raw material is fed in from one end, while a burner is attached on the other end of the slope. The length of the kiln varies between 100-180 meters depending on the production capacity. The hot gases generated from the burner travel upwards through the kiln heating the raw materials that are flowing downwards through “Feed In”. The burner pipe could be adapted to use a variety of traditional fuels including, gas, fuel oil, pulverised coal, and petroleum coke. The burner could also be utilised to burn alternative fuels, which is covered in the later sections. The raw material going downwards through the kiln goes through the steps of drying, calcination, and sintering. In the first stage, the heat energy provided through the burner is used for evaporation of existing moisture in the raw materials before the temperature gets hot enough for the process of calcination to begin. At around 900 °C, the carbonate compounds in the raw material go through an endothermic chemical process called calcination, where it decomposes in the presence of oxygen to form respective metal oxides while releasing CO2 as a by-product. This chemical reaction is the source for 50% of the CO2 emissions generated in the cement plant and is the primary basis for emission reduction through clinker substitution.

The hot exhaust gas combined with the CO2 generated during calcination goes out of the kiln from the exhaust gas outlet which is adjacent to the “Feed In”. The kiln at the same time rotates on its horizontal axis at a speed of 60-90 revolutions per hour, and the electrical energy required to drive the rotor depends on the weight of the content inside the kiln. The exhaust gas is let out into pre-heater assembly where it heats up the incoming raw material called “rawmix”, which refers to ground up limestone and other additives. Pre-heater assembly is an optional part of the cement plant, which improves the plant efficiency, especially Specific Thermal Energy (SEC-Th) consumption, which refers to the amount of thermal energy consumed for production of a unit of clinker. The SEC-Th is directly proportional to the emissions from the cement plant, depending on the source of thermal energy. The pre-heater assembly varies between different cement plants, with anywhere between 1 to 6 stages of cyclones being utilised, with Fig. 15 showing an illustration of a 4-stage preheating system. Furthermore, the efficiency of various pre-heater assemblies is depicted in Table 5, which is later utilised in the model for determining the energy consumption of the target plant.

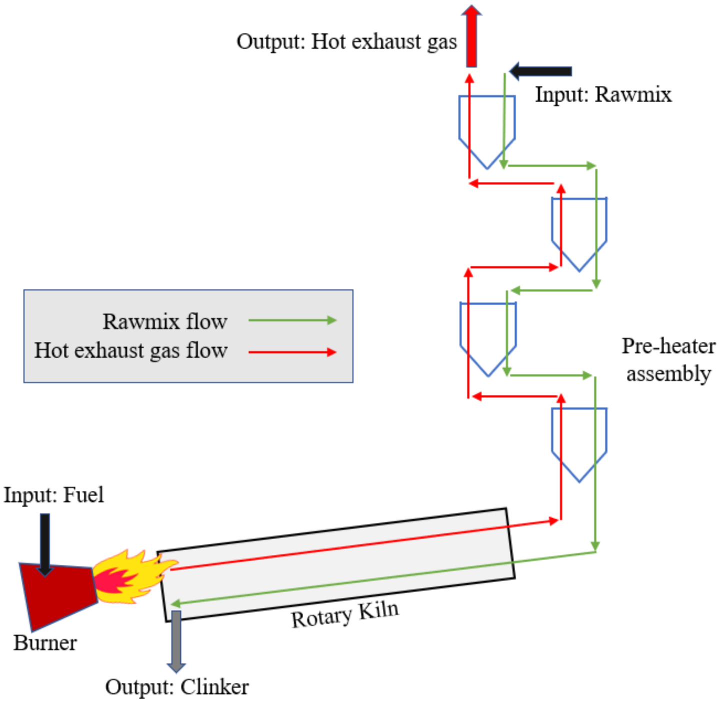

Fig. 15. Schematic illustration of a 4-stage pre-heater system connected to a rotary kiln

Table 5. Energy Consumption for production of clinker for different cement kiln arrangements (International Energy Agency, 2007)

Cement Kiln arrangement	**Energy Consumption (GJ/ton of clinker)**
Wet Process	5.9 – 6.7
Dry Process	4.6
1-Stage Cyclone Preheater	4.2
2-Stage Cyclone Preheater	3.8
3-Stage Cyclone Preheater	3.3
4-Stage Cyclone Preheater	3.1
5-Stage Cyclone Preheater	3.0 – 3.1
6-Stage Cyclone Preheater	2.9

At the kiln exit, the newly formed clinker comes out in form of small nodules, with size ranging from 3-25 mm. The clinker is then cooled from 2000 °C to 150 °C by blowing fresh air over it.

- Grinding of clinker and substitutes: After the clinker is sufficiently cooled, it is mixed with additives such as Gypsum and is sent to the ball mills. The ball mills are essentially large rotating cylinders, filled with metal balls. Once the clinker and its additives are crushed to a certain size, the final product, cement, is obtained. The finished product is then stored in silos or packed in bags before being dispatched via trucks, trains, or ships.

2.2 Emission reporting mechanism in the Cement Industry

Production of cement requires a large amount of energy, both in form of heat and electricity. Grinding equipment such as ball mills have specific energy consumption, requiring approximately 36 kWh for crushing a ton of limestone. On average, calcination of limestone requires 800 kcal per kilogram of clinker produced (GNR Project, n.d.). Depending on the emission factors of the fuel and electricity used, the production of cement leads to a significant amount of CO2 emissions as discussed in the previous chapters. Apart from emissions from energy use, the chemical process of calcination leads to release of significant amount of CO2 from the raw materials as seen in (3) and (4). For measuring the emissions from cement industry, Cement Sustainability Initiative[4] (CSI) and World Business Council for Sustainable Development (WBCSD) have published a standard for measuring and reporting emissions from various plant processes, which would be utilised in the model ("CO2 Accounting and Reporting Standard for the Cement Industry," 2011).

The first step for reporting CO2 emissions from cement manufacturing process is setting up the organisational boundaries. All the processes described in the previous sections can be either carried out in a single integrated cement plant or divided among multiple facilities that are owned and operated by different business entities. The resultant CO2 emissions from the manufacturing process is accordingly attributed to the specific business entity undertaking the operations. The major installations relevant to cement manufacturing include:

- Limestone extraction from quarries, crushing and grinding, and production of clinker.
- Grinding of clinker, along with addition of substitutes such as Fly Ash, Blast Furnace Slag, Gypsum.
- Preparation and processing of raw material such as clinker additives and fuels.
- Generation of electricity including preparation of additional fuels as required.

Once organisational boundaries are determined, operational boundaries need to be set, which are subdivided into Direct and Indirect emissions. The emissions from various processes and installations relevant to cement manufacturing can be either measured or calculated. In case of a measurement, the CO2 emissions are determined based on the continuous monitoring of their concentration in the exhaust air flow streams from the various facilities in the cement plant. The accuracy of these measurements depends on the instruments and the sampling methodology used. In case of a calculation, the CO2 emissions are determined based on the characteristics of input raw materials, such as percentage of carbon content, gross calorific value, etc., of fuels used as the energy source. CSI and WBCSD recommend using the calculation approach as the measurement approach is limited by the accuracy of the instruments in measuring the volume of the exhaust air flow streams and lack of substantial experience in comparing the measured data with calculated data. For measurement of CO2 emissions, CSI and WBCSED divides the operational boundaries into following scopes:

- Scope 1: Includes all the emissions that are directly resulting from sources owned and operated by the cement plant, such as rotary kilns, crushing and grinding equipment, on-site transport vehicles, etc.
- Scope 2: Includes all the emissions that are indirectly resulting from production of cement within the plant, such as emissions due to generation of purchased electricity.
- Scope 3: Optional category that includes emissions that are resultant as a consequence of final finished product but occurs at sources or facilities not controlled by the target

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[4] The Cement Sustainability Initiative is a global effort by major cement producers with operations in more than 100 countries for development of a framework for sustainable development and provide context for stakeholder engagement in the cement domain

cement plant, such as procurement of pre-processed raw materials and alternative fuels, transportation of materials from source to the plant site.

2.2.1 Direct Emissions

These are the emissions that are generated from the processes and facilities operated by the entity whose CO2 emissions are to be calculated. Direct emissions include emissions resulting from the process of calcination of raw materials, combustion of fuels to provide heat energy in the rotary kiln, combustion of fuels for non-kiln activities such as in processing and drying of raw materials, and combustion of fuels for generation of captive electricity.

- Process of calcination: The amount of CO2 emissions from calcinations is directly proportional to the clinker production. The CO2 emissions from calcination are calculated either based on the volume and carbon content of the rawmix (input) or the volume and composition of the clinker (output). The later method is more widely adopted in plants across the world, including Europe. When calculating the emissions from the output, the volume of the clinker and the emission factor per ton of clinker is considered. The emission factor is based on the composition of Calcium Oxide and Magnesium Oxide in the finished product. CSI and WBCSD recommend the value of 525 kg CO2/ton of clinker as the default value in case a chemical analysis of the clinker is not available. Apart from the raw materials, emissions from the kiln dust also need to be calculated. The calcined kiln dust flows along with the hot exhaust gases and is typically collected in an Electrostatic Precipitator (ESP) or a bag filter. The volume of the collected dust is then utilised for calculation of the CO2 emissions. CSI and WBCSD recommend using 0 if the plant is using the dry process, or 2% of clinker CO2 if using the wet process.
- Combustion of fuels: For providing the required heat energy to the rotary kiln, cement plants employ the use of variety of conventional fuels including coal, natural gas, oil, and petcoke. The CO2 emissions from the combustion is calculated based on the quantity of fuel utilised and its relevant emission factor. In case of non-conventional fuels such as biomass, no CO2 emissions are accounted as the IPCC considers them as “climate-neutral”. Alternative fuels such as Refuse Derived Fuels (RDF) and Tire Derived Fuels (TDF) are however not considered climate-neutral, and their emission factor is considered for calculation of CO2 emissions. In case of mixed fuels, the emissions are calculated based on their respective proportions in the fuel mixture. CO2 emissions from fuel use related to transportation using plant owned vehicles is also accordingly accounted in the measurement process. The transportation covers movement of raw materials, substitute materials, and fuels both from the source to the plant, and as well as within the plant facilities.
- Captive electricity production: CO2 emissions from the use of fuel for production of electricity is also calculated as part of the direct emissions. The emissions are calculated on the basis of fuel (coal, oil, etc.) or renewable energy source (solar, wind, waste heat, etc.) used for generating electricity. The respective emission factors are utilised as discussed in the earlier section for determining the CO2 emissions.

2.2.2. Indirect Emissions

These are the emissions that are generated as a result of the activities of the entity whose CO2 emissions are to be calculated but occurs at facilities and processes operated by a different entity. Indirect emissions include emissions from production of electricity bought from either the grid or an external supplier, emissions from production of clinker (additional clinker that is bought from other entities), external production and processing of kiln fuels, and transportation of raw materials and finished cement.

- Purchased electricity: The CO2 emissions from the electricity purchased from either external provider or the regional grid is calculated based on the amount of electricity utilised and the emission factor of the source (or grid emission factor if procured from the regional grid). If the specific emission factor of the source is unavailable, CSI and WBCSD recommends using the average emission factor of the country in which the plant is situated.
- Purchased clinker: For cement plants that procure clinker from a different entity instead of producing it within the premises, need to calculate the CO2 emissions from the purchased clinker based on the emission factor. In absence of data, CSI and WBCSD recommends using the default emission factor from GNR project database (GNR Project, n.d.).

2.3 Mitigation strategies for reducing CO2 emissions from cement manufacturing

As a significant source of CO2 emissions, several mitigation strategies are being currently explored in the cement domain at different stages of implementation. The most popular strategies featured in the literature reviewed in the previous section is described in this section.

2.3.1. Waste Heat Recovery (WHR)

Majority of the modern cement plant installations feature multi-stage preheating systems, as illustrated in Figure 10, as well as pre-calciners to recover a portion of the heat energy escaping through kiln exhaust gases. Additionally, the clinker which is formed in the rotary kiln is immediately air cooled after exiting the kiln, with the temperatures of the subsequent exhaust air between 250 to 340 °C. The hot air is then usually released into the atmosphere after passing it through electrostatic precipitator or bag filter for removing suspended particulate matter. The hot exhaust gas from pre-heater assembly is also used to additionally dry the raw materials in some certain cement plant installations. Despite utilising the waste heat for the aforementioned functions, there is still a lot of heat energy left in the flue gas that is released into the atmosphere. As cement manufacturing processes do not require low temperature heating, the waste heat in the flue gases could be instead utilised for generation of electricity. The generated electricity could offset the amount of electricity that the cement plant would need to buy from an external entity or the regional grid. If the cement already has a captive power plant running on fossil fuels, the electricity generated from waste heat could lead to savings in fuel consumption at the captive power plant. By doing so, it would reduce the net CO2 emissions from the plant, and also softens the impact of fluctuating fuel and energy tariffs in the regional market. It also additionally improves the plant efficiency by lower the specific energy consumption as the energy escaping into the atmosphere in form of the waste heat is recovered.

The heat energy is recovered from the flue gas by the means of Rankine Cycle. The Rankine Cycle works on a thermodynamic basis, wherein, the source of heat converts water (or any equivalent liquid) into high pressure vapour. The pressurised gas is then passed through a turbine, where the high pressure is converted into electrical energy with the help of a generator connected to the turbine. Depending on the heat available, a cement plant can either choose Steam Rankine Cycle (SRC), which uses water as the working fluid, or an Organic Rankine Cycle (ORC), which uses organic liquids such as cyclo-pentane or R134a (refrigerant). In the context of this study, following are the major differentiating factors between the two:

- SRC being a traditional technology, requires manual interventions at various stages of the process, which necessitates the need for full-time operators, thereby increasing the operational expenditure of the plant. ORC can be fully automated reducing the need for full-time operators, thereby resulting in a lower operational expenditure.
- The capital expenditure required for setting up a WHR plant based on SRC is relatively less expensive than setting up a WHR plant based on ORC.
- SRC is more efficient at recovering heat at higher temperatures whereas ORC is significantly more efficient at recovering heat from low temperature sources.

The potential for recovering heat in a cement plant depends on the existing efficiency of the plant, on which the preheater arrangement has a significant influence. The heat available for recovery is depicted in Table 6 which has been adopted from IFC report on WHR ("Waste Heat Recovery for the Cement Sector," 2014).

Table 6. Heat available for recovery in the exhaust gases in a typical cement plant, adapted from ("Waste Heat Recovery for the Cement Sector," 2014)

Pre-heating system configuration	**Plant production capacity (TPD)**	**Exhaust gas temperature (°C)**	**Heat available in exhaust gas temperature (GJ/ton of clinker)**	**Specific Energy Consumption – Thermal (GJ/ton of clinker)**
4-stage cyclone pre-heater	1000-2500	390	0.904	3.55
	2000-8000	360	0.754	3.14
5-stage cyclone pre-heater		316	0.649	3.01
6-stage cyclone pre-heater		282	0.586	2.93

At a power conversion efficiency rate of 25%, the heat available from a 5000 TPD capacity plant with a 6-stage cyclone pre-heater could be utilised for generation of upto 9 MW of electricity (assuming 100% of the waste heat is utilised). 9 MW of the power generated could potentially reduce the need for purchasing electricity from external sources by 30% (assuming the specific electricity consumption of the plant to be global average of 106 kWh per ton of cement produced).

2.3.2 Clinker substitution

Within the cement manufacturing process, production of clinker is the most energy intensive and CO2 emitting component. The clinker to cement ratio plays an important role in determining the carbon emissions in a cement manufacturing plant. OPC, which is the most popular variant used in the world, has a clinker to cement ratio of 0.95.

(Ali et al., 2011) in their review of emission analysis in the cement industry has stated that reducing the clinker to cement ratio has been very effective in the reduction of overall CO2 emissions. The ratio can be reduced by replacing clinker in the cement with different additives like volcanic ash, fly ash, blast furnace slag, etc based on their availability at the location of the cement manufacturing plant. These substitute materials are termed "pozzolanic" materials, which can be added to cement without significantly altering its properties. (Bosoaga et al., 2009) estimated that by replacing clinker with alternate substances and producing blended cement, there is a potential to reduce CO2 emissions from cement industry by 5 to 20%. Most pozzolanic substitutes do not require any additional pyro-processing, thereby reducing the overall energy consumption in production of cement.

(Worrel et al., 2001) report that the potential of utilising blended cements to reduce CO2 emissions ultimately depends on the availability of the additives needed for replacing the clinker. The costs of blending raw materials also plays a significant role in the profitability of the cement industry as countries with limited availability of blending additives need to spend much higher amount for transportation costs than with countries with wide scale availability. Additionally, legislations of certain countries restrict the usage of fly ash and blast furnace slug as additives as they are classified as hazardous waste, thereby preventing mitigation measures through the use of blended cement. There are numerous substitutes that can be used to substitute a portion of the clinker and the ones that are featured in the model attached to this study include:

- Fly Ash: It is a by-product generated in coal-based thermal power plants. It is the fine particulate matter that is generated in the coal fired boiler and is ejected out along with the exhaust gases. The exhaust gases are passed through either an electrostatic precipitator or a bag filter where these fine particles are collected and stored in silos. Fly ash when dumped into landfills is a hazardous waste capable of contaminating the local ecosystem including ground water. Instead of dumping into landfills, fly ash can be instead utilised as a substitute for clinker in the cement industry. Apart from reducing CO2 emissions by reducing the need for clinker production, it also improves the properties of the cement such as plasticity, permeability, durability, and chemical resistance ("Fly Ash in Concrete," 2017). It also, however, increases the time it requires for the cement to obtain its strength after it is cast. The Fly Ash availability in a region is directly proportional to the local thermal energy generation using coal. The share of electricity generation using coal in the 5 largest cement producing countries is tabulated in Table 7.

Table 7. % of electricity generation using coal, among 5 largest cement producing countries. Sourced from World Bank database ("Electricity production from coal sources," 2015; M. Garside, 2022)

Country	Annual cement production in 2020 (million tons)	Share of electricity production from coal in 2015 (%)
China	2200	70.3
India	340	75.3
Vietnam	96	29.6

United States of America	90	34.2
Indonesia	73	55.8

- Wet Ash: Similar to Fly Ash, it is also a by-product generated in coal-fired boilers. However, instead of being ejected from the system along with the exhaust gases, it is collected at the bottom of the boiler along with unburnt particles of coal. The ash collected from here is usually stored in designated open areas called “ash ponds”. These ash ponds pose an environmental threat and unlike Fly Ash, they cannot be directly used as a substitute for clinker as it contains anywhere between 25 to 40% moisture. The moisture needs to be evaporated and the dried ash needs to be crushed and ground to a required consistency before being used as a replacement to clinker. In places where the availability of fly ash is unreliable, wet ash can be used as an alternative. The total ash generated in a coal-based thermal power plant can be either disposed in landfill in case of fly ash or ash pond in case of wet ash. However, the ash can also be diverted and supplied to cement manufacturing plants, where it could be utilised as a substitute for clinker. While fly ash can directly be used as a substitute, wet ash needs to be processed before it is used as a clinker replacement. The cement manufactured using fly ash eventually will be used in construction activities and after a period of time, the constructed buildings will be replaced and the waste material consisting of ash would eventually end up in landfills.

- Blast Furnace Slag: It is a by-product of the steel and iron industry, which is obtained by using liquid to cool the slag formed on top of molten metal in the blast furnace. The primary challenge of using blast furnace slag is availability as its use is only viable in regions with a significant iron and steel industry. Addition of slag to cement, enhances the properties such as chemical resistance and compressive strength.

2.3.3 Alternative fuels

Cement industry is one of the largest industrial consumers of energy, majority of which is utilised for supporting the process of calcination in the cement kiln. Currently, pulverised coal is the most widely used kiln fuel in the cement industry. Fossil fuels such as pulverised coal, natural gas, or petcoke can be replaced by alternative fuels such as refuse-derived-fuels and tyre wastes which would lead to a noticeable reduction in overall CO2 emissions related to the kiln process. The various alternative fuels that are being explored as an co-firing option in the cement kilns are tabulated in Table 8. Co-firing is a process of utilising 2 or more fuels for combustion in the kiln, which requires special multi-fuel burners to operate. Typically, the usability of the alternative fuel depends on the type of existing burner, i.e., existing gas, liquid, or solid fuel can be replaced by an alternative fuel that is in the same state.

Table 8. Alternative fuels for co-firing in the cement kilns, adapted from (Chinyama, 2011)

Type	**Fuels**
Gas	Refinery waste gas, landfill gas, pyrolysis gas, natural gas

Liquid	Tar, chemical wastes, distillation residues, waste solvents, used oils, wax suspensions, petrochemical waste, asphalt slurry, paint waste, oil sludge
Solid	Paper waste, rubber residues, pulp sludge, sewage sludge, used tyres, battery cases, plastics residues, wood waste, domestic refuse, rice husks, refuse derived fuel, nut shells, oil-bearing soils, diapers, etc.

Among the various alternative fuels applicable to the cement kiln, the ones featured in the model attaching in this study include:

- Refuse Derived Fuels (RDF): Municipal solid wastes refer to the waste that has been generated by the public, including domestic and industrial waste, that is typically dumped in landfills or further processed for recycling or waste-to-energy generation. The challenges of RDF include segregation and processing of the waste to a form compatible for co-firing with existing fuels being utilised in the cement kiln. Apart from the processing aspect, the chemical composition of the waste is also an important parameter for its suitability for use in a cement kiln as it can potentially introduce materials into the rotary kiln which may be detrimental to its operation. Additionally, presence of sulphur and nitrogen compounds would lead to the formation of Nitrous Oxides and Sulphur Oxides, which requires capital investment for additional equipment to treat flue gas before being released into the atmosphere in order to comply with local emission regulations. The challenge of shredding the RDF before being fed into the kiln are manageable as most existing burners being used in a cement kiln can handle particles sized upto 50 mm (Expert Committee Constituted by Ministry of Housing and Urban Affairs (MoHUA), 2018). Additionally, the size of the particles combined with the oxygen rich environment generally present in a clinker cooler would mean that RDF would combust immediately with majority of the burnt particles pushed out through the kiln chamber along with the exhaust gases. Installation of alternative fuel burner for RDF specifically is not capital intensive and would not require a significant downtime in an active cement plant. The high temperatures in the kiln, which range upto 1400 ºC, is beneficial for the utilisation of RDF as it ensures that the fuel is completely combusted and does not leave behind any significant residue that may affect the characteristics of the clinker. Any acidic gases that may be generated from the combustion of RDF is automatically treated as the raw materials used in the cement kiln are alkaline in nature. Any neutralised non-combustible residue left behind in the kiln is completely integrated within the clinker structure during the process of sintering.
- Tire Derived Fuels (TDF): Used tyres are typically considered as one of the most appropriate alternative fuels that can be utilised in the cement kilns. The waste tyres have a high calorific value and any incombustible components in them like iron from the frames are easily integrated with the clinker structure at the high temperatures present in the kilns. However, like RDF, the tyres need to be shred to a particular size in order to be compatible with the burners fitted to a cement kiln. Depending on the source of the coal, tyres typically contain lower sulphur content than coal, so it would not necessitate the installation of equipment such as “scrubbing” systems for removal of Sulphur Oxides in order to satisfy the required emission norms in the region where the cement plant is located. Compared with RDF, the efficiency of conversion of TDF into energy is relatively higher due to significantly lower moisture content. TDF is

also considered as partially carbon neutral and due to significant amount of biomass content, the emission factor is lower than coal and petcoke as seen in Table 9.

Table 9. Fraction of Biomass in scrap tires, adapted from ("Scrap Tires and Tire-Derived Fuel," n.d.)

	Used Passenger Vehicle Tires	Used Heavy Vehicle Tires	Coal (high grade)	Petcoke
Biomass (average %)	18.3%	29.1%	0%	0%
Carbon (average %)	69%	61.1%	66%	90.5%
GCV (kcal/kg)	7213.14	6305.53	6209.99	7643.03

2.3.4. Carbon Capture

Carbon capture is an umbrella term used for any process that involves capturing of CO2 in the exhaust gases either through chemical or physical means. The various techniques currently being explored in the industries include Amine Scrubbing, Calcium looping, Oxy-fuel combustion, biofuel production using algae, and direct capture. The most significant challenge in implementation of carbon capture techniques in a cement plant include:

- Shutdown time: For majority of the carbon capture methods, the cement plant needs to be shut down during the duration of the time it takes for setting up the equipment necessary for the CO2 capture process (Hills et al., 2016). This downtime would have significant financial impact on the plant alongside the capital investment needed for setting up the CO2 capture plant.
- Plant upgradation: In order to retrofit the equipment necessary for the CO2 capture, the existing plant layout would require significant modifications, which further adds on to shut down time and expenditure. The amount of modifications necessary depend on the type of CO2 capture being implemented, which is further discussed in later sections.
- Space constraints: The equipment needed for implementation of some of the CO2 capture methods require a significant amount of space which may not be available in some cement installations. In order to accommodate them in the existing place, it would warrant a considerable amount of reorganisation of the plant layout, which would again increase both the shutdown time and as well as the capital expenditure of setting up the plant.

Among the various available methods of carbon capture, the following are explored in the model featured in this study:

- Carbon Capture and Storage (CCS): As the name suggests, this method involves capture of CO2 in the exhaust gases from the various cement manufacturing processes. The captured CO2 is compressed and transported to designated off-shore or on-shore sites where it is stored underground for the foreseeable future. The primary challenge of implementing CCS in the cement industry are the prohibitive costs for setting up and storage of the captured CO2.
- Indirect Carbonation Method: As described by (Proaño et al., 2020), this method comprises of 4 major steps, conditioning of flue gas, preparation of absorbent solution, crystallisation of carbon, and filtration. The exhaust flue gases generated

from the various cement manufacturing processes are cooled to 50 °C and the water vapour present in it is condensed. The dry and cool exhaust air containing CO2 is then sent into the crystalliser where the process of carbonation takes place. Chemical solutions such as Barium Hydroxide and Sodium Hydroxide are used as the inputs in the crystalliser which reacts with the CO2 inside the exhaust gases to form their respective carbonates, that is, Barium Carbonate and Sodium Carbonate. These by-products can be additionally sold in the regional market to partially offset the operational cost of this method. This process of carbonation method is visualised as seen in Fig. 16.

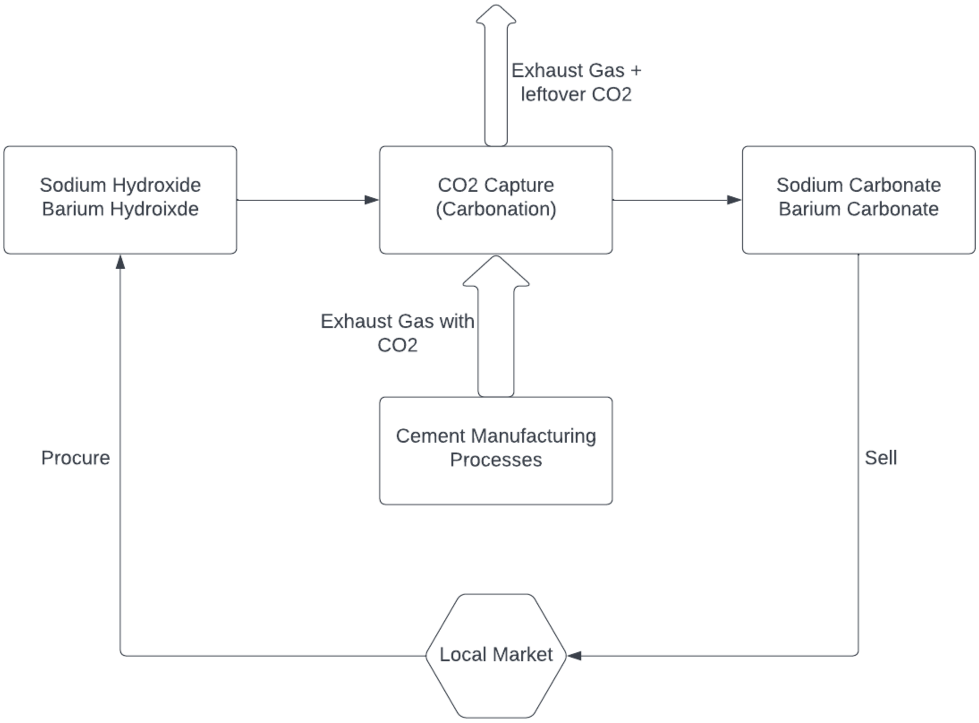


Fig. 16. Indirect Carbonation Method, based on (Proaño et al., 2020).

- Microalgae generation: These are tiny, microscopic organisms that utilise CO2 in the presence of sunlight to rapidly multiply. The total amount of biomass contained in these organisms would increase upto twice in a period of 24 hours (Zamalloa et al., 2011). The CO2 in the flue gas is captured by these microalgae and is converted into bicarbonates under the presence of carbonic anhydrase (Mondal et al., 2017). The biomass generated from these microalgae can be then utilised as a feedstock for production of biofuel. The most significant challenge in implementation of this technique is the initial capital requirement for setting up the necessary equipment for producing microalgae using the CO2 emissions from kiln exhaust gases and then using then further processing the biomass into fuel. Additionally, with the current technologies, the energy required for production of biofuel using this method is not very attractive when compared to the energy stored in the fuel. However, in the locations where the emission factor of the electrical energy is low, this could be a viable method for reducing CO2 emissions from the cement plant. The biofuel generated using the microalgae could also be utilised as an alternative fuel in the kiln as the CO2 emissions from biofuels are not counted as the IPCC considers them as "climate-neutral" ("CO2 Accounting and Reporting Standard for the Cement Industry," 2011).

2.3.5. Efficiency improvements

By improving the efficiency of energy usage, a significant reduction of CO2 emissions can be achieved through more optimal usage of fuel and electricity. Worrell et al. (Worrel et al., 2001) says that noticeable improvements can be achieved by simply replacing older equipment with newer, more efficient installations and further tweaking the cement making process to newer standards. (Worrel et al., 2001) further estimated that in older cement installations constructed prior to 1990s, improvements in efficiency of shaft kilns have a potential to reduce the energy requirement by 10-30%. Following are the units of measurements used to compare the energy efficiency of cement plants:

- Specific Thermal Energy Consumption (SEC-Th): It is total amount of thermal energy spent for producing 1 unit of the finished product.

$$SEC_{Th} = \frac{Thermal\ Energy\ used}{Amount\ of\ Finished\ Product\ produced} \tag{1}$$

- Specific Electrical Energy Consumption (SEC-E): It is the total amount of electrical energy spent for producing 1 unit of the finished product.

$$SEC_{E} = \frac{Electrical\ Energy\ used}{Amount\ of\ Finished\ Product\ produced} \tag{2}$$

The specific energy consumption in the cement plants can be improved by upgrading the plant process to include newer pre-heating system and pre-calciner as it can be seen in Table 7. The upgradation cost depends on a wide range of factors and is often very specific to each existing cement plant. The upgradation of plant process would also result in a downtime, which incurs additional cost. Additionally, employing other mitigation methods such as WHR would also provide opportunities for further improving plant efficiency by modifying existing equipment such as Induced Draft (ID) fans to make use of Variable Frequency Drives (VFD). The ID fans are used to create negative suction force in the exhaust ducts to direct the flue gas out of the rotary kiln and eventually into Electrostatic Precipitator or bag filter before being released into the air. If a WHR system is set up, it generates additional negative suction force by itself, so the ID fans do not require to spin at the same speed as before. However, a large percentage of cement plants do not have the mechanism to control the speed of the ID fans and they operate at their maximum capacity throughout the duration of their lifetime. By introducing VFDs, the ID fan speed could be changed to a desired level to accommodate the extra negative suction created by the new WHR system in the plant. This consequently improves the specific electrical energy consumption of the cement plant.

3. LITERATURE REVIEW

3.1 Decision Support Systems for Climate Change Mitigation

Decision Support Systems (DSS) is a computer-aided information system that supports stakeholders and high-level management in decision-making activities. A DSS does not make decisions by itself but assists stakeholders in taking better decisions by enabling assessment of trade-offs involved in picking one decision over the other. Following are the types of decisions that are relevant to management bodies:

- Structured decisions: These are repetitive in nature and decision-makers can follow definitive procedures for problem resolution.
- Semi-structured decisions: These are applicable in situations in which only a part of the problem has a definitive procedure for problem resolution.
- Unstructured decisions: These require significant involvement from the decision maker, in form of insights, evaluation, and judgement, for problem resolution.

In a typical organisation, structured decisions are more prevalent at lower management levels, whereas unstructured decisions are common among higher management levels. (Ralph H. Sprague and Eric Carlson, 1982) discussed that a DSS is characteristically, aimed at unstructured problems that are faced by upper-level management, combines the use of models or analytical techniques, focuses on features that make it easier to utilise, and emphasises on flexibility and adaptability to accommodate various decision-making approaches.

Typically, DSS utilises a combination of raw data, personal knowledge, and business models to aid in decision-making (Thor Olavsrud, 2020). There are several categories of DSS, which are:

- Communication driven DSS: These are targeted at internal teams with an emphasis on collaboration and coordination to analyse the problem and perform decision-making tasks as a group.
- Data driven DSS: These allow the stakeholders to access and manipulate structured data stored on underlying databases or data warehouse.
- Document driven DSS: These facilitate the integration of storage and query system for document retrieval and analysis.
- Knowledge driven DSS: These provide specialised problem-solving expertise in a specific domain, typically utilised for tasks such as classification, diagnosis, interpretation, planning, and prediction.
- Model driven DSS: These are complex systems that aid with analysing decisions and choosing between various available options. They are typically standalone systems that allow for analysis of “what-if” scenarios.

DSS, in relevant situations, utilise various data visualisation tools to assist the stakeholders in identifying patterns and relationships in large amounts of data, that otherwise would have been strenuous to interpret if the data was instead presented in form of lists of text and numbers.

DSS have been utilised in the past for addressing issues related to climate change in domains such as agriculture, forestry, and industries. (Czimber and Gálos, 2016) have devised a DSS for evaluating the impact of climate change on agriculture and forestry, and subsequently identify various mitigation options. The DSS devised in their study allows for risk assessment based on the generated projections, thereby allowing the stakeholders to develop various mitigation strategies. The authors conclude the study reiterating that DSSs are efficient tools for assessing the impact of climate change and for projecting the future conditions, while catering towards the interests of the relevant stakeholders. Similarly, (Wenkel et al., 2013) devised a model driven DSS, "LandCaRe", for assessing the impact of climate change in the agricultural sector and evaluate potential agricultural land use adaptation strategies. The DSS devised in their study allows for spatial, multi-ensemble, and multi-model simulations at regional scale as well as assessment of adaptation strategies at local scale. The primary objective of the study is to provide insights into long-term impacts of climate change and assist stakeholders with analysing various management options for adaptation through "what-if" questions. The authors reiterate that the core philosophy of the DSS is based on the assumption that there are multiple solutions to every problem, therefore their system aims to provide all of the necessary tools for the stakeholders to explore and identify various solutions to their problems. (G.L. Velthof et al., 2012) devised a DSS, titled "MITERRA-DSS" for assessing the effectiveness of various CO_2, CH_4, and N_20 mitigation strategies in the agricultural sector. There are several strategies available for reducing each greenhouse gas, but some strategies while decreasing one parameter, may lead to increase in other parameters. The authors conclude that the sum of emissions reduced from single strategies differs from combination of strategies, thereby indicating interactions between various strategies. The DSS in this study could be utilised as a tool for policy makers to formulate and optimise various combinations of mitigations strategies while accounting for the various economic and environmental constraints.

(Madsen et al., 2004) has devised a DSS for pollution control in the cement sector, which allows for identification of logistical solutions for reducing pollution while minimising the costs. The study utilises 3 major modules – a) modelling module, which is tasked with functions necessary for calculating the pollution and regeneration of environment, b) logistic module, which is interfaced with various pollution monitoring equipment in the plant, and c) optimisation module, which is tasked with determining the optimal production schedule such that the required pollution level norms are met. (Porzio et al., 2013) devised a DSS for reducing energy consumption and subsequently CO2 emissions in energy intensive industries by assisting the plant decision makers in identifying the best strategies for emission reduction while minimising the costs. The study includes a simulation system for various plant processes and a case-study for iron and steel industry in order to demonstrate the utility of the DSS.

In complex systems in which there are a large number of interactions between various processes and systems, the data available for the purpose of decision-making is increasing overtime. In such circumstances, computer simulation is recognised as a capable decision support tool and considered to be the "most dynamic element in the management systems hierarchy" (Edmonds and O'Connor, 1999). The use of computer simulation allows for constructing and analysing various "what-if" scenarios without having to disrupt or modify existing systems and incurring significant costs in the process. Multiple simulation approaches have been widely utilised as a decision support tool in management domain, including discrete event simulation and SD. Among the aforementioned simulation approaches, discrete event simulation is considered to be more relevant for decision-making at an operational/tactical level while SD is utilised mostly at a strategic level (Tako and Robinson, 2012). As such, this section will henceforth emphasise on the use of SD as a component of DSS in applications within the domain of climate change mitigation. (Liu et al., 2009) has devised a DSS, titled “Taiwan Water Resources Assessment Program to Climate Change”, for assessing the impact of climate change on water supply systems. The DSS additionally facilitates the integration of SD model for simulating the water supply and demand in the region. The SD model is intended to represent the various water reservoirs in the region along with their related inflow and outflow channels. The authors then analyse various water use scenarios under different climate change patterns for identifying water shortages at different time intervals. The authors expect the DSS to provide government stakeholders insights into instituting water use policies and allocation measures for irrigational water. (Sontamino Phongpat and Drebenstedt Carsten, 2011) have devised a DSS for minimising the environmental impact of coal mining through the utilisation of SD modelling technique. The DSS is intended to assist policymakers in drafting optimal planning and management policies in coal mining sector. The authors claim that the results from the model would allow for identification of both negative and positive impacts of various strategies and would subsequently enable the decision makers to pick the optimal decisions related to management and economic questions. Additionally, through utilisation of SD, the study aims to investigate the relationships between various variables within the coal mining sector. (Mamatok et al., 2019) devised a DSS using SD for evaluating CO2 mitigation strategies applicable to seaports. The study evaluates the CO2 emissions from seaport operations under different scenarios and provides insights for decision makers to reduce CO2 emissions while optimising operating time and container throughput at the seaport. The author concludes the study stating that SD models could serve as useful decision-making tools for stakeholders in the seaport sector for strategic planning and sustainable development. (Sharma and Sehrawat, 2019) devised a DSS using SD for addressing the issue of pollution related to increased tourism in Amsterdam. The SD model in this study was used for integrating various interacting factors relevant to the issue of pollution in the canal ecosystem. The authors intended for the DSS to support the decision makers in analysing different scenarios while incorporating their decisions. The authors conclude the study stating that SD, with the integration of aspects of a DSS, was an effective approach for evaluating systemic performance of chosen scenarios.

As observed in the aforementioned studies, DSS could be an essential instrument in allowing the stakeholders to make informed choices and decisions in the domain of climate change mitigation. Such a tool could not only be utilised by decision-makers in the respective domains, but also government policy makers for formulating effective policies. The decision problem being addressed in this study, i.e., identifying the optimal strategies for CO2 mitigation in a cement plant, could be addressed using simulation. One of the effective simulation approaches for policy and decision making is SD, which is further elaborated in Chapter 3.2.

3.2 System Dynamics

Various methodologies have been considered for modelling and analysing complex systems, with excelling in solving specific problems. Jonker et al. (Jonker et al., 2017) has studied various literature on dynamic modelling methodologies and have assessed their suitability on the basis of the following parameters:

- Problem Identification: Whether the methodology would enable the conceptualisation of the system enclosed within a boundary.
- Flexibility: Whether the methodology can assimilate inputs from various sources.
- Accuracy of the outcome: Whether the results from the simulation are reliable considering the amount of computation time is taken.
- Identification of effects over time: Whether the simulation deliver results as a function of time and can be used for modelling future projects.

Based on the comparisons provided by Jonker et al. (Jonker et al., 2017) in Table 10, System Dynamics (SD) is considered as a suitable approach to modelling complex systems such as cement plants with a significant amount of causal relationships and the need for identification of effects of strategies and policies over time.

Table 10. Comparison of various modelling methodologies, extracted from (Jonker et al., 2017)

Methodology	Strengths	Weaknesses
Econometrics	Based on historical trends. Fulfils problem identification and as well as effects over time.	Lack of feedback effects
Optimisation	Provides an accurate estimation whether a target can be achieved under given conditions. Fulfils outcome accuracy.	Does not identify the causes leading to the achievement of goals.
System Dynamics	Simulation driven by cause-and-effect relationships, accurately captures dynamics and feedback effects. Fulfils problem identification, outcome accuracy, identification of effects over time, and is flexible.	Requires detailed input parameters and relevant data to be obtained across all sectors.
Discrete Event Simulation	Simulates event driven systems, whether random or ordered, where entities have to take part in processes. Fulfils identification of effects over time.	The stochastic nature coupled with rigid sequencing of events leads to variation in the results, thereby requiring multiple runs.
Agent-based modelling	By working at agent level, it captures emergent phenomena. Fulfils problem identification and is flexible.	It is computation-intensive and not very adept at integration of actors from different sectors on the same platform.
Network Modelling	Identifies the most important entities in complex systems and determines the relationships between them which would be otherwise difficult to identify. Fulfils problem identification and is flexible.	It has limited ability to work with, or produce quantitative values or parameters.

SD was first conceptualised in the 1950s by Professor Jay W. Forrester at the Massachusetts Institute of Technology. While the original use for the system was to build an aircraft simulator for the U.S. Navy and to find solutions for engineering challenges, it was quickly adapted in the following decades to handle social systems, which were considered to be much harder to understand and control when compared to physical systems. SIMPLE (Simulation of Industrial Management Problems with Lots of Equations) and DYNAMO (Dynamic Models) were the first simulation languages to be developed within the SD framework (“Origin of System Dynamics,” n.d.). Jay W. Forrester was also involved in the development of SD models for socioeconomic systems called WORLD1 and WORLD2. These SD models linked various relationships such as population, production, and pollution and were used to identify and test various policy decisions in a global setting for extensive periods of time. Dennis Meadows later built a model called WORLD3, which was a more elaborate version of WORLD2 (Robinson, 1973). The core model contained several interacting sub-systems for food, industry, resources, pollution and population. The model has been simultaneously adapted for different parts of the world such as Bariloche model for the Latin American region and as well as speciality models for studying the impact of economic policies such as the FUGI model (Johr, 1981). The major characteristic of these SD models is the utilisation of circular causality and dynamic feedback systems for emphasising connections between the different parts of the system. The SD models employ diagramming techniques such as casual loop and stock flow diagrams to visualise the structure of these feedback systems. The SD model typically "consists of an interlocking set of differential and algebraic equations developed from relevant experiential data" (John D. Sterman, 2000). "System Dynamics National Model" by (Jay W. Forrester et al., 1976) is one of the first models to focus upon the socio-economic behaviours in regard to the policy planning. The model incorporates various sub-systems for government, trade, Finance, households, demographics, labour and production for the United States. The model offered the tools to link these sub-systems as per the proposed policies and test their impact at a much lower cost compared to "real-life social experiments" which might take a significant amount of time to be properly evaluated. The idea is that it would allow the stake-holders to accept or reject different policies based on their results from the testing within the laboratory environment. Forrester stated that the model should "clarify the issues, shorten the debate, and increase the percentage of public actions that yield desirable results". Today, SD models are being increasingly used for assistance in decision making and policy planning in even wider range of sectors and applications across different geographic and demographic conditions. SD is also widely utilised for portfolio simulation by introducing dynamics into models such as the growth-share matrix, which is originally static in nature and ignores feedback. It was also effectively used in product development and supply chain management (Victor Tang and Samudra Vijay, 2001). It also found its usage in the public health services sector where (Taylor and Lane, 1998) have identified the potential of utilising SD methodology over discrete event simulation in models dealing with dynamic complexities where the consequences of cause and effect relationships are not obvious. Similarly (Homer and Hirsch, 2006) further discusses the opportunities of utilising SD approach to solve dynamically complex health issues such as prevention of chronic diseases. (Ford, 1997) published an article aggregating and summarising several applications of SD in the domain of policy-making in the electric power industry showing an increasing use for this approach.

Causal loop diagrams (CLDs) and stock-and-flow diagrams are typically used for the visual representation of SD models. A CLD allows for dynamically describing complex systems through the use of varying combinations of positive reinforcing loops, acting as a self-reinforcing mechanism (as seen in Fig. 17), and negative balancing loops, which act as a corrective, goal-seeking mechanism (as seen in Fig. 18). An example of positive, reinforcing loops is depicted in Fig. 17, in which the demand for newer infrastructure leads to a higher production of cement, which in turn results in higher availability of cement in this particular region, which further stimulates the demand for infrastructure. A negative, balancing loop is depicted in Fig. 18, in which the increase in carbon emissions leads to higher implementation of carbon mitigation projects, which subsequently leads to a reduction in carbon emissions.

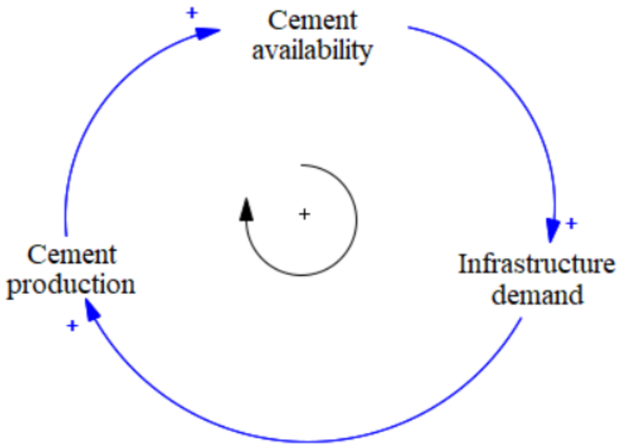


Fig. 17. Example illustration of a causal loop diagram (CLD) showing a positive reinforcing loop. Extracted from (Kunche and Mielczarek, 2021).

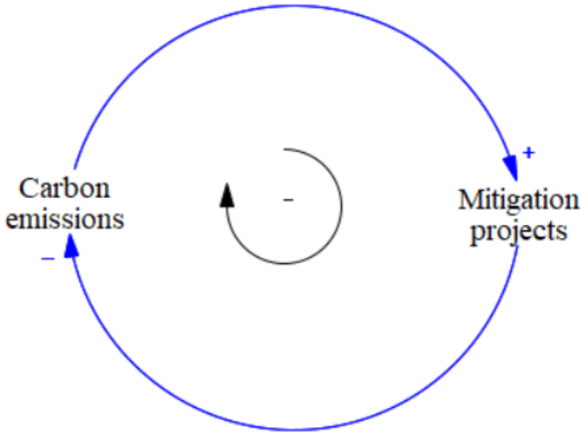


Fig. 18. Example illustration of a causal loop diagram (CLD) showing a negative balancing loop. Extracted from (Kunche and Mielczarek, 2021).

Stocks and flows are integral equations that represent the accumulation and transfer of resources between different entities of a system over a continuous period of time. An example of a simple stock-and-flow diagram is presented in Fig. 19. In this exemplary model, “Cement availability” is a stock, which refers to the amount of cement available at a given instance of time. The “Cement production” and “Cement sales” are the the flows which represent the transatctions that are altering the value of the stock they are connected to. The “Cement production” and “Cement sales” are influenced by both, amount of cement stock available as well as external demand. The variable, “Cement demand” is influenced by the current stock of the cement available in the region, as well as external factors which are outside of the system boundary.

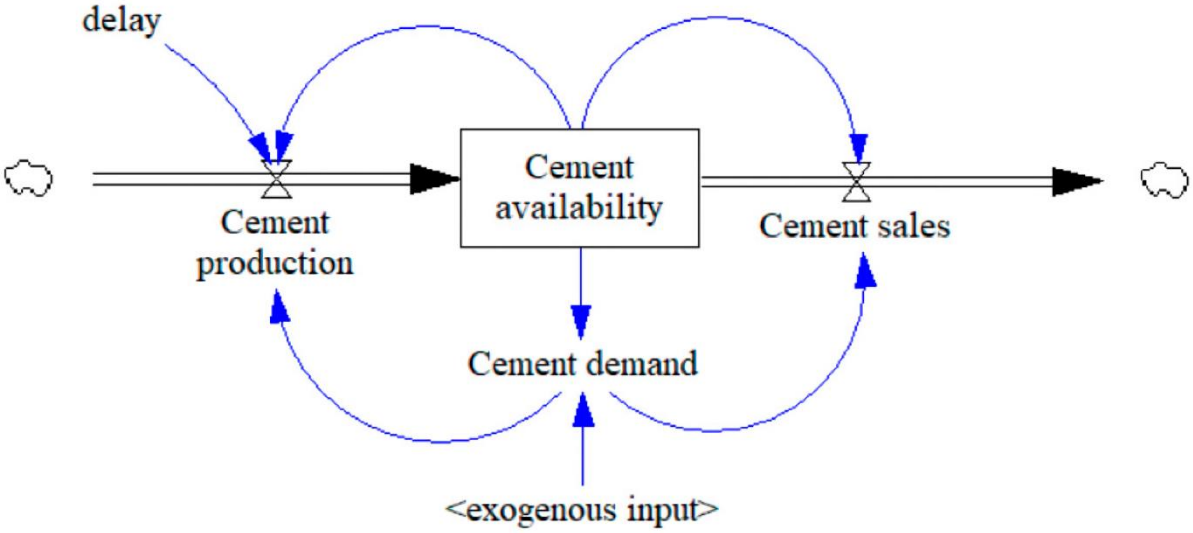


Fig. 19. Example illustration of a simple system dynamics (SD) model represented as a stock-and-flow diagram. Extracted from (Kunche and Mielczarek, 2021).

Equation (1) is an integral equation where the *Inflow (s)* represents the value of the inflow at any given time *s* between the initial time *t₀* and the current time *t* (John D. Sterman, 2000). The net change in stock is the derivative of the difference between outflow and inflow, as in Equation (2). In case of Figure 7, Cement production is the inflow, and “Cement sales” is the outflow.

$$\mathrm{Stock(t)} = \int_{t_0}^{t} [\mathrm{Inflow(s)} - \mathrm{Outflow(s)}]\,\mathrm{ds} + \mathrm{Stock(t_0)} \tag{3}$$

$$\mathrm{d(Stock)/dt} = \text{Net Change in Stock} = \mathrm{Inflow(t)} - \mathrm{Outflow(t)} \tag{4}$$

As described by Sterman (John D. Sterman, 2000), the stocks assist with providing the decision makers or the stakeholders with information on the current state of the system which is a necessary prerequisite for them to take actions that would influence the system in the future. In case of the example provided in Fig. 19, the cement plant stakeholders would need to know the current stock of the cement available before taking an action to either produce more or suspend production. Additionally, stocks provide the systems with memory of the past actions as its value can only change through either inflow or outflow. The stocks can also act as a delay, whose output lags behind its input, there is a time gap between production of cement and its sale. By absorbing the differences between inflow and outflow, stocks allow for the inflows and outflows to differ. The stocks and flows are recognised in various fields with different terminology as tabulated in Table 11.

Table 11. Terminology for stocks and flows in different domains, extracted from (John D. Sterman, 2000)

Domain	Stocks	Flows
Mathematics, Physics, and Engineering	Integrals, states, state variables, stocks	Derivates, rates of change, flows
Manufacturing	Buffers, inventories	Throughput
Economics	Levels	Rates
Accounting	Balance sheet items	Cash flow or income statement items

As it is not feasible to model the entire system in its entirety, it is required to define boundaries in form of endogenous and exogenous variables, as visualised in Fig. 20, which contains “thoroughly modelled endogenous variables”, whose selection is crucial to the system that is being modelled and would represent the core system behaviour. “Superficially modelled endogenous variables” aid in improving the representation of the real-world system in the model, but are not crucial. “Exogenous” variables influence the model and its variables, but are unaffected by any changes in the system, i.e., a one-way relationship. “Deliberately excluded variables” are considered to be outside of the system boundary, i.e., the scope of the model.

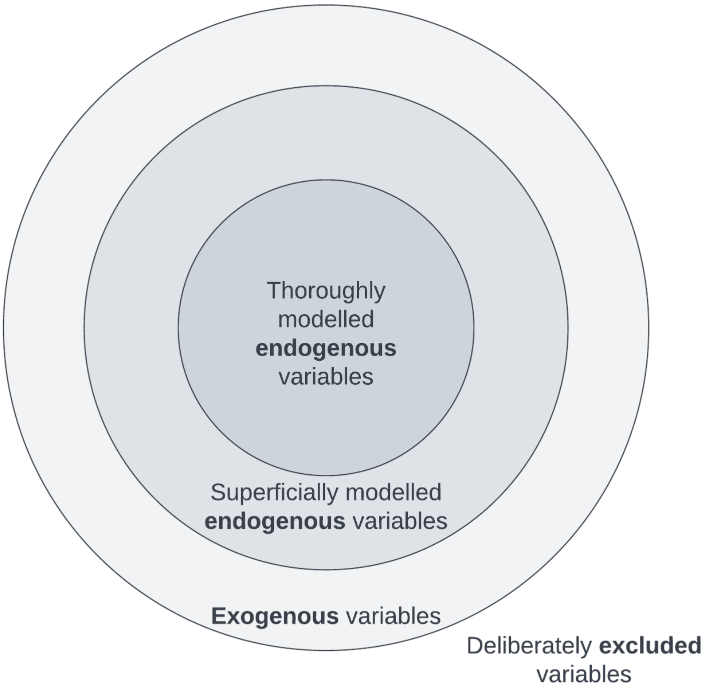


Fig. 20. System boundaries, adapted from (Clifford-Holmes, 2018)

The SD approach is generally utilised to represent large, complicated systems for modelling and studying the relationships between the various variables in the system than the individual transactions between them. Through the use of CLD, it provides an effective way to depict the underlying structures of the system, allowing the study of behavioural patterns across time. Furthermore, SD modelling enables for mental model improvisation, which contributes to better decision making in dynamic circumstances (James K. Doyle and David N. Ford, 1998; Kunche and Mielczarek, 2021). By facilitating changes and experimentation in the mental models by the stakeholders, it bolsters its decision-making capabilities, which allows the approach to be utilised in both quantitative and qualitative research in a range of topics, such as management, healthcare, policy, sustainability, sociology, market dynamics, process planning, and decision making.

Despite the advantages provided by the modelling approach, the growth in its utilisation is hindered due to lack of awareness of its value among stakeholders (David Rumeser and Margaret Emsley, 2016). In order for the model to be impactful, it needs to be implemented with the involvement of all its important stakeholders during the development stage. The stakeholders also need to validate the dynamic hypothesis, which further slows down the implementation of potent new models (Pagoni and Georgiadis, 2020). The majority of the SD models tend to be built in order to describe the dynamic aspects of the system, but their omission of fitting historic data and the lack of ability to provide passable quantitative forecasts impacts the acceptability of the models among the stakeholders. For testing policy interventions, it is also important to identify the most impactful parameters that would allow tracking of useful changes in the system.

3.2 System Dynamics in the domain of climate change and CO2 emissions

System dynamics modelling has been previously utilised for models representing the energy sector as means to study policy implications. FOSSIL2 has been specifically built for policy planning of the energy sector and was used for studying various policy options to mitigate GHG emissions in the 1990s by the United States Department of Energy (Naill et al., 1992). It was also utilised for assessing GHG reduction potential and cost effectiveness of various technology policies and had a definitive impact on several international treaties for GHG reduction during that time period. This model has two sectors – the energy demand sector which compromises of all major energy consumption divisions like transportation, industries, commerce, and residences; and the energy production sector which compromises of energy supply divisions like oil, gas, coal and other forms of electricity generation. For studying the impact of GHG reduction policies, the model also considered the cost of reduction technologies and as well as the feasibility of implementing them in various sectors. The authors have studied the impact of carbon tax as one of the policy options with the model and estimated that it was capable of about 20% reduction in 1990 level GHG emissions from various sectors in the United States of America (USA) by 2030.

The FOSSIL2 model eventually paved the way for utilising SD models for estimation and policy planning of GHG emissions in various industrial sectors. ENERGY2020 and Long-range Energy Alternatives Planning System (LEAP) are couple of other SD models for policy planning and CO2 mitigation, which are being increasingly used and being adapted to different sectors and geographic regions. LEAP in particular was used in various studies such as by (Bala, B. K., 1997) to model the energy system and CO2 emissions in rural Bangladesh; Cai, Wang, Chen, Zhang & Lu (Cai et al., 2008) used it study and compare various mitigation policy options for CO2 emissions in various sectors such as electricity, iron and steel, pulp and paper, cement, and transport. Phdungsilp (Phdungsilp, 2010) has also used LEAP to simulate CO2 emissions under different policy options for the various sectors in the city of Bangkok, Thailand.

Numerous other SD models have also been built and extensively used for studying the impact of policy and project implementations related to GHG mitigation in a wide range of domains such as Energy Sector (Chentouf and Allouch, 2018; Feng et al., 2013; Robalino-López et al., 2014; Saysel and Hekimoğlu, 2013; Sun et al., 2016), Transportation sector (Barisa and Rosa, 2018; Han et al., 2008; Han and Hayashi, 2008; Procter et al., 2017), Iron and steel industry (Kim et al., 2014), Cement industry (Anand et al., 2006; Ansari and Seifi, 2013; Jokar and Mokhtar, 2018), and as well as across all the domains in a particular region (Ángel Isidro Mena Nieto et al., 2009; Wen et al., 2016). The recurring objective among all these studies is to project the CO2 emissions over a period of time for different policy scenarios and examine how the mitigation projects would impact the outcome of the scenarios. The targeted area in these studies varied from a single project implementation (Procter et al., 2017) to a city/district level and even the entirety of the country.

(Procter et al., 2017) studied the impact of implementing a modern transportation system at a district level in the state of North Carolina, USA on the urban growth and carbon emissions. The study specifically focused on a light railway project between the towns of Durham and Chapel Hill, which have set an emission target of 30% reduction in CO2 at 2005 levels. (Procter et al., 2017) developed a dynamic model to simulate the changes in urban developments and the resultant energy consumption that would arise from the construction of the railways under different policy scenarios and estimate the carbon emissions. Interestingly, the simulated projections until the year 2040 concluded that the light rail project would contribute to higher regional economic growth and therefore result in a significant increase in energy use and CO2 emissions than compared to the business as usual (BAU) scenario. It is however estimated that it would lower the emission intensity and when coupled with policies that promote energy efficiency and renewable energy in the region, it would enable the benefits of the light rail at a minimal environmental cost. Similarly, (Azhaginiyal and G.Umadevi, 2014) built a SD model to project CO2 emissions from the transportation sector until 2026 in the city of Chennai in India comparing the BAU scenario with mitigation focused policies. On a much larger scale, Han and Hayashi evaluated the policies for CO2 mitigation in the transportation sectors of China and India respectively using a SD model (Han et al., 2008; Han and Hayashi, 2008). The study focussed on the intercity modes of transportation including railways, waterways, roadways and aviation and projected the CO2 emissions until the year 2020 under various mitigative policies and as well as BAU scenario. The study concluded that the mitigative policies considered in this research would result in a decrease of 26% to 32% and 5%-12% in CO2 emissions in China and India respectively. (Barisa and Rosa, 2018) developed a SD based model with a strong emphasis on forecasting CO2 emissions in the transportation sector of Latvia until the year 2030. The model was designed to be compatible with wide range of mitigation policies allowing for greater degree of experimentation for studying the impact of policies on GHG emissions. (Azmi and Tokai, 2016) developed a dynamic probabilistic model to determine the GHG emissions from Malaysia’s transportation sector. The study focused on various vehicle fleet policies and as well as different combination of these policies and determined that the total emissions from this sector can be reduced by 80% in 2040 compared to BAU scenario.

(Saysel and Hekimoğlu, 2013) have built a dynamic simulation model to analyse the available options for carbon mitigation in the Turkish electric power industry. Model incorporated investor behaviour along with different module for each power generation source as well as resource availability. The model was intended to be served as an experimental platform for analysing future policies for mitigating GHG in the industry. In a similar manner, (Chentouf and Allouch, 2018) used the SD approach to study the impacts of renewable energy on the CO2 emissions in the Moroccan electric power industry. They have compared the BAU scenario with alternate scenarios to determine the best policy for Morocco to achieve their 2030 mitigation targets. The research concluded that choosing the best possible scenario would result in an increase of renewable energy to 36% of the total energy generated by 2030. (Kazemi and Hosseinzadeh, 2016) built a SD model for assessing all the available policies for the supply allocation in Iran's energy sector. GHG emissions is considered as the main output parameter and the model takes into account the relationships between the production and consumption of crude oil, gas and electricity to determine the CO2 emissions. (Sun et al., 2016) presented a SD model for analysing the CO2 emissions under various policies for China's electric power industry, which accounts for 40% of the total emissions in the country. The system was modelled around various variables such as Gross Domestic Product (GDP), electricity demand and consumption, production cost of existing technologies, and cost of research for new technologies. The study compared BAU scenario with 2 other scenarios focused on mitigation in a simulation from 2012 to 2020 and concluded that a reduction of 27.5% in carbon emissions can be achieved with the most mitigation-oriented scenario.

(Ángel Isidro Mena Nieto et al., 2009) developed a SD model using the kaya identity to determine CO2 emission trends in the district of Cartagena de Indias in Colombia. The model utilises different subsystems for population, GDP, energy production and consumption to determine the trends in CO2 emissions in the region. Similarly, (Robalino-López et al., 2014) also developed a SD model using the kaya identity as a basis to estimate the CO2 emissions in Ecuador's electric power industry. The model studies the relationship between changes in energy matrix & GDP and how it impacts the CO2 emissions. The study concludes that despite the high growth in GDP, a shift in policy to promote the growth of renewable energy would result in lower CO2 emissions than in BAU scenario. (Feng et al., 2013) developed SD model to study the relationship between energy consumption and CO2 emissions in the city of Beijing, China. The model relates the consumption and demand of energy in various sectors such as agriculture, industry, residential, transport, and service with the GDP and population changes to determine the trends in CO2 emissions. (Wen et al., 2016) developed another model for the city of Beijing, but only focusing on the carbon emissions from the industrial sector. The model incorporates 3 interacting sub systems for population, economy and energy to determine the trends for CO2 emissions.

(Kim et al., 2014) used the SD approach to investigate the CO2 emissions and mitigation potential of various technologies implementations in South Korea's iron and steel industry. The study utilises the IPCC guidelines for estimating the CO2 mitigation potential. It compares the BAU scenario with a mitigation scenario which incorporates 6 different CO2 reduction technologies at various stages of the iron and steel manufacturing process. The paper concludes that the mitigation scenario can result in reduction of CO2 emissions by 5.26 million tons compared to BAU scenario by 2030.

3.3 System Dynamics in Cement Industry for CO2 Mitigation

(Kunche and Mielczarek, 2021) reviewed the existing literature on the utilisation of SD to analyse the mitigation scenarios in the cement domain. In order to fetch all relevant articles indexed by Web of Science (WoS) and Scopus, the search queries (5) and (6) were formulated respectively in the study.

$$(((\text{system NEAR}/0\text{ dynamic}*)\text{ OR SD})\text{ AND }((\text{CO}2\text{ or carbon }*)\text{ AND emissi }*)\text{ AND }((\text{mitigat }*\text{ OR evaluat }*\text{ OR reduct }*)\text{ OR }(\text{policy NEAR}/0\text{ analy }*))) \tag{5}$$

$$(((\text{system pre}/0\text{ dynamic}*)\text{ OR SD})\text{ AND }((\text{CO}2\text{ or carbon }*)\text{ AND emissi }*)\text{ AND }((\text{mitigat }*\text{ OR evaluat }*\text{ OR reduct }*)\text{ OR }(\text{policy pre}/0\text{ analy }*))) \tag{6}$$

The search strings (1) and (2) fetched 357 and 442 relevant records on WoS and Scopus respectively, as of March 2021. Further affixing “AND cement” to filter the articles related to the cement domain, the results narrowed down to 13 and 9 on WoS and Scopus respectively.

The utilisation of SD in for GHG mitigation in the cement industry is relatively sparse when compared to other domains. (Kunche and Mielczarek, 2021) reviewed the articles relevant to the cement domain, with Tables 6-11 describing the modules utilised in each study and Table 12 summarising the studies reviewed.

(Nehdi, M et al., 2004) built a SD model to primarily study the impact of clinker substitution in reducing CO2 emissions in the cement industry. The model utilised 5 sub-systems as listed in Table 12. For the purpose of simulation, the study assumed that the cement consumption is directly proportional to the GDP growth and population in case of developing and developed countries respectively. The study considers various production cases for the coal-based thermal power plants and steel industry, which determined the amount of substitutes that were available for replacing clinker in the cement. One of the production case assumes that better technologies are increasingly utilised, thereby significantly increasing the efficiency of coal based thermal power plants and steel industry, reducing the amount of substitute material available for substitution in the cement industry. Another case assumes that the wealth gap between developed and developing countries remains unchanged, which results in less efficient thermal and steel industry, thereby increasing the substitute material available for substitution. The results from the study were consistent with other studies such as (Bosoaga et al., 2009), which determined that CO2 emissions from cement industry can be reduced upto 20% using clinker substitution as mitigation strategy.

Table 12. Analysis of subsystems in (Nehdi, M et al., 2004)’s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Forecast	Forecasts the cement consumption based on population or GDP growth
Fly ash concrete	Calculates the volume of fly ash concrete being utilised
Slag concrete	Calculates the volume of slag concrete being utilised
Ordinary Portland cement concrete	Calculates the volume of OPC concrete being utilised
CO2 emissions	Calculates the combined amount of emissions released from the cement industry

(Vargas and Halog, 2015) built a SD model to study the impact of upgraded fly ash on CO2 emissions in the cement industry. The study differentiates itself from (Nehdi, M et al., 2004)’s approach by assuming that the fly ash obtained from the coal-based thermal power plants does not always meet the quality requirements for its use as clinker substitute. The study considers an upgradation process of the incompatible fly ash to make it usable as a clinker substitute. The model incorporates the additional energy use by the upgradation process when calculating the CO2 emissions from the cement plant. The study then compares emissions between a) reference plant with no clinker substitution, b) cement plant with fly ash as a clinker substitute, and c) cement plant with upgraded fly ash as a clinker substitute, under various lifecycle scenarios. The study also assumes that cement production rate is constant, as its objective is to investigate the effect of using fly ash and upgraded fly ash as clinker substitutes when compared to regular cement with no substitute materials. The authors have not explicitly discussed the structure of the sub-systems utilised in their study.

(Anand et al., 2006) built a SD model the investigate the reduction in CO2 emissions under different mitigation scenarios such as clinker substitution, renewable energy, and WHR. In comparison to the previous studies, the model has much wider perspective that considers the role of GDP and population growth on the cement demand and subsequently emissions from the cement production. While (Nehdi, M et al., 2004) and (Vargas and Halog, 2015) have only considered clinker substitution as a mitigation strategy, this study incorporates fuel substitution and WHR recovery as additional strategies when comparing the CO2 emissions across various scenarios. The study calculates the amount of thermal waste heat available (for calculation of electricity that can be generated through WHR) based on the amount of clinker used and its specific thermal energy requirement. The availability of fly ash and blast furnace slag is calculated based on the regional coal consumption in thermal power plants and pig iron production respectively. The model consists of 5 sub-models with described in Table 13. The study then considered 3 scenarios – a baseline scenario, in which the cement demand, production and population growth rate remains constant at 2000 levels, and two modified scenarios in which the population growth stabilises in 2011 and 2020 respectively. In each of these scenarios, following policy options are investigated:

- 25% of the energy is obtained from renewable sources from 2010
- The specific energy consumption decreases from 3.06 to 2.9 during the simulation period
- 30% of the total thermal energy requirement is obtained from WHR
- A combination of policies specified above

Table 13. Analysis of the subsystems in (Anand et al., 2006)'s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Demand and production	Estimates the cement demand and production based on variables such as population, GDP and exports
Energy consumption	Estimates the electrical and thermal energy consumed for production of cement. The energy sources are further divided into conventional and renewable energy. WHR mitigation is incorporated as a source of thermal energy
Availability of slag and fly ash	Fly ash and furnace slag availability is calculated based on the regional consumption of coal and production of pig iron respectively
CO2 emissions from plant operations	Calculates the total CO2 emissions from the clinker production, electricity usage for machinery and the thermal energy use during the operation of the cement

	plants
CO2 emissions from transportation	Calculates the CO2 emissions from the transportation of raw materials to the cement plant and as well as the finished products to the destination

(Ansari and Seifi, 2013) utilised the SD approach to assess the impact of energy price reforms and export policies on the net CO2 emissions from the cement industry in Iran. The model utilises 4 sub-systems to achieve its objectives, as depicted in Table 14. The study aims to simulate the impact of mitigative approaches such as clinker substitution and WHR on the CO2 emissions from the regional cement industry under different subsidy policies for fuel and electricity. Various scenarios are considered such as, a) the energy efficiency of cement production remains unchanged, b) a moderate increase in efficiency with a reduction in emission intensity from energy use, and c) a significant increase in efficiency with widespread adoption of WHR and clinker substitution. In contrast to the previous studies, (Ansari and Seifi, 2013)'s model does not have the provision to calculate the availability of fly ash and blast furnace slag and rather resorts to combining all the mitigation measures into a single metric which limits the scope for experimentation.

Table 14. Analysis of subsystems in (Ansari and Seifi, 2013)'s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Demand	Similar to Anand et al.'s (2005) demand and production module, this calculates the cement demand based on the changes in population and GDP
Production	Calculates the changes in production capacity based on the desired capacity, which takes into account the domestic demand and as well as exports
Energy consumption	Energy consumption is divided into thermal and electrical components and the requirement is calculated based on energy efficiency of the cement production in the region. Energy price is considered as a factor effecting the energy efficiency
CO2 emission	Calculates the total CO2 emissions from clinker production, electricity generation, and fuel consumption

(Jokar and Mokhtar, 2018) improved upon existing studies by additionally including economic and social subsystems for determining the manufacturer profit, based on the production costs and cement market tariffs under various production and policy scenarios. The model utilises 6 subsystems as listed in Table 15. The study then combines the 2 scenarios – 89% and 100% utilisation of regional cement production capacity respectively, with the following policies, a) Business as usual without any mitigation approach, b) using WHR for generation of electricity and selling it to the regional grid, c) utilisation of alternate fuels, and d) clinker substitution. The model allows for experimentation through provisions for modifying the values for policy options. The study then compares the results from the various combinations of scenarios and policies and determined that while clinker substitution is the most effective method for reducing CO2 emissions, WHR is the most effective in increasing the profitability of the cement production in case of Iran. The model assumes that the raw materials necessary for mitigation strategies such as clinker substitutes are always available, when in most cases, their availability is tied to the production scenarios of other domains such as electricity and iron production in the region. Furthermore, the model does not consider the feedback between various mitigation strategies which limits the experimentation of scenarios in which the industry adopts multiple mitigative approaches simultaneously.

Table 15. Analysis of the subsystems in (Jokar and Mokhtar, 2018)'s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Cement production capacity	Calculates the cement production based on capacity utilisation, nominal capacity and rate of capacity expansion
Clinker production capacity	Calculates the clinker production based on the cement capacity and the average clinker ratio for accounting blended cements
Energy consumption	Utilises thermal and electrical SEC for calculating the energy requirement of the cement industry
CO2 emissions	Calculates the total CO2 emissions based on clinker production and the average emission intensity of the electricity and fuel used for production
Economic module	Industry profits are calculated by determining production costs and manufacturer income through cement market prices
Social module	Determines the rate of capacity expansion based on manufacturer profit and investment costs. Additionally, it calculates the labour requirement

(Tang et al., 2020) study emphasises on the development of framework for building SD models that focuses upon inter-regional interactions, in which carbon emissions of a region is forecasted when taking into consideration the energy and carbon flow with hits neighbouring regions. The model recommends the use of 3 sub-models as described in Table 16 for measuring emissions from any industrial domain. The study then conducts a case-study for the region of Chongqing in China under 2 different scenarios, a) business as usual, in which the existing trends remain unchanged and b) low carbon consumption, in which the cement industry is assumed to adopt CO2 mitigative measures such clinker substitutes, alternative fuels, energy efficiency improvements as well as increased production capacity. The mitigative measures are incorporated into the model in form of exogenous input parameter which is used for setting the ratio of utilisation of each mitigation measure as per the scenario being tested. However, the study assumes that the ratio of utilisation of these mitigation measures remains constant throughout the simulation period. Furthermore, the economic impact of implementing a low-carbon scenario on the industry is not investigated in this study.

Table 16. Analysis of subsystems in (Tang et al., 2020)'s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Demand	Calculates the cement demand from the local population as well as additional external demand from adjacent regions
Supply	Calculates the inter-regional cement production based on the demand while taking into consideration the

	technological differences within the adjacent region, i.e., differences in specific energy consumption
CO2 emission	Calculates emissions based on net energy used for cement production as determined in the supply subsystem

(Ekinci et al., 2020)’s model aims to study the long-term impact of the cement industry on the regional air quality, with an emphasis on the role of population growth and infrastructure demand. In contrast to the other studies featured in this section, this study excludes the technicalities of cement production and instead measures the CO2 emissions based on the regional cement production capacity based on yearly GDP and infrastructure development. Additionally, the model does not evaluate any specific mitigation approach, but instead uses a single provision in the model for policy experimentation to set the amount of emission reduction during the simulation run. The study does not explicitly describe the various subsystems used in the model and concludes by stating the corelation between regional air quality, infrastructure demand, and cement production.

(Proaño et al., 2020) studied the economic and mitigative impact of utilising indirect carbonation method to capture CO2 produced in the cement manufacturing process. Unlike the previous studies, this model utilises a single reference plant instead of a macro-level approach encompassing the entire regional cement industry. Additionally, the study utilises an economic subsystem for simulating the impact of cost of project implementation as well as the returns from the sale of additional by-products generated during indirect carbonation method. The list of sub-models used in this study are depicted in Table 17. While the study exclusively focuses on carbon capture using indirect carbonation method, it also considers the role of capital expenditure when implementing the project. The model utilises a separate sub-system for estimating the CO2 emission capture potential depending on the calculated amount of CO2 generated from the cement production process. The study considers the following technical scenarios a) business as usual with no carbon capture, b) use of Sodium-based solvents, c) use of Barium-based solvents, and d) use of Calcium-based solvents respectively for capture of CO2. Each of the aforementioned technical scenarios are paired with various market and policy conditions and the authors concluded that implementation of carbon capture technologies could be fostered through the adoption of carbon taxation.

Table 17. Analysis of subsystems in (Proaño et al., 2020)’s model, extracted from (Kunche and Mielczarek, 2021)

Subsystem	**Objective**
Cement demand	Calculates the cement demand based on the regional GDP growth
Cement production	Calculates the cement production by factoring in cement demand and production capacity of the reference plant
CO2 estimation and capture	Calculates the CO2 capture rate and by-product production based on the amount of cement produced and type of carbon solvent used. The module assumes the clinker content in cement as a static value of 73.7%
Costs and profit	Calculates the production cost based on energy and fuel consumption, raw material requirements, administrative and maintenance costs. It then estimates

	the profits through the sale of cement and by-product sales as well as emission subsidies

(Kunche and Mielczarek, 2021) summarised the studies discussed in this section in Table 18, with the gaps in existing literature are further discussed in Section 2.7. None of the studies discussed in this section provide the entire set of equations that allows for reproducibility and practical evaluation of the models utilised in the respective studies. The model complexity is determined based on the explicit information provided by the author or deduced from the stock-and-flow diagrams, if included in the literature. The mitigation approaches investigated in each of the studies, either through input parameters or policy scenarios, are also listed in the Table 18.

Table 18. Summary of the studies reviewed, extracted from (Kunche and Mielczarek, 2021)

Reference	Primary Objective	Scope	Complexity	Model Equations	Model Validation	Mitigation Methods Featured or Facilitated	Analysis of Economic Impact of Mitigation Policies on Cement Industry
(Nehdi, M et al., 2004)	To forecast the impact of replacing clinker with substitutes such as fly ash and slag on carbon emissions in the cement industry and provide a tool for analysing policy scenarios.	Coalescence of regional cement industry; estimates carbon emissions from cement industry by calculating the total regional cement production based on demand for different blended cements	Undisclosed	None	Unspecified	Clinker substitution	No

(Anand et al., 2006)	To estimate the total CO2 emissions from the cement industry in India	Coalescence of regional cement industry; estimates carbon emissions based on total energy consumption in the cement industry as well as the emissions from transporting raw materials. Also calculates the availability of clinker substitutes that can be used for reducing emissions	5 stocks 5 flows	Partially described	Validated using historical data, structural verification test and dimensional consistency test	Clinker substitution, alternate fuels, and WHR	No
(Ansari and Seifi, 2013)	To analyse carbon emissions from the Iranian cement industry under different policy scenarios	Coalescence of regional cement industry; estimates carbon emissions based on thermal and electrical efficiency factors of cement production. Calculates the energy demand of cement industry based on the regional energy prices	11 stocks 17 flows	Partially described	Validated using historical data	Thermal and electrical efficiency improvements	No
(Vargas and Halog, 2015)	To estimate the reductions in carbon emissions when using upgraded fly ash in the cement industry	Single reference plant; calculates emissions from production of cement, transportation of raw materials, and as well as	5 stocks 5 flows 14 converters	Partially described	Unspecified	Clinker substitution	No

		process of upgrading fly ash					
(Jokar and Mokhtar, 2018)	To simulate the impact of mitigation measures on carbon emissions in the Iranian cement industry	Coalescence of regional cement industry; estimates carbon emissions based on the total energy consumed and clinker ratio. Also calculates the production costs of cement based on the energy consumption and as well as non-energy factors	5 stocks 10 flows	None	Validated using historical data	Clinker substitution, alternate fuels, and WHR	Yes
(Tang et al., 2020)	To present a framework for estimating carbon emissions in an "inter-regional context between neighbouring regions" and applying it on cement industry as a case study	Coalescence of regional cement industry; estimates carbon emissions based on the fuel and electricity consumption of the cement industry	3 stocks 3 flows	Partially described	Validated using historical data, structural verification test and dimensional consistency test	Clinker substitution, alternate fuels, and WHR	No
(Ekinci et al., 2020)	To predict the contribution of cement industry to the regional air pollution levels through a holistic approach	Coalescence of regional cement industry; calculates the contribution of cement production to regional air pollution using streaming data of pollution metrics and	Undisclosed	None	Validated using one-way ANOVA test	None, study excludes technicalities of cement production	No

		economic activity						
(Proaño et al., 2020)	To evaluate the use of indirect carbonation mitigation approach in cement industry for emission reductions	Single reference plant; calculates the carbon emissions based on the cement produced and reductions related to using indirect carbonation method to capture CO2 from post-process flue gas exhaust. Incorporates the cost of implementation and maintenance of carbon capture approach and as well as the sale of by-products	11 stocks 14 flows	None	Validated using historical data and structural verification test	Carbon capture	Yes	

3.4 Summary and implications

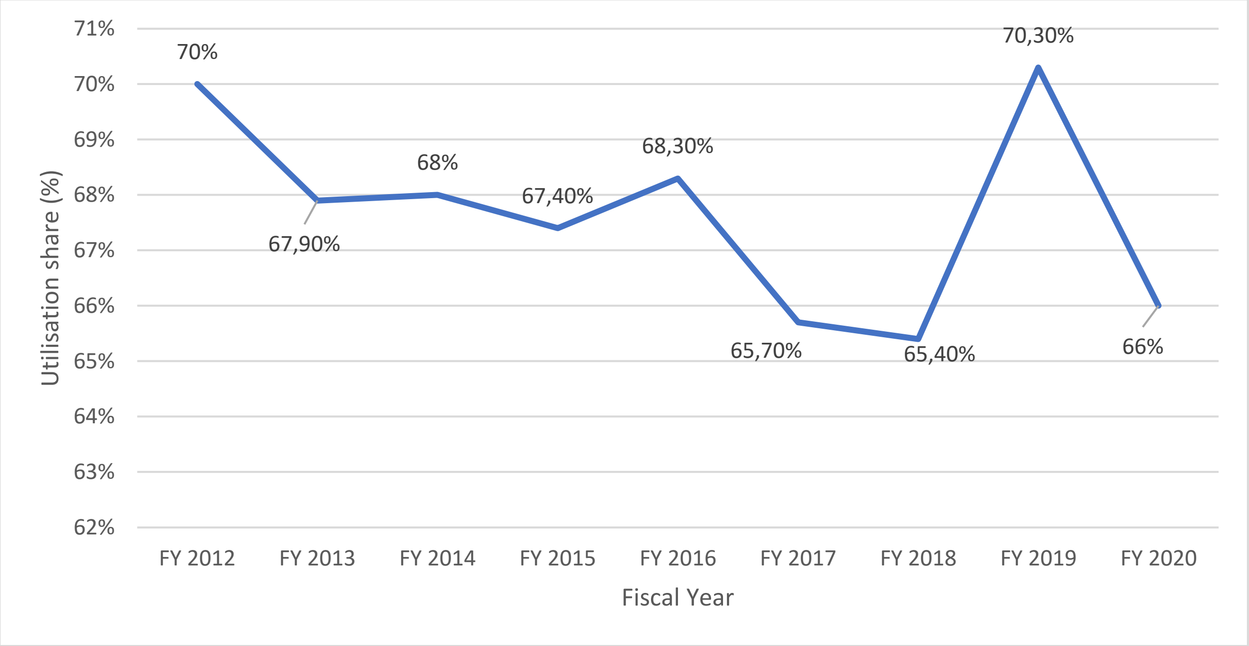
In order for a model to be a promising decision-making and analysis tool, it needs to facilitate the analysis of the most prospective mitigation techniques currently available in the cement industry. The scope of the model plays a major role in determining its applicability to stakeholders responsible for decision-making in the cement industry. The models that include economic analysis of mitigation project implementations are more relevant to decision-making, as the payback periods of the capital investment of the mitigation projects often depend on various dynamic factors such as energy and maintenance costs. Among the studies discussed in the previous section, only (Jokar and Mokhtar, 2018) and (Proaño et al., 2020) have included provisions in the models for calculating the financial impact of implementing the mitigation strategies while the remaining studies exclusively focus on forecasting the carbon emissions under different policy scenarios and CO2 mitigation approaches. Implementing strategies such as WHR, carbon capture, and plant efficiency improvements involve significant capital expenditure, thereby having an impact on the plant profitability depending on the payback period of the project. Therefore, determining the economic feasibility of the project is one of the foremost concerns for the stakeholders responsible for decision making in the cement industry.

Furthermore, depending on the regional markets and existing energy policies, different mitigation strategies would fair differently for each cement plant. The studies featured in the previous section do not integrate all the most popular mitigation options available in the cement domain in their models, which prevents them from being utilised as an effective decision-making tool to compare the impact of various combination of mitigation strategies on a specific plant. Table 12 indicates the various mitigation strategies adopted by each study, with (Nehdi, M et al., 2004) and (Vargas and Halog, 2015) solely focusing on clinker substitutes, (Anand et al., 2006) and (Ansari and Seifi, 2013) omitting alternative fuels, and (Proaño et al., 2020) exclusively focusing upon carbon capture using indirect carbonation in the cement industry.

Additionally, all of the studies, with exception of (Proaño et al., 2020) and (Vargas and Halog, 2015), simulate the impact of CO2 mitigation projects on a macro scale, i.e., the entire cement industry in the region instead of an individual plant. Such an approach is applicable to policymakers when analysing the impact of mitigation strategies on the cement industry at a macro scale, but lacks the flexibility in case of stakeholders investigating the impact on a specific cement plant. A significant proportion of the cement industries manage and operate a single production plant, with some of them only performing a part of the cement manufacturing process such as production of clinker exclusively or operation of grinding mills (Peter Edwards, 2017). The majority of the studies reviewed in the previous section do not have provision for simulating emissions from individual cement manufacturing installations that are only being utilised for a portion of the cement manufacturing process. Moreover, even large cement manufacturing companies that own multiple plants at different locations, often take decisions on implementation of mitigation projects on a plant-to-plant basis as the availability of materials and economic feasibility of the mitigation varies by region and market conditions.

The interactions between the various mitigation approaches is also ignored in the previous studies, for example, in plants which are already replacing a portion of their clinker with substitute materials such as blast furnace slag and fly ash, the amount of heat generated during the clinker production process varies depending on the changes in substitution percentage and plant utilisation rate, thereby directly effecting the amount of electricity that can be generated through WHR. (Anand et al., 2006), (Ansari and Seifi, 2013), and (Jokar and Mokhtar, 2018) have featured WHR mitigation in their studies, but ignore the aforementioned input criteria for measuring the net electricity generated from WHR which would have a decisive impact on determining the viability of such projects as most cement plants rarely operate at their full production capacity. For reference, the national average cement utilisation rate in India was at 66% in 2020 as depicted in Fig. 21.

Fig. 21. Utilisation share of cement production capacity in India, from fiscal years[5] 2012 to 2020 (Madhumitha Jaganmohan, 2021).



With exception of (Proaño et al., 2020), none of the other SD studies featured the study of upcoming carbon capture techniques such as indirect carbonation in the cement domain. Major cement manufacturers such as LafargeHolcim have been actively investing into CO2 mitigation using carbon capture and an all-encompassing model featuring these newer techniques would have enabled other cement plants to accordingly investigate the cost-benefit of utilising carbon capture over other strategies (“LafargeHolcim launches carbon capture project in Canada,” 2019).

Based on the gaps discussed in this section, the current study involves construction of a model that would be feature a) all the mitigation strategies that are being currently pursued in the cement domain, b) facilitate evaluation of a combination of mitigation strategies with interacting parameters, and c) provisions for investigating the mitigation strategies on individual plant installations to aid with the decision-making process.

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[5] India's fiscal year begins in April and ends in March

4. MODELLING PROCESS

Based on the scope for implementation of mitigations strategies in the cement industry, which was discussed in the previous chapter, following strategies are chosen for implementation in this current study:

- Captive Power Generation: WHR, Solar Photovoltaic (SPV), and conventional fuels (e.g., coal, natural gas, fuel oil).
- Clinker Substitution Module: Fly Ash, Wet Ash, and Blast Furnace Slag.
- Fuel Substitution Module: RDF, TDF, and biofuels (from microalgae).
- Carbon Capture Module: Indirect Carbonation, Carbon Capture and Storage (CCS), and generation of biofuel using microalgae.
- Efficiency Improvements Module: For efficiency related upgrades specific to individual cement plant including upgradation of production process (wet to dry, semi-dry to dry, etc.,), pre-heater arrangement (none to 1-stage, 2-stage, 3-stage, 4-stage, 5-stage, and 6-stage), pre-calciner, introduction of VFD to ID fans, etc.

4.1 Conceptualisation

The previously discussed mitigation strategies have been conceptualised into the following model, as seen in Fig. 22. The elements from the various strategies have been accordingly colour coded as follows:

- Red – Captive Power Generation
- Cyan – Fuel Substitution
- Indigo – Clinker Substitution
- Purple – Carbon Capture
- Orange – Efficiency Improvements

The black text represents the mutual elements that bind together all the strategies that can be simultaneously implemented in a cement manufacturing plant. The element “Company financial resources” refers to the budget of the cement plant related to modules featured in the model, including capital investment, operational costs, carbon taxation, subsidies, income from sale of by-products, and savings from implementation of specific mitigation strategies. Similarly, “Local Government Budget” refers to the budget of the local government allocated to policies for encouraging CO2 mitigation, which is replenished through carbon taxes collected from the cement plant.

As described in the previous chapter, the polarity on the links between the various elements indicates whether two elements are positively related, wherein increase in one element leads to an increase in the connected element, or negatively related, wherein increase in one element leads to a decrease in the connected element.

In case of captive power generation, higher the company financial resources, more it can invest into generation of power exclusively for the plant operations, from both conventional and non-conventional sources. The captive power generation in turn, would reduce the dependency of the plant on purchase of electricity from external entities or regional grid, thereby reducing the plant expenditure on purchased electricity. Consequently, captive generation of electricity from renewable sources reduces the amount of emissions attributed to the plant energy consumption, thereby reducing the expenditure through carbon tax. Depending on the local government policy, the plant may be also additionally rewarded through subsidies for undertaking mitigation strategies which will enable the sustenance of the adopted mitigation strategies and other plant operations.

For fuel substitution, the higher the company financial resources, more it can invest in procuring alternative fuels as a replacement to fossil fuels. Some alternative fuels would require additional processing before they can be used in the cement kiln, which in turn incurs a slight increase in energy expenditure, but depending on the fuel used would significantly reduce the emissions from fuel utilisation when compared to traditional fossil fuels such as coal and petcoke. This would lead to fewer taxes on CO2 emissions, and possibly subsidies depending on the local government policy.

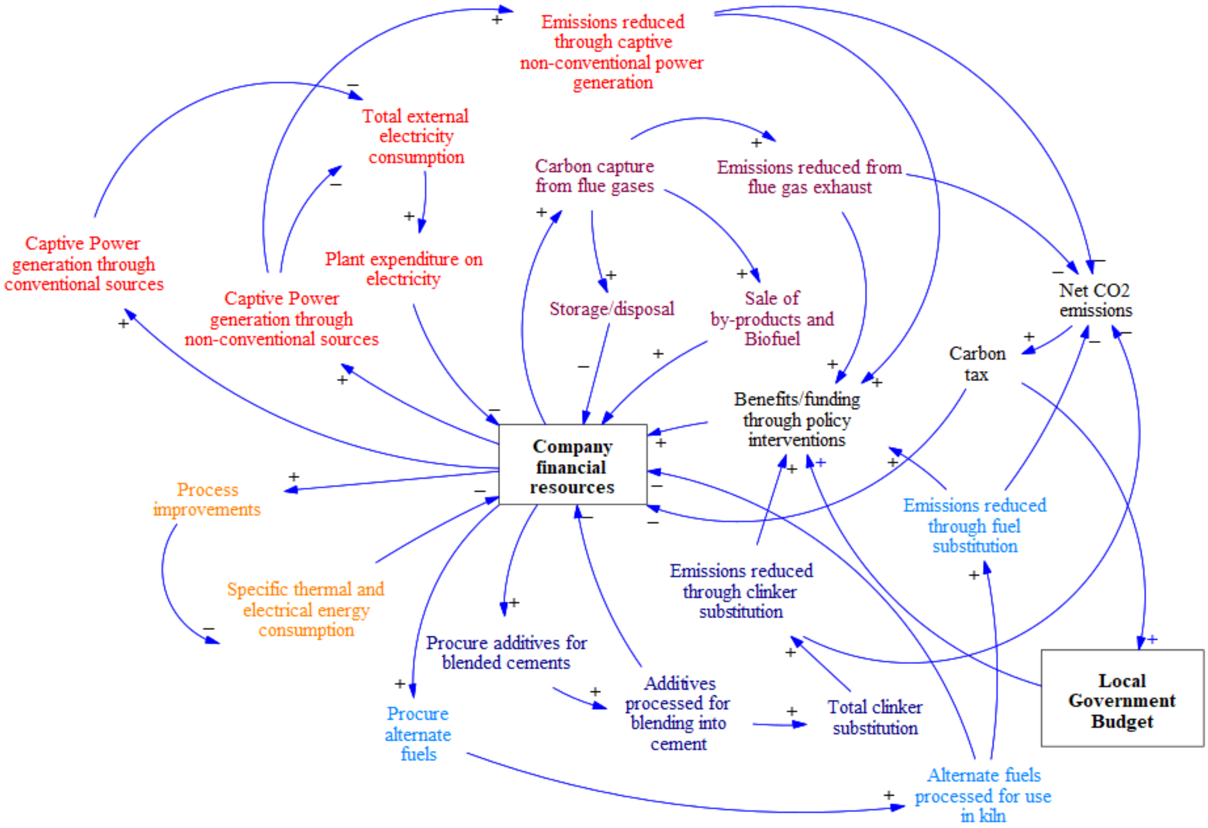

Fig. 22. Conceptualisation of the model encompassing all the included mitigation strategies applicable to a cement manufacturing plant. The various colours indicate the division of elements as per each specific mitigation strategy, with red – captive power generation, purple – carbon capture, orange – efficiency improvements, cyan – fuel substitution, and indigo – clinker substitution.

For clinker substitution, the higher the company financial resources, more it can procure alternative materials that can be processed as a partial clinker replacement. Processing of these alternative materials incurs an increase in energy expenditure, but still reduces emissions from production of clinker that is being replaced. The reduced emissions would lead to fewer taxes on CO2 emissions and possibly subsidies depending on the local government policy.

For carbon capture, availability of company financial resources would allow for implementation of various CO2 capture strategies, some of which would lead to additional benefits for the company, such as production of biofuels or by-products which can be either sold in the local market or used in the plant processes.

For efficiency improvements, availability of resources would enable the implementation of upgradation projects to improve electrical and thermal efficiency of the various processes in the cement plant. The improvements in energy efficiency would consequently lead to fewer CO2 emissions and as well as plant expenditure. The reduction in CO2 emissions would further lead to fewer carbon taxes. The various strategies described in Figure 22 are further expanded in sections 4.1.1 to 4.1.5.

4.1.1. Captive Power Generation

The causal loop diagram of the captive power generation module is visualised in Fig. 23. This strategy enables the cement plant to procure fewer units of electricity from external sources and the local grid, thereby leading to a considerable reduction in CO2 emissions and as well as plant expenses on procuring electricity depending on the grid emission factor and the regional electricity tariffs, respectively. Depending on the availability of company financial resources, the cement plant will be able to adopt and commission captive power plants that generate electricity either through conventional sources such coal, natural gas, and petcoke or through non-conventional sources such as solar, or through WHR. Based on the regional grid emission factor or the emission factor of the external provider, captive power generation gives control to the cement plant stakeholders to reduce significant amount of CO2 emissions by utilising WHR or non-conventional sources. Alternatively, captive generation using conventional sources could also lead to reduction in CO2 emissions by using a more efficient fossil fuel, i.e., if the regional grid is predominantly powered by coal, the plant can captively generate using natural gas which has a lower emission factor. Captive Power plant projects require significant capital expenditure and as well as monthly operational costs for maintenance and raw material procurement, which could potentially limit the amount of resources the cement plant may spend on other mitigation strategies. However, the captive power generation would also lead to savings in expenditure previously allocated to external purchase of electricity, which could potentially offset the operation and maintenance costs. Depending on the local government policies, reduction in CO2 emissions would also lead to savings in carbon tax and other additional subsidies, which could subsequently strengthen the company financial reserves.

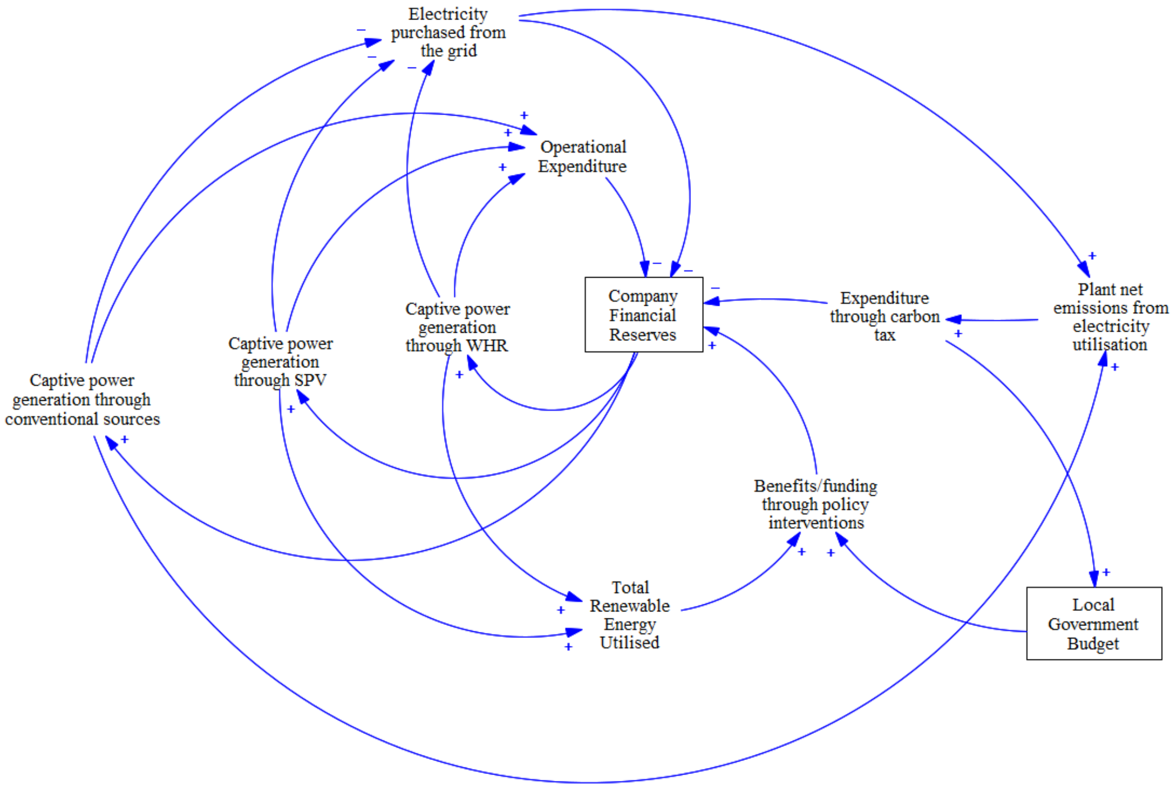

Fig. 23. Conceptualisation of sub-model for captive power generation

4.1.2. Clinker Substitution

The causal loop diagram of the clinker substitution module is visualised in Fig. 24. This strategy allows for the cement plant to replace a portion of the clinker with alternative substitutes such as fly ash, wet ash, and blast furnace slag. By reducing the amount of clinker in the final product of cement, i.e., the clinker to cement ratio, the plant needs to produce less clinker in the rotary kiln while producing the same amount of end product, i.e., the cement. As clinker production is the most emission intensive process within the cement manufacturing plant (through the chemical process of calcination and as well as the thermal energy required by it), the reduction in amount of clinker produced directly leads to a decrease in overall CO2 emissions from the plant. Additionally, depending on the source of limestone (whether it is captive mining or procuring from external entity), it could also lead to significant savings in plant expenditure. Additional savings are achieved through reduced taxes on CO2 emissions and as well as any applicable subsidies based on the local government policies. Unlike other raw materials, the substitutes such as blast furnace slag and fly ash are only available at the location of other industrial plants, such as steel plants and thermal power plants respectively. The locations of these industries could be far away from the cement plant, which could lead to expenditure and as well as emissions from the transportation (WBCSD and CSI guidelines on emission reporting recommend calculation of emissions from transportation). Once procured, the clinker substitutes need to be processed and ground to a suitable size before being mixed with the other constituents of cement. The additional processing includes drying, which consumes thermal energy, and grinding which consumes electrical energy, both of which lead to auxiliary emissions. Additionally, local government regulations limit how much clinker in the Portland cement can be replaced by substitutes.

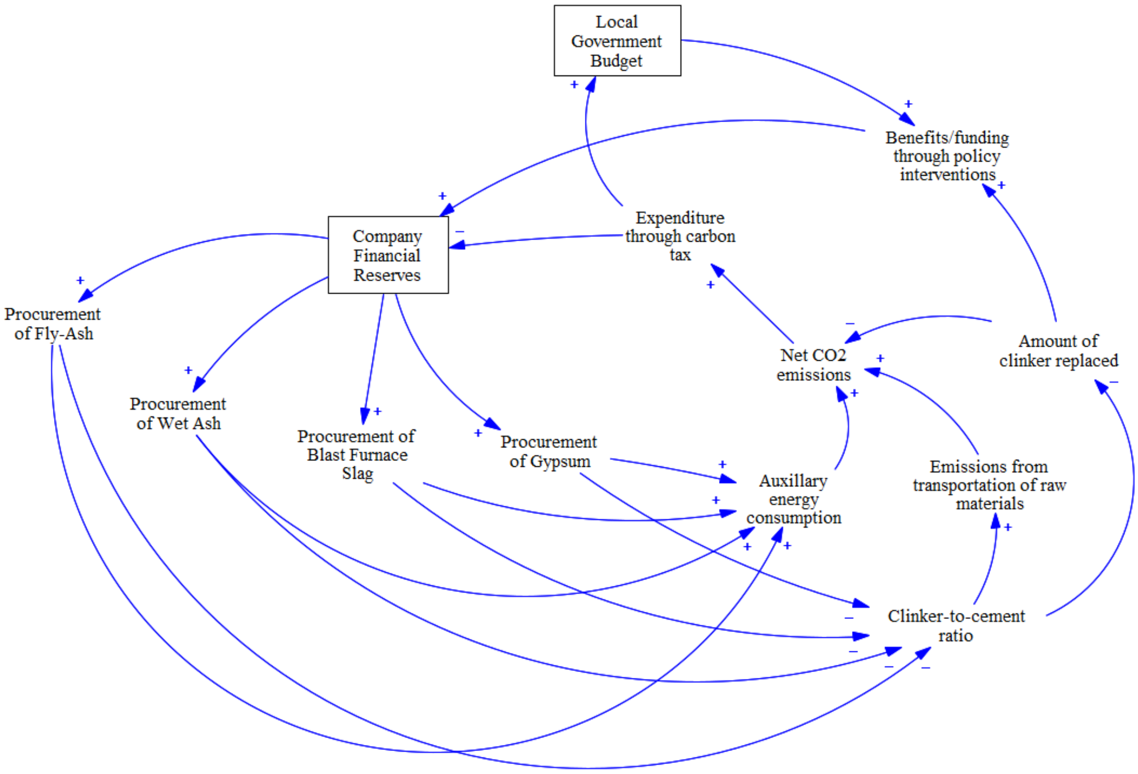

Fig. 24. Conceptualisation of sub-model for clinker substitution

4.1.3. Fuel Substitution

The causal loop diagram of the fuel substitution module is visualised in Fig. 25. This module allows for assessing the benefits of replacing a portion of fossil fuels used in the rotary kiln (and additionally for drying of raw materials) with alternative fuels such as RFD, TDF, and Biofuels (producing using microalgae in the carbon capture plant, further described in later sections 3.1.4 and 3.2.4).

Emissions from Biofuels are not counted as per IPCC as it is considered “climate-neutral” (“CO2 Accounting and Reporting Standard for the Cement Industry,” 2011). However, emissions from TDF and RDF are considered are partially climate-neutral due to significant organic content. The emission factor of both TDF and RDF are lower than conventional fuels currently used in kiln such as coal and petcoke. Additionally, depending on the availability of waste, the cost of utilising alternative fuels is significantly cheaper than conventional fuels. However, if the wastes are captively processed within the plant, this may incur additional expenditure in form of energy use, specifically for operating and maintenance of shredding and drying equipment. The expenses can be either fully or partially offset my reduction in plant expenditure in procuring conventional fuels and carbon taxes. Additionally, certain countries like India have existing policies that provide subsidies for utilising alternative fuels like RDF, which further enhances the financial sustainability of this mitigation approach to reduce emissions. The biofuels used in this module are based on the amount that can be generated through CO2 capture using microalgae, thereby the amount of fuel produced is dependent on the net CO2 emissions generated within the cement plant.

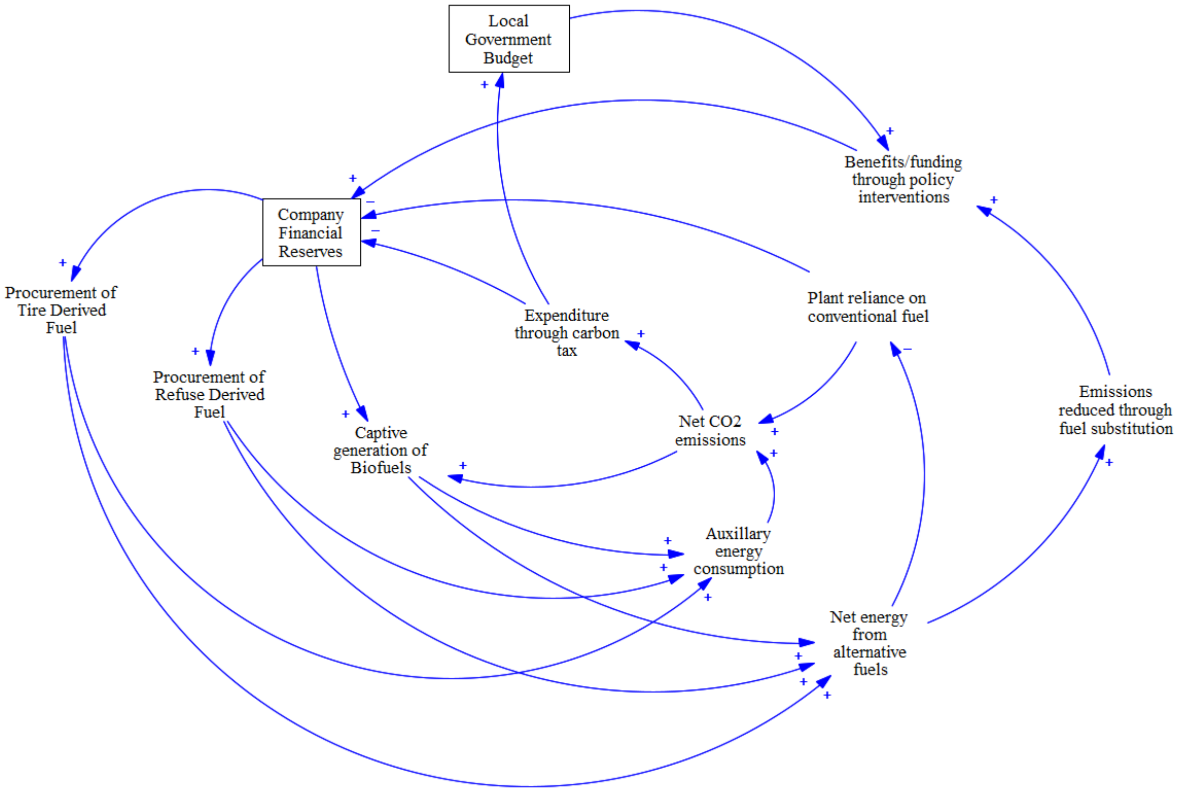

Fig. 25. Conceptualisation of sub-model for fuel substitution

4.1.4. Carbon Capture

The causal loop diagram of the carbon capture module is visualised in Fig. 26. This module assesses the benefits of using carbon capture technologies such as indirect carbonation, capture and storage, and growing microalgae as a means to reduce CO2 emissions within a cement plant. Compared with rest of the mitigation strategies discussed in this chapter, carbon capture techniques require large amounts of capital investment to set up the equipment necessary for commencing operations and the strategies are relatively new and are in experimental stage. Some of the carbon capture strategies provide additional value to the plant such as the biomass from the microalgae can be processed into biofuel, which can be later utilised in the rotary kiln, generating savings for the plant by reducing their need for procuring conventional fuels. The indirect carbonation method generates by-products that can be sold for recovering a portion of the operational expenditure depending on their market value. The carbon capture and storage methods requires additional efforts to manage a logistical network for transporting the compressed CO2 and storing it either in designated off-shore or on-shore sites. All of the methods also require auxiliary energy for operation of the required equipment and thereby generate a portion of CO2 emissions by themselves. As a relatively new mitigation strategy, it would require suitable policy support for it to be a sustainable strategy within the cement industry for reduction in CO2 emissions.

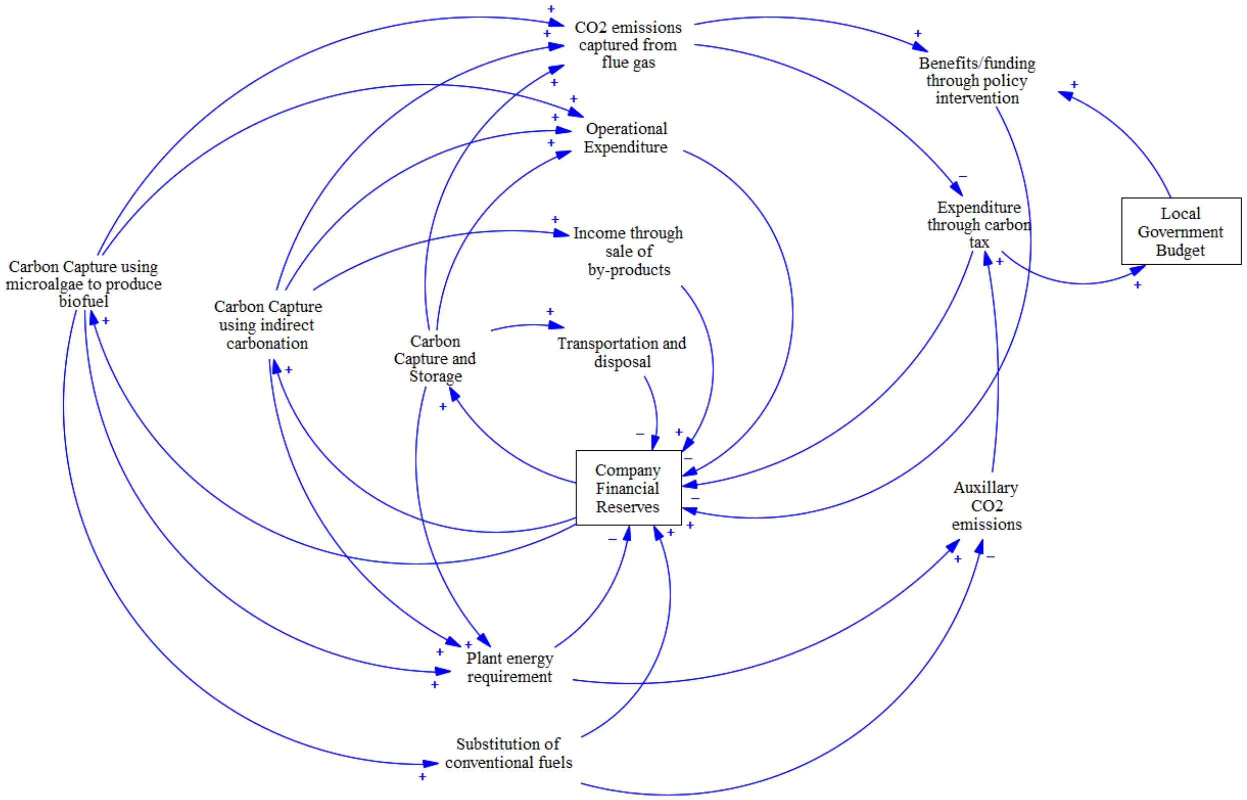

Fig. 26. Conceptualisation of sub-model for carbon capture

4.1.5. Efficiency Improvements

The causal loop diagram of the efficiency improvements module is visualised in Fig. 27. The module facilitates comparisons of upgrading old plants to modern processes with other mitigation strategies, for assisting the cement plant stakeholders in choosing an upgrade path which would lead to a significant capital investment and plant downtime, or achieve similar reduction in CO2 emissions by employing other strategies at a lower capital cost and downtime. The modernisation of plant processes primarily leads to improvement of thermal efficiency, thereby requiring less thermal energy for production of cement. Similarly, upgradation of plant equipment such as forced draft fans and grinding equipment (such as ball mills) would lead to improvement of electrical energy efficiency, thereby consuming less electricity for production of cement. Improvements in energy efficiency leads to fewer overall CO2 emissions and thereby reduced expenditure through carbon tax, depending on the local government policy.

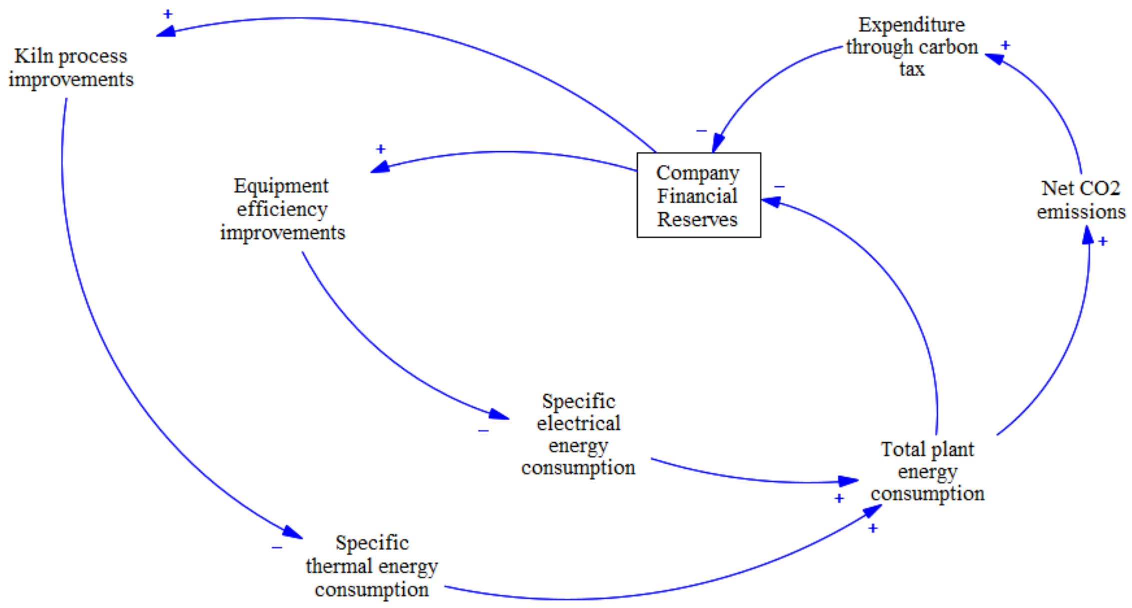

Fig. 27. Conceptualisation of sub-model for efficiency improvements

4.2 Construction of Sub-Models

The primary model consists of various modules facilitating experimentation of specific mitigation strategies such as clinker substitution, alternative fuels, carbon capture, captive power generation, and general efficiency improvements. The sub-models are further described in the later sections. For the purpose of this study, the monetary units are labelled as INR (Indian Rupee) as the subsequent experiments and scenarios are tested from an Indian cement plant perspective. The variables, stocks, and flows utilised in the primary model for connecting the various sub-models are described in Table 19. The model and its subentities are visualised in Appendix I, while the code to re-construct the model is provided in Appendix II.

Table 19. Description of variables, stocks, and flows utilised in the primary model

Nomenclature	Description	Equation[6]	Units/ Timestep
Emissions from plant processes	Combined amount of carbon-di-oxide (CO2) emissions from the following sub-models: • Clinker Substitution Module • Fuel Substitution Module	"Captive Power Generation Module" -> "Monthly emissions" + "Clinker Substitution Module" -> "Monthly emissions" + "Fuel Substitution Module" -> "Monthly emissions"	tCO2

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[6] The sub-models, datasets, and variable names are all enclosed in double quotes. The notation “A -> B” refers to a variable or dataset “B” which belongs to the Sub-model “A”

	- Captive Power Generation Module		
Carbon tax rate	Input dataset consisting of forecasted carbon tax rate value throughout the duration of the simulation.	N/A	INR/tCO2
Applicable Carbon tax	Calculated amount of tax to be paid at each time-step	"Carbon tax rate" -> "INR/tCO2" * "Emissions/Month"	INR
Emissions/Month	Calculated monthly CO2 emissions from the plant	"Emissions from plant processes" - "Carbon Capture Module"->"Monthly emissions"	tCO2
Expenditure/Month	Calculated monthly expenditure of the plant activities related to the mitigation strategies	"Captive Power Generation Module"->"Monthly expenditure" + "Clinker Substitution Module"->"Monthly expenditure"+"Carbon Capture Module"->"Monthly expenditure" + "Efficiency Module"->"Monthly expenditure" + "Fuel Substitution Module"->"Monthly expenditure" + "Applicable Carbon tax"	INR
Carbon tax collected (CT)	Monthly tax collected by the local government for CO2 emissions from the cement plant	"Applicable Carbon tax"	INR
Expenditure through subsidies (ES)	Monthly subsidies awarded by the local government for CO2 mitigation strategies implemented by the cement plant	"Captive Power Generation Module"->"Subsidy" + "Clinker Substitution Module"->"Applicable green subsidies" + "Fuel Substitution Module"->"Green subisdy"	INR
Net Policy Cost	Holds the net income/expenditure of the local government for policies applicable on the cement plant. Initialised to 0.	$Net\ Policy\ Cost\ (t) = \int_{t0}^{t} [CT(s) - ES(s)]\, ds + "Net\ Emissions"\ (t0)$	INR
Net Emissions[2]	Holds the total amount of CO2 emissions from the plant at the end of the simulation run. Initialised to 0.	$Net\ Emissions\ (t) = \int_{t0}^{t} "Emissions/Month"(s)\, ds + "Net\ Emissions"\ (t0)$	tCO2

Net Expenditure[1]	Holds the total expenditure of the plant activities related to the mitigation strategies at the end of the simulation run. Initialised to 0.	$Net\ Expenditure\ (t) = \int_{t0}^{t} "Expenditure/Month"(s)\ ds + "Net\ Expenditure"\ (t0)$	INR

[2] Where t is the current time-step, t0 is the initial time-step, and s is a time-step between t and t0

4.2.1. Captive Power Generation Module

For realising the captive power module described in the previous chapter, the list of exogenous variables and input parameters necessary for running the simulation are described in Table 20. The input parameters taken from the other modules in the model are described in Table 21, while the variables from this model that are used as input parameters in other modules in the model are described in Table 22. The list of variables whose values are calculated during the simulation run are described in Table 23. Subsequently, the list of stocks and flows used in this module are listed in Tables 24 and 25 respectively.

Table 20. List of input parameters and exogenous variables used in Captive Power Generation Module

Nomenclature	**Description**	**Equation**	**Units/Timestep**
Specific Flue Gas generation	Amount of flue gas generated per unit of clinker produced	Input parameter	NM3/kg
ΔT	Temperature differential for calculating the amount of recoverable heat energy from flue gas	Input parameter	degC
Flue gas flow	Calculates the flow rate of flue gas	("CSM: Clinker produced"/30)*"Specific Flue Gas generation"*100	NM3/hr
Heat available (mcΔT)	Calculates the heat available for generating electricity from flue gas	"Flue gas flow"*"ΔT"*0.25	Kcal/hr
Target share of WHR generation	For setting the target share of electrical energy that is to be generated using WHR. Since it depends on the available heat in the plant processes, if the target share is set to higher than available energy, it will default to maximum possible generation using waste heat	Input parameter	%
OPEX - WHR	Cost of operation and maintenance of the equipment required for generating electricity	Input dataset	INR/kWh

	using WHR		
CAPEX - WHR	Capital expenditure required for setting up the equipment necessary for generating electricity using WHR. Can be set to one time cost or a recurring expenditure	Input parameter	INR
Target share of SPV	For setting the target share of electrical energy that is to be generated using Solar Photovoltaic cells (SPV)	Input dataset	%
OPEX – SPV	Cost of operation and maintenance of the equipment required for generating electricity using SPV	Input dataset	INR/kWh
CAPEX - SPV	Capital expenditure required for setting up the equipment necessary for generating electricity using WHR. Can be set to one time cost or a recurring expenditure	Input parameter	INR
Target share of thermal power using fossil fuels	For setting the target share of thermal energy that is to be generated fossil fuels	Input parameter	%
OPEX – Thermal power	Cost of operation and maintenance of the equipment required for generating electricity using WHR	Input dataset	INR/kWh
CAPEX – Thermal power	Capital expenditure required for setting up the equipment necessary for generating electricity using WHR. Can be set to one time cost or a recurring expenditure	Input parameter	INR
Grid Emission Factor	Amount of emissions released per unit of electricity used from the grid	Input dataset	tCO2/kWh
Grid Electricity Tariff	Cost of electricity per unit when purchasing from the grid	Input dataset	INR/kWh
Subsidy rate	Amount of subsidy awarded for 1 unit of green captive electricity generated	Input dataset	INR/kWh
GCV	Gross calorific value, i.e., amount of	Input dataset	kcal/kg

	heat energy per unit of fuel, of either coal or natural gas used for captive power generation		
Coal Tariff	Cost of procuring a ton of coal	Input dataset	INR/ton
Heat Rate - Coal	Amount of heat required for converting one unit of coal into electrical energy	Input parameter	kcal/kWh
Emission factor (coal)	Amount of CO2 emissions released for one unit of electricity generated using coal	Input parameter	Tons/kWh

Table 21. List of input parameters that are taken from other modules, to be used in Captive Power Generation Module

CSM: Electricity requirement for clinker and substitutes	Total amount of electricity required for production of clinker and substitutes	Input from Clinker Substitution Module	kWh
CSM: Clinker produced	Total amount of clinker produced	Input from Clinker Substitution Module	tons
CCM: Electricity requirement for Carbon capture	Total amount of electricity required in the carbon capture module	Input from Carbon Capture Module	kWh
FSM: Electricity requirement for substitute fuel processing	Total amount of electricity required for processing alternative fuels	Input from Fuel Substitution Module	kWh

Table 22. List of variables from Captive Power Generation module that are used as input parameters in other modules

Net plant electricity consumption	Total amount of electricity consumed in the plant operations	"Plant Electricity Requirement"	kWh
CSM: Electricity Emission factor	Effective emission factor of the electricity utilised in the plant, after accounting for the various configuration and sources	"Calculated emission factor"	tCO2/kWh
CSM: Electricity tariff	Effective cost spent on a unit of electricity utilised in the plant, after accounting for the various configuration and sources	"Calculated Electricity tariff"	INR/kWh

Table 23. List of dynamic variables utilised in Captive power Generation

Max WHR	Calculates the maximum amount of	(("Heat available (mcΔT)"/650)/5)	kW

	electricity that can be generated using waste heat available in the plant		
Plant Electricity Requirement	Calculates the total amount of electricity required by all the plant activities featured in this model	("CCM: Electricity requirement for Carbon capture"+"CSM: Electricity requirement for clinker and substitutes"+"FSM: Electricity requirement for substitute fuel processing") - (("CCM: Electricity requirement for Carbon capture"+"CSM: Electricity requirement for clinker and substitutes"+"FSM: Electricity requirement for substitute fuel processing")*"EIM: % reduction in thermal energy requirement"/100)	kWh
Electricity generated from WHR	Calculates the amount of electricity that is to be generated from WHR	if (("Heat available (mcΔT)"/650)/5)*720 <= ("Plant Electricity Requirement"*"Target share of WHR generation"("time")) then (("Heat available (mcΔT)"/650)/5)*720 else ("Plant Electricity Requirement"*"Target share of WHR generation"("time"))	kWh
Cost of power generation - WHR	Calculates the cost of power generation through WHR based on the input parameters	(("CAPEX - WHR"("time")*"Electricity generated from WHR")/720)+("OPEX - WHR"("time")*"Electricity generated from WHR")	INR
Electricity purchased from grid	Calculates the total amount of electricity purchased from the grid based on the input parameters	"Plant Electricity Requirement"-("Electricity generated from SPV"+"Electricity generated from thermal power"+"Electricity generated from WHR")	kWh
Electricity generated from SPV	Calculates the total amount of electricity generated from SPV based on input parameters	"Plant Electricity Requirement"*"Target share of SP"("time")	kWh
Cost of power generation - SPV	Calculates the cost of power generation through SPV based on input parameters	(("CAPEX - SPV"("time")*"Electricity generated from SPV")/720)+("OPEX - SPV"("time")*"Electricity generated from SPV")	INR
Emissions from grid electricity	Calculates the emissions generated from the use of electricity purchased from the grid	"Electricity purchased from grid"*"Grid Emission Factor"("time")/1000	tCO2
Renewable energy generated	Calculates the total amount of renewable	"Electricity generated from SPV"+"Electricity generated	kWh

	energy generated captively	from WHR"	
Cost of power generation from thermal power	Calculates the cost of captive power generation from conventional fuels such as coal and natural gas	(("CAPEX - Thermal Power"("time")*"Electricity generated from thermal power")/720)+ (0.01*"OPEX - Thermal Power"("time")*"Electricity generated from thermal power")+ "Fuel tariffs"*"Electricity generated from thermal power"	INR
Emissions from captive power generation	Calculates the total amount of emissions generated from the captive generation of electricity	"Electricity generated from thermal power"*"Emission factor"	tCO2
Cost of captive power generation	Calculates the total cost of generating captive electricity from all of the applicable sources and configurations	"Cost of power generation - SPV"+"Cost of power generation - WHR"+"Cost of power generation from thermal power"	INR
Calculated Electricity tariff	Calculates the average cost of a unit of electricity utilised in the plant	("Cost of captive power generation"+"Cost of purchased electricity")/"GV: Plant electricity utilised"	INR/kWh
Calculated emission factor	Calculates the average emissions per unit of electricity utilised in the plant	"Monthly emissions"/"Plant Electricity Requirement"	tCO2/kWh

Table 24. List of stocks used in Captive Power Generation Module

Net Expenditure [Captive Power Module]	Holds the total expenditure of electricity utilisation, including purchases from the grid and captive power generation, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \left(Monthly\ Expenditure\ (s)\right) ds + Net\ Expenditure\ (t0)$	INR
Net Emissions [Captive Power module]	Holds the total amount of CO2 emissions from the plant electricity utilisation, including emissions from grid and captive power generation, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \left(Monthly\ Emissions\ (s)\right) ds + Net\ Emissions\ (t0)$	Tons

Table 25. List of flows used in Captive Power Generation Module

Monthly Expenditure	Calculates the total expenditure related to electricity utilisation,	"Cost of captive power generation"+"Cost of purchased electricity"-	INR

	including purchases from grid and captive power generation	"Subsidy"	
Monthly Emissions	Calculates the total amount of CO2 emissions released through electricity utilisation, including purchases from the gird and captive power generation	"Emissions from captive power generation"+"Emissions from grid electricity"	Tons

4.2.2. Clinker Substitution Module

For realising the clinker substitution module described in the previous chapter, the list of exogenous variables and input parameters necessary for running the simulation are described in Table 26. The input parameters taken from the other modules in the model are described in Table 27, while the variables from this model that are used as input parameters in other modules in the model are described in Table 28. The list of variables whose values are calculated during the simulation run are described in Table 29. Subsequently, the list of stocks and flows used in this module are listed in Tables 30 and 31 respectively.

Table 26. List of input parameters and exogenous variables used in Clinker Substitution module

Nomenclature	Description	Equation	Units/Timestep
Limestone tariffs	Cost of limestone procurement, either purchased or captively mined at the cement plant	-	INR/ton
Plant utilisation rate	Ratio of clinker produced to maximum production capacity	-	%
Clinker-to-cement ratio	Ratio of clinker to non-clinker constituents of cement	(100-("% Blast Furnace Slag"+"%: Fly Ash"+"% Gypsum"+"% Wet Ash"))/100	%
% Wet Ash	The parameter is used to set the composition of wet ash in cement	-	%
% Fly Ash	The parameter is used to set the composition of fly ash in cement	-	%
% Blast Furnace Slag	The parameter is used to set the composition of blast furnace slag in cement	-	%
% Gypsum	The parameter is used to set the composition of gypsum in cement	-	%
Fly Ash Cost	Cost for procuring 1 ton of Fly Ash	Input dataset	INR/ton
Gypsum Cost	Cost for procuring 1 ton of Gypsum	Input dataset	INR/ton
Blast Furnace Slag Cost	Cost for procuring 1 ton of Blast Furnace Slag	Input dataset	INR/ton

Average Distance from raw material source	The parameter is use to set the average distance from the source of raw material to the cement plant	Input parameter	KM
Emission factor of transportation	Amount of CO2 emissions released in the process of transporting 1 ton of raw materials to the plant per kilometre of distance	Input dataset	(tCO2/ton)/KM
Clinker substitution: Subsidy rate	The parameter is used to set the subsidy rate for emissions reduced through clinker substitution	Input dataset	INR/tCO2
Plant capacity (per month)	Maximum amount of clinker that can be produced in the plant per month	Input parameter	tons
Misc. expenditure %	Miscellaneous expenditure related to production of clinker as a percentage of total costs (excluding energy costs). Can be utilised for including licensing cost (for limestone mining) and related workforce costs	Input parameter	%
Emission factor: Calcination	Amount of CO2 emissions released from 1 ton of limestone during the process of calcination	Input parameter	tCO2/ton
Toggle: Automatic thermal energy requirement calculation	Toggle for enabling automatic thermal energy requirement for drying of raw materials	Input parameter	-
Input: % Moisture per ton	Amount of moisture present in ton of raw materials	Input parameter	%
Drying Efficiency %	For setting the efficiency of the drying process	Input parameter	%
Fly Ash: Thermal energy requirement	For setting the specific thermal consumption of processing fly ash as a clinker substitute	Input parameter	kcal/ton
Fly Ash: Electrical energy requirement	For setting the specific electrical consumption of processing fly ash as a clinker substitute	Input parameter	kWh/ton
Gypsum: Thermal energy requirement	For setting the specific thermal consumption of processing gypsum as a clinker substitute	Input parameter	kcal/ton
Gypsum: Electrical energy requirement	For setting the specific electrical consumption of processing gypsum as a clinker substitute	Input parameter	kWh/ton
Blast Furnace Slag:	For setting the specific	Input parameter	kcal/ton

Thermal energy requirement	thermal consumption of processing blast furnace slag as a clinker substitute		
Blast Furnace Slag: Electrical energy requirement	For setting the specific electrical consumption of processing blast furnace slag as a clinker substitute	Input parameter	kWh/ton
Wet Ash: Conversion efficiency	For setting the efficiency of the drying process for converting wet ash into fly ash	Input parameter	%
Wet Ash: Moisture Content	For setting the amount of moisture content in wet ash	Input parameter	%
Electricity requirement per ton of wet ash	For setting the amount of electrical energy required for converting a ton of wet ash into fly ash	Input parameter	kWh/ton
Wet Ash: CAPEX+OPEX/ton (excluding energy)	Expenditure for processing a ton of wet ash into fly ash, excluding energy costs	Input dataset	INR/ton
Wet Ash: Transportation Costs	Cost of transporting wet ash to the cement plant	Input dataset	INR/ton

Table 27. List of input parameters that are taken from other modules, to be used in Clinker Substitution Module

Electricity Tariff	Cost per unit of electricity, whether generated captively or purchased from the regional grid	Input from *Captive Power Module*	INR/kWh
Electricity Emission Factor	CO2 emissions per unit of electricity, whether generated captively or purchased from the regional grid	Input from *Captive Power Module*	tCO2/kWh
Fuel Tariff	Cost per unit of fuel, whether conventional or alternative fuel	Input from *Fuel Substitution Module*	INR/kcal
Fuel Emission Factor	CO2 emissions per unit of fuel consumed, whether conventional or alternative fuel	Input from *Fuel Substitution Module*	tCO2/kcal
Clinker: Specific Thermal Energy Consumption	Amount of thermal energy consumed for producing 1 unit of final product	Input from *Efficiency Improvement Module*	kcal/kg
Specific Energy Consumption – Electrical (Until Clinkerisation)	Amount of Electricity consumed until the process of clinkerisation for producing 1 unit of final product. Consists of electricity consumption in	Input from *Efficiency Improvement Module*	kWh/ton

	the preparation of raw materials		
Specific Energy Consumption – Electrical (After Clinkerisation)	Amount of Electricity consumed after the process of clinkerisation for producing 1 unit of final product	Input from *Efficiency Improvement Module*	kWh/ton

Table 28. List of variables from Clinker Substitution Module that are used as input parameters in other modules

EIM:Clinker produced	Total amount of clinker produced	“Clinker produced”	Tons
EIM:Clinker-to-cement ratio	Amount of clinker in the final finished product, i.e., cement	“Clinker-to-cement ratio”	%

Table 29. List of dynamic variables utilised in Clinker Substitution Module

Amount of Fly Ash required from wet ash	Amount of fly ash generated after processing the wet ash as per the targeted composition	("Clinker-to-cement ratio"*"Clinker Produced")*("% Wet Ash"/100)	Tons
Amount of dry Fly Ash required	Amount of fly ash required as per the targeted composition	("Clinker-to-cement ratio"*"Clinker Produced")*("%: Fly Ash"/100)	Tons
Amount of Blast Furnace Slag required	Amount of blast furnace slag required as per the targeted composition	("Clinker-to-cement ratio"*"Clinker Produced")*("% Blast Furnace Slag"/100)	Tons
Amount of Gypsum required	Amount of Gypsum required as per the targeted composition	("Clinker-to-cement ratio"*"Clinker Produced")*("% Gypsum"/100)	Tons
Cost of procurement – Pozzolanic Materials	Combined amount of pozzolanic materials procured as per the targeted composition	("Amount of blast furnace slag required"*"Blast Furnace Slag Cost"("time")) + ("Amount of dry fly ash required"*"Fly Ash Cost"("time")) + ("Amount of Gypsum required"*"Gypsum cost"("time")) + "Wet Ash processing"->"Cost of wet ash (Excluding energy requirement)"	INR
Heat Energy Requirement for processing pozzolanic materials	Amount of heat energy required for processing the procured pozzolanic materials. Additionally calculates the heat energy needed for drying the raw materials based on the input parameter for moisture content	(("Amount of dry fly ash required"*"Fly Ash: Thermal energy requirement") + ("Amount of blast furnace slag required"*"Blast Furnace Slag: Thermal energy requirement") + ("Amount of Gypsum	kcal

		required"*"Gypsum: Thermal energy requirement") + "Wet Ash processing"->"Total thermal energy required for processing Wet Ash into Fly Ash") + (if "Toggle: Automatic thermal energy requirement calculation"=1 then ((70*0.24*(1-("Input: % Moisture per ton"/100))*1000)+ (("Input: % Moisture per ton"/100)*1000*650))/("Drying Efficiency %"/100) else 0)	
Electrical Energy requirement for processing pozzolanic materials	Amount of electricity required for processing the procured pozzolanic materials	("Amount of blast furnace slag required"*"Blast Furnace Slag: Electrical energy requirement") + ("Amount of dry fly ash required"*"Fly Ash: Electrical energy requirement") + ("Amount of Gypsum required"*"Gypsum: Electrical energy requirement") + "Wet Ash processing"->"Total electrical energy required for processing Wet Ash into Fly Ash"	kWh
Clinker Substituted	Total amount of clinker substituted by procured pozzolanic materials	"Amount of blast furnace slag required" + "Amount of dry fly ash required" + "Amount of Gypsum required" + "Amount of fly ash required from wet ash"	Tons
Emissions from transportation of pozzolanic materials	Amount of emissions generated as a result of transporting pozzolanic materials from their source to the cement plant	"Average distance from raw material source"("time")*"Clinker substituted"*"Emission factor of transportation"	Tons
Emissions from substitutes	Amount of emissions generated as a result of processing the pozzolanic materials before being blended with clinker	("Heat Energy Requirement for processing pozzolanic materials"*"fuel emission factor") + ("Electrical Energy Requirement for processing pozzolanic materials"*"Electricity emission factor")	Tons

Energy Cost of processing substitutes	Total cost of energy for processing the pozzolanic materials before being blended with clinker	("Heat Energy Requirement for processing pozzolanic materials"*"fuel tariff") + ("Electrical Energy Requirement for processing pozzolanic materials"*"Electricity tariff")	INR
Applicable green subsidies	Calculated amount of subsidy awarded to the plant for emissions reduced through clinker substitution	"Emissions reduced"*"Clinker substitution: subsidy rate"("time")	INR
Cost of limestone/ton of clinker	Calculated cost of limestone required for producing 1 ton of clinker. 1 Ton of clinker approximately requires 1.65 tons of limestone (Natural Environment Research Council, 2005)	"Limestone tariffs"("time")*1.65	INR/ton
Cost of clinker production (excluding electricity)	Total cost of producing clinker excluding electricity utilisation	("Clinker Produced"*"Misc. expenditure %")+ ("Cost of limestone/ton of clinker"*"Clinker Produced")	INR
Clinker Produced	Total amount of clinker produced, calculated based on the plant utilisation rate	("Plant utilisation rate"("time"))*100*"Plant capacity (per month)"	Tons
Heat energy requirement for clinker	Amount of heat energy required for producing 1 ton of clinker	"Clinker Produced"*"Clinker: Specific Thermal Energy Consumption"*1000	kcal
Emissions reduced	Calculated amount of emissions reduced by replacing a portion of clinker with pozzolanic materials	("Clinker substituted"*"Emission factor: Calcination")-"Emissions from substitutes"	Tons
Emissions from calcination process	Total emissions generated during the chemical process of calcination when producing clinker	"Clinker Produced"*"Emission factor: Calcination"	Tons
Electrical energy requirement for clinker	Total amount of electrical energy required for production of clinker	"Clinker Produced" * ("Specific Energy Consumption - Electrical (Until clinkerisation)"+ + "Specific Energy Consumption - Electrical (After clinkerisation)")	kWh
Wet Ash: Thermal energy required	Amount of thermal energy required for converting a ton of wet ash into fly ash.	((70*0.24*(1-"Wet Ash: Moisture Content")*1000)+ ("Wet Ash: Moisture Content"*1000*650))/"Wet Ash: Conversion efficiency"	kcal/ton
Total thermal energy	Total amount of	"Amount of wet ash	kcal

required for processing Wet Ash into Fly Ash	thermal energy required for converting the procured amount of wet ash into fly ash	procured"*"Wet Ash: Thermal energy required"	
Amount of wet ash procured	For calculating the total amount of wet ash procured for recovering the recovered amount of fly ash	("Clinker Substitution Module"->"Amount of fly ash required from wet ash")*(1-"Wet Ash: Moisture Content")	Tons
Cost of wet ash (Excluding energy requirement)	For calculating the total cost of procurement and processing of wet ash into fly ash, excluding energy costs	("Amount of wet ash procured"*"Wet Ash: CAPEX+OPEX/ton (excluding energy)"("time"))+("Wet Ash: Transportation Costs"("time")*"Amount of wet ash procured")	INR
Total electrical energy required for processing Wet Ash into Fly Ash	For calculating the total amount of electrical energy required for processing the procured wet ash into fly ash	"Amount of wet ash procured"*"Electricity requirement per ton of wet ash"	kWh

Table 30. List of stocks used in Clinker Substitution Module

Net Expenditure [Clinker Substitution Module]	Holds the total expenditure of clinker production, excluding electricity utilisation and fuel consumption, at the end of the simulation run. Initialised to 0.	$Net\ Expenditure\ (t) = \int_{t0}^{t} \left(Monthly\ Expenditure\ (s)\right) ds + Net\ Expenditure\ (t0)$	INR
Net Emissions [Clinker substitution module]	Holds the total amount of CO2 emissions from the plant through clinker production, excluding electricity utilisation and fuel consumption, at the end of the simulation run. Initialised to 0.	$Net\ Emissions\ (t) = \int_{t0}^{t} \left(Monthly\ Emissions\ (s)\right) ds + Net\ Emissions\ (t0)$	Tons
Net electrical Energy Consumption [Clinker Substitution	Holds the total amount of electricity consumed during clinker	$Net\ electrical\ Energy\ Consumption\ (t) = \int_{t0}^{t} \left(CPM{:}\ Monthly\ Electrical\ Energy\ Consumption\ (s)\right) ds + CPM{:}\ Monthly\ Electrical\ Energy\ Consumption\ (t0)$	kWh

Module]	production at the end of the simulation run. Initialised to 0.		
Net Thermal Energy Consumption [Clinker Substitution Module]	Holds the total amount of heat energy consumed during clinker production at the end of the simulation run. Initialised to 0.	$Net\ Thermal\ Energy\ Consumption\ (t) = \int_{t0}^{t} \left(FSM\!: Monthly\ Thermal\ Energy\ Consumption\ (s)\right) ds + FSM\!: Monthly\ Thermal\ Energy\ Consumption\ (t0)$	kcal

Table 31. List of flows used in Clinker Substitution Module

Monthly Expenditure	Calculated monthly expenditure of clinker production (excluding electricity utilisation and fuel consumption)	"Carbon tax on emissions"+"Cost of clinker production (excluding electricity)"+"Energy cost of processing substitutes"-"Applicable green subsidies"+"Cost of procurement - Pozzolanic materials"	INR
Monthly Emissions	Calculated monthly emissions from clinker production (excluding electricity utilisation and fuel consumption)	"Emissions from clinker production (excluding electricity)"+"Emissions from substitutes"+"Emissions from transportation of pozzolanic materials"	Tons
CPM: Monthly Electrical Energy Consumption	Calculated monthly electrical energy consumed during clinker production	"Electrical energy requirement for clinker"+"Electrical Energy Requirement for processing pozzolanic materials"	kWh
FSM: Monthly Thermal Energy Consumption	Calculated monthly thermal energy consumed during clinker production	"Heat energy requirement for clinker"+"Heat Energy Requirement for processing pozzolanic materials"	kcal

4.2.3. Fuel Substitution Module

For realising the Fuel Substitution Module described in the previous chapter, the list of exogenous variables and input parameters necessary for running the simulation are described in Table 32. The input parameters taken from the other modules in the model are described in Table 33, while the variables from this model that are used as input parameters in other modules in the model are described in Table 34. The list of variables whose values are calculated during the simulation run are described in Table 35. Subsequently, the list of stocks and flows used in this module are listed in Tables 36 and 37 respectively.

Table 32. List of input parameters and exogenous variables used in Fuel Substitution Module

Nomenclature	Description	Equation	Units/Timestep
Share of thermal energy	For setting the share of	Input parameter	%

requirement from Coal	thermal energy requirement that is to be met from using Coal as a fuel		
Share of thermal energy requirement from PETCOKE	For setting the share of thermal energy requirement that is to be met from using PETCOKE as a fuel	Input parameter	%
Share of thermal energy requirement from other conventional fuels	For setting the share of thermal energy requirement that is to be met from using any other conventional fuel	Input parameter	%
Share of thermal energy requirement from RDF	For setting the share of thermal energy requirement that is to be met from using RDF as a fuel	Input parameter	%
Share of thermal energy requirement from TDF	For setting the share of thermal energy requirement that is to be met from using TDF as a fuel	Input parameter	%
Average GCV of other conventional fuels	For setting Gross Calorific Value (GCV) of any other conventional fuel. GCV is the amount of heat released during the combustion of the fuel	Input parameter	kcal/kg
PETCOKE: GCV (avg)	For setting the average GCV of PETCOKE	Input parameter	kcal/kg
Coal: GCV (avg)	For setting the average GCV of Coal	Input parameter	kcal/kg
Emission Factor of other conventional fuels	For setting the amount of emissions per ton of other conventional fuels utilised	Input parameter	tCO2/ton
PETCOKE: Emission Factor	For setting the amount of emissions per ton of PETCOKE utilised	Input parameter	tCO2/ton
Coal: Emission Factor	For setting the amount of emissions per ton of coal utilised	Input parameter	tCO2/ton
Toggle: Alternative Fuel	Toggle for choosing the captive alternative fuel processing mode: • Input of “1” chooses Refuse Derived Fuel (RDF) mode • Input of “2” chooses Tire Derived Fuel (TDF) mode • Input of “3” chooses mixed mode which utilises both RDF and TDF • Input of “4” disables captive alternative fuel processing mode	Input parameter	-

Algae GCV	For setting the GCV of the biofuel generated from the algae in Carbon Capture Module	Input parameter	kcal/kg
Other conventional fuel tariffs	Cost for procuring 1 ton of other conventional fuels	Input dataset	INR/ton
Coal tariffs	Cost for procuring 1 ton of Coal	Input dataset	INR/ton
PETCOKE tariffs	Cost for procuring 1 ton of PETCOKE	Input dataset	INR/ton
RDF: Gross calorific value	For setting the GCV of the refuse derived fuel	Input parameter	kcal/kg
RDF: CAPEX	Cost for setting up a captive RDF processing plant of 100 tons per day capacity (TPD)	Input parameter	INR/100TPD
Tariff of processed RDF	Cost of procuring pre-processed RDF for use without investing into a captive processing plant	Input dataset	INR/ton
RDF: Emission Factor	Amount of CO2 emissions released during combustion of 1 ton of RDF	Input parameter	tCO2/ton
RDF: OPEX/ton (excluding energy)	Cost of operating a captive RDF processing plant excluding energy	Input dataset	INR/ton
RDF: Electrical Energy Requirement	Amount of electrical energy required for processing a ton of RDF	Input parameter	kWh/ton
Tariff of processed TDF	Cost of procuring pre-processed TDF for use without investing into a captive processing plant	Input dataset	INR/ton
TDF: Emission Factor	Amount of CO2 emissions released during combustion of 1 ton of TDF	Input parameter	tCO2/ton
TDF: OPEX/ton (excluding energy)	Cost of operating a captive TDF processing plant excluding energy	Input dataset	INR/ton
TDF: Electrical Energy Requirement	Amount of electrical energy required for processing a ton of TDF	Input parameter	kWh/ton
TDF: Gross calorific value	For setting the GCV of the tyre derived fuel	Input parameter	kcal/kg
TDF: CAPEX	Cost for setting up a captive RDF processing plant of upto 360 TPD	Input parameter	INR/360TPD
Subsidy rate for alternative fuels	Subsidy awarded for utilisation of ton of alternative fuels	Input dataset	INR/ton
RDF: Moisture content of raw material	Amount of moisture present in 1 ton of raw material used for RDF processing	Input parameter	%
TDF: Moisture content of raw material	Amount of moisture present in 1 ton of raw material used for TDF processing	Input parameter	%
Toggle: RDF - Captive processing	Toggle for enabling captive processing of RDF, i.e., process the raw	Input parameter	-

	material into fuel within the plant. Possible inputs: 0 – Purchase pre-processed fuel 1 – Purchase raw material and process them into fuel for using in the kiln		
Toggle: TDF - Captive processing	Toggle for enabling captive processing of TDF, i.e., process the raw material into fuel within the plant. Possible inputs: 0 – Purchase pre-processed fuel 1 – Purchase raw material and process them into fuel for using in the kiln	Input parameter	-

Table 33. List of input parameters that are taken from other modules, to be used in Fuel Substitution Module

% Reduction in thermal energy requirement	% of reduction in overall thermal energy requirement through implementation of efficiency improvement projects	Input from efficiency improvement module	%
Monthly thermal energy consumption	Total amount of thermal energy consumed during the production of clinker	Input from Clinker Substitution Module	Kcal
CCM: Algae available	Total amount of biofuel available, which is generated through the use of algae in the carbon capture module	Input from Carbon Capture Module	Tons

Table 34. List of variables from Fuel Substitution Module that are used as input parameters in other modules

CSM: Fuel Emission factor	Amount of CO2 emissions released per kcal of thermal energy generated	"Average Emission Factor of fuel used"	Tons/kcal
CSM: Fuel tariff	Cost of fuel for generating 1 kcal of thermal energy	"Monthly expenditure"/"Thermal Energy requirement"	INR/kcal
CPM: Electricity requirement for processing alternate fuels	Amount of electricity required for processing alternative fuels such as RDF and TDF	"Amount of refuse derived fuels procured"->"RDF: Total Electricity requirement"+"Amount of tire derived fuels procured"->"TDF: Total Electricity requirement"	kWh

Table 35. List of dynamic variables utilised in Fuel Substitution Module

Thermal Energy	Calculates the total	("CSM: Monthly thermal energy	kcal

requirement	amount of thermal energy required for plant operations	consumption"-"Amount of thermal energy available from Algae") - ("CSM: Monthly thermal energy consumption"*"EIM: % reduction in thermal energy requirement"/100)	
Amount of thermal energy available from Algae	Calculates the amount of thermal energy available through the use of biofuels generated from microalgae in the Carbon Capture Module	"CCM: Algae available"*"Algae GCV"*1000	kcal
Amount of Coal procured	Calculates the total amount of coal that needs to be procured for generating the given share of thermal energy	("Thermal Energy requirement"*("Share of thermal energy requirement from Coal"/100))*"Coal: GCV (avg)"*1000	Tons
Amount of PETCOKE procured	Calculates the total amount of PETCOKE that needs to be procured for generating the given share of thermal energy	("Thermal Energy reuirement"*("Share of thermal energy requirement from PETCOKE"/100))*"PETCOKE: GCV (avg)"*1000	Tons
Amount of other conventional fuels	Calculates the total amount of other conventional fuels that needs to be procured for generating the given share of thermal energy	("Thermal Energy requirement"*("Share of thermal energy requirement from other conventional fuels"/100))*"Average GCV of other conventional fuels"*1000	Tons
Share of thermal energy from conventional sources	Calculates the total share of thermal energy that is generated using conventional fuel sources	("Amount of Coal procured"*"Coal: GCV (avg)") + ("Amount of PETCOKE procured"*"PETCOKE: GCV (avg)") + ("Amount of other conventional fuels"*"Average GCV of other conventional fuels")	kcal
Cost of coal usage	Calculates the total cost of Coal that is to be procured for generating the given share of thermal energy	"Amount of Coal procured"*"Coal tariffs"("time")	INR
Emissions from coal usage	Calculates the total emissions released from use of coal for generating thermal energy	"Amount of Coal procured"*"Coal: Emission Factor"	tCO2
Cost of PETCOKE usage	Calculates the total cost of PETCOKE that is to be procured for generating the given share of thermal energy	"Amount of PETCOKE procured"*"PETCOKE tariffs"("time")	INR
Emissions from PETCOKE usage	Calculates the total emissions released from use of PETCOKE for generating thermal	"Amount of PETCOKE procured"*"PETCOKE: Emission Factor"	tCO2

	energy		
Cost of other conventional fuel usage	Calculates the total cost of other conventional fuels that is to be procured for generating the given share of thermal energy	"Amount of other conventional fuels"*"Other conventional fuel tariffs"("time")	INR
Emissions from other conventional fuel usage	Calculates the total emissions released from use of other conventional fuels for generating thermal energy	"Amount of other conventional fuels"*"Emission Factor of other conventional fuels"	tCO2
Cost of RDF usage	Calculates the total cost of RDF that is to be procured or captively processed for generating the given share of thermal energy	select case "Amount of refuse derived fuels procured"->"Toggle: RDF - Captive processing"=0 :"Amount of refuse derived fuels procured"->"Cost of procured RDF" case "Amount of refuse derived fuels procured"->"Toggle: RDF - Captive processing"=1:"Amount of refuse derived fuels procured"->"Cost of captively processed RDF" default: 0	INR
Cost of TDF Usage	Calculates the total cost of TDF that is to be procured or captively processed for generating the given share of thermal energy	select case "Amount of tire derived fuels procured"->"Toggle: TDF - Captive processing"=0 :"Amount of tire derived fuels procured"->"Cost of procured TDF" case "Amount of tire derived fuels procured"->"Toggle: TDF - Captive processing"=1:"Amount of tire derived fuels procured"->"Cost of captively processed TDF" default: 0	INR
CO2 emissions from alternative fuels	Calculates the total amount of CO2 emissions generated as a result of using alternative fuels such as RDF and TDF	(select case "Toggle: Alternative Fuel" = 1 or 3 :"Amount of refuse derived fuels procured"-> "Emissions from use of RDF" default: 0) + (select case "Toggle: Alternative Fuel" = 2 or 3 :"Amount of tire derived fuels procured"-> "Emissions from use of TDF" default: 0)	tCO2
Amount of alternative fuel utilised	Calculates the total amount of alternative fuels such as RDF and TDF utilised for	"Amount of refuse derived fuels procured"->"Amount of RDF required"+"Amount of tire derived fuels procured"->"Amount of TDF	tons

	generating thermal energy	required"	
Green subsidy	Calculates the amunt of subsidy awarded for substituting conventional fuels with alternative fuels such as RDF and TDF	"Amount of alternative fuel utilised"*"Subsidy rate for alternative fuels"("time")	INR
Share of Thermal Energy from RDF	Calculates the share of thermal energy that is to be generated using RDF	"Thermal Energy requirement"*("Share of thermal energy requirement from RDF"/100)	kcal
Amount of RDF required	Calculates the amount of RDF required to generate the given share of thermal energy	select case "Fuel Substitution Module"->"Toggle: Alternative Fuel" = 1 or 3: "Share of Thermal Energy from RDF"/("RDF: Net calorific value"*1000) default: 0	tons
Cost of procured RDF	Calculates the cost of procuring pre-processed RDF required for generating the given share of thermal energy	select case "Toggle: RDF - Captive processing"=0: "Tariff of processed RDF"("time")*"Amount of RDF required" default: 0	INR
Emissions from use of RDF	Calculates the net emissions released from the use RDF for generating the given share of thermal energy	"Amount of RDF required"*"RDF: Emission Factor"	tCO2
RDF: CAPEX Cost - TPD	Calculates the cost of setting up a captive processing plant for RDF based on the given share of thermal energy that is to be generated using RDF	select case "Toggle: RDF - Captive processing"=1: if ("Amount of RDF required"/30) < 100 then "RDF: CAPEX"("time") else (("Amount of RDF required"/30)*"RDF: CAPEX"("time"))/100 default: 0	INR
RDF: Thermal Energy Requirement	Calculates the total amount of thermal energy required for processing raw materials into RDF, depending on the moisture content	"Amount of RDF required"*("RDF: Moisture content of raw material"/100)	kcal
RDF: Total Electricity requirement	Calculates the total amount of electrical energy required for processing the raw materials into RDF	"Amount of RDF required"*"RDF: Electrical Energy Requirement"	kWh
RDF: Cost of captively processed RDF	Calculates the total cost of captively processing raw material into RDF for generating the required amount of thermal energy	if "Toggle: RDF - Captive processing" = 1 then "Amount of RDF required"*"RDF: OPEX/ton (excluding energy)"("time")+"RDF: CAPEX Cost - TPD"+"Auxiliary Cost" else	INR

		0	
Auxiliary Cost	Calculates the auxiliary energy cost for processing raw material into RDF	("RDF: Thermal Energy Requirement"/"RDF: Net calorific value")*"RDF: OPEX/ton (excluding energy)"("time")	INR
Share of Thermal Energy from TDF	Calculates the share of thermal energy that is to be generated using TDF	"Thermal Energy requirement"*("Share of thermal energy requirement from TDF"/100)	kcal
Amount of TDF required	Calculates the amount of TDF required to generate the given share of thermal energy	select case "Fuel Substitution Module"->"Toggle: Alternative Fuel" = 2 or 3: "Share of Thermal Energy from TDF"/("TDF: Net calorific value"*1000) default: 0	tons
Cost of procured TDF	Calculates the cost of procuring pre-processed TDF required for generating the given share of thermal energy	select case "Toggle: TDF - Captive processing"=0: "Tariff of processed TDF"("time")*"Amount of TDF required" default: 0	INR
Emissions from use of TDF	Calculates the net emissions released from the use TDF for generating the given share of thermal energy	"Amount of TDF required"*"TDF: Emission Factor"	tCO2
TDF: CAPEX Cost - TPD	Calculates the cost of setting up a captive processing plant for TDF based on the given share of thermal energy that is to be generated using RDF	select case "Toggle: TDF - Captive processing"=1: if "Amount of TDF required" < 10800 then "TDF: CAPEX"("time") else ("TDF: CAPEX"("time")*"Amount of TDF required")/10800 default: 0	INR
Cost of captively processed TDF	Calculates the total cost of captively processing raw material into TDF for generating the required amount of thermal energy	"Amount of TDF required"*"TDF: OPEX/ton (excluding energy)"("time")+"TDF: CAPEX Cost - TPD"	INR
TDF: Total Electricity requirement	Calculates the total amount of electrical energy required for processing the raw materials into TDF	"Amount of TDF required"*"TDF: Electrical Energy Requirement"	kWh

Table 36. List of stocks used in Fuel Substitution Module

Net Expenditure [Fuel Substitution Module]	Holds the total expenditure of fuel consumption, excluding electricity utilisation, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \left(Monthly\ Expenditure\ (s)\right) ds + Net\ Expenditure\ (t0)$	INR

Net Emissions [Fuel substitution module]	Holds the total amount of CO2 emissions from the plant through fuel consumption, excluding electricity utilisation, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \left(Monthly\ Emissions\ (s)\right) ds + Net\ Emissions\ (t0)$	Tons

Table 37. List of flows used in Fuel Substitution Module

Monthly Expenditure	Calculated monthly expenditure of fuel consumption (excluding electricity utilisation)	"Cost of coal usage"+"Cost of other conventional fuel usage"+"Cost of PETCOKE usage"+"Cost of RDF usage"+"Cost of TDF Usage"-"Green subisdy"	INR
Monthly Emissions	Calculated monthly emissions from fuel consumption (excluding electricity utilisation)	"CO2 emissions from alternative fuels"+"Emissions from coal usage"+"Emissions from PETCOKE usage"+"Emissions from other conventional fuel usage"	Tons

4.2.4. Carbon Capture Module

For realising the Carbon Capture Module described in the previous chapter, the list of exogenous variables and input parameters necessary for running the simulation are described in Table 38. The input parameters taken from the other modules in the model are described in Table 39, while the variables from this model that are used as input parameters in other modules in the model are described in Table 40. The list of variables whose values are calculated during the simulation run are described in Table 41. Subsequently, the list of stocks and flows used in this module are listed in Tables 42 and 43 respectively.

Table 38. List of input parameters and exogenous variables used in Carbon Capture Module

Nomenclature	**Description**	**Equation**	**Units/Timestep**
Toggle: Operation Mode	Toggle for setting the mode of operation of this module: 1 – Sodium Carbonate 2 - Barium Carbonate 3 - CO2 compression and storage 4 - Microalgae -> Renewable fuel 5 – None Input of 5 disables the use of this module in the plant simulation	Input parameter	-
Raw material tariff: Sodium Hydroxide	Cost of procuring 1 ton of Sodium Hydroxide to the plant location	Input dataset	INR/ton

Raw material tariff: Barium Hydroxide	Cost of procuring 1 ton of Barium Hydroxide to the plant location	Input dataset	INR/ton
OPEX: Sodium Hydroxide	Cost of operating the equipment necessary for indirect carbonation per ton of Sodium Hydroxide	Input dataset	INR/ton
OPEX: Barium Hydroxide	Cost of operating the equipment necessary for indirect carbonation per ton of Barium Hydroxide	Input dataset	INR/ton
CAPEX	Total capital investment required for setting up the necessary equipment to facilitate indirect carbonation in the cement plant	Input parameter	INR
By-product tariff: sodium carbonate	Income through the sale of 1 ton of sodium carbonate, which is a by-product of the indirect carbonation process	Input dataset	INR/ton
By-product tariff: Price of Barium carbonate	Income through the sale of 1 ton of Barium Carbonate, which is a by-product of the indirect carbonation process	Input dataset	INR/ton
Electricity requirement for compression	Amount of electrical energy required for compressing 1 ton of flue gas	Input parameter	kWh/ton
Electricity requirement for capture	Amount of electrical energy required for capturing 1 ton of flue gas	Input parameter	kWh/ton
Capture and storage: OPEX	Cost of operating the equipment necessary for facilitating capture and compression of 1 ton of flue gas	Input dataset	INR/ton
Microalgae: OPEX	Cost of operating equipment necessary for the growth of microalgae and conversion of the biomass into fuel	Input dataset	INR/ton
Microalgae: Energy required	Amount of electrical energy required in the production of fuel from biomass	Input parameter	kWh/ton
Microalgae: Biofuel generated per ton of CO2	Amount of biofuel generated per every ton of CO2 available in the exhaust flue gases	Input parameter	ton (biofuel)/tCO2

Table 39. List of input parameters that are taken from other modules, to be used in Carbon Capture Module

Monthly CO2 emissions from plant processes	Total amount of CO2 emissions generated within the plant	Input from main model	Tons

Table 40. List of variables from Carbon Capture Module that are used as input parameters in other modules

FSM: Biofuel (Alternative fuel) generated	Amount of biofuel generated using micro-algae	"Alternative CO2 capture using Algae (incomplete)"->"Biofuel generated"	Tons
CPM: Total electricity requirement	Total amount of electrical energy required for operation of equipment necessary for functioning of this module	("CO2 captured and concentrated for storage"*"Electricity requirement for capture") + ("CO2 captured and concentrated for storage"*"Electricity requirement for compression")	kWh

Table 41. List of dynamic variables utilised in Carbon Capture Module

CO2 emissions mitigated	Total amount of emissions mitigated through various CO2 capture techniques employed in this module	"Alternative CO2 capture using Algae (incomplete)"->"Emissions reduced" + ("Monthly CO2 emissions from plant processes"*("Capture efficiency"/100)) tons	Tons
Capture efficiency	Efficiency of the CO2 capture techniques employed in this module, i.e., efficiency of x% indicates that only x% of the CO2 emissions will be captured.	select case "Toggle: Operation Mode"=1 : 98 case "Toggle: Operation Mode"=2 : 65 case "Toggle: Operation Mode"=3 : 90 case "Toggle: Operation Mode"=4 : 0 default: 0	%
Raw material requirement: Sodium Hydroxide	Calculates the amount of Sodium Hydroxide required by the process to generate the required amount of Sodium carbonate	"Amount of Sodium Carbonate generated"*1.325	Tons

Amount of Sodium Carbonate generated	Calculates the amount of Sodium Carbonate generated during the process of indirect carbonation depending on the capture efficiency.	if "Toggle: Operation Mode" = 1 then
		(("Monthly CO2 emissions from plant processes"*("Capture efficiency"/100))*1.37)
		else
		0
			Tons

Sodium Hydroxide: Cost of procurement	Calculates the total cost of procurement of Sodium Hydroxide required by the indirect carbonation process	"Raw material requirement: Sodium Hydroxide"*"Raw material tariff: Sodium Hydroxide"("time")	INR
Barium Hydroxide: Cost	Calculates the total cost	"Raw material requirement:	INR

of procurement	of procurement of Barium Hydroxide required by the indirect carbonation process	Barium Hydroxide"*"Raw material tariff: Barium Hydroxide"("time")	
Raw material requirement: Barium Hydroxide	Calculates the amount of Barium Hydroxide required by the process to generate the required amount of Barium carbonate	"Amount of Barium Carbonate generated"*1.1517	Tons

Amount of Barium Carbonate generated	Calculates the amount of Barium Carbonate generated during the process of indirect carbonation depending on the capture efficiency.	if "Toggle: Operation Mode" = 2 then
		(("Monthly CO2 emissions from plant processes"*("Conversion efficiency"/100))*4.467)
		else
		0
			Tons

Sodium Carbonate: Revenue from sales	Calculates the total revenue generated from the sale of the by-product, Sodium Carbonate	"Amount of Sodium Carbonate generated"*"By-product tariff: sodium carbonate"("time")	INR
Carbonation methods: Operational expenditure	Calculates the total operational expenditure of the indirect carbonation method per timestep	("OPEX: Barium Hydroxide"("time")*"Raw material requirement: Barium Hydroxide")+("OPEX: Sodium Hydroxide"("time")*"Raw material requirement: Sodium Hydroxide")	INR
Green subsidy	Calculates the applicable green subsidy for capture of CO2 emissions in this module	"CO2 emissions mitigated"*"Subsidy rate for carbon capture"("time")	INR
Barium Carbonate: Revenue from sales	Calculates the total revenue generated from the sale of the by-product, Barium Carbonate	"Amount of Barium Carbonate generated"*"By-product tariff: Price of Barium carbonate"("time")	INR
CO2 captured and concentrated for storage	Calculates the total amount of CO2 captured and concentrated for storage	"Monthly CO2 emissions from plant processes"*("Conversion efficiency"/100)	Tons
CO2 capture and storage: Expenditure	Calculates the total cost for capture and concentration of CO2 in the flue gases	"Capture and storage: OPEX"*"CO2 captured and concentrated for storage"	INR
Microalgae: Expenditure	Calculates the operational expenditure for maintaining the equipment necessary for growth of microalgae and conversion of biomass into fuel	"Biofuel generated"*"OPEX"("time")	INR
Microalgae: Biofuel generated	Calculates the amount of fuel generated from the biomass generated using microalgae	"Monthly CO2 emissions"*"Biofuel generated per ton of CO2"*("Capture efficiency"/100)	Tons

Microalgae: Emissions reduced	Calculates the amount of CO2 emissions reduced through its capture using microalgae	"Monthly CO2 emissions"*"Capture efficiency"	Tons

Table 42. List of stocks used in Carbon Capture Module

Net Expenditure [Carbon Capture Module]	Holds the total expenditure of carbon capture excluding electricity utilisation, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \big(Monthly\ Expenditure\ (s)\big)\, ds + Net\ Expenditure\ (t0)$	INR
Net Emissions Reduction [Carbon Capture Module]	Holds the total amount of CO2 emission reductions from the plant through carbon capture, excluding auxillar, at the end of the simulation run (156 months). Initialised to 0.	$\int_{t0}^{t} \big(Monthly\ Emissions\ reduction\ (s)\big)\, ds + Net\ Emissions\ reduction\ (t0)$	Tons

Table 43. List of flows used in Carbon Capture Module

Monthly Expenditure	Calculates the total expenditure incurred in the current time step within the Carbon Capture Module	"Alternative CO2 capture using Algae (incomplete)"->"Expenditure" + "Barium Hydroxide: Cost of procurement" +"Sodium Hydroxide: Cost of procurement" +"CO2 capture and storage: Expenditure" +"Carbonation methods: Operational expenditure" +"CAPEX" -"Barium Carbonate: Revenue from sales" -"Sodium Carbonate: Revenue from sales" -"Green subsidy"	INR
Monthly Emissions reduction	Calculates the total CO2 emission reductions achieved in the current timestep within the Carbon Capture Module	"CO2 emissions mitigated"	Tons

4.2.5. Efficiency Improvements Module

For realising the Efficiency Improvements Module described in the previous chapter, the list of exogenous variables and input parameters necessary for running the simulation are described in Table 44. The list of stocks and flows used in this module are listed in Tables 45 and 46 respectively.

Table 44. List of input parameters and exogenous variables used in Efficiency Improvements Module

Nomenclature	Description	Equation	Units/Timestep
Input: STC	For setting the clinker production process configuration from the following options: 1) Wet Process 2) Long Dry Process 3) 1 Stage Pre-heater 4) 2 Stage Pre-heater 5) 4 Stage Pre-heater (without Calciner) 6) 4 Stage Pre-heater 7) 5 Stage Pre-heater 8) 6 Stage Pre-heater 9) Custom: Provide input dataset	Input parameter	-
Dataset: STC	For setting the specific thermal consumption for production of 1 kg of clinker	Input dataset	kcal/kg
Specific Electricity Consumption per ton of Cement	Calculates the specific electrical energy consumption for producing 1 ton of the final product, i.e., cement	"Plant electricity consumption"/("Clinker produced"/"Clinker-to-cement ratio")	kWh/ton
Cost of improvement	For setting the capital cost for executing an efficiency improvement project in the cement plant. Can be set to onetime expense, or a recurring expenditure	Input parameter	INR
CPM: % of reduction in overall electricity consumption	For setting the % of reduction in plant electricity consumption due to executing of an efficiency improvement project in the cement plant	Input parameter	%
FSM: % of reduction in thermal energy requirement	For setting the % of reduction in plant thermal consumption due to executing of an efficiency improvement project in the cement plant	Input parameter	%
SEC - Until clinkerisation	Amount of electrical energy required prior to the process of clinkerisation. Includes the energy requirement pre-processing the raw materials	Input dataset	kWh/ton
SEC - After clinkerisation	Amount of electrical energy required after the process of clinkerisation. Includes activities such as grinding and blending the finished clinker with other substitutes	Input dataset	kWh/ton
Plant electricity consumption	Total amount of electrical energy required in the plant	Input from Captive Power Module	kWh

Clinker produced	Total amount of clinker produced in the plant	Input from Clinker Substitution Module	tons
Clinker-to-cement ratio	Amount of clinker present in a ton of the finished product, i.e., cement	Input from Clinker Substitution Module	%

Table 45. List of stocks used in Carbon Capture Module

Net Expenditure [Efficiency Improvements Module]	Holds the total expenditure involving the capital expenditure for efficiency improvement projects, at the end of the simulation run. Initialised to 0.	$\int_{t0}^{t} \left(Monthly\ Expenditure\ (s)\right) ds + Net\ Expenditure\ (t0)$	INR

Table 46. List of flows used in Carbon Capture Module

Monthly Expenditure	The total cost	"Cost of improvement"	INR

4.3 Model Validation

The model is validated using sensitivity analysis and dimensional consistency checks before running the experiments described in Chapter 5. For construction and running experiments with the model, “SilicoAI” is used, which is a simulation platform tool designed for allowing business stakeholders to import plant data, build models, simulate, run, and explore what-if scenarios for optimising plant operations (“SilicoAI,” n.d.). The process for collecting data is described in Chapter 5 with the data and sources are presented in Appendix-II and Appendix-III respectively. After construction of the model, each simulation scenario is run for a period of 156 months with timesteps of 1 month. The units of measures are used to check the model for dimensional consistency.

- Boundary Adequacy:

As per the objectives discussed earlier in the previous chapters, the model in this study is designed to represent a single cement plant, involving activities from raw material sourcing until the production of the final finished product, i.e., the cement is obtained as an output. The datasets for parameters that are not directly influenced by the plant activities such as raw material tariffs, energy tariffs, regional grid emission factors are all prepared exogenously based on published forecast data or extrapolation of current market trends for the geographical region where the cement plant in the experiments is located. The metrics computed endogenously within the system are listed and described in Appendix III.

- Sensitivity Analysis:

Sensitivity analysis is conducted to check whether alterations in key parameters result in relatable shifts in model outputs. Net plant emissions and net plant expenditure are directly dependent on the amount of clinker produced in the plant, therefore the sensitivity of the model to these parameters is described as follows:

a) “Baseline” case, where the clinker produced is constant throughout the simulation period.
b) “Moderate decrease” case, where the amount of clinker produced reduces by 20% linearly by the end of the simulation.
c) “Moderate increase” case, where the amount of clinker produced increases by 20% linearly by the end of the simulation.
d) “High increase” case, where the amount of clinker produced increases by 75% by the end of the simulation.

The impact of changes to net expenditure and CO_2 emissions is examined by modifying the amount of clinker produced per month in the plant. The featured cases, moderate decrease, moderate increase, and high increase have an equivalent impact on the observed variables as seen in Fig. 28 and Fig. 29; therefore, the model is deemed sensitive to changes in the key parameters.

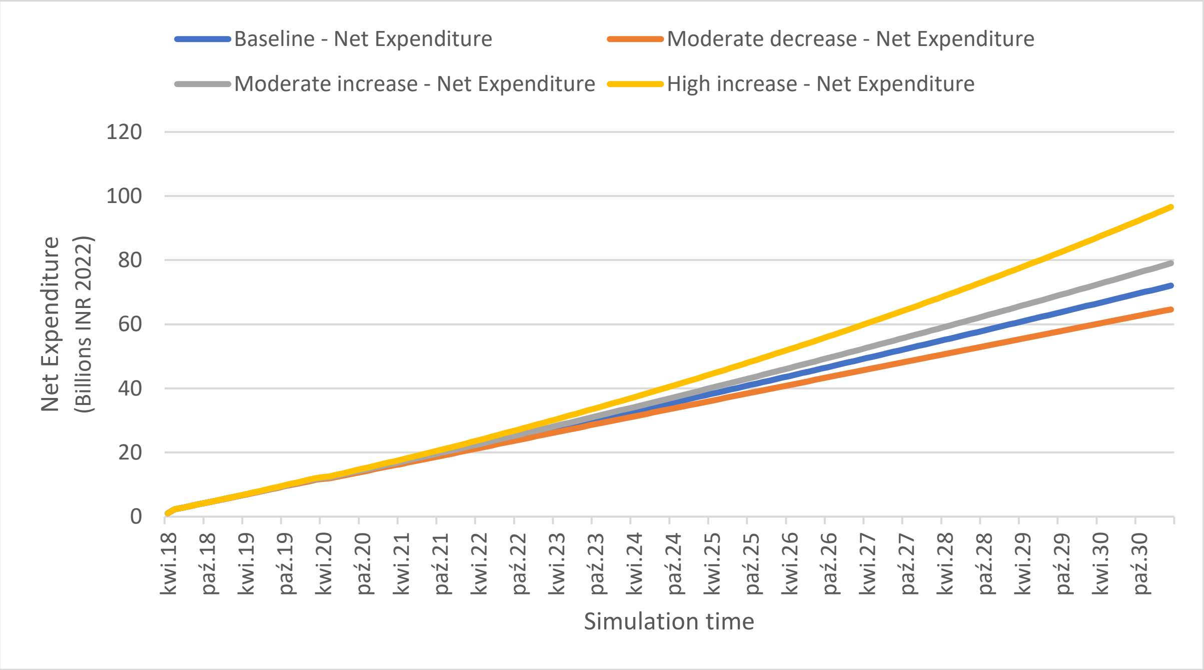

Fig. 28. Net expenditure of the plant under different test cases for clinker production

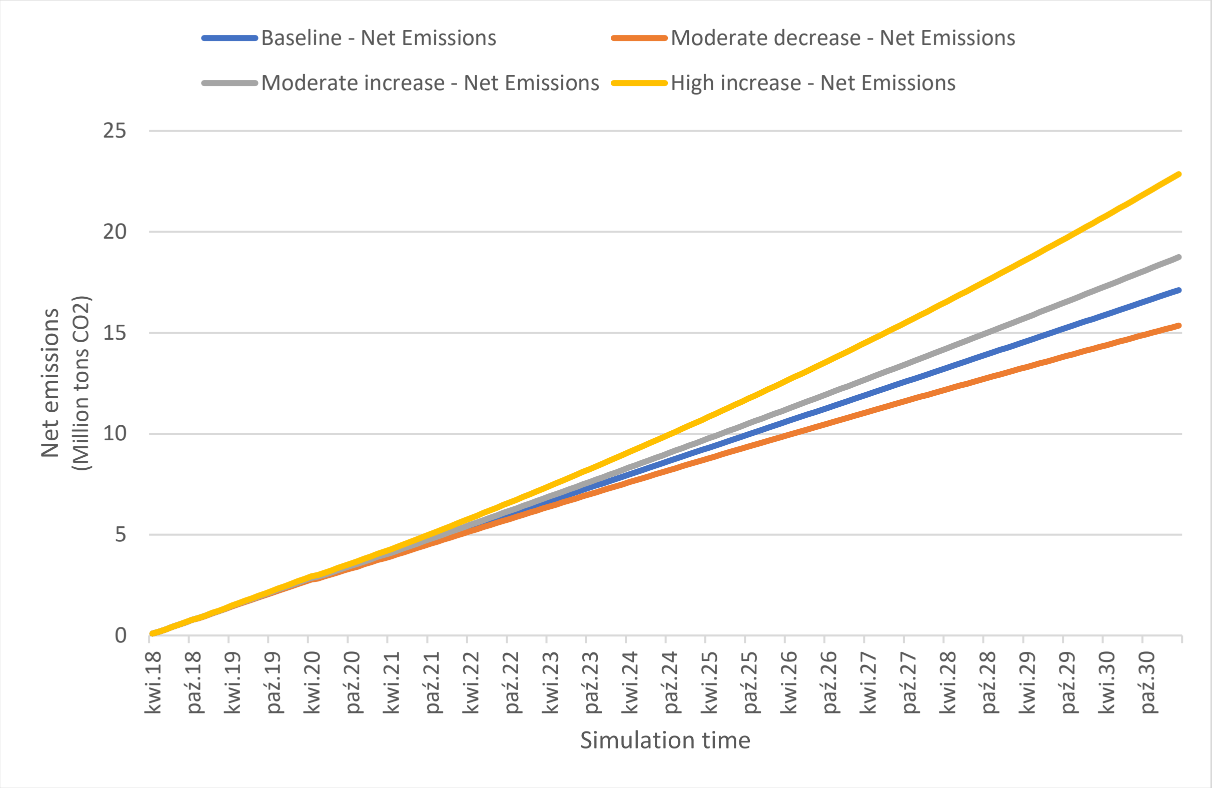

Fig. 29. Net CO2 emissions of the plant under different test cases for clinker production

- Stakeholder Validation:

The parameters used, their relationships with other entities, and formulas used for calculations have been mapped in collaboration with a cement plant management. Additionally, the final model and the featured causal relationships has been checked for logical correctness. The results obtained from the model simulations for the configurations already adopted by the current cement plant has been verified and approved by the stakeholders from April 2018 to March 2021.

5. EXPERIMENTS

For demonstrating the utility of the model, sample data ("default plant operation mode" in Appendix–III) was collected from a reference plant in India. Hourly and daily operational logs are collected either in computerised database or physical logbooks, and accordingly processed before being fed into the system. For raw material tariffs, historic price data from online marketplaces between the years 2014 to 2019 is utilised and is subsequently extrapolated to cover the duration of the simulation period in base scenario. There is currently no carbon tax applicable over cement plants located in India, hence it is not considered in the base scenario. Three different policy scenarios are designed, BAU (base scenario), LME, and HME which are further elaborated in Section 5.1 and their respective datasets in Appendix-III. The simulation is then run for various combinations of mitigation strategies discussed in Chapter 2 under the three policy scenarios using SilicoAI, a web-based modelling and simulation tool. The specifics on the configurations chosen for each mitigation strategy and the subsequent results are presented in Chapter 6.

5.1 Scenario Design

For the scenario comparisons, a cement plant of 4000TPD size in Telangana - India, was considered. Monthly operational plant data was collected from the cement plant logs from April 2018 to March 2021, and annual operational data from 2011-12 to 2017-18 FY. The model and the underlying calculations for the various technical variables has been developed in consultation with the cement plant management. The collected operational data includes clinker produced, coal consumed (for both clinker kiln and captive power plant), fly ash consumed, gypsum consumed, average Gross Calorific Value (GCV) of the fuel utilised, specific energy consumption for production of cement (electrical and thermal; includes clinker production), specific energy consumption for production of clinker (by-product). Future production trends for April 2021 to March 2031, i.e., clinker produced, is determined based on the projected data for cement demand and average plant utilisation in India (India Brand Equity Foundation, 2021; Madhumitha Jaganmohan, 2021). Coal consumption is calculated based on the combined values of a) the clinker produced, SEC-Th, and coal GCV; b) clinker produced, SEC-E, and heat rate. Fly ash and gypsum consumed are calculated based on the clinker produced and cement-to-clinker ratio. Future trends for specific energy consumption for clinker produced is determined by extrapolation of existing historic trends at the plant. In case of raw material tariffs, historic price trends from online marketplaces are extrapolated for the duration of the chosen simulation period. The data provided for rest of the input variables is tabulated in Appendix – III, A to C for BAU/default plant operation mode, Low CO2 mitigation effort (LME), and High CO2 mitigation effort (HME) respectively. The section 5.1.1 is considered as the base scenario which takes into account the current policies on carbon tax, applicable subsidies, electricity, fuel, and equipment tariffs in the state of Telangana in India, the values of which are provided in Appendix – III A.

Payback period is defined as the amount of time it takes for a project or strategy to recover the cost of the investment (i.e., capital expenditure). It is a very important metric that determines the attractiveness of a specific CO2 mitigation strategy to the cement plant stakeholders. As majority of the strategies involve reducing emissions by improving the efficiency of the plant, it is bound to result in savings in form of reduced energy consumption or in carbon taxes. Therefore, smaller the payback period, the more inclined the plant stakeholders would be to implement that particular CO2 mitigation strategy. The payback period could be further enhanced through subsidies for the plant for implementing strategies to reduce CO2 emissions.

$$Payback\ period\ (in\ months) = \ Initial\ capital\ investment/Net\ monthly\ cash\ inflows \quad (7)$$

In the current study, three different policy scenarios are considered, the first being the base scenario or “Business As Usual” (BAU), in which the current policy and market trends would remain unchanged throughout the duration of the simulation period, i.e.,

- Raw material and energy tariffs would continue to follow the existing trends.
- No changes or introduction of subsidies or carbon taxes apart from the ones existing at the beginning of the scenario.
- Regional grid emission factor follows existing trends.

The second scenario is titled “low mitigation effort” in which it is assumed that government policies and market trends slightly favour the implementation of mitigation strategies, such as

- The energy tariffs of fossil fuels would also increase an additional 10% higher than the BAU scenario to reflect the effects of the government policy.
- Introduction of minor subsidies for activities that reduce CO2 emissions from the plant and as well as a minor increase in carbon tax (introduction of carbon tax if it is nor currently present in the region).
- Regional grid emission factor reduces quicker than BAU scenario to reflect local government action in introduction of greener sources of power.
- Minor increase in tariffs of substitute fuels and materials to reflect the increased demand in the cement industry for their procurement.

The third scenario is titled “high mitigation effort” in which it is assumed that government policies and market trends strongly favour the implementation of mitigation strategies, such as

- The energy tariffs of fossil fuels would also increase an additional 20% higher than the BAU scenario to reflect the effects of the government policy.
- Major increase in both subsidies for activities that reduce CO2 emissions from the plant and as well as carbon tax on CO2 emissions from the plant.
- Regional grid emission factor reduces much quicker than previous two scenarios to reflect the strong local government action in reduction of CO2 emissions from electricity production.
- Moderate increase in tariffs of substitute fuels and materials to reflect the increased demand for mitigation among the cement plant installations.

Under the three scenarios previously described, various combinations of mitigation strategies are tested, and overall expenditure and CO2 emission reductions for both local government policies and cement plant expenditure are compared. Additionally, the payback periods for the capital expenditure on mitigation strategies are compared under these scenarios. Section 5.1.1 additionally lists the plant parameters in its current operational mode, i.e., such as clinker substitution ratio, type of fuels used in the kiln, source of electricity, etc.

5.1.1. Base Scenario (BAU) and default plant operation mode

The following parameters are chosen as the inputs for the cement plant, based on real world data from a medium-sized cement plant of 4000 TPD capacity. This plant has an existing captive power plant that meets its entire electricity requirement that operates on coal. Additionally, the plant currently substitutes 30% of the clinker in the final product, with fly ash. As a rotary kiln fuel, a mix of imported and Indian coal is used and the average tariffs are considered accordingly. The cement plant is a moderately old installation that is using a 4-stage pre-heater with a calciner. In case of exogenous variables, the local electricity tariffs and emission factor is sourced for the state of Telangana, in which the plant is situated. Similarly, all capital and operational expenditures are calculated based on local market tariffs. The list of input parameters and datasets used in the model are described in Appendix III A.

5.1.2. Low CO2 mitigation effort (LME)

In this scenario, the same plant is considered, i.e., 4000 TPD sized cement plant based in Telangana, India. The plant operation mode will change as per the mitigation strategy being considered. The carbon tax is considered INR 750 (approximately USD 9.83; March 2022) per ton of CO2 with a 5% increase each year until the end of the simulation run. The energy tariffs on fossil fuels is considered to increase by an additional 10% by the end of the simulation run, when compared to BAU. Similarly, the grid electricity tariffs are set to increase by an additional 8% each year when compared to BAU. Additionally, subsidy of INR 2000 (USD 26.22; March 2022) per ton of RDF or TDF used to substitute fossil fuels. Similarly, a subsidy of ₹1 (US Cents 1.3; March 2022) is provided for a unit of green energy (WHR or SPV) generated captively to foster adoption of mitigation strategies related to electricity consumption. Unless specified in the tables found in Appendix III B, all the parameters are considered to be same as BAU scenario.

5.1.3. High CO2 mitigation effort (HME)

The same plant from the previous scenarios is considered here, i.e., 4000 TPD plant in Telangana, India. The plant operation mode will change as per the mitigation strategy being considered. The carbon tax is considered INR 2500 (approximately USD 32.77; March 2022) per ton of CO2 with an 8% increase each year until the end of the simulation run. The energy tariffs on fossil fuels are considered to increase by an additional 50% at the end of the simulation run when compared to BAU. Similarly, the grid electricity tariffs are set to increase by 15% each year when compared to BAU. Additionally, subsidy of INR 3500 (USD 52.43; March 2022) per ton of RDF or TDF used to substitute fossil fuels. Similarly, a subsidy of INR 2 (US Cents 2.6; March 2022) is provided for a unit of green energy (WHR or SPV) generated captively to foster adoption of mitigation strategies related to electricity consumption. Unless specified in the tables found in Appendix III C, all the parameters are considered to be same as “Low CO2 mitigation effort” scenario.

6. RESULTS

Under the three distinct scenarios described in the previous sections, the cost of implementing and operating various combinations mitigation strategies is tested and compared. Additionally, the payback periods for the capital expenditure are calculated wherever applicable.

The following strategies are individually compared with the existing plant configuration:

- Clinker substitution: 30% substitution of clinker with BFS or fly ash or wet ash with 5% substitution of clinker (default for ordinary Portland cement)
- Alternative fuels: 10%, 30% substitution of fuel for kiln with RDF and TDF. Both captive processing and procuring pre-processed fuels are compared to using 100% coal.
- Captive power generation: 100% purchased from grid; 100% from captive thermal power plant using coal; maximum amount possible from WHR and rest from Captive Coal Thermal plant or regional grid; maximum possible from WHR and 30% from Solar Photovoltaic (SPV) and rest from regional grid.
- Carbon capture: Indirect carbonation using Sodium Hydroxide and Barium Hydroxide is compared with carbon capture and storage.

Furthermore, a combination of above strategies is compared:

- Clinker substitution and captive power generation
- Clinker substitution, alternative fuels, and captive power generation
- Clinker substitution, alternative fuels, captive power generation, and carbon capture

6.1 Comparisons

The existing plant configuration is simulated under the 3 scenarios described in the previous section, with the results graphed in Fig. 31-34. As expected, the cost of operating the plant in its stock configuration in LME and HME scenarios is noticeably higher than BAU at the end of the simulation run, i.e., 12 years. In the current configuration, the plant relies on fossil fuels such as coal for both as a kiln fuel and as well as for captive power generation, leading to a large amount of CO2 emissions, which subsequently results in higher carbon taxes.

From the total plant expenditure, the amount spent on electricity utilisation is shown in Fig. 31, fuel consumption in Fig. 32, and clinker production in Fig. 33. Amount the various plant processes, the production of clinker has the highest increase in both LME and HME scenarios, due to increase a likely increase in costs of procurement for fly ash, which the existing plant currently utilises for substituting upto 30% of clinker. Similarly, cost of fuel utilisation increases as the prices of the currently used fuel, i.e., coal are set to increase in LME and HME scenarios. While there is a small increase in expenditure for captive electricity generation in the current plant configuration, i.e., 100% from captive thermal plant using coal, in the LME scenario, the gap widens with the HME scenario where there is a significant increase in conventional fuel tariffs.

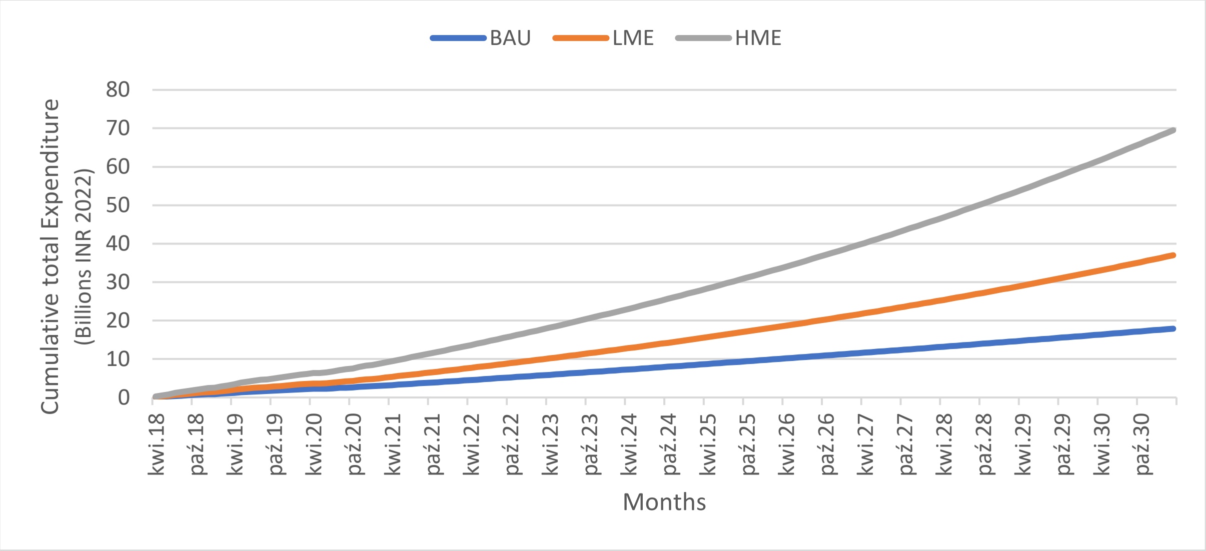

Fig. 30. Net expenditure over time for the cement plant in its base configuration, in various scenarios.

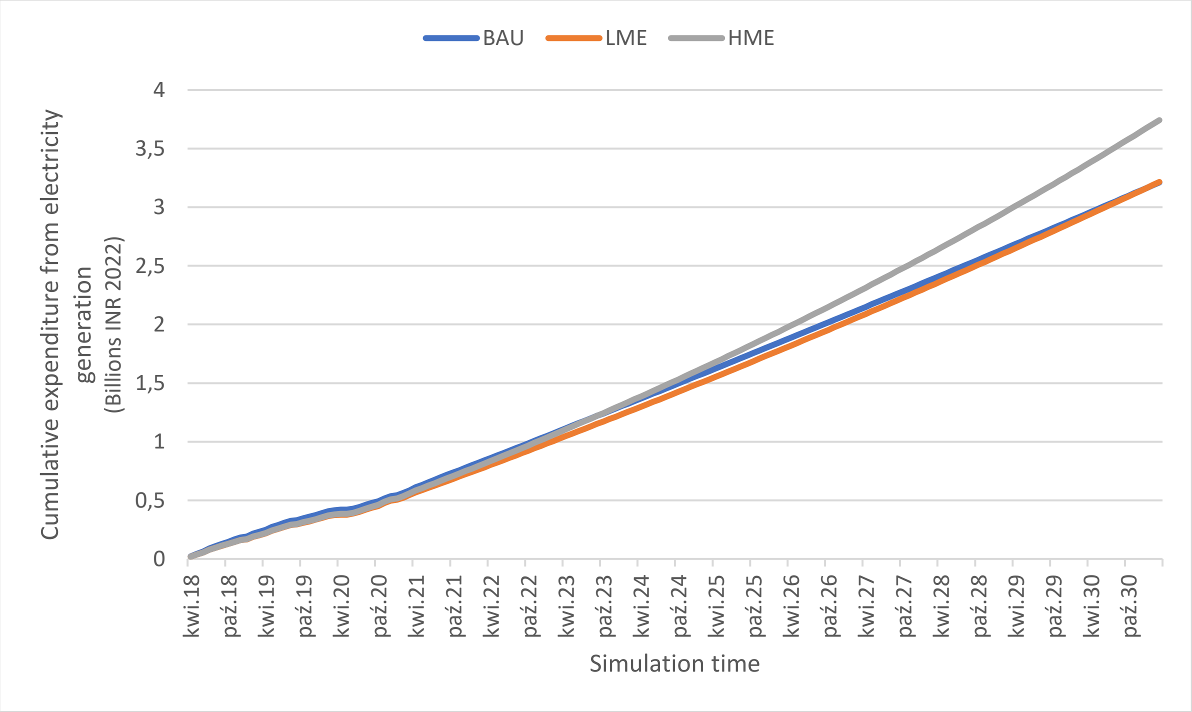

Fig. 31. Net expenditure on electricity generation over time for the cement plant in its base configuration, in various scenarios.

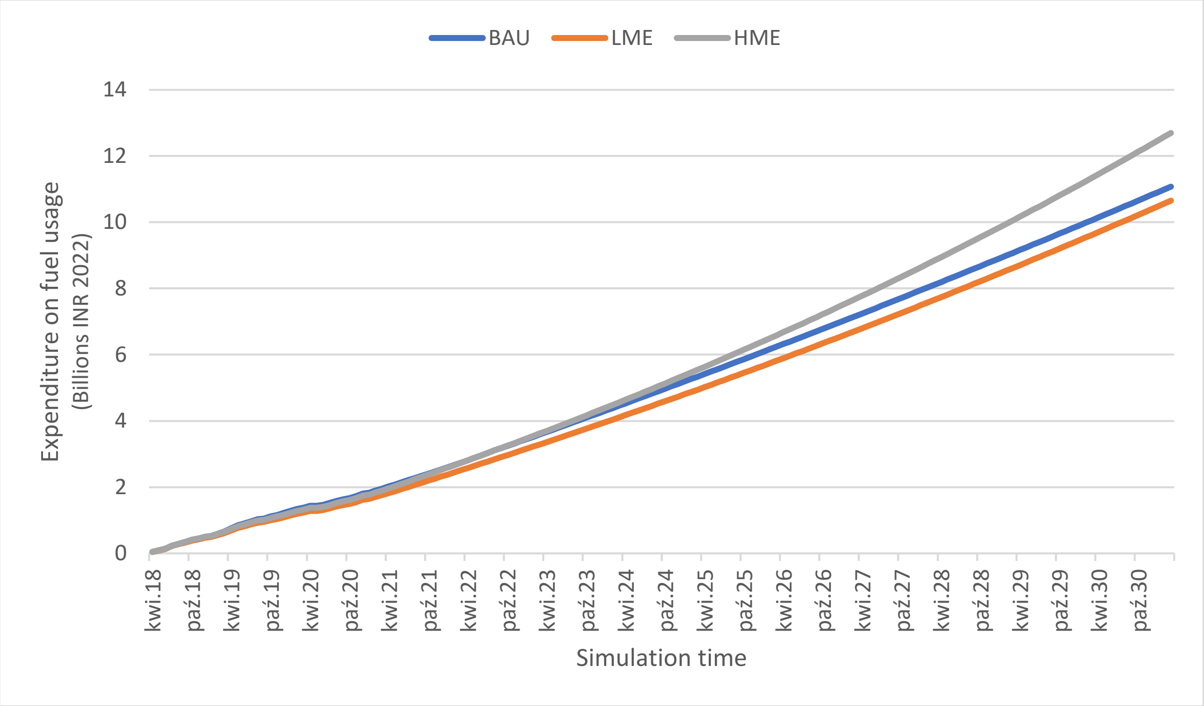

Fig. 32. Net expenditure on fuel utilisation over time for the cement plant in its base configuration, in various scenarios.

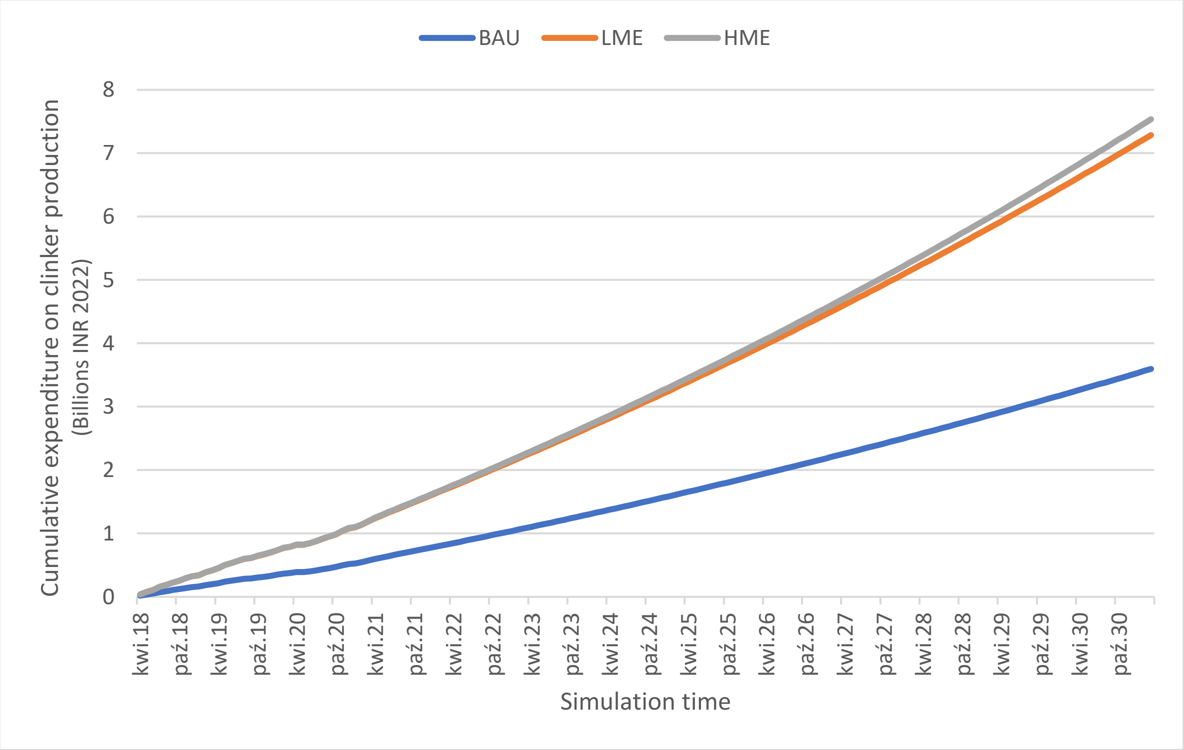

Fig. 33. Net expenditure on clinker production over time for the cement plant in its base configuration, in various scenarios.

In section 6.1.1, the various options available for each mitigation strategy is compared individually with an assumption that only one CO2 mitigation strategy is implemented within the base plant. For the purpose of this simulation, the same parameters from the base plant are used with relevant modifications to test various options within each strategy as discussed earlier.

In section 6.1.2., multiple combinations of mitigation strategies are compared, i.e., the plant would implement more than one CO2 mitigation strategy in the plant, to test the synergy between the various options. As there are multiple options to choose within each mitigation strategy, the most optimal option (i.e., highest reduction of CO2 emissions at the lowest increase in expenditure) is chosen based on the results from section 6.1.1. when combined with other mitigation strategies.

6.1.1. Single mitigation strategy approach

As described earlier, each CO2 mitigation strategy has various options available to choose from, so their impact on plant CO2 emissions and expenditure is explored in this section as follows:

a) Clinker Substitution: In this strategy, four options are considered which are i) OPC – Ordinary Portland Cement, ii) 30% Fly Ash – FA (existing configuration of the plant), iii) 30% Wet Ash - WA, and iv) 30% Blast Furnace Slag (BFS). The Ordinary Portland Cement consists of 95% clinker and 5% gypsum in the final finished product, while rest of the options have 65% clinker, 30% substitute material, and 5% gypsum. The maximum amount of substitute material is regulated based on local standards, and in India, maximum of 30% substitute is allowed. Hence, the configurations tested here is capped to 30% for all the substitutes.

   The cumulative expenditure of each of these configurations for clinker substitute materials under the BAU scenario is depicted in Figure 34. The cost of using blast furnace slag as a clinker substitute is the most expensive option due to the local market tariffs in India. In all the 4 options, the amount of clinker produced is the similar, but the final plant output, i.e., cement changes as per the substitution ratio. For example, production of 100 tons of clinker in OPC option would lead to production of 105 tons of cement, while in all other options, it leads to production of 135 tons of cement as additional material is added to the clinker mixture. Therefore, clinker substitution would lead to an increase in overall production capacity of cement when compared to OPC, assuming the plant utilisation rate to be same in all the options.

   The cumulative CO2 emissions reduced through clinker substitution when using Fly Ash and Wet Ash is compared in Fig. 34. As wet ash requires additional processing that requires thermal and electrical energy, it leads to fewer emission reduction than fly ash. By the end of the simulation run, fly ash would be able to reduce 200,000 tons of CO2 more than wet ash.

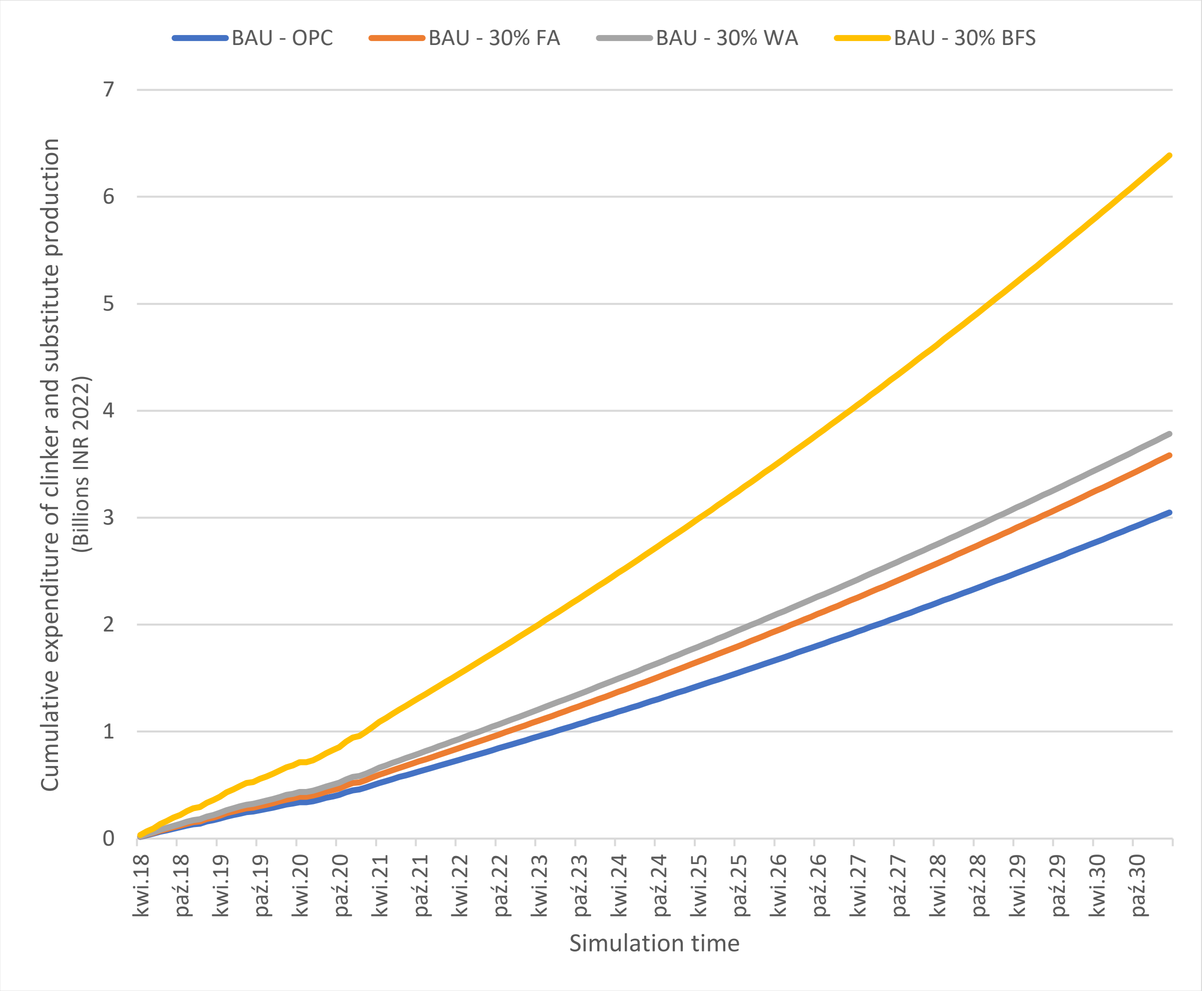

Fig. 34. Cumulative expenditure of clinker production for various configurations under the BAU scenario.

However, the Fig. 35 compares the overall plant expenditure (cumulative) when using fly ash and wet ash, which shows that wet ash leads to a small reduction in overall cumulative expenditure at the end of the simulation run, especially in LME scenario. Given that this strategy is tested under base plant configuration that uses 100% coal for the thermal energy requirement, using alternative fuels might further reduce the expenditure when using wet ash. As availability of fly ash is soon becoming a challenge in India as the government mandates its disposal and its current utilisation rate is 94% in 2020-21 FY (“Govt introduces penalty regime for non-compliance of fly ash utilisation,” 2022). The wet ash is largely unutilised and is stored in large reservoirs close to thermal power plants and would be more economical for cement plants to process and use it as a clinker substitute than fly ash whose tariffs are increasing due to market conditions in India. As seen in Fig. 36, except for the BAU scenario, use of wet ash leads to the least expenditure in the other 2 scenarios. The expenditure in HME scenario for all options is driven up the increasing costs of conventional fuel as the plant configuration used in this test is using 100% coal as its kiln fuel. The Fig. 37 depicts the cumulative plant expenditure when using various substitute materials under BAU, LME, and HME scenarios.

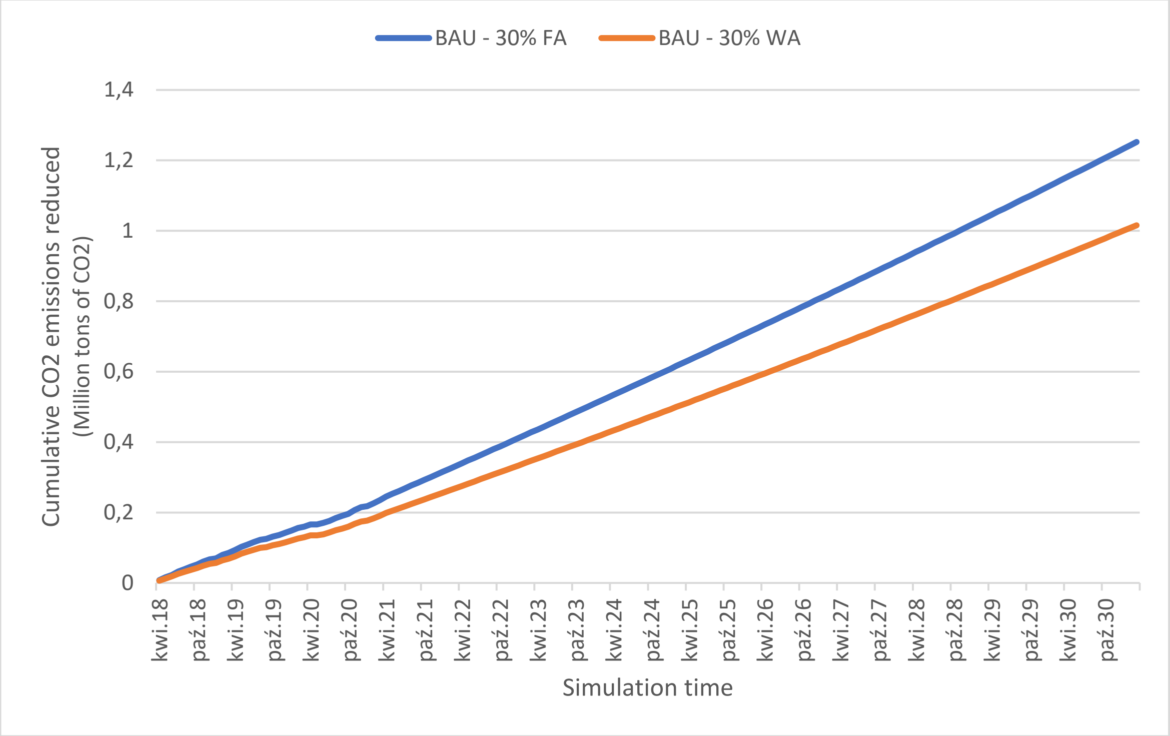

Fig. 35. Cumulative CO2 emissions reduced by clinker substitution in the final product, i.e., cement for Fly Ash (FA) and Wet Ash (WA) options under BAU scenario.

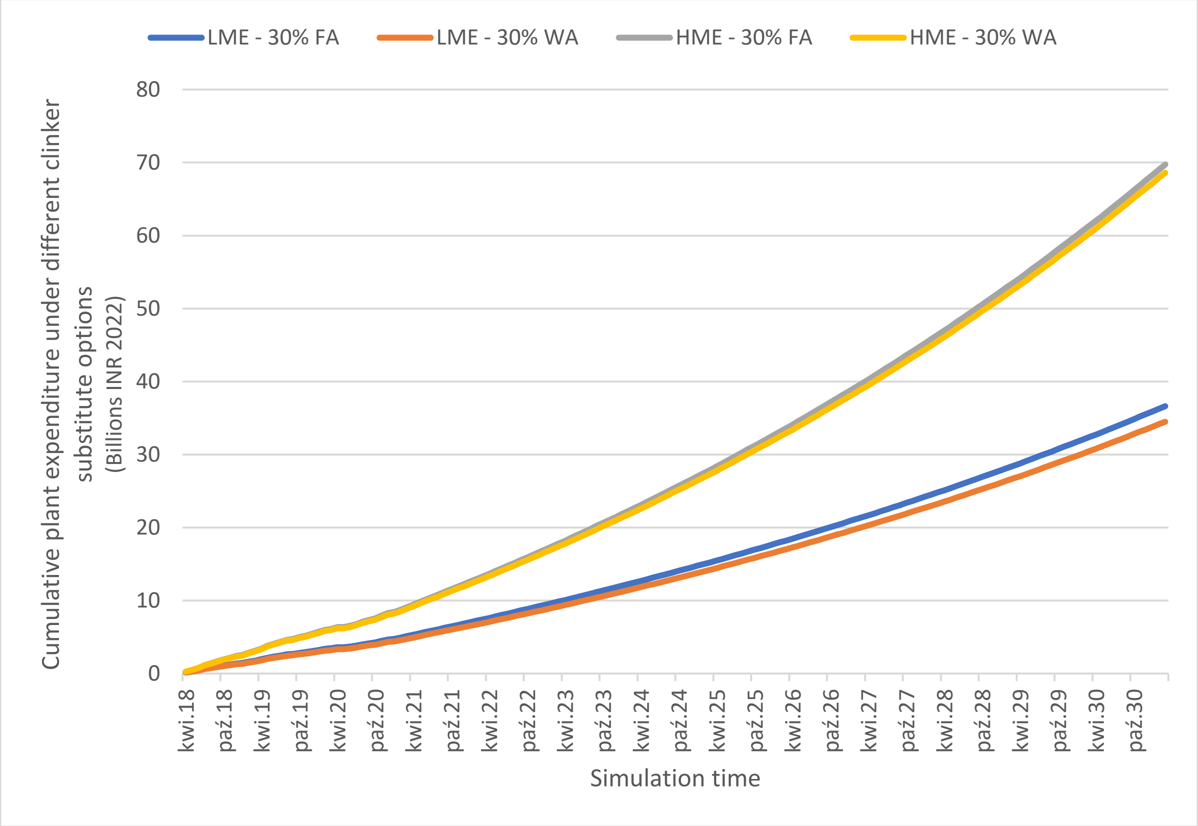

Fig. 36. Cumulative plant expenditure when utilising wet ash and fly ash as clinker substitutes under LME and HME scenarios.

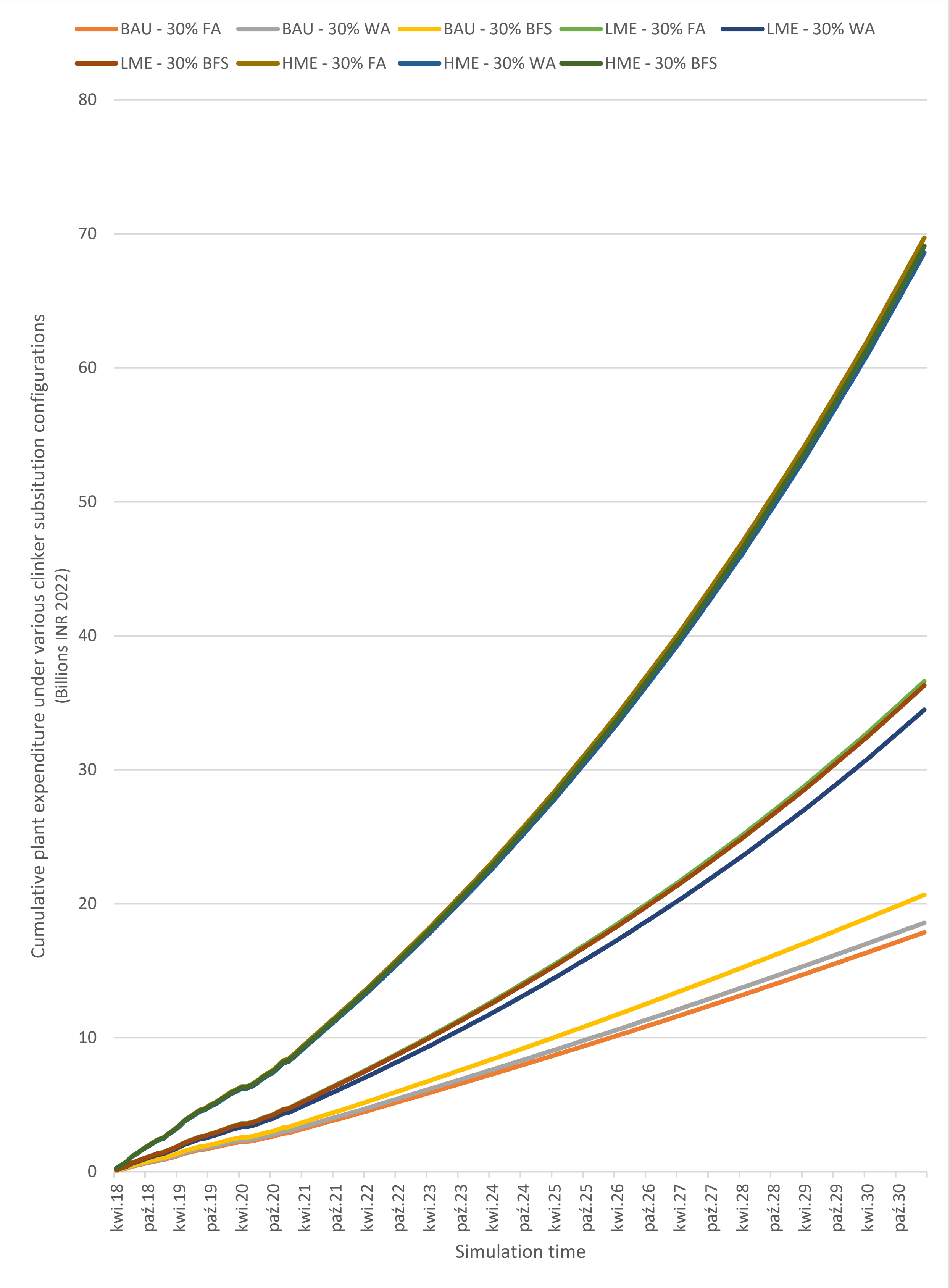

Fig. 37. Cumulative plant expenditure when utilising the various clinker substitution options under BAU, LME, and HME scenarios.

b) Alternative Fuels: In this strategy, 5 options are considered as kiln fuels, which are i) 100% coal (existing configuration of the plant), ii) 90% coal, 10% tyre derived fuel (TDF), iii) 90% coal, 10% refuse derived fuel (RDF), iv) 70% coal, 30% TDF, and v) 70% coal, 30% RDF. All the fuels are in solid form and can be used with the existing burner in the kiln once processed into appropriate sizes. As the availability of the alternative fuels, RDF and TDF is a constraint in India, only 30% is considered as the maximum possible replacement in these tests. The challenge with RDF is the transportation of waste, which is often at sites far away from the plant locations and the challenge with TDF is lack of general availability of raw materials (waste tyres) in India (and hence need to be imported). In the options being tested, alternative fuels, i.e., RDF and TDF, are mixed with coal in the proportions indicated, which is either 90:10 or 70:30. The cumulative expenditure of fuel consumption under these 5 options is depicted in Fig. 38. Despite the higher prices of waste tyres (when compared to RDF), the option with 70% coal and 30% TDF has the least expenditure in the BAU scenario. This is due to the significantly high calorific value of TDF (8000 kcal/kg) when compared to coal and RDF (approximately 4500 kcal/kg). Additionally, the initial equipment to set up captive processing of TDF is cheaper than RDF as it requires fewer processing steps. For processing RDF, a large amount of thermal energy is required as the moisture content within the raw material is quite high. The cumulative emissions of the fuel consumption are shown in Fig. 39 for these 5 options in this mitigation strategy. The lower emission factor of RDF and TDF when compared to coal means that all the options would lead to lower CO2 emissions than 100% coal option. The use of 30% TDF as an alternative fuel leads to a reduction of approximately a million tons of CO2 when compared to using 100% coal. The cumulative emissions for 70% coal, 30% RDF at the end of the simulation run are similar to the emissions for 90% coal, 10% TDF. The cost of using 100% coal under BAU, LME, and HME scenarios is depicted in Fig. 40. The cumulative expenditure of operating the plant in LME and HME scenario is expectedly higher than BAU as the cost of coal and as well as the applicable carbon taxes on the CO2 emissions increases over time.

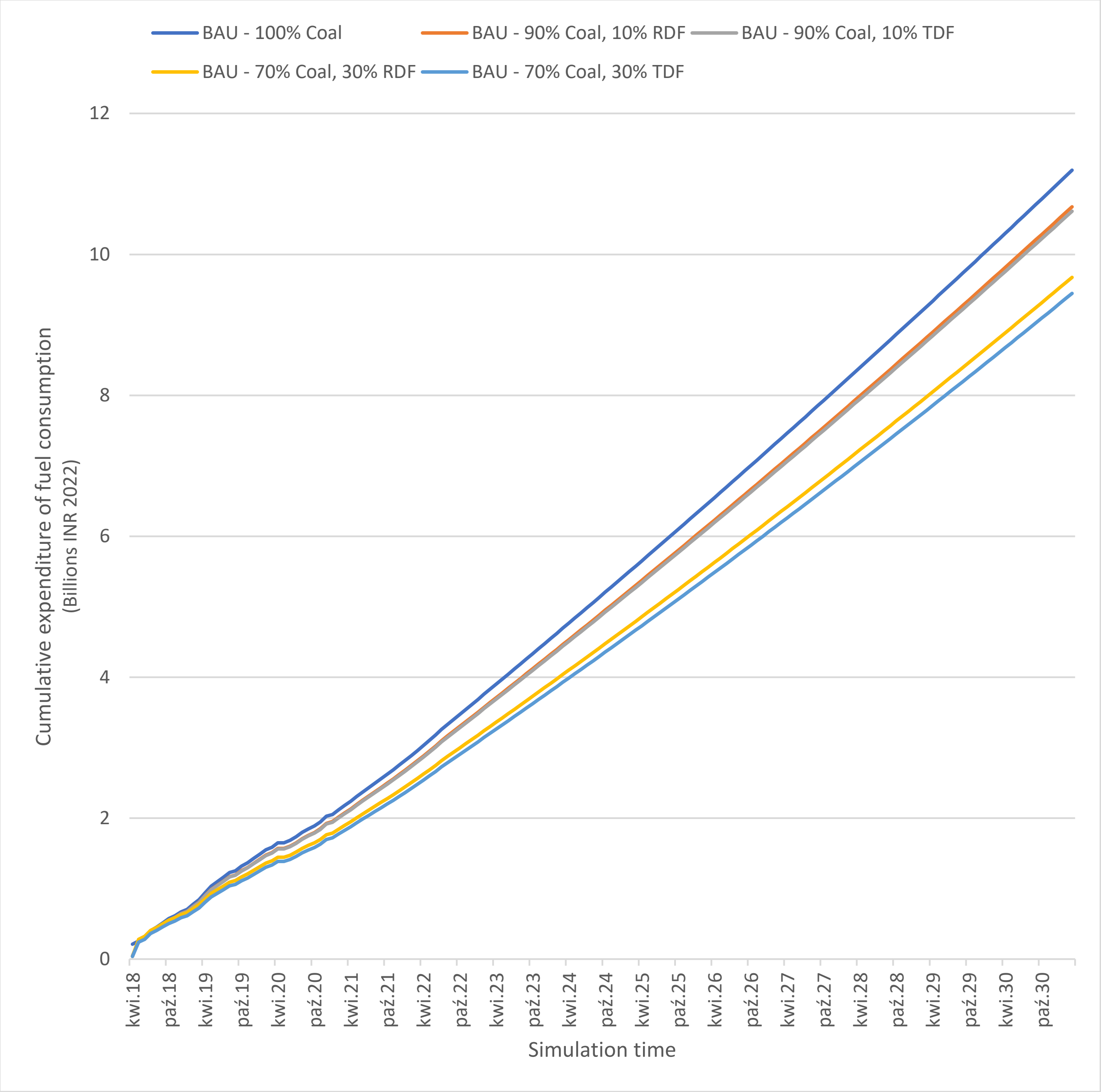

Fig. 38. Cumulative expenditure of fuel consumption for various alternative fuel options for the cement plant under BAU scenario.

Among the available options, 70% coal, 30% TDF seems to be the most optimal choice when considering both, the expenditure and as well as CO2 emission mitigation, as seen in Fig. 41.

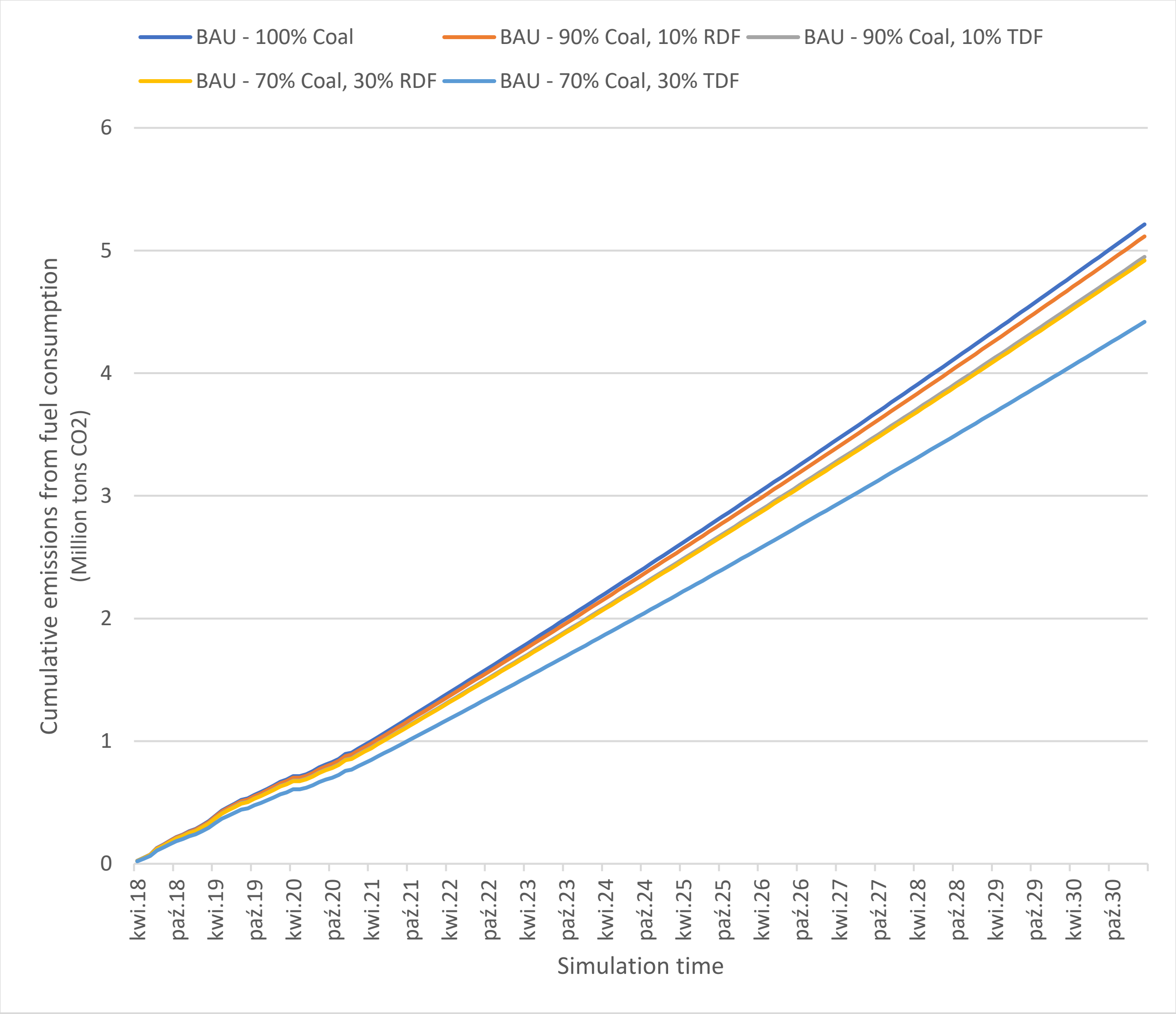

Fig. 39. Cumulative emissions from the fuel consumption for various alternative fuel options for the cement plant under BAU scenario.

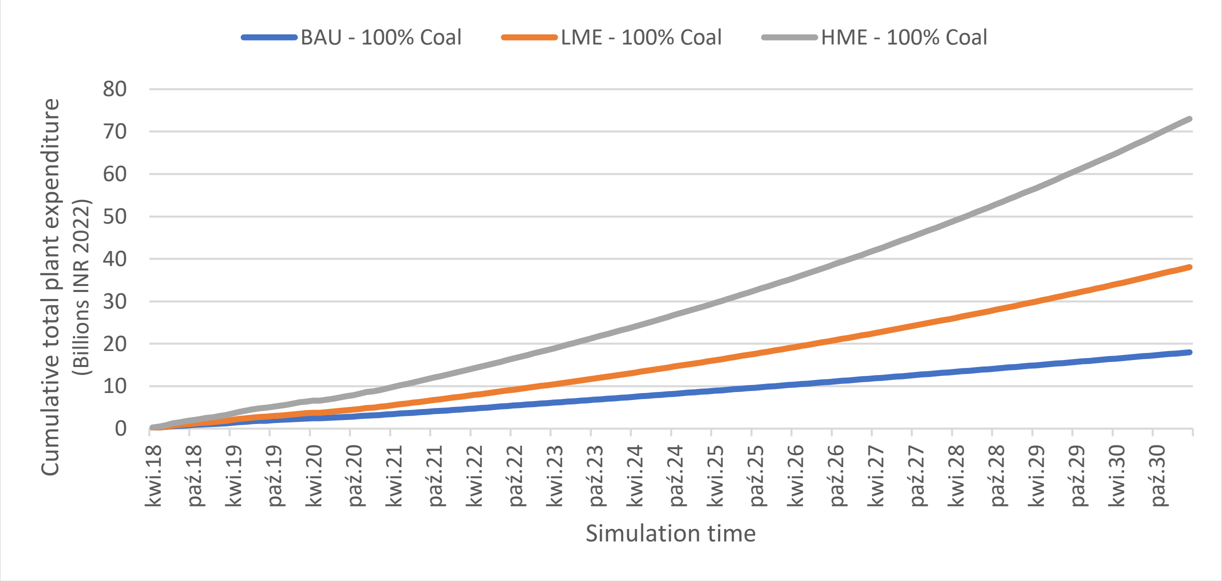

Fig. 40. Cumulative total plant expenditure when using 100% coal as a fuel under BAU, LME, and HME scenarios.

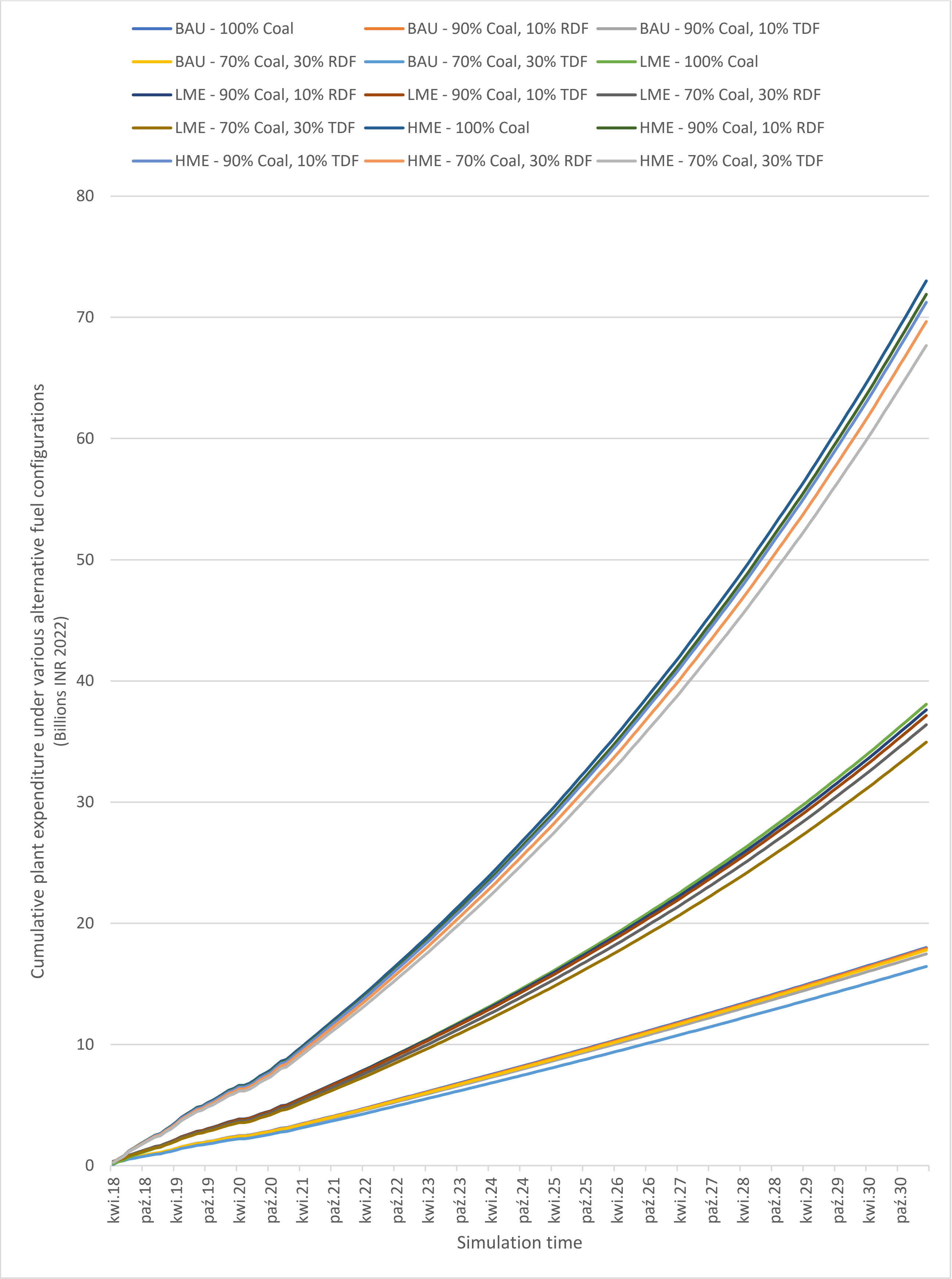

Fig. 41. Cumulative plant expenditure for various alternative fuel configurations under the BAU, LME, and HME scenarios.

c) Captive Power Generation: In this mitigation strategy, following options are considered, i) 100% Grid, ii) 100% captive coal (existing configuration of the plant), iii) WHR + Grid, iv) WHR + Coal, and v) WHR + SPV + Grid. In the first option, the plant's entire electricity requirement is procured from the local grid and is subject to their tariffs and grid emission factor. In the second option, the plant utilises a captive thermal power plant that uses coal to supply the entire electricity requirement of the plant. In the third and fourth options, a mix of waste heat recovery and either coal or grid supply is used for the plant electricity requirement. As the waste heat recovery is capped by the amount of heat available in the plant, it is not theoretically possible to generate 100% of the plant's electricity requirement through this method. In the final option, a combination of WHR, 30% SPV and grid is utilised for plant electricity requirement. The maximum possible electricity is generated using WHR based on the heat available and is combined with electricity from solar photovoltaic which provides upto 30% of the plant electricity requirement, and the rest is procured from the regional grid. The cumulative plant CO2 emissions for each of these 5 options under BAU scenario is depicted in Fig. 42.

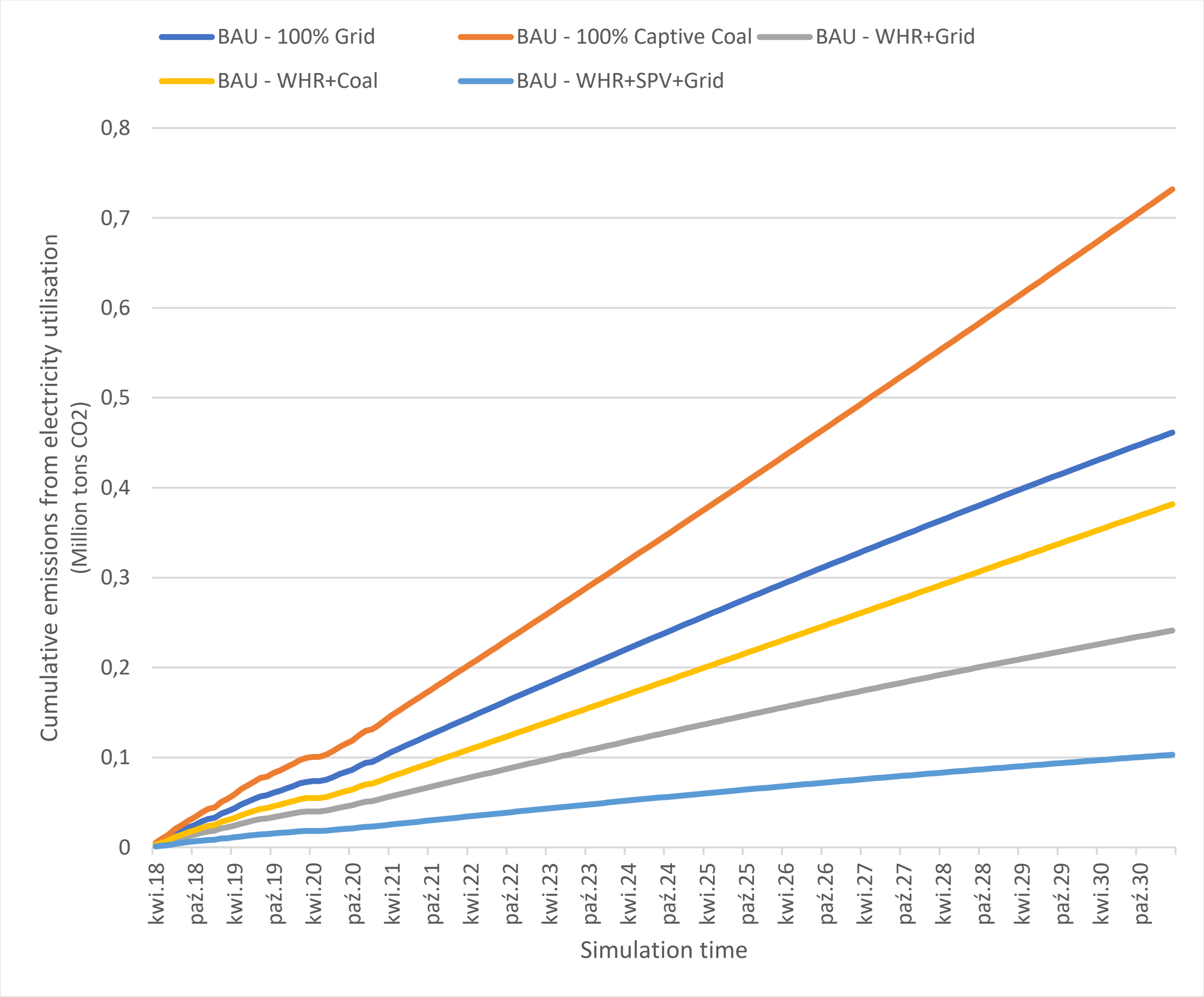

Fig. 42. Cumulative plant CO2 emissions from electricity utilisation for various options available for the captive power generation strategy, under BAU scenario.

Expectedly, exclusively utilising captive power generation using coal leads to the highest amount of CO2 emissions, approximately 7 times higher than the option with the least emissions. The power generation scenario of the regional grid in India is diverse, with a sizeable share of electricity from hydropower, solar, and nuclear sources, leading to a noticeable decrease in emission factor when compared to using 100% captive coal thermal power. Relying on 100% grid leads to the most options in the power generation scenario as seen in Fig. 43. The spike in expenditure during the first time-step represents the initial capital investment required for the respective captive power generation options. The improvements in cost and emission reduction are tabulated in Table 47 with the combination of WHR, SPV, and Grid having the most CO2 emission reductions in BAU scenario while also having the most decrease in expenditure on electricity, which is 38%.

Table 47. The percentage change in emissions and expenditure at the end of the simulation run for each of the captive power generation options, when compared to the base plant configuration of 100% captive thermal power plant using coal.

	Decrease in emissions (%)	**Increase in electricity expenditure (%)**		
		BAU	**LME**	**HME**
WHR + Grid	67%	3.76%	13.78%	46.61%
WHR + Coal	48%	-25.01%	-34.19%	-43.85%
WHR + SPV + Grid	86%	-38.07%	-44.86%	-41.96%

In the HME scenario, a combination of WHR and SPV with the rest procured from grid, as seen in Fig. 44 leads to the least expenditure among the available options. As seen in the Table 47, the LME scenario would provide the most incentives for the plant to switch to the most effective combination available for CO2 mitigation on electricity utilisation.

As such, the most optimal option for electricity sourcing for this particular cement plant would be to use a combination of WHR, SPV and procure the rest from the regional grid.

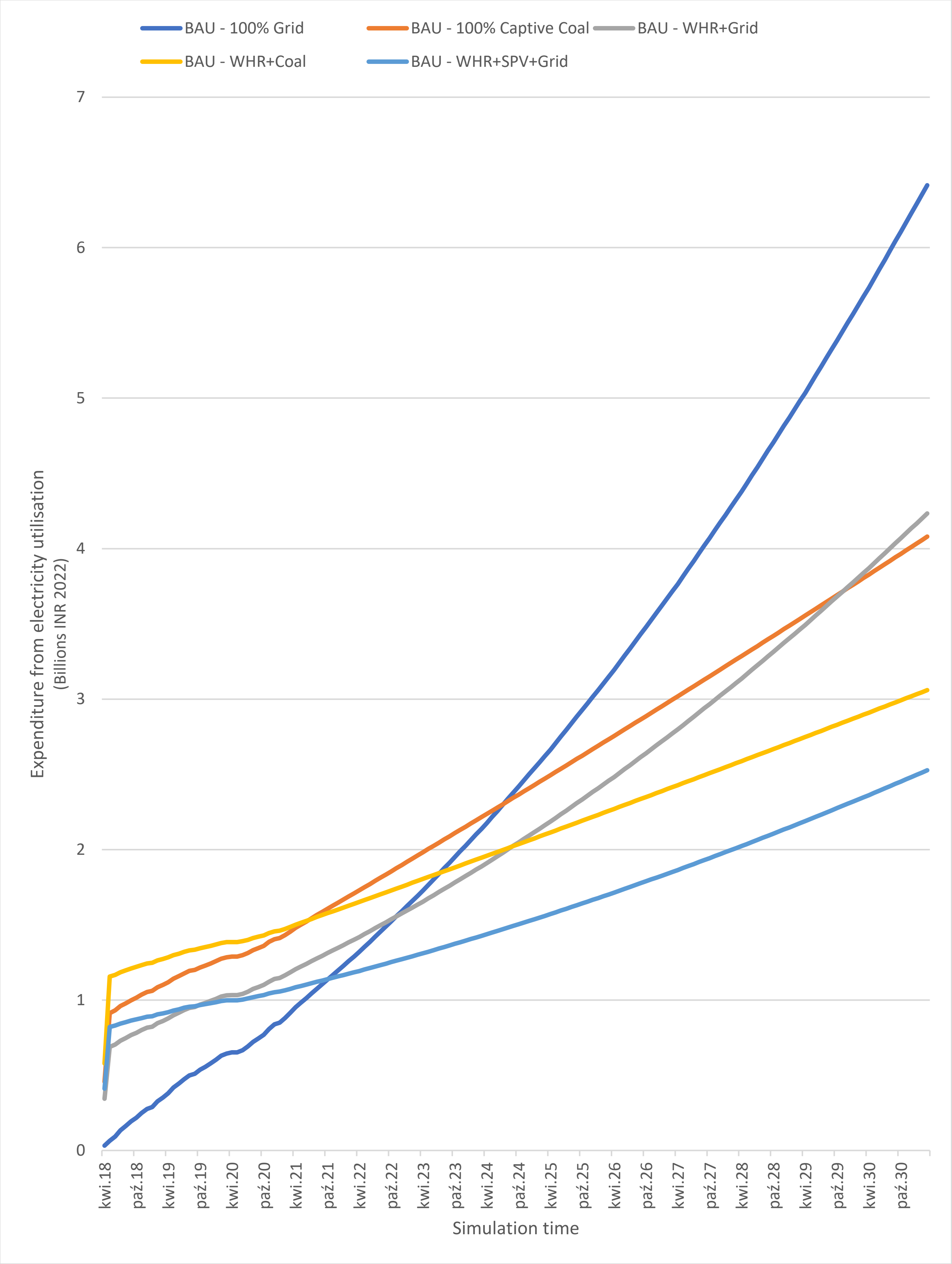

Fig. 43. Cumulative expenditure of plant electricity utilisation for various options available for the captive power generation strategy under BAU scenario.

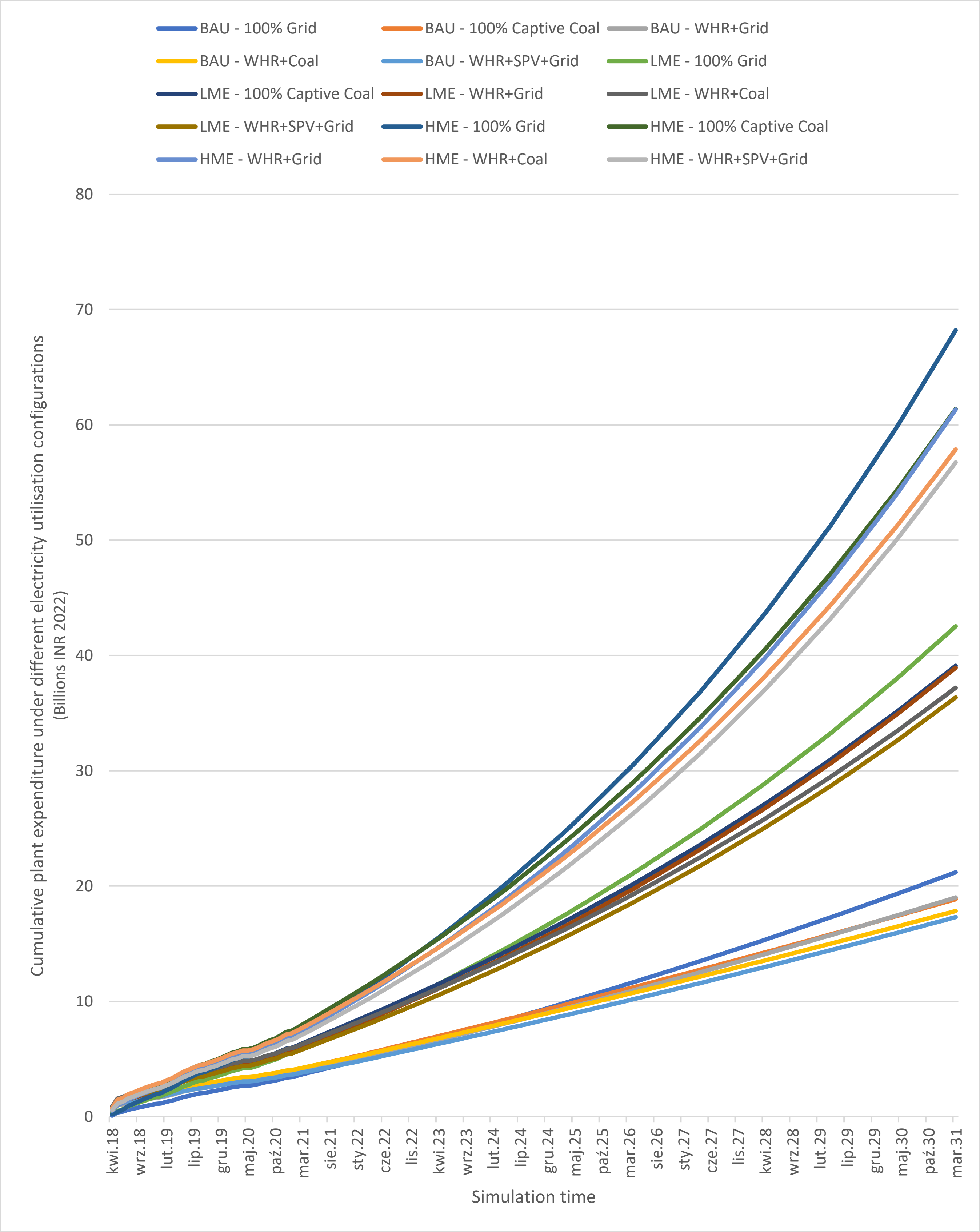

Fig. 44. Cumulative total plant expenditure when utilising various captive power generation options under BAU, LME, and HME scenarios.

d) Carbon Capture: In this strategy, following options are considered, i) Indirect carbonation using Sodium Hydroxide, ii) Indirect carbonation using Barium Hydroxide, and iii) Carbon capture and storage (CCS). In the first two options, additional raw materials need to be procured from the market which affects the overall operating cost. In case of CCS, the compressed CO2 needs to be transported and stored in designated locations which also incurs additional cost. All 3 methods require a sizeable amount of electricity utilisation, therefore leading to auxiliary emissions and cost of electricity depending on the configuration of the plant. The variation in cost of operating indirect carbonation using Sodium Hydroxide (NaOH) is depicted in Fig. 45.

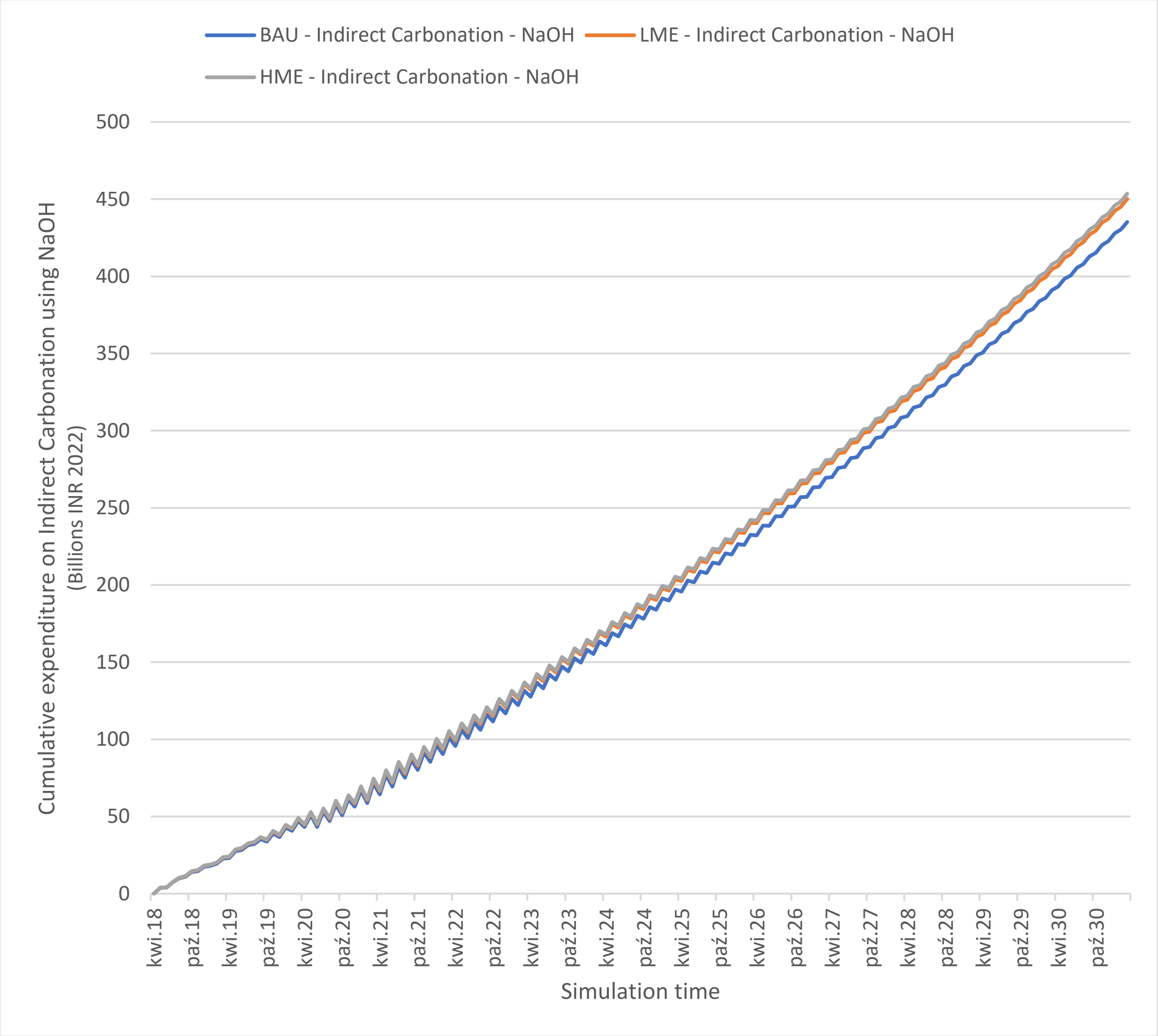

Fig. 45. Cumulative expenditure of utilising indirect carbonation method using Sodium Hydroxide (NaOH) under BAU, LME, and HME scenarios.

The cumulative emissions reduced through each of these carbon capture techniques is depicted in Fig. 46. The emission reductions largely depend on the efficiency of the capture technology, as tabulated in Table 48.

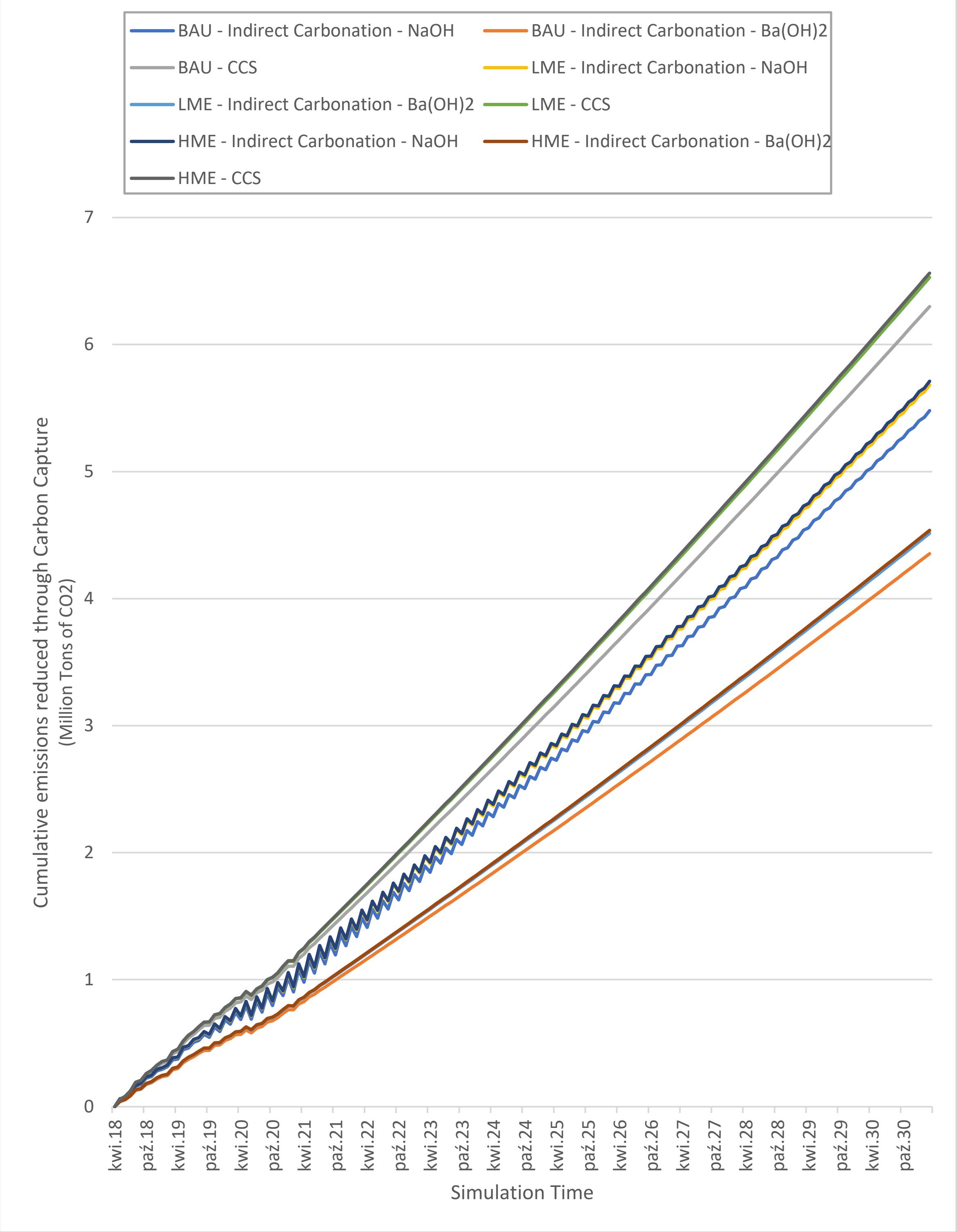

Fig. 46. Cumulative emissions reduced through various Carbon Capture options under BAU, LME, and HME scenarios.

Table 48. Efficiency of carbon capture technologies, based on (Proaño et al., 2020).

Capture technology	**Efficiency**
Indirect Carbonation – Sodium Hydroxide	98%
Indirect Carbonation – Barium Hydroxide	65%
Carbon Capture and Storage	90%

The cumulative expenditure of these various carbon capture options is depicted in Fig. 47. The indirect carbonation method is significantly more expensive to operate than CCS as it requires additional raw materials and the selling price of the by-products, i.e., Sodium Carbonate and Barium Carbonate is not high enough to offset the operating costs. The carbon capture and storage have variable costs associated with it as the storage location of compressed CO2 may change over time. The LME scenario favours the implementation of Carbon capture more than the HME and BAU scenarios as seen in Fig. 47. For the purpose of the next section where a combination of these mitigation strategies will be used, CCU is considered as the most optimal carbon capture option within this module.

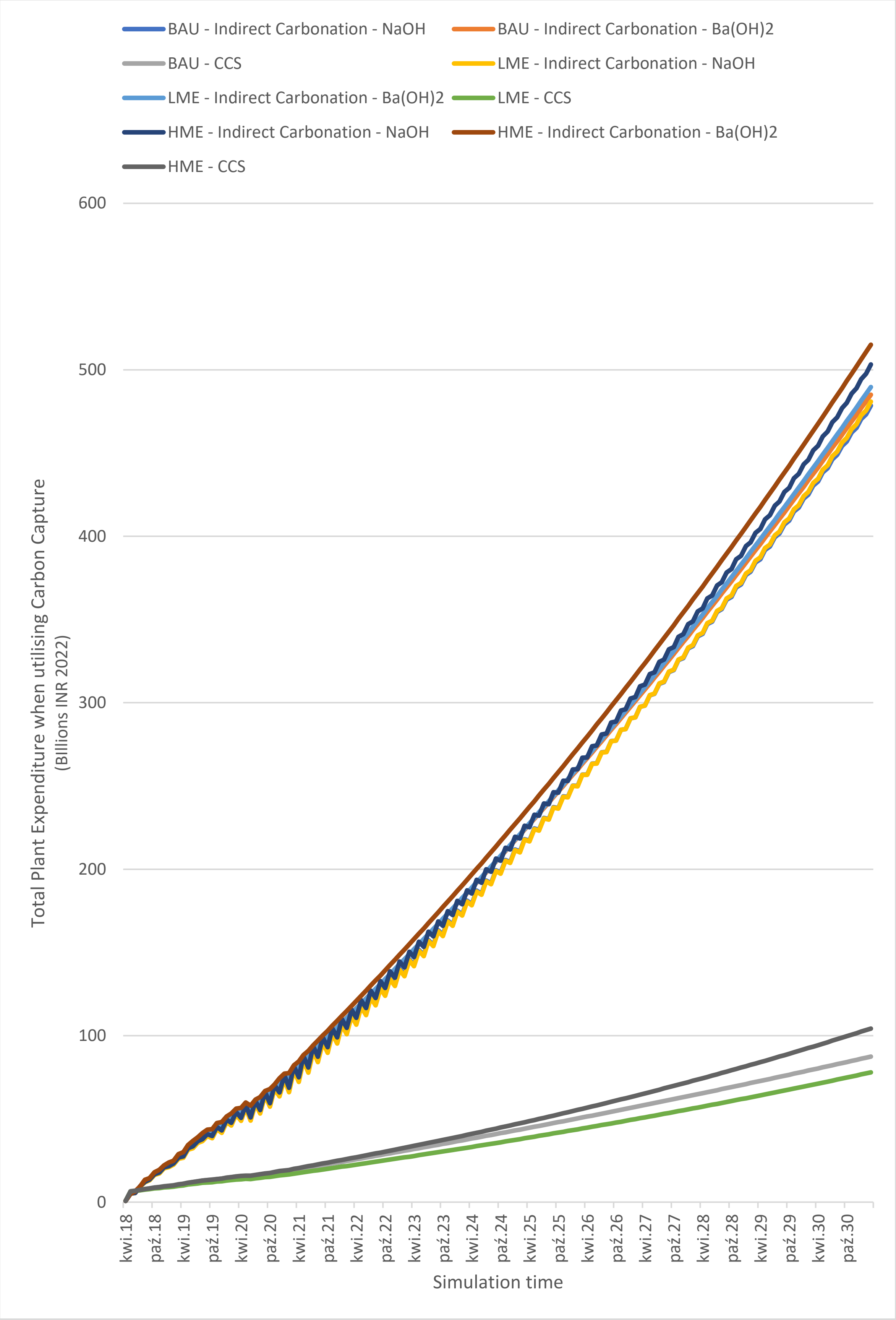

Fig. 47. Cumulative expenditure when utilising the various carbon capture options under BAU, LME, and HME scenarios.

6.1.2. Multiple mitigation strategy approach

As discussed in the previous section, a combination of mitigation strategies are further tested to find the best possible configuration for the plant for obtaining the maximum amount of CO2 reductions with the least impact on plant expenditure. Following combinations are tested, Combination 1 - Clinker substitution and captive power generation, Combination 2 - Clinker substitution, alternative fuels, and captive power generation, and Combination 3 - Clinker substitution, alternative fuels, captive power generation, and carbon capture. As each strategy has multiple configurations, the most option as deducted from Section 6.1.1. is used for each strategy here, which are:

- Clinker substitution – Wet Ash
- Captive Power Generation – WHR + SPV + Regional Grid
- Fuel Substitution – 70% Coal and 30% TDF
- Carbon capture – CCU

The cumulative plant expenditure for combination 1 under BAU is depicted in Fig. 48 where the cost of running the plant significantly increases in HME scenario. The increased carbon taxes in HME scenario resulted in more unused income for the local government as indicated in Fig. 49 when compared to LME scenario.

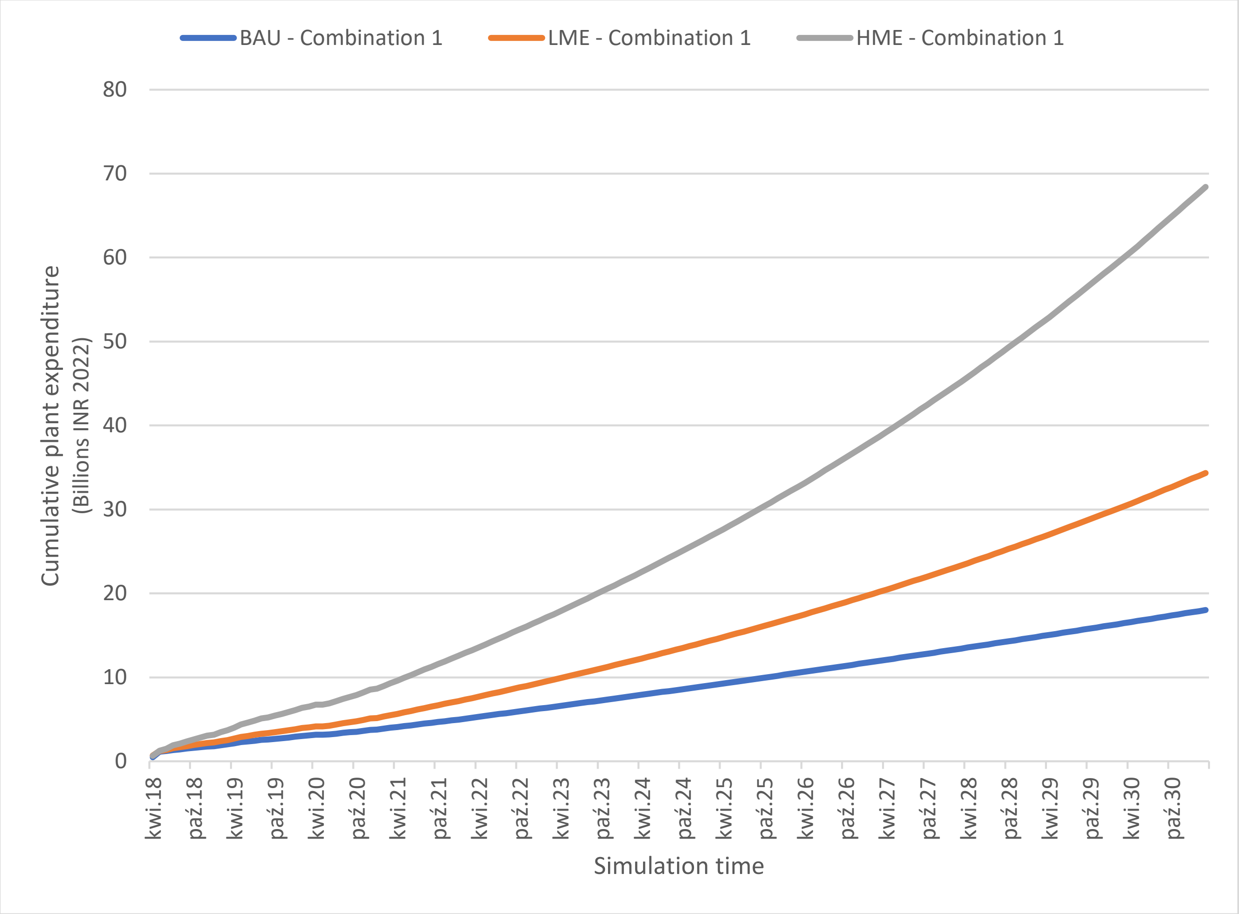

Fig. 48. Cumulative plant expenditure for combination 1 under BAU, LME, and HME scenarios.

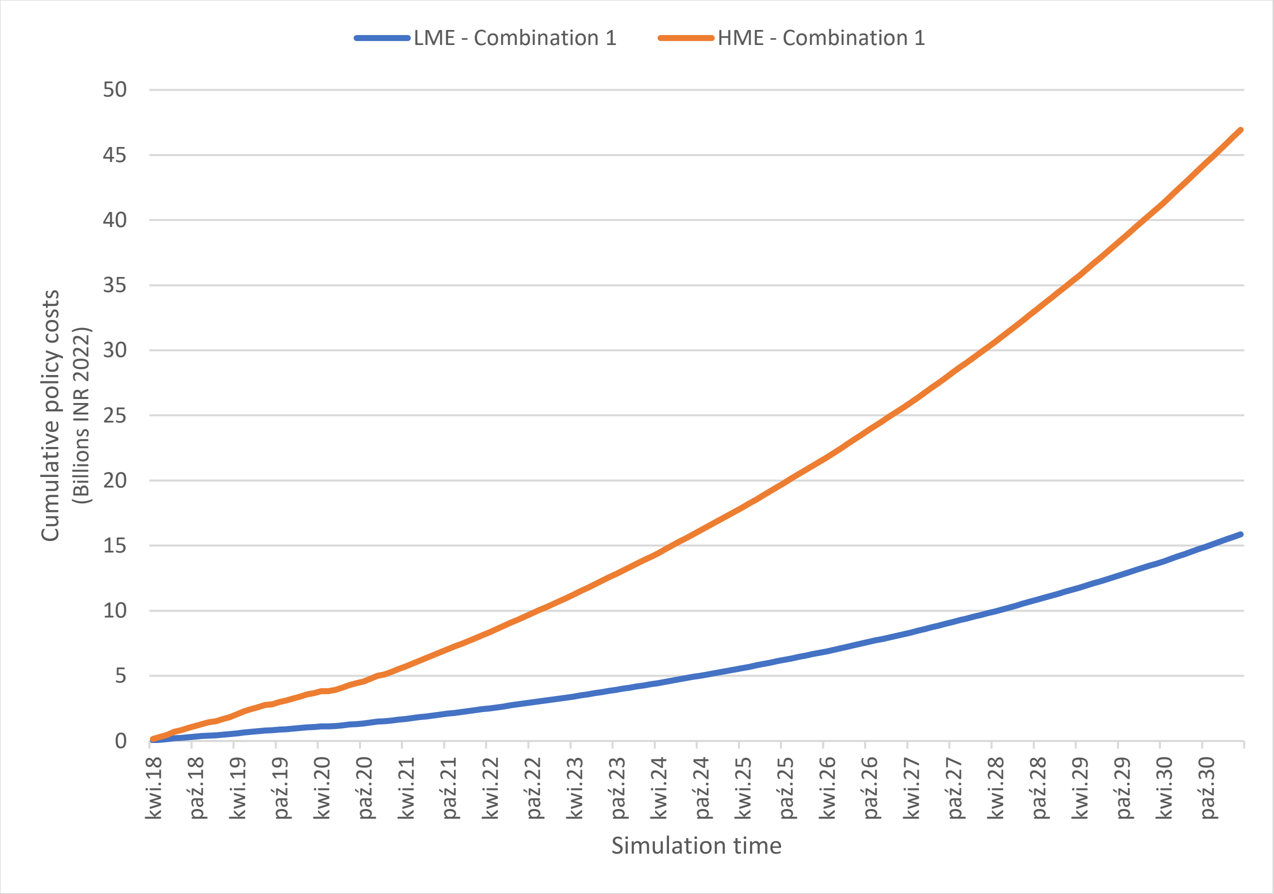

Fig. 49. Cumulative policy costs for combination 1 under LME and HME scenarios. Positive value indicates income (through carbon taxes), negative value indicates expenditure for local government.

The improvement of the various combinations in mitigating CO2 emissions when compared to existing plant configuration is tabulated in Table 49. As expected, combination 3 with the carbon capture strategy results in the highest reduction in CO2 emissions, followed by combination 2.

Table 49. Percentage increase in emissions for various combinations under the previously defined scenarios when compared to existing plant configuration. Green or negative number indicates a decrease in CO2 emissions while orange or positive number indicates a net increase in cumulative CO2 emissions.

BAU - Combination 1	4.68
BAU - Combination 2	-3.16
BAU - Combination 3	-44.72
LME - Combination 1	5.20
LME - Combination 2	-2.65
LME - Combination 3	-44.58
HME - Combination 1	5.70
HME - Combination 2	-2.16
HME - Combination 3	-44.52

The cumulative expenditure of various combinations under BAU, LME, and HME scenarios is depicted in Fig. 50. The graph additionally includes the metrics from the existing plant configuration in all 3 scenarios. Across all the scenarios, Combination 2 leads to the lowest plant expenditure when compared to Combination 1 and Combination 3. Since the cumulative expenditure for existing plant is lower than Combination 3 in across all 3 scenarios, there is not enough incentive for the plant to implement Carbon Capture in the given regional conditions.

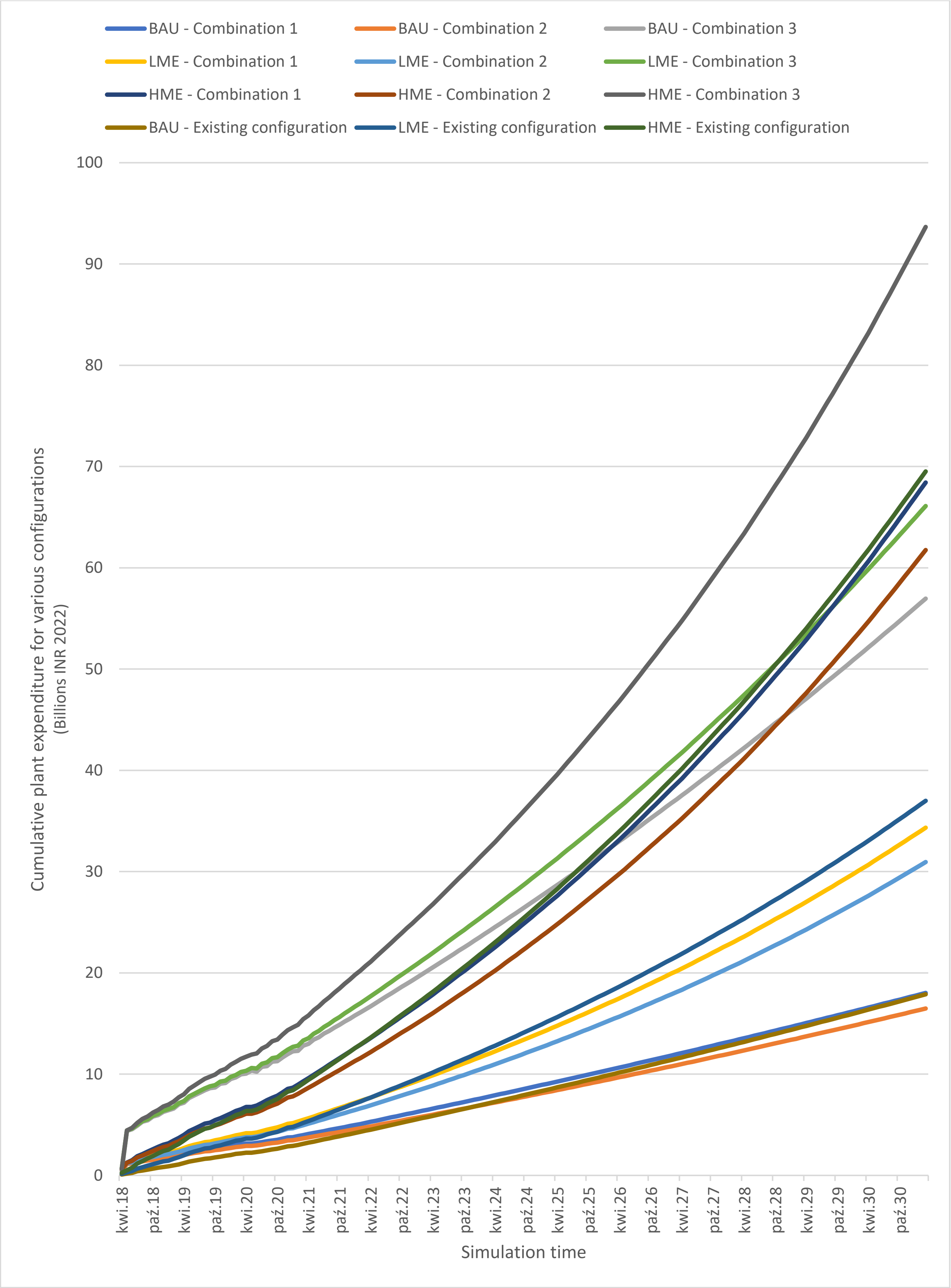

Fig. 50. Cumulative expenditure for different combinations of mitigation strategies, under BAU, LME, and HME scenarios.

Further increasing the carbon tax would only result in increasing the overall operational expenditure and would likely make production of cement unsustainable, depending on the market tariffs for cement. As seen in Fig. 52, the local government has a lot of unused income from carbon tax which could be reused for subsidies in order to provide a much greater incentive for the cement plant to implement mitigation strategies. Currently HME scenario with Combination 3 is the most expensive arrangement for the plant, which will be used for modified scenario HME-Mod, whose parameters are tabulated in Table 50. The objective of HME-Mod is to make implementation of Combination 3 more viable by making utilising more of the funds collected via Carbon tax.

Therefore, a new scenario is considered based on HME, with the following changes to the subsidies:

Table 50. Proposed changes to HME strategy to improve

	Subsidy	
	Old	**New**
Carbon capture	-Nil-	INR 3000/ton (USD 39.52)
Captive Power Generation	INR 2/kWh (USD 0.03)	INR 4/kWh (USD 0.05)
Clinker Substitution	-Nil-	INR 500/ton (USD 6.59)
Fuel Substitution	INR 3000/ton (USD 39.52)	INR 5000/ton (USD 65.86)

The cumulative expenditure for the plant in existing configuration is compared with Combination 3, under HME-mod scenario in Fig. 51. The plant expenditure at the end of the simulation run is now similar to the existing plant configuration, which would prompt the cement plant stakeholders to implement mitigation strategies that while reducing CO2 emissions, but would not lead to significant additional expenditure. The expenditure for the local government at the end of the simulation run is in negative, i.e., there is a net inflow of cash through carbon taxes than outflow through subsidies as depicted in Fig. 52. The additional, unused funds could be agglomerated from various cement plants within the region of the local government and could be further utilised in CO2 mitigation strategies in other domains including green electricity production, which would further reduce the emissions from the cement plant under Combination-3, which uses electricity purchased from the regional grid.

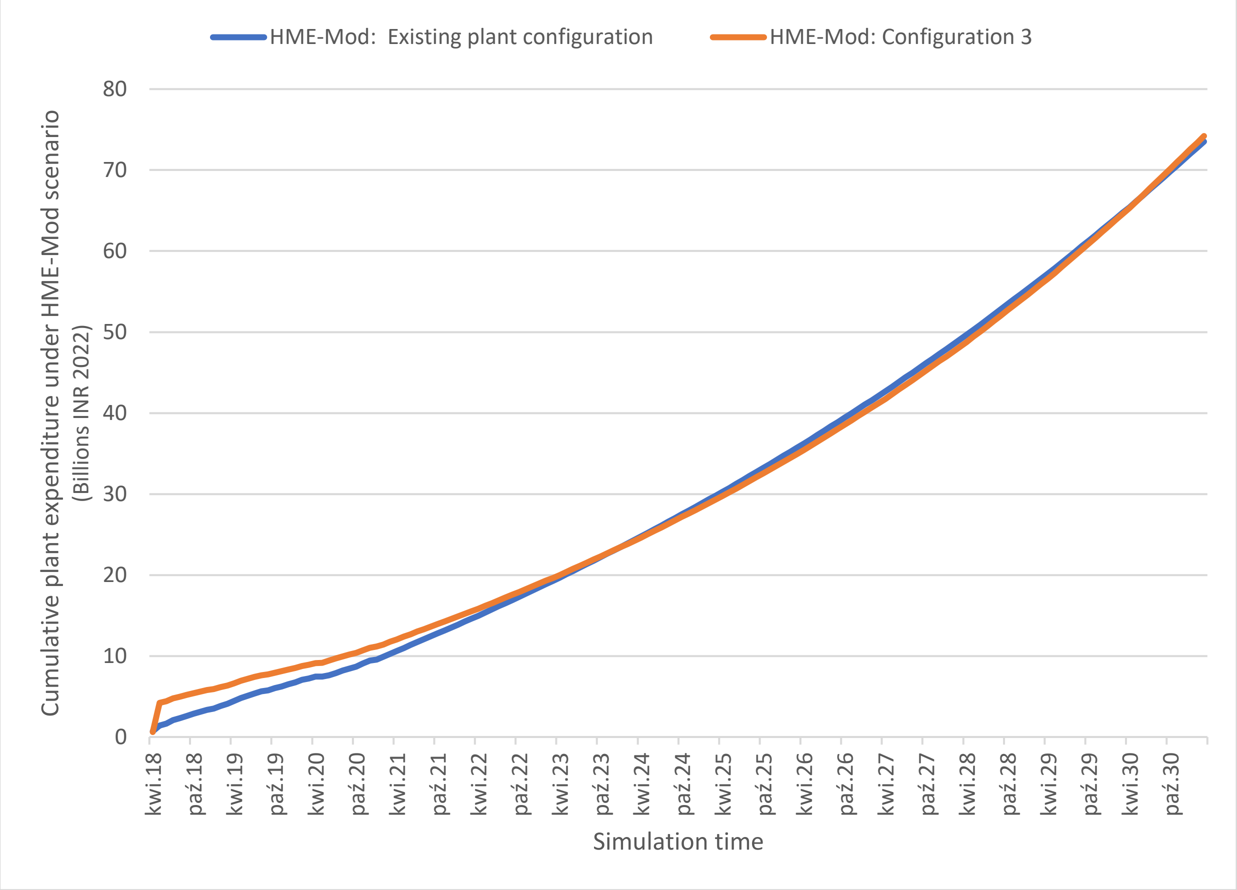

Fig. 51. Cumulative plant expenditure for the new HME-Mod scenario, comparing Combination 2 with existing plant configuration.

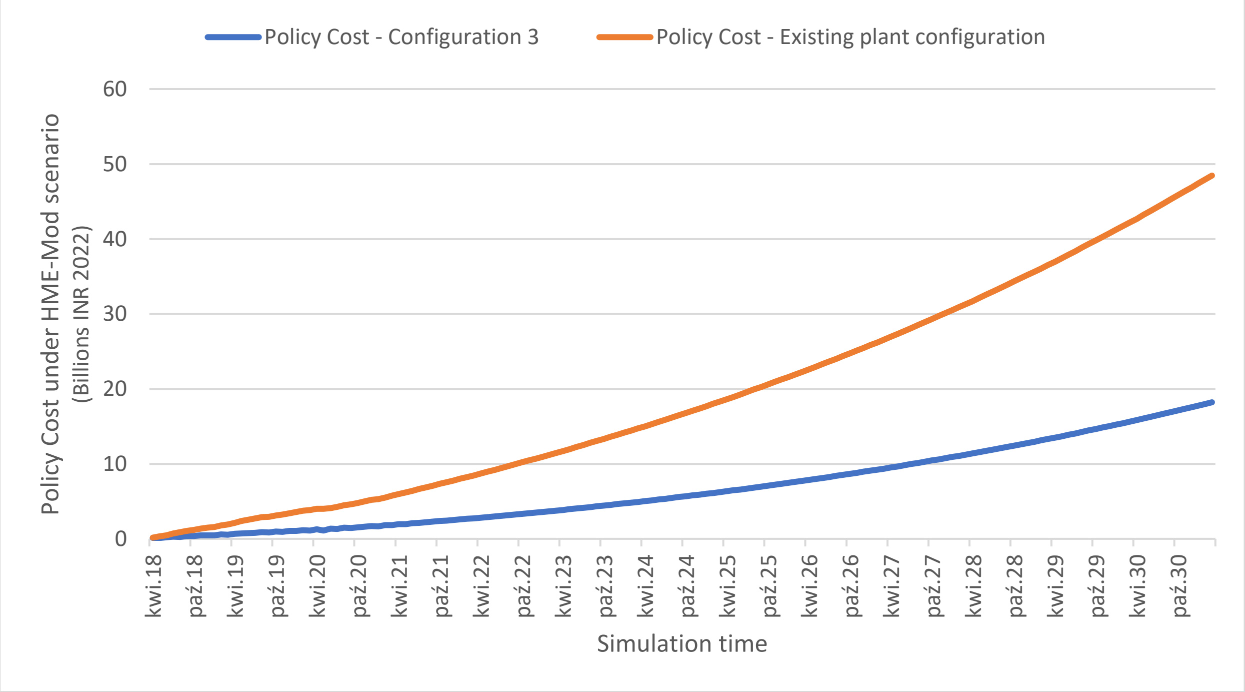

Fig. 52. Cumulative policy cost for the local government under the HME-Policy when the plant is in Combination-2 configuration.

5.1.3. Payback period

The payback period is defined as the time it takes to recover the cost of an investment. The implementation of mitigation projects such as Waste Heat Recovery (WHR), Solar Photovoltaic (SPV) or procurement & commissioning of machinery needed for processing alternative fuels such as Refuse Derived Fuels (RDF) or Tire Derived Fuels (TDF) requires significant capital investment which acts as hinderance in widespread adoption of these strategies. As majority of the mitigation strategies discussed in this study directly or indirectly lead to increase in energy efficiency of the plant, they subsequently result in lower operational costs than compared to a typical cement plant with no improvements. Therefore, payback period can be used for assessing the benefits of both short-term and long-term projects. Additionally, payback period can be utilised for preliminary evaluation or as a project-screening device for high-risk projects in times of financial uncertainty (Coker, 2007). A shorter payback time makes adoption of mitigation strategies more sustainable, as such the payback periods of the following projects is assessed in BAU, LME, and HME scenarios:

- WHR
- SPV
- RDF
- TDF
- Wet Ash

The payback period in case of Wet Ash is compared with a cement plant that is currently using fly ash. As discussed in the previous chapters, as the Indian government has mandated the use of fly ash in the cement industry which led to high demand and shortages of fly ash. Wet ash has the same properties as fly ash, after it is dried and ground to required size, and can be used in place of fly ash.

The payback period here is determined by comparing the modified plant with a default plant with no improvements and the time it takes to reach break-even point is noted. The results are presented in Table 51. "Nil" indicates that the mitigation strategy in that particular scenario would not be able to recover its capital cost and incurs higher cumulative expenditure to the plant at the end of the simulation run.

Table 51. Payback period of various mitigation strategies under different scenarios

	BAU	**LME**	**HME**
	Months		
WHR	56	43	35
SPV	19	14	11
RDF	Nil	6	1
TDF	1	1	1
Wet Ash	Nil	1	1

In case of WHR, it takes about 4.6 years to recover the capital investment under BAU scenario, while it reduces to 3.6 and 2.9 years respectively for LME and HME scenarios. For SPV supplying 30% of the plant's electricity requirement, the payback period is relatively quicker, with 1.6, 1.1, and 0.9 years respectively. For setting up a captive RDF plant supplying 30% of the plant's thermal energy requirement, the project is not viable in BAU scenario, but the payback periods in LME and HME are 6 and 1 month respectively. Compared with RDF, the cost of setting up TDF is much lower as it only requires a shredding machine to cut the waste tyres to a required size. As a result, the payback period in all 3 scenarios is 1 month. The challenge in implementing TDF is ability to procure the raw material, i.e., waste tyres at a consistent price. In the BAU scenario, Fly Ash tariffs are already regulated by the Government and are made available to cement industry at a nominal price (fly ash that is generated in Government operated thermal power plants) and the only notable expense to cement plant is the cost of transportation. However, the existing policy led to shortages of fly ash in regions with large number of cement industries and are forced to import from faraway thermal power plants, increasing the cost of transportation. In the LME and HME, the fly ash prices are assumed to be market driven and the current price trends of fly ash (which is generated in privately owned thermal power plants) is considered. Thereby, Wet Ash will not be viable in BAU when the fly ash is made available at a nominal price, but the payback period is 1 month in both scenarios of LME and HME.

7. DISCUSSION

The results from the simulation of previously described scenarios indicate the utility of the model in quickly providing preliminary decision-making support regarding the practicality and effectiveness of a mitigation strategy on an individual cement plant depending on the prevailing energy market conditions in the region.

Among the single mitigation strategy options simulated for the reference cement plant, the following approaches stood:

- Wet ash among the available options for substituting clinker. While fly ash has been identified as the most effective substitute in the BAU scenario, wet ash has led to notable reduction in expenditure to the plant in LME and HME scenarios. As discussed earlier, in the region of the current plant situated in India, the fly ash tariffs are currently regulated and are made available to the cement industry at nominal prices for substitution. However, as the demand for fly ash has been increasing, its availability has become a concern. In such a scenario, wet ash is a more suitable alternative considering the increase in emissions due to additional processing is only marginal when compared to fly ash. When tasked between choosing to revert to increased ratio of clinker in cement and procuring fly ash from long distances, this model has helped to identify wet ash as a possible alternative for the cement plant.
- Among the options available for alternative fuels, TDF was identified as the most suitable fuel in case of both emission reduction and plant expenditure. The capital expenditure required for setting up the equipment necessary for processing TDF is significantly lower when compared to RDF. However, depending on the region, the availability of waste tyres could be a concern, but RDF is more readily available in most regions, especially around large urban regions. Additionally, the adoption of RDF and TDF to existing coal burner does not require any significant downtime to plant operations as existing burner can be readily adapted to use the new fuels.
- For the cement plant’s electricity requirement, a combination of WHR, SPV, and existing grid has led to both, the least expensive strategy over time, as well as the most effective CO2 mitigation strategy. Due to the technical nature of its generation, WHR and SPV cannot provide the entire electricity required by the plant. The existing solutions for storage of electrical energy from SPV for its using during the night are expensive, with its costs increasing exponentially with the capacity of the storage. However, by utilising the existing grid in combination of SPV and WHR, the proposition becomes viable and the most suitable in case of the reference plant. Furthermore, as the regional grid continues to invest into renewable energy, the grid emission factor reduces over time, making it even more suitable for reducing CO2 emissions.
- Carbon capture is a relatively new and upcoming strategy in the cement domain, and among the options investigated, i.e., indirect carbonation using either NaOH or $Ba(OH)_2$ and CCS, the later has been identified as a more suitable alternative in this region. The current regional market tariffs of Na_2CO_3 and $BaCO_3$ and their future trends are not high enough for the process to be viable through the sale of by-products alone. The CCS approach is identified as the most effective carbon

> capture strategy currently, but its expenditure would continue to increase as it requires compressed CO2 to be transported and stored in designated locations. In case of the reference plant, the storage capacity of the compressed CO2 has been considered to be infinite as it is situated close to the seacoast, making off-shore CO2 storage a possibility.

Among the combinations of mitigation strategies tested, the best performing option BAU, LME, and HME scenarios, i.e., the approach that led to the lowest cost per unit of CO2 mitigated, is chosen for captive power generation, clinker substitution, alternative fuels, and carbon capture modules. As discussed above, wet ash, a combination of WHR, SPV, and grid, TDF, and CCU are chosen as the most effective approaches in their respective strategies. Among the three combinations of strategies tested, the plant expenditure widens significantly with time between HME and the other two scenarios, despite the provision of subsidies. As expected, “Combination 3”, with three different strategies adopted simultaneously led to both, the highest reduction in CO2 emissions and as well as the highest increase in cumulative plant expenditure. However, when considering the cost per unit of CO2 mitigated, “Combination 2” with wet ash as clinker substitute, TDF, and a combination of WHR, SPV and grid was observed to be the lowest for the reference cement plant across scenarios.

It is further observed that in the HME scenario, the ratio of carbon tax collected and local government expenditure on subsidies for the reference plant is skewed towards the former, i.e., more carbon tax is collected than money spent on subsidising mitigation costs. Through series of further experiments, more potent subsidies values are determined as depicted in Table 50 for the carbon tax tariffs considered in this scenario. By appropriately tweaking carbon tax and subsidies, the payback period for capital expenditure for implementing mitigation strategies can be strategically lowered to promote the adoption of CO2 mitigation.

While the simulation experiments were run on a reference plant in India, it can be adopted to any plant by feeding the relevant input datasets into the model. This contributes to universality of the model in the most appropriate mitigation strategy and as well as the tax-subsidy policy for any cement installation in the world. The data from the reference plant is embedded into the model in Appendix II for reproducibility. The model also has embedded datasets for technical metrics for different plant configurations, which readily supports experimentation on other cement plants in the existing region. The results obtained from this model, thereby contributes towards preliminary decision support for the cement plant stakeholders in identifying suitable mitigation strategies before conducting more extensive studies prior to their implementation. Furthermore, the model can be utilised by governmental bodies for investigating the impact of climate change policies on individual cement plants and further tweak their policies to ensure it encourages the plant to adopt mitigation strategies, without overwhelming them with carbon taxes.

The study can be further improved by integration of mitigation strategies which are not fully realised in the existing model, such as use of microalgae generated using the CO2 emissions from the plant as a fuel. Furthermore, embedding regional data from different countries within the model would further improve the utility of the model among the cement plant stakeholders to quickly analyse the mitigation options without having to first source and append relevant datasets from their region. The future studies can employ more accurate forecast data for running the simulations and obtain precise expenditure and CO2 mitigation results from the model. Finally, the model can be expanded to allow for the cement stakeholders to compare the costs of improving efficiency of existing production lines with the costs of expansion of the plant's production capacity.

SUMMARY

Cement industry is one of the most significant contributors of CO2 emissions in the world today. Despite the availability of various mitigation strategies, their adoption rates have been relatively low as implementation of these approaches require significant capital investment. Choosing the appropriate mitigation strategy involves the top-level management in the cement plant, thereby this study proposes a decision support tool to assess the impact of various CO2 mitigation strategies applicable to specific cement plant configurations under varying market conditions. Therefore, for realising the primary goal in this study, this research chooses to develop a decision support tool using SD modelling approach for the stakeholders in cement industry to identify and investigate the outcomes of implementing various CO2 mitigation strategies in a specific cement plant. The mitigation strategies featured in this study are described elaborately to provide context to the model construction.

As a prerequisite to development of the model, existing studies utilising SD in the cement domain for CO2 mitigation are reviewed and relevant gaps were identified. Subsequently, a SD model was developed, taking into consideration the existing gaps in the research, to represent a typical cement plant encompassing all the relevant technical requisites for calculating the emissions and expenditure at each time step. For the secondary goal, the potential for utilising the chosen simulation method is investigated by feeding in relevant datasets specific to a cement plant based in India, and then running a series of experiments using different combination of mitigation strategies under different policy conditions. The results demonstrated the ability of chosen method in providing information for the cement plant management in identifying the optimal combinations of strategies that would minimise both CO2 emissions and as well as plant expenditure. Based on the results obtained, the optimal options for each strategy were identified for this specific plant, which were a) captive power generation – WHR + SPV + Grid, b) clinker substitution – Wet ash, c) alternative fuels - TDF, and d) carbon capture - CCS. Three different policy scenarios were crafted and analysed in combination with the aforementioned mitigation strategies.

Then, as part of the tertiary goal, a combination of these approaches was investigated across the scenarios, in terms of CO2 emissions reduced and expenditure incurred. The combinations tested were a) Combination 1 – wet ash and WHR+SPV+Grid, b) Combination 2 – wet ash, TDF and WHR+SPV+Grid, and c) Combination 3 – wet ash, TDF, WHR+SPV+Grid and CCU. Among them, Combination 2 was identified as the optimal strategy for the cement plant configuration utilised in the simulation. It was further identified that in the scenarios tested, there has been a large disparity between the carbon tax collected from the plant and the amount of subsidies allocated to the plant for promoting the adoption of mitigation strategies. Thereby, through experimentation, a new policy was devised with higher subsidies to balance the amount collected and spent by the local governing body on the given plant. Additionally, the payback periods for each of the strategies is determined under each policy scenario.

The experiments and results demonstrate the utility of the model as a decision support tool for the cement plant stakeholders in identifying the optimal strategies for their plant. The study contributes to management science discipline through advancement of existing decision support tools for CO2 mitigation by emphasising on solving the high-level strategic decision-making challenges relevant to the cement sector. The study concludes with suggestions for

the future research, which is, integration of more mitigation strategies in the model, embedding regional data to speed up the time required to set up the model for simulating a specific cement plant, and utilisation of more accurate forecast data to obtain more precise results in future studies using this model.

ABBREVIATIONS

- BAU - Business As Usual
- CCS - Carbon Capture and Storage
- CO2 - carbon-di-oxide
- CSI - Cement Sustainability Initiative
- CIS - Commonwealth of Independent States
- ESP - Electrostatic Precipitator
- GCV – Gross Calorific Value
- GHG - Greenhouse Gases
- GDP - Gross Domestic Product
- HME - High CO2 mitigation effort
- ID - Induced Draft
- IPCC - Intergovernmental Panel on Climate Change
- IEA - International Energy Agency
- LME - Low CO2 mitigation effort
- NDC - Nationally Determined Contribution
- OPC - Ordinary Portland Cement
- RDF - Refuse Derived Fuels
- SPV - Solar Photovoltaic
- SEC-E - Specific Electrical Energy Consumption
- SEC-Th - Specific Thermal Energy Consumption
- SD - System Dynamic
- TDF - Tire Derived Fuels
- VFD - Variable Frequency Drives
- WHR - Waste Heat Recovery
- WBCSD - World Business Council for Sustainable Development

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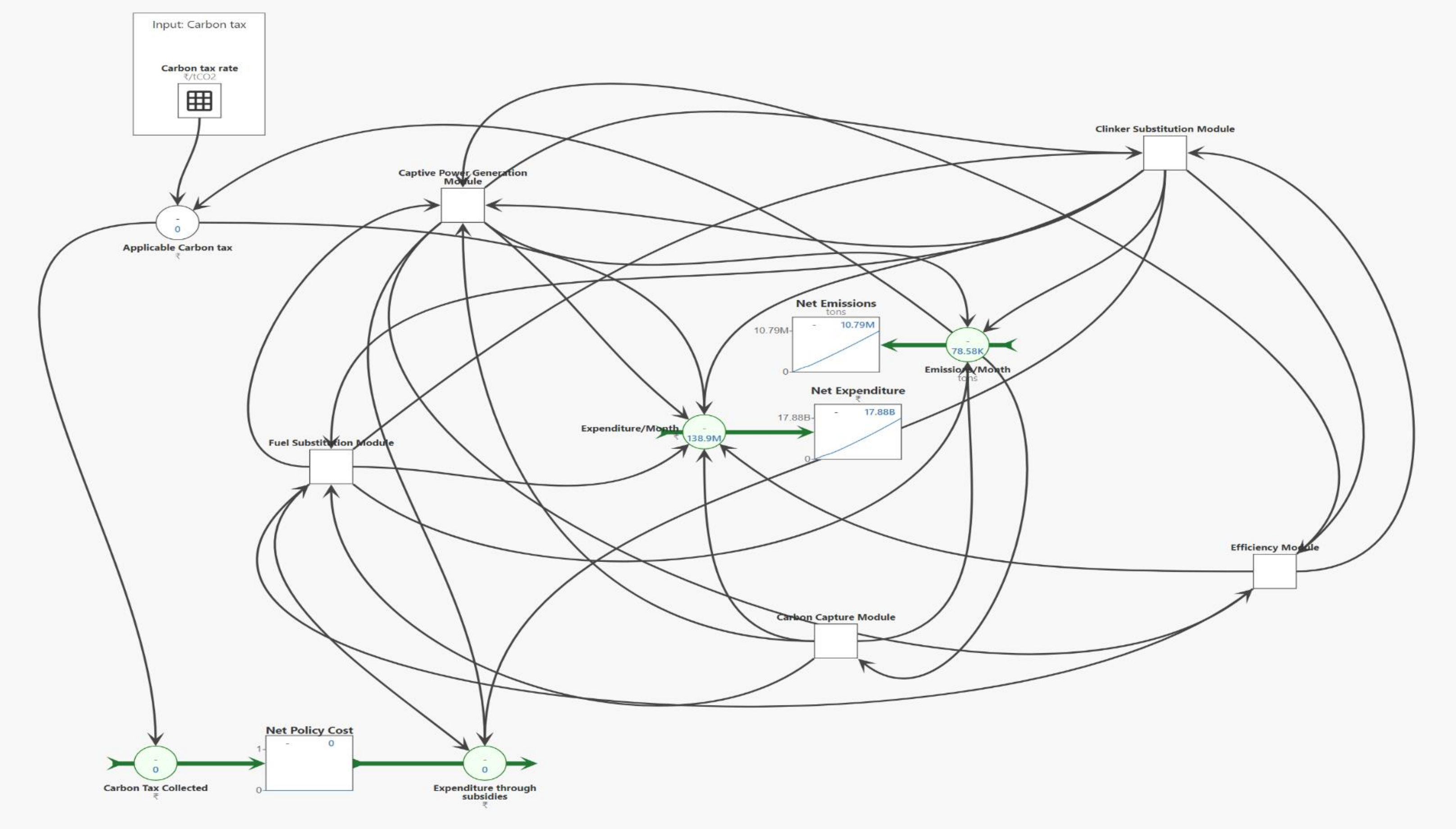
LIST OF FIGURES

LIST OF TABLES

APPENDIX – I

Stock and flow diagrams of the model and its sub-models[7]

A. Primary Model



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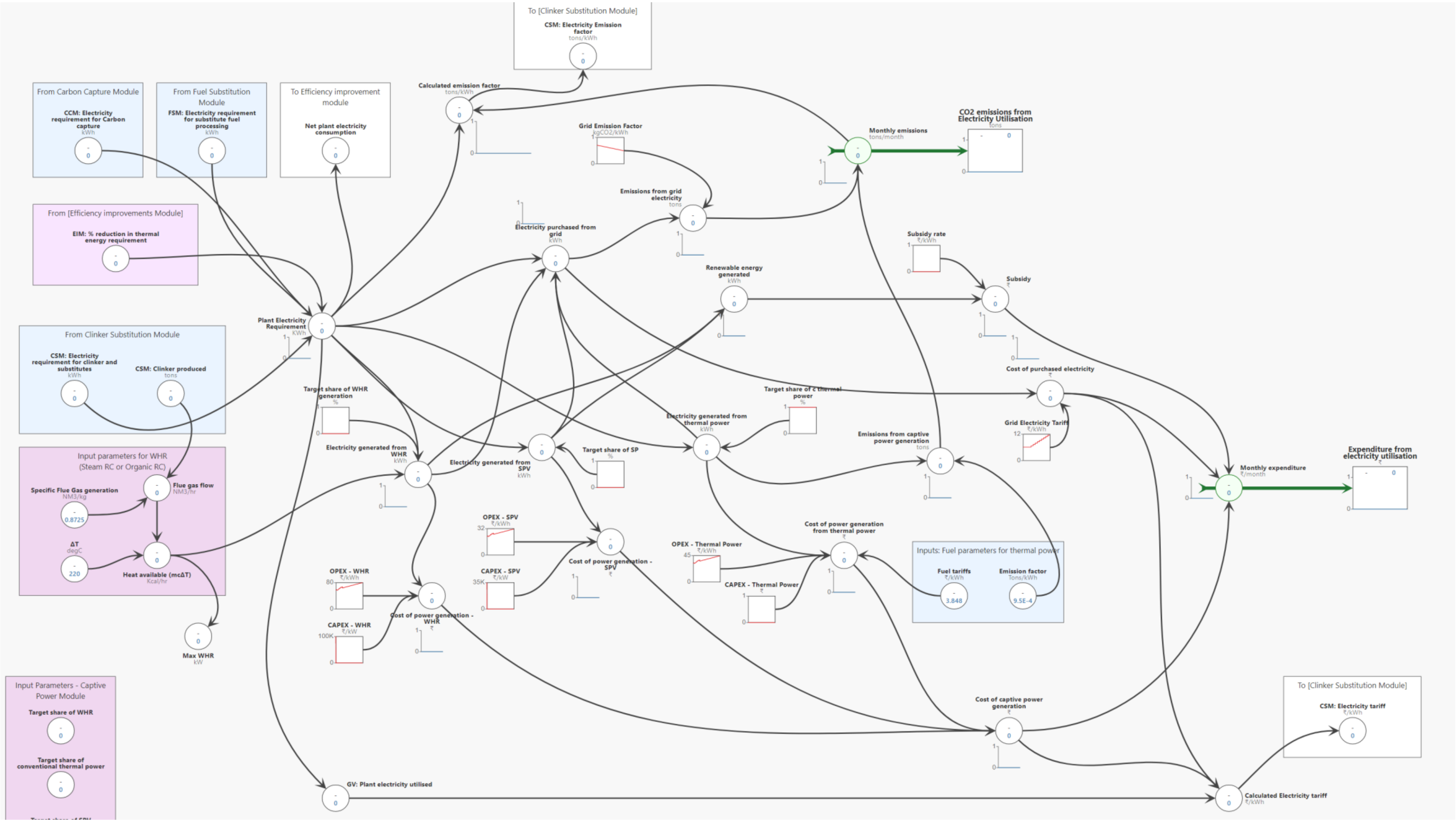
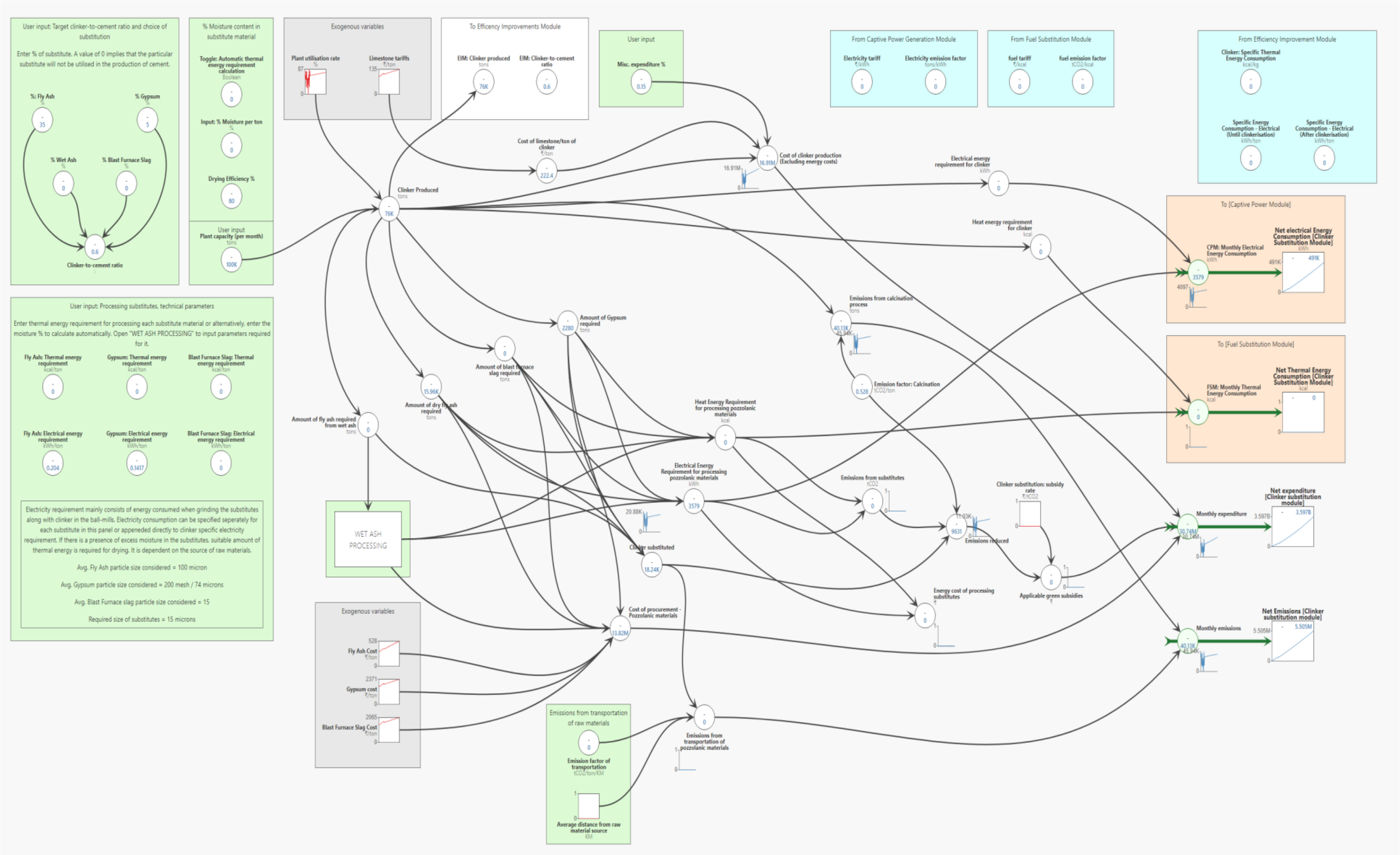
[7] High resolution images can be found here.

B. Captive Power Generation Module



C. Clinker Substitution Module



User input: Target clinker-to-cement ratio and choice of substitution

Enter % of substitute. A value of 0 implies that the particular substitute will not be utilised in the production of cement.

User input: Processing substitutes, technical parameters

Enter thermal energy requirement for processing each substitute material or alternatively, enter the moisture % to calculate automatically. Open "WET ASH PROCESSING" to input parameters required for it.

Electricity requirement mainly consists of energy consumed when grinding the substitutes along with clinker in the ball-mills. Electricity consumption can be specified seperately for each substitute in this panel or appeneded directly to clinker specific electricity requirement. If there is a presence of excess moisture in the substitutes, suitable amount of thermal energy is required for drying. It is dependent on the source of raw materials.

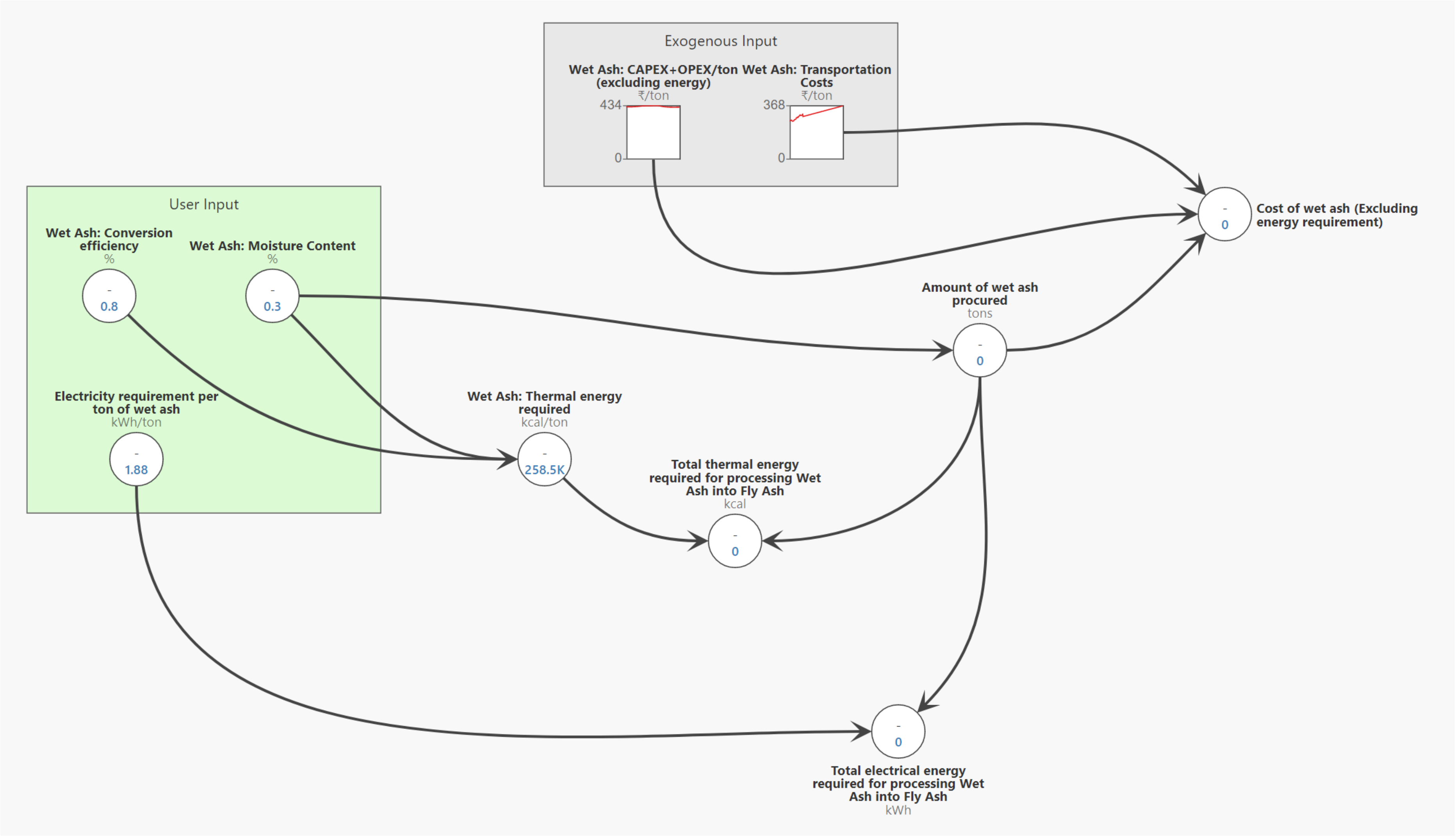
Avg. Fly Ash particle size considered = 100 micron

Avg. Gypsum particle size considered = 200 mesh / 74 microns

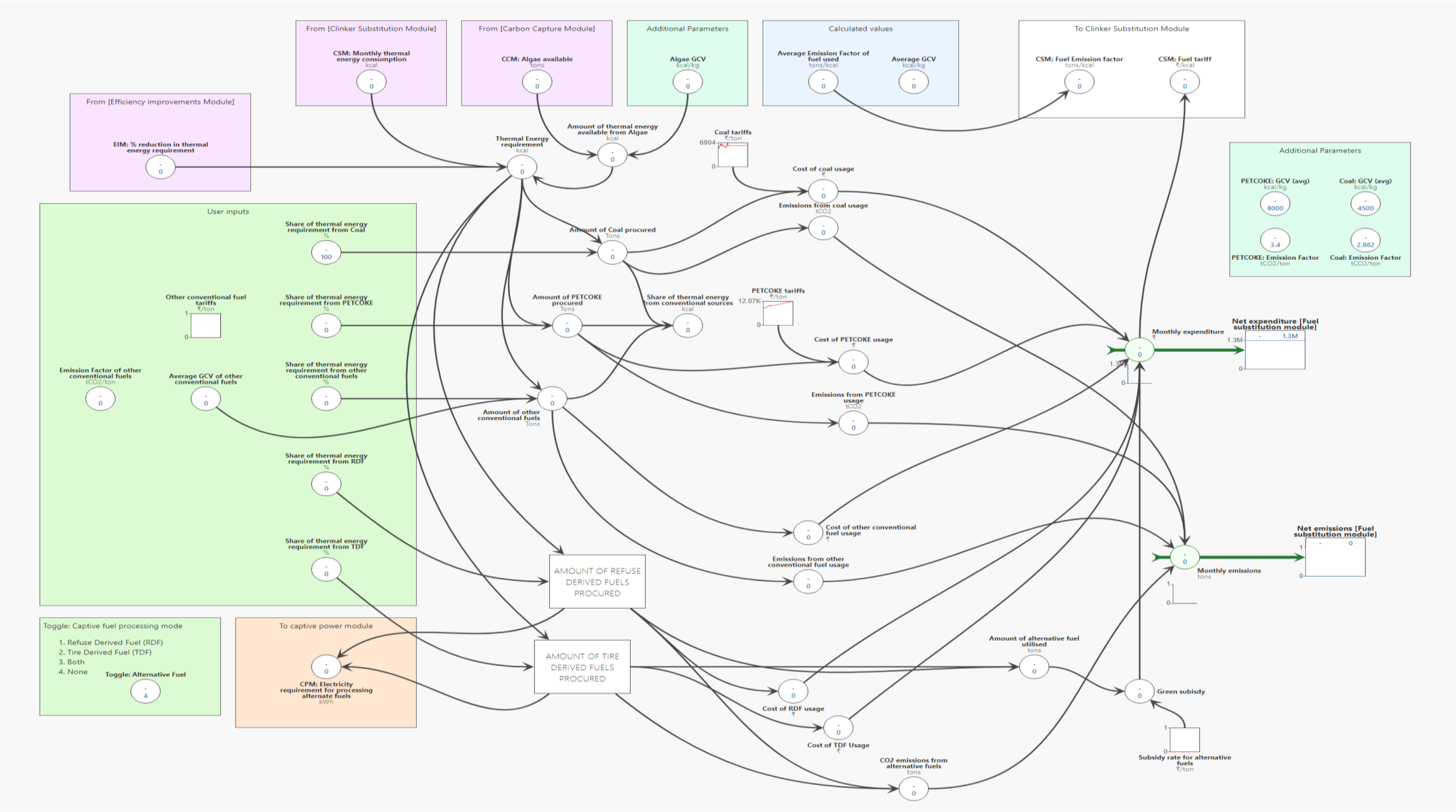
Avg. Blast Furnace slag particle size considered = 15

Required size of substitutes = 15 microns

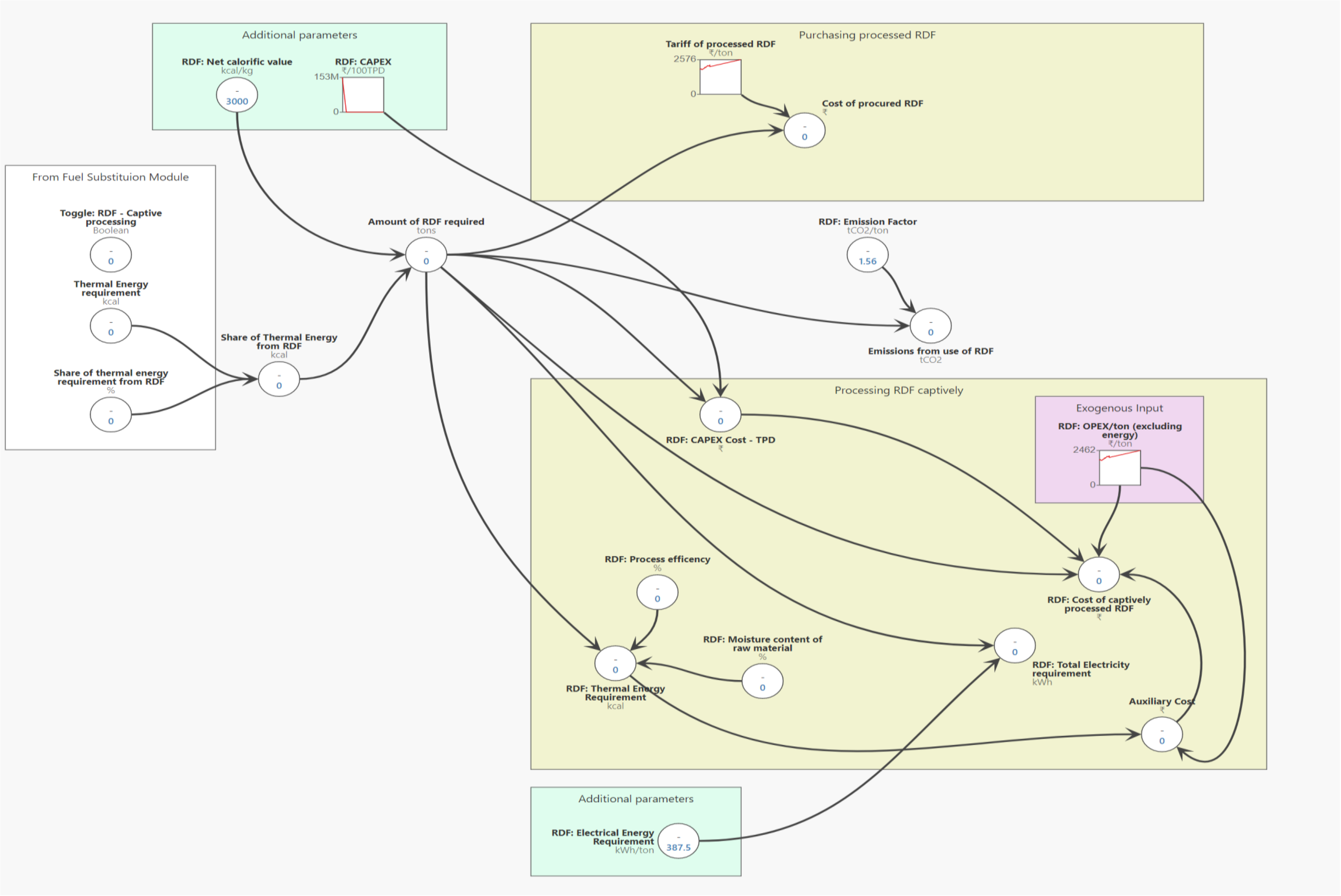
C1.Wet Ash Processing



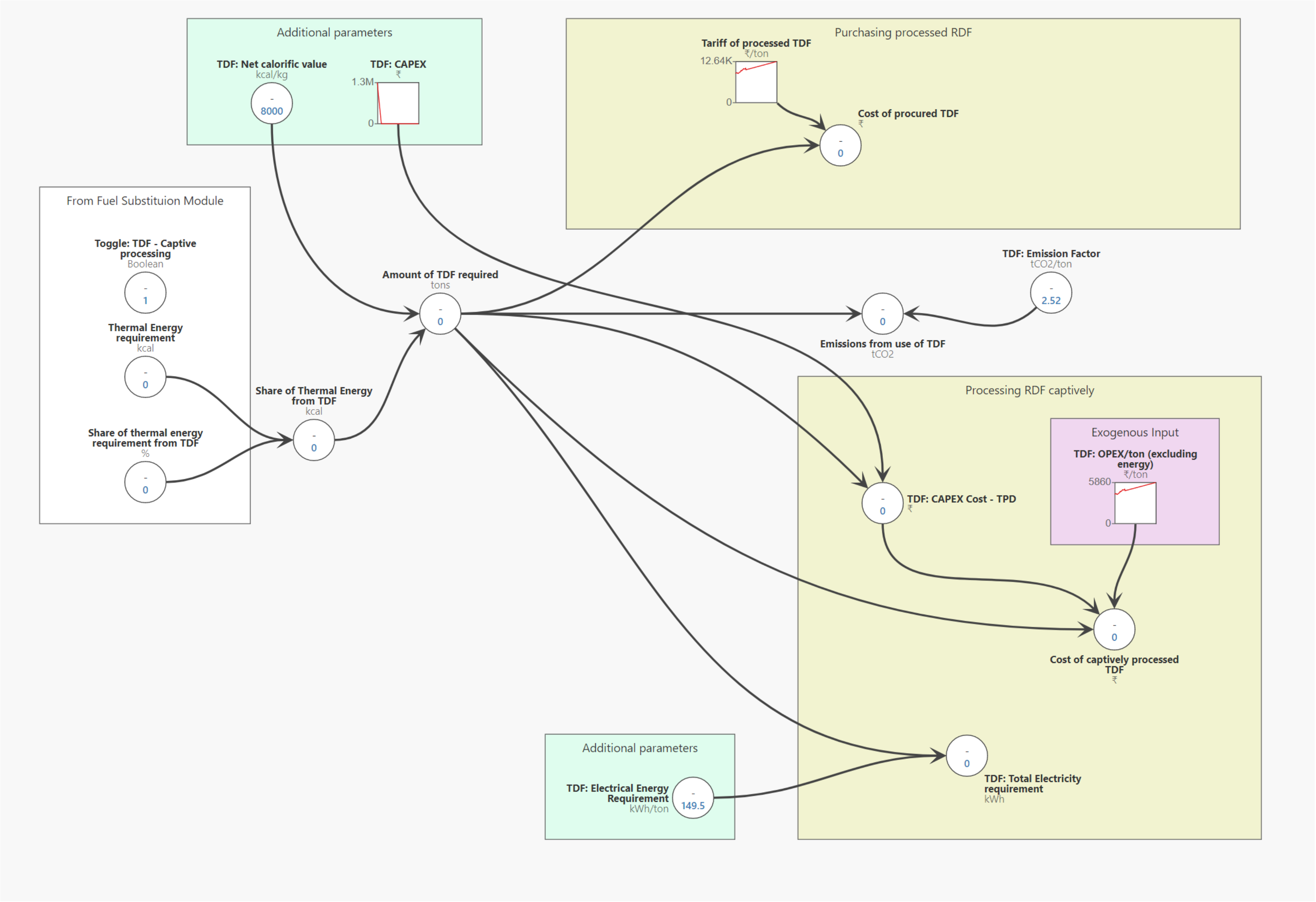
D. Fuel Substitution Module



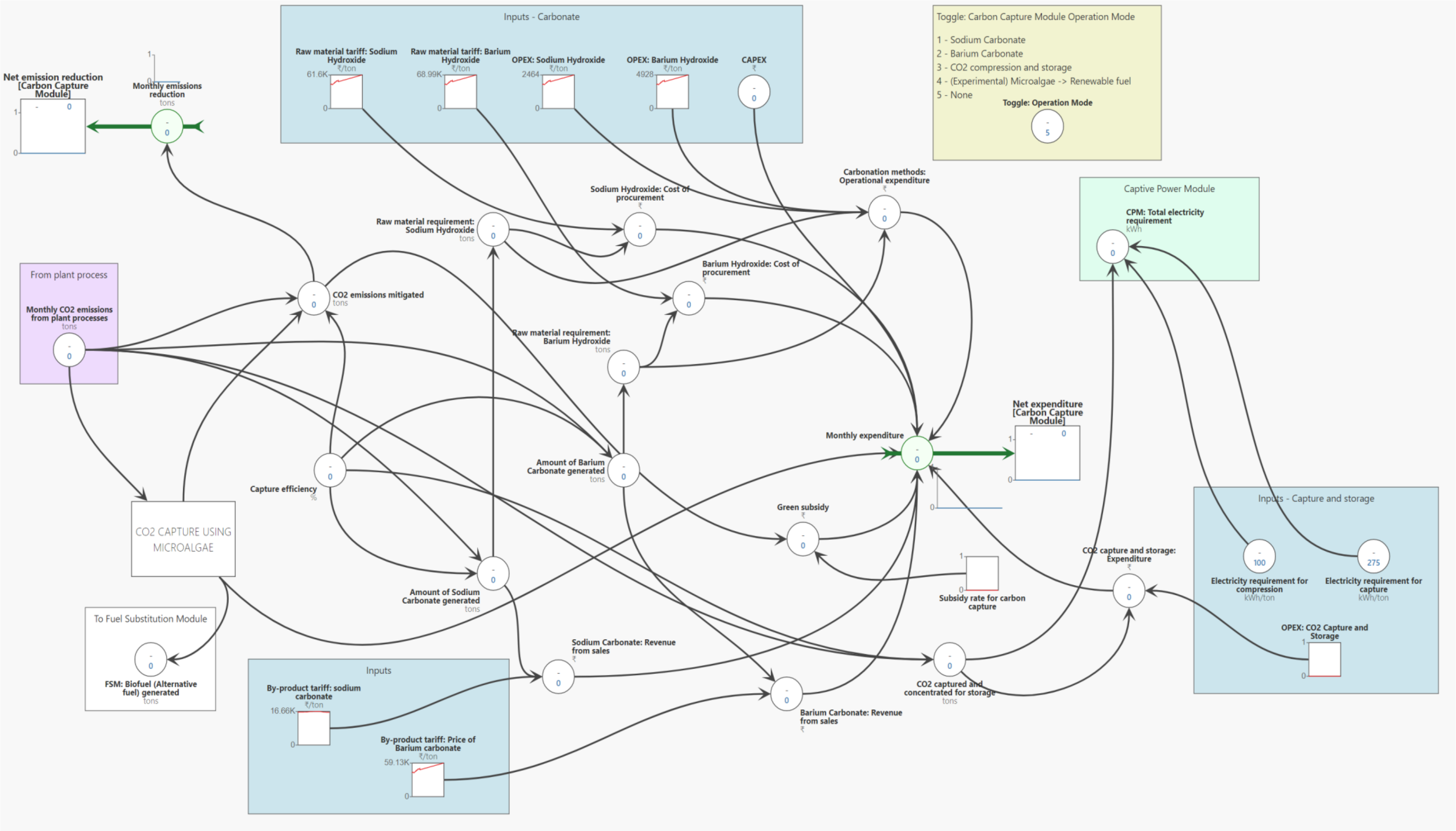
D1. RDF Processing



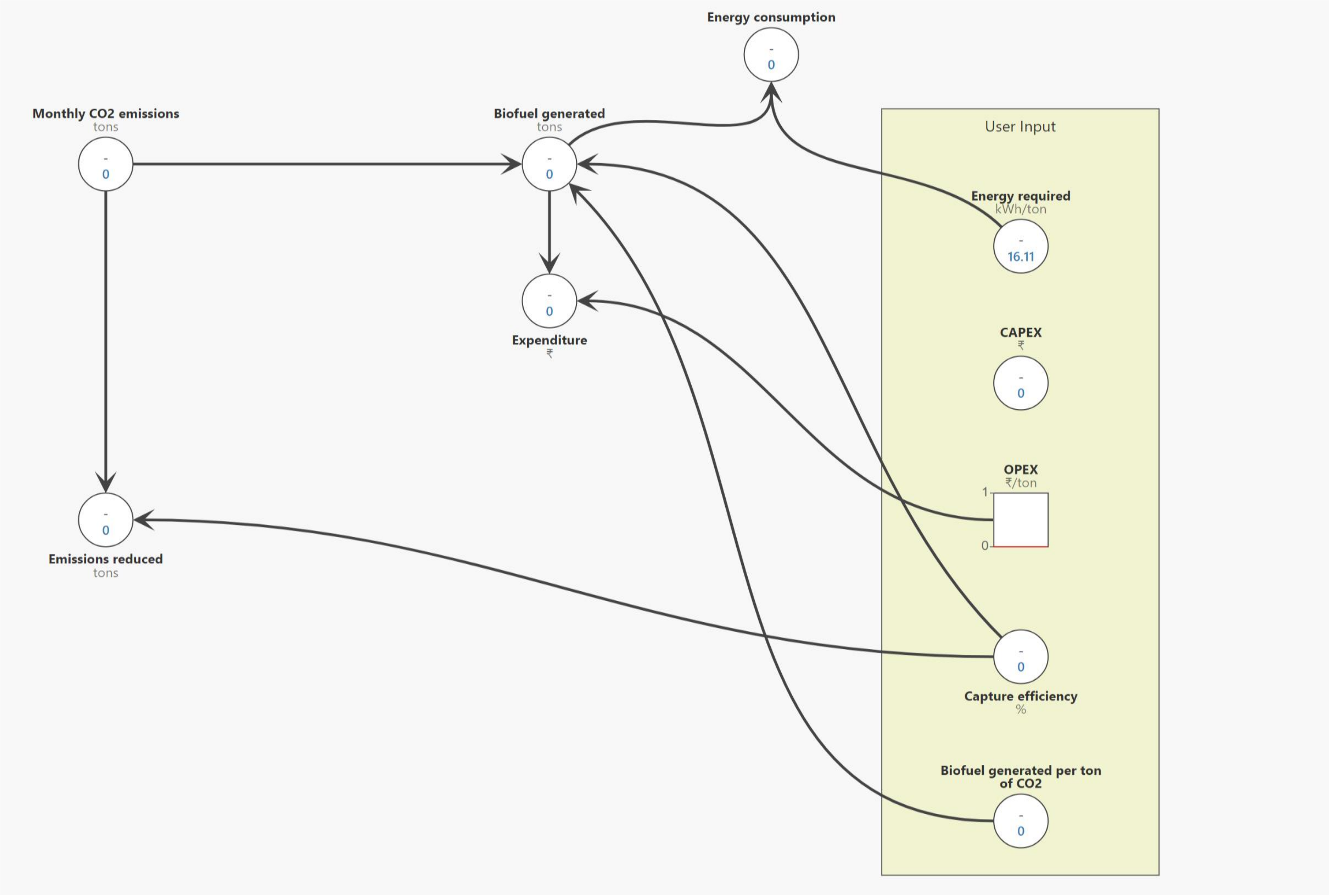
D2. TDF Processing



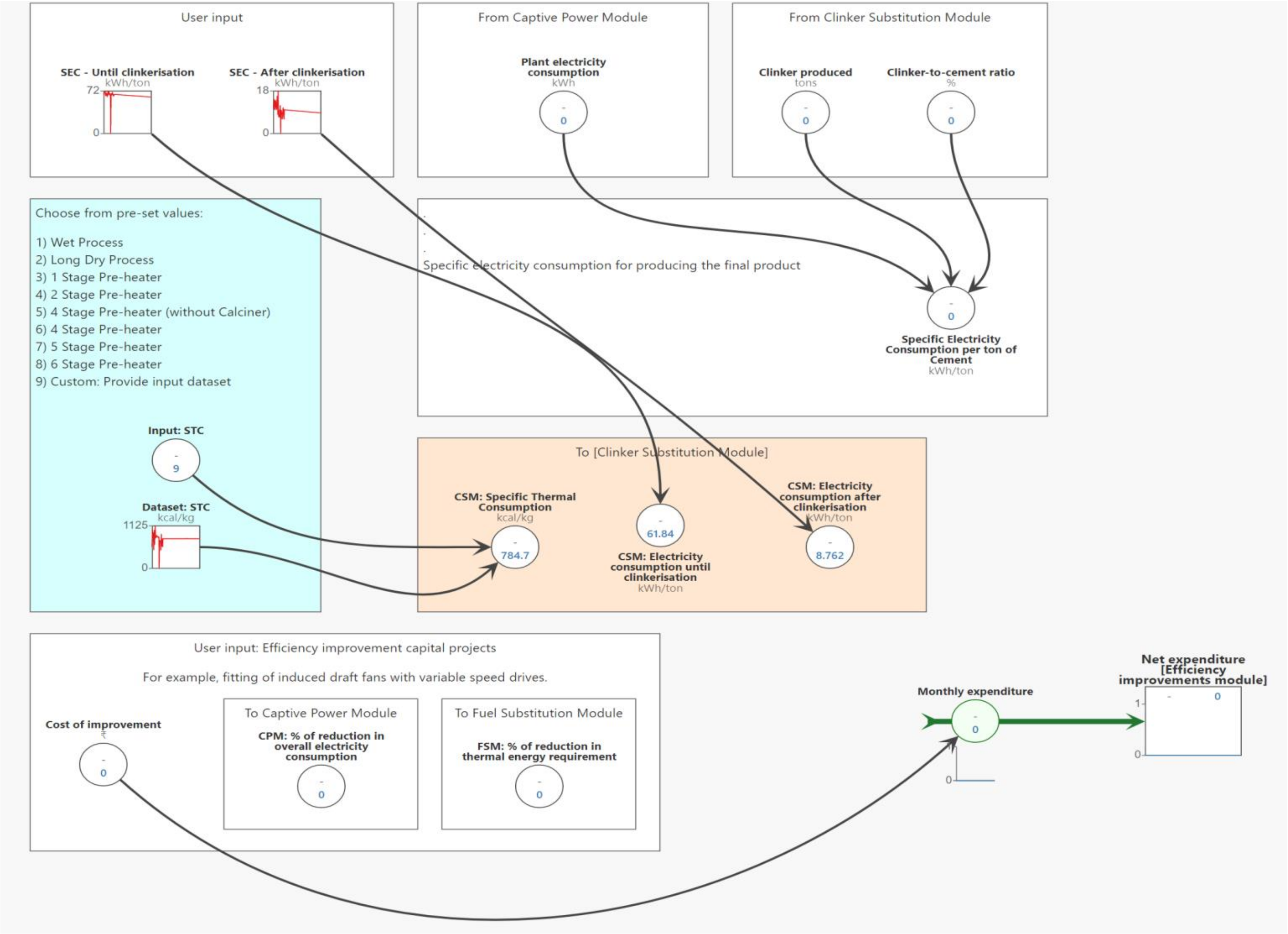
E. Carbon Capture Module



E1. Biofuel from Algae



F. Efficiency Improvements Module



Choose from pre-set values:

1) Wet Process
2) Long Dry Process
3) 1 Stage Pre-heater
4) 2 Stage Pre-heater
5) 4 Stage Pre-heater (without Calciner)
6) 4 Stage Pre-heater
7) 5 Stage Pre-heater
8) 6 Stage Pre-heater
9) Custom: Provide input dataset

Specific electricity consumption for producing the final product

For example, fitting of induced draft fans with variable speed drives.

APPENDIX – II

SilicoAI code for the model is attached as a supplementary file – Model.spf. It can be also accessed online through cloud storage here.

Alternatively, the live model with embedded data for BAU scenario can be accessed at https://silico.app/@akhilkunche/cement-co2-mitgation_dss_bau-scenario?s=9ZsQG3JrS0Cy7ZXboOWoKQ

The link to the live model grants necessary permissions for modification of the model structure as well as for replacement of existing datasets for conducting further experiments or reproducing the results demonstrated in this study.

APPENDIX – III

List of Input parameters and datasets used in each scenario

A. Base Scenario (BAU) and default plant operation mode

- **Clinker Substitution Module:**

Nomenclature	Input parameters/Dataset preparation
Limestone tariffs[8]	Cement plant has captive limestone mines, so only the OPEX pricing is considered based on local wages
Plant utilisation rate	Historical data sourced from plant from 2011-2021, future trends are computed based on cement demand forecast in the Indian market (India Brand Equity Foundation, 2021)
% Wet Ash	0
% Fly Ash	35
% Blast Furnace Slag	0
% Gypsum	5
Fly Ash Cost[2]	Pricing sourced from the nearby thermal power plant, the tariffs for future trend are considered constant, as the fly ash from Government operated power plants is regulated to be sold at a nominal price by the local government
Gypsum Cost[2]	Historical pricing sourced from local market; future trends are computed based on consumer price index; Sourced from (National Integrated Information Platform, n.d.)
Blast Furnace Slag (BFS) Cost[2]	Historical pricing sourced from local market; future trends are computed based on consumer price index
Average Distance from raw material source	14 KM (BAU – Sourcing waste from nearby Thermal Power Plant)
Emission factor of transportation[5]	0.0001 tCO2/ton/KM; Sourced from ("India Specific Road Transport Emission Factors," 2015)[9]
Clinker substitution: Subsidy rate	0
Plant capacity (per month)	100,000 tons
Misc. expenditure %	1.5%
Emission factor: Calcination	0.528 tCO2/ton of clinker; Sourced from (GNR Project, n.d.)
Toggle: Automatic thermal energy requirement calculation	0
Fly Ash: Thermal energy requirement[10]	0 kcal/ton
Fly Ash: Electrical energy requirement[11]	0.204 kWh/ton
Gypsum: Thermal energy requirement[7]	0 kcal/ton
Gypsum: Electrical energy requirement[8]	0.1417 kWh/ton
Blast Furnace Slag: Thermal energy requirement[7]	0 kcal/ton
Blast Furnace Slag: Electrical energy requirement[8]	0 kWh/ton
Wet Ash: Conversion efficiency	80%
Wet Ash: Moisture Content	30%, based on ash ponds next to nearby thermal power plant
Electricity requirement per ton of wet ash	1.88 kWh/ton
Wet Ash: CAPEX+OPEX/ton (excluding	CAPEX and OPEX based on assessment provided by local energy

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[8] Includes loading, handling, and transportation costs

[10] No additional thermal energy is required if the substitutes contain less than 5% moisture as the heat generated in the grinding mills would be sufficient to remove the moisture content.

[11] Calculated based on the average particle size of the material and ball mill energy consumption for grinding. Raw materials such as BFS can be sourced in different sizes, some of which do not require any additional grinding

energy)	company. Calculations attached in Appendix 1, trend for OPEX was calculated on the basis of projections for Consumer Price Index
Wet Ash: Transportation Costs	Cost calculated based on local tariffs, for a distance of 14 KM, which is the distance to the nearest ash ponds

- **Fuel Substitution Module:**

Nomenclature	Input parameters/Dataset preparation
Share of thermal energy requirement from Coal	100%
Share of thermal energy requirement from PETCOKE	0%
Share of thermal energy requirement from other conventional fuels	0%
Share of thermal energy requirement from RDF	0%
Share of thermal energy requirement from TDF	0%
PETCOKE: GCV (avg)	8000 kcal/kg
Coal: GCV (avg)	4500 kcal/kg
PETCOKE: Emission Factor	3.4 tCO2/ton
Coal: Emission Factor	2.882 tCO2/ton
Toggle: Alternative Fuel	0
Coal tariffs	Tariffs calculated based on the National Coal Index, sourced from (Ministry of Coal, n.d.).
PETCOKE tariffs	Historical pricing sourced from local market; future trends are computed based on consumer price index
RDF: Gross calorific value	3000 kcal/kg
RDF: CAPEX	153 million INR/100 TPD plant
Tariff of processed RDF	Historical pricing sourced from local market; future trends are computed based on consumer price index
RDF: Emission Factor	1.5595 tCO2/ton; sourced from (Nutongkaew et al., 2014)
RDF: OPEX/ton (excluding energy)	Data sourced from RDF Guidelines published by Government of India (GoI); future trends are computed based on consumer price index
RDF: Electrical Energy Requirement	Data sourced from RDF Guidelines published by GoI (Expert Committee Constituted by Ministry of Housing and Urban Affairs (MoHUA), 2018)
Tariff of processed TDF	Historical pricing sourced from local market; future trends are computed based on consumer price index
TDF: Emission Factor	2.520 tCO2/ton (Assumption: 70% carbon content in TDF)
TDF: OPEX/ton (excluding energy)	Data computed based on the operational cost of shredding equipment; includes price of the raw material. Historical pricing of raw material, i.e., tyres, sourced from local market; future trends are computed based on consumer price index
TDF: Electrical Energy Requirement	149.5 kWh/ton
TDF: Gross calorific value	8000 kcal/ton
TDF: CAPEX	1.3 million INR, based on the price of shredding equipment in the local market
Subsidy rate for alternative fuels	0
RDF: Moisture content of raw material	0
TDF: Moisture content of raw material	0

- **Captive Power Module:**

Nomenclature	Input parameters/Dataset preparation
Specific Flue Gas generation	0.872 NM3/kg
ΔT	220
Target share of WHR generation	0

OPEX - WHR	1.25% of CAPEX/year; future trends are computed based on consumer price index
CAPEX - WHR	100,000 INR/kW; sourced from (“Waste Heat Recovery for the Cement Sector,” 2014)
Target share of SPV	0
OPEX – SPV	1.25% of CAPEX/year; future trends are computed based on consumer price index
CAPEX - SPV	35000 INR/kW
Target share of c thermal power	100
OPEX – Thermal power	2.5% of CAPEX/year; future trends are computed based on consumer price index
CAPEX – Thermal power	65000 INR/kW (0 in case of this plant, as it has an existing plant)
Grid Emission Factor	Historic data sourced from Central Electricity Authority, GoI; future trends are computed based on extrapolation of existing data
Grid Electricity Tariff	Historic data sourced from Southern Power Distribution, Telangana Government
Fuel Tariffs	Tariffs for coal calculated based on the National Coal Index, sourced from (Ministry of Coal, n.d.)
Subsidy rate	0
Heat Rate - Coal	2867 kcal/kWh
Emission factor (coal)	$0.95*10^{-3}$ tons/kWh

- **Efficiency Module:**

Nomenclature	**Input parameters/Dataset preparation**
SEC - Until clinkerisation	Historical data sourced from plant from 2011-2021, future trends are computed based on extrapolation of collected data
SEC - After clinkerisation	Historical data sourced from plant from 2011-2021, future trends are computed based on extrapolation of collected data

B. Low CO2 mitigation effort (LME)

- **Clinker Substitution Module:**

Nomenclature	**Input parameters/Dataset preparation**
Plant utilisation rate	Historical data sourced from plant from 2011-2021, future trends are computed based on cement demand forecast in the Indian market (India Brand Equity Foundation, 2021)
% Wet Ash	Depends on the mitigation strategy being considered
% Fly Ash	
% Blast Furnace Slag	
% Gypsum	
Fly Ash Cost[2]	It is assumed that the demand for fly ash will increase within the cement industry as more plants would likely invest into mitigation strategies, hence the fly ash at nominal prices from government operated power plants would not be available. Hence existing market tariffs of fly ash in other parts of India where there are no government regulated sources available.
Blast Furnace Slag (BFS) Cost[2]	It is assumed that the demand for BFS will increase within the cement industry as more plants would likely implement clinker substitution as a mitigation strategy within the plant. The price for BFS in this scenario is considered to be 10% higher than the BAU scenario by the end of the simulation run.
Average Distance from raw material source	As the demand for the substitute material increases, it would be more likely that the plant would need to import materials from relatively far away locations. 250 KM is considered as the average distance from raw material source in this scenario.

Emission factor of transportation[5]	0.0001 tCO2/ton/KM; Sourced from (“India Specific Road Transport Emission Factors,” 2015)[12]
Clinker substitution: Subsidy rate	No subsidy for clinker substitution is considered in this scenario
Plant capacity (per month)	100,000 tons
Misc. expenditure %	2.5%
Emission factor: Calcination	0.528 tCO2/ton of clinker; Sourced from (GNR Project, n.d.)
Toggle: Automatic thermal energy requirement calculation	Depends on the mitigation strategy being considered
Fly Ash: Thermal energy requirement[13]	0 kcal/ton
Fly Ash: Electrical energy requirement[14]	0.204 kWh/ton
Gypsum: Thermal energy requirement[7]	0 kcal/ton; No drying is necessary if the moisture content is less than 5%. The heat generated during the grinding will be sufficient.
Gypsum: Electrical energy requirement[8]	0.1417 kWh/ton
Blast Furnace Slag: Thermal energy requirement[7]	0 kcal/ton and 0 kWh/ton; Pre-processed BFS is available in the local market that can be readily mixed with clinker without additional processing, hence no additional energy is necessary for this particular region and plant
Blast Furnace Slag: Electrical energy requirement[8]	
Wet Ash: Conversion efficiency	80%
Wet Ash: Moisture Content	30%, based on ash ponds next to nearby thermal power plant
Electricity requirement per ton of wet ash	1.88 kWh/ton
Wet Ash: CAPEX+OPEX/ton (excluding energy)	CAPEX and OPEX based on assessment provided by local energy company. Trend for OPEX was calculated on the basis of projections for Consumer Price Index
Wet Ash: Transportation Costs	Cost calculated based on local tariffs, for a distance of 14 KM, which is the distance to the nearest ash ponds. Compared with fly ash, the wet ash availability is much higher, so it can be sourced from the same locations as in the previous scenario.

- **Fuel Substitution Module:**

Nomenclature	**Input parameters/Dataset preparation**
Share of thermal energy requirement from Coal	Depends on the mitigation strategy being considered
Share of thermal energy requirement from PETCOKE	
Share of thermal energy requirement from other conventional fuels	
Share of thermal energy requirement from RDF	
Share of thermal energy requirement from TDF	
Toggle: Alternative Fuel	
Coal tariffs	Tariffs calculated based on the National Coal Index, with an additional 10% cost appended to the BAU by the end of the simulation run, sourced from (Ministry of Coal, n.d.).
PETCOKE tariffs	Historical pricing sourced from local market; future trends are

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[13] No additional thermal energy is required if the substitutes contain less than 5% moisture as the heat generated in the grinding mills would be sufficient to remove the moisture content.

[14] Calculated based on the average particle size of the material and ball mill energy consumption for grinding. Raw materials such as BFS can be sourced in different sizes, some of which do not require any additional grinding

	computed based on consumer price index. An additional 10% cost is appended to the BAU price by the end of the simulation run.
Subsidy rate for alternative fuels	2000 INR/ton
RDF: Moisture content of raw material	0
TDF: Moisture content of raw material	0

- **Captive Power Module:**

Nomenclature	**Input parameters/Dataset preparation**
Fuel Tariffs	Tariffs calculated based on the National Coal Index, with an additional 10% cost appended to the BAU by the end of the simulation run, sourced from (Ministry of Coal, n.d.).
Grid Emission Factor	Current data sourced from Central Electricity Authority, GoI; In this scenario, the grid emission factor is considered to drop an additional 8% at the end of the simulation period when compared to BAU.
Grid Electricity Tariff	Current data sourced from Southern Power Distribution, Telangana Government. The grid electricity tariffs is expected to increase by 8% each year as cost of power production increases to accommodate greener electricity generation (from renewable sources or less emission intensive fuels)
Subsidy rate	Subsidy of INR 1 per every unit (kWh) of green electricity generated captively

- **Carbon Capture Module:**

Nomenclature	**Input parameters/Dataset preparation**
Toggle: Operation Mode	Depends on the mitigation strategy being compared
Raw material tariff: Sodium Hydroxide	Historical pricing sourced from local market; future trends are computed based on consumer price index.
Raw material tariff: Barium Hydroxide	
OPEX: Sodium Hydroxide	Calculated based on the study by Proaño et al. (Proaño et al., 2020)
OPEX: Barium Hydroxide	
CAPEX	
By-product tariff: sodium carbonate	Historical pricing sourced from local market; future trends are computed based on consumer price index.
By-product tariff: Price of Barium carbonate	
Electricity requirement for compression	100 kWh/ton, sourced from (Jackson and Brodal, 2018)
Subsidy rate for carbon capture	200 INR/ton
Electricity requirement for capture	275 kWh/ton, sourced from (Jackson and Brodal, 2018)
Capture and storage: OPEX	Spot price calculated based on (Adam Baylin-Stern and Niels Berghout, n.d.), future trends are computed based on consumer price index.
Microalgae: OPEX	Computed based on (Mondal et al., 2017; Zamalloa et al., 2011)
Microalgae: Energy required	
Microalgae: Biofuel generated per ton of CO2	

C. High CO2 mitigation effort (HME)

- **Clinker Substitution Module:**

Nomenclature	**Input parameters/Dataset preparation**
Plant utilisation rate	Historical data sourced from plant from 2011-2021, future trends are computed based on cement demand forecast in the Indian market (India Brand Equity Foundation, 2021)
% Wet Ash	Depends on the mitigation strategy being considered
% Fly Ash	
% Blast Furnace Slag	
% Gypsum	
Fly Ash Cost[2]	It is assumed that the demand for fly ash will significantly increase within the cement industry as substitution of clinker with Fly Ash becomes a more widespread practice to reduce CO2 emissions, hence the cost of fly ash is further expeditated by 10% over the market tariffs used in the "Low CO2 mitigation effort" scenario by the end of the simulation run.
Blast Furnace Slag (BFS) Cost[2]	It is assumed that the demand for BFS will also significantly increase, similar to Fly Ash, as greater number of cement plants would attempt to replace a portion of the clinker with substitute materials. The price for BFS in this scenario is considered to be 15% higher than the BAU scenario by the end of the simulation run.
Average Distance from raw material source	As the demand for the substitute material increases, it would be more likely that the plant would need to import materials from relatively far away locations. 500 KM is considered as the average distance from raw material source in this scenario.
Emission factor of transportation[5]	0.0001 tCO2/ton/KM; Sourced from ("India Specific Road Transport Emission Factors," 2015)[15]
Clinker substitution: Subsidy rate	No subsidy for clinker substitution is considered in this scenario
Plant capacity (per month)	100,000 tons
Misc. expenditure %	3.5%
Emission factor: Calcination	0.528 tCO2/ton of clinker; Sourced from (GNR Project, n.d.)
Toggle: Automatic thermal energy requirement calculation	Depends on the mitigation strategy being considered
Fly Ash: Thermal energy requirement[16]	0 kcal/ton
Fly Ash: Electrical energy requirement[17]	0.204 kWh/ton
Gypsum: Thermal energy requirement[7]	0 kcal/ton; No drying is necessary if the moisture content is less than 5%. The heat generated during the grinding will be sufficient.
Gypsum: Electrical energy requirement[8]	0.1417 kWh/ton
Blast Furnace Slag: Thermal energy requirement[7]	0 kcal/ton and 0 kWh/ton; Pre-processed BFS is available in the local market that can be readily mixed with clinker without additional processing, hence no additional energy is necessary for this particular region and plant
Blast Furnace Slag: Electrical energy requirement[8]	
Wet Ash: Conversion efficiency	80%
Wet Ash: Moisture Content	30%, based on ash ponds next to nearby thermal power plant
Electricity requirement per ton of wet ash	1.88 kWh/ton
Wet Ash: CAPEX+OPEX/ton (excluding	CAPEX and OPEX based on assessment provided by local energy

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[16] No additional thermal energy is required if the substitutes contain less than 5% moisture as the heat generated in the grinding mills would be sufficient to remove the moisture content.

[17] Calculated based on the average particle size of the material and ball mill energy consumption for grinding. Raw materials such as BFS can be sourced in different sizes, some of which do not require any additional grinding

energy)	company. Calculations attached in Appendix 1, trend for OPEX was calculated based on projections for Consumer Price Index
Wet Ash: Transportation Costs	Cost calculated based on local tariffs, for a distance of 14 KM, which is the distance to the nearest ash ponds. Compared with fly ash, the wet ash availability is much higher, so it can be sourced from the same locations as in the previous scenario.

- **Fuel Substitution Module:**

Nomenclature	**Input parameters/Dataset preparation**
Share of thermal energy requirement from Coal	Depends on the mitigation strategy being considered
Share of thermal energy requirement from PETCOKE	
Share of thermal energy requirement from other conventional fuels	
Share of thermal energy requirement from RDF	
Share of thermal energy requirement from TDF	
Toggle: Alternative Fuel	
Coal tariffs	Tariffs calculated based on the National Coal Index, with an additional 50% cost appended to the BAU price by the end of the simulation run, sourced from (Ministry of Coal, n.d.).
PETCOKE tariffs	Historical pricing sourced from local market; future trends are computed based on consumer price index. An additional 50% cost is appended to the BAU price by the end of the simulation run.
Subsidy rate for alternative fuels	3500 INR/ton
RDF: Moisture content of raw material	0
TDF: Moisture content of raw material	0

- **Captive Power Module:**

Nomenclature	**Input parameters/Dataset preparation**
Fuel Tariffs	Tariffs calculated based on the National Coal Index, with an additional 20% cost appended to the base price at each time step, sourced from (Ministry of Coal, n.d.).
Grid Emission Factor	Current data sourced from Central Electricity Authority, GoI; future factors are expected to drop by 15% by the end of the simulation run as a response to government action on CO2 mitigation
Grid Electricity Tariff	Current data sourced from Southern Power Distribution, Telangana Government. The grid electricity tariffs is expected to increase by 15% each year as cost of power production increases to accommodate greener electricity generation (from renewable sources or less emission intensive fuels)
Subsidy rate	Subsidy of INR 2 per every unit (kWh) of green electricity generated captively

- **Carbon Capture Module:**

Nomenclature	**Input parameters/Dataset preparation**
Toggle: Operation Mode	Depends on the mitigation strategy being compared

Raw material tariff: Sodium Hydroxide	Historical pricing sourced from local market; future trends are computed based on consumer price index.
Raw material tariff: Barium Hydroxide	
OPEX: Sodium Hydroxide	Calculated based on the study by Proaño et al. (Proaño et al., 2020)
OPEX: Barium Hydroxide	
CAPEX	
By-product tariff: sodium carbonate	Historical pricing sourced from local market; future trends are computed based on consumer price index.
By-product tariff: Price of Barium carbonate	
Electricity requirement for compression	100 kWh/ton, sourced from (Jackson and Brodal, 2018)
Electricity requirement for capture	275 kWh/ton, sourced from (Jackson and Brodal, 2018)
Capture and storage: OPEX	Spot price calculated based on (Adam Baylin-Stern and Niels Berghout, n.d.), future trends are computed based on consumer price index.
Subsidy rate for carbon capture	500 INR/ton
Microalgae: OPEX	Computed based on (Mondal et al., 2017; Zamalloa et al., 2011)
Microalgae: Energy required	
Microalgae: Biofuel generated per ton of CO2	