QUANTIFICATION OF GREENHOUSE GAS EMISSIONS IN A CEMENT COMPANY AND SYSTEM DYNAMICS MODELING TOWARD CARBON NEUTRAL CONDITION

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Abstract

The cement industry is one of the sectors that produces carbon dioxide (CO_2) emissions due to its raw material processing and energy requirements. CO_2, as a greenhouse gas (GHG) emission, contributes to global warming, leading to environmental, health, and economic losses. To address these issues, Indonesia is committed to reducing GHG emissions in the industrial sector by 2050. To effectively plan for the reduction of GHG emissions generated by companies, this study aims to quantify emissions from a cement company, representing the cement industry in Indonesia, to understand the current state of the company's carbon footprint and identify feasible mitigation measures. The cement industry utilizes a GHG quantification system to calculate emissions from raw material processing, thermal energy consumption, and electricity purchases. The calculation results from a cement company are used for system dynamics modeling with Vensim PLE software for the period from 2021 to 2050, under business-as-usual (BAU) conditions with various emission reduction strategies. The results show that GHG emissions under BAU conditions with emission reduction strategies do not achieve carbon neutrality by 2050. More intensive adoption of decarbonization technologies, research on process optimization, and government policies such as carbon taxes and carbon trading are required to achieve carbon neutral goals.

Keywords: *cement, emission mitigation, greenhouse gas emissions, emission quantification, system dynamics*

Introduction

Global warming is caused by greenhouse gases (GHG) such as carbon dioxide (CO_2) and other gases that have an impact on the climate which is estimated to increase by 1.5°C in 2030 - 2052 (Fankhauser et al., 2021; Huang & Tzai, 2021). As an archipelagic region, Indonesia is projected to be affected by climate change with a potential economic loss of 545 trillion from 2020 to 2024 (Bappenas, 2021). To address climate issues, Indonesia has ratified the Paris Agreement through Law No. 16 of 2016 as a government commitment to addressing climate change, through the Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050 which provides a direction for long-term national policy on climate change. The Ministry of Industry has set a net zero emission target in the industrial process and product use (IPPU) sector by 2050 for emission-intensive industries, namely cement, basic chemicals (ammonia fertilizers, nitric acid, other petrochemicals), iron and steel manufacturing, and metal smelters

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such as nickel, gold, aluminum, bauxite, and others (KLHK, 2021).

Cement production consumes large amounts of raw materials, heat and electricity from the decomposition of raw materials, fuel combustion and electricity use in the form of indirect emissions (Zhou et al., 2016). The main emissions from cement production are atmospheric pollutants from the kiln system, and come from the physico-chemical reactions of the raw material calcination process in the form of limestone decarbonization and fuel combustion which cause large amounts of air emissions due to high fossil fuel consumption (Zhang et al., 2016).

Cement companies under the umbrella of the Global Cement and Concrete Association (GCCA) have agreed on a methodology for calculating and reporting CO_2 emissions in the Cement CO_2 Protocol. The GCCA calculation method calculates all direct and indirect sources of CO_2 emissions related to the cement production process, both in absolute and specific terms or by unit. Emission quantification is used to monitor and report internal management of environmental performance, public corporate environmental reporting, CO_2 taxation schemes, and CO_2 compliance schemes (voluntary or negotiated agreements, emissions trading systems), industry benchmarking, and product life cycle analysis (WBCSD, 2011).

The quantified CO_2 emissions are then simulated using a dynamic system to investigate industrial processes that will provide time simulations to predict GHG trends with energy variables, production technologies, technical process factors and optimization scenarios (Song & Chen, 2014). Vensim software is used to visualize and communicate complex systems dynamically by analyzing the relationships between variables through casual loop diagrams, defining assumed conditions and then creating stock-flow diagrams (Wen, et al. 2016). The model allows stakeholders to determine the combination of mitigation methods that can be used to optimize the balance between overall mitigation effectiveness by knowing the behavioral patterns regarding which mitigation options are preferred under certain conditions and as a consequence provide potential input for further action (Kunche & Mielczarek, 2021). Some decarbonization scenarios that have been carried out by the cement industry are substituting raw materials and fuels, using energy efficiency and waste heat recovery, and the possibility of using carbon capture and storage (Jokar and Mokhtar, 2018; Junianto et al., 2023; Tang et al., 2020).

This study aims to quantify the greenhouse gas emissions emitted by a cement company to better understand the current emission levels within the cement industry. By utilizing system dynamics modeling, the research explores and evaluates mitigation options, helping to identify cement industry's practical strategies for decarbonization. These efforts are intended to guide the industry toward reaching net zero emissions by the year 2050.

Research Methodology

The research is in the form of a study of greenhouse gas emission quantification of cement company PT X to carry out a scenario towards carbon neutral conditions using dynamic system modeling from 2021 to 2050. Emission quantification is carried out using the method provided by GCCA for the production process in scope one in the form of direct emissions from the calcination process and thermal energy generation in the furnace and scope two which calculates electrical energy from external sources. Emissions from the cement production process are then subjected to dynamic system modeling using the Vensim PLE application to determine the amount of emissions that can be mitigated by the decarbonization steps taken. Modeling is carried out under two conditions, namely in business-as-usual conditions and emission reduction with a decarbonization scenario of raw material substitution, use of alternative energy, energy efficiency, waste heat recovery, carbon sequestration.

Emission Quantification

Cement production data, fuel and electricity usage are secondary data obtained from the company and the Ministry of Energy and Mineral Resources of the Republic of Indonesia. Calculations using the method provided by GCCA (WBCSD, 2011), to calculate direct emissions, namely emissions from the calcination process, thermal energy generation in the furnace and indirect emissions in the form of electricity acquisition from external sources in the form of CO_2 are shown in equations (1) to (5).

CO_2 Raw Materials = Clinker × EFcli / 1000 + BypassD leaving kiln system × EFcli / 1000 + CKD leaving kiln system × EFCKD + Raw Meal Consumed × fTOCRM × 3,664 (1)

where:

CO_2 Raw Materials = Total CO_2 contained in the raw materials (tCO_2/year)

Clinker = Clinker production (tons/year)

EFkli = CO_2 emission factor for clinker, standard value = 525 kg CO_2/ton clinker

EF_{CKD} = CO_2 emission factor for partially calcined kiln dust, for dry processes= 0 tCO_2/ton CKD

$fTOC_{RM}$ = Fraction of total organic carbon in the raw materials (dimensionless), standard value = 0.2%

Bypass Dust leaving the kiln system = Amount of bypass dust exiting the cement kiln (tons/year);

CKD leaving the kiln system = Amount of CKD exiting the kiln system (tons/year);

Raw material consumption = Amount of raw materials consumed per unit of clinker production, default value = 1.55.

CO_2 from conventional fossil kiln fuels (Ton CO_2) = Fossil Fuel Consumption (TJ) • Fuel Emission Factor (Ton CO_2/TJ) (2)

CO_2 from alternative fossil kiln fuels (Ton CO_2) = Alternative Fossil Fuel Consumption (TJ) • Fuel Emission Factor (Ton CO_2/TJ) (3)

CO_2 from purchased electricity emissions = total electricity usage (MWh/ year) x Grid Emission Factor (ton CO_2/MWh) (4)

Total CO_2 Emissions = CO_2 from raw materials + CO_2 from conventional fossil kiln fuels + CO_2 from alternative fossil kiln fuels (fossil wastes) + CO_2 from fossil carbon of mixed (alternative) kiln fuels and non-kiln fuels (excluding on-site power generation) + CO_2 from non-kiln fuels excluding CO_2 from on-site power generation (5)

System Dynamics Modeling

Dynamic system modeling is a simulation with qualitative and quantitative approaches to problem-solving that is actively used in decision making, planning policies, and evaluation in various industrial fields, including carbon mitigation. Using a causal and feedback system approach, dynamic systems help in identifying complex behavioral patterns over time allowing the study of unforeseen long-term consequences and policy rejections. Modeling is done by combining written and numerical data with mental models to create the underlying structure and feedback relationships that are responsible for the system behavior to reveal various aspects of the system that may be relevant to different stakeholders in the system (Kunche & Mielczarek, 2021).

In the cement industry, dynamic system modeling shows the relationship between demand for new infrastructure causing increased cement production resulting in increased carbon emissions causing greater emphasis on mitigation measures, which in turn will lead to emission reductions (Kunche & Mielczarek, 2021). The research method process begins with a qualitative analysis by building a CLD which is converted into a stock and flow diagram. The structure of the flow diagram contains level (state) and rate variables. The level variable is the accumulation (i.e. population) in the system, while the rate variable represents the flow in the system as an action resulting from the decision-making process. The quantitative analysis begins with the mathematical formulation of the stock and flow diagram consisting of differential equations, and with a numerical solution through simulation (Pagoni & Patroklos, 2019).

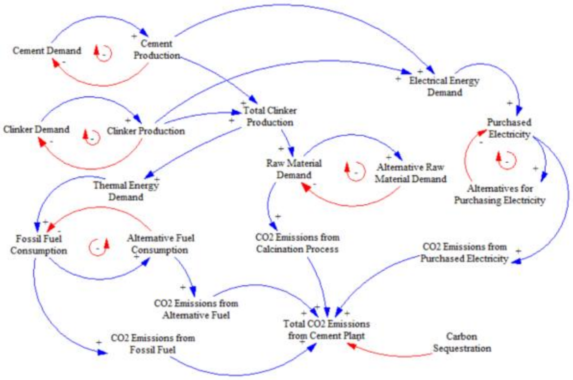

Figure 1. Causal loop diagram of PT X process and emissions

The CLD of the cement industry process and the decarbonization steps taken by the company are shown in Figure 1. The rate of cement and clinker production is influenced by market demand. Increasing production will increase the total production of clinker, as the main component of cement. The increase in the clinker manufacturing process (calcination process) results in an increase in CO_2 emissions due to raw material processing, thermal energy consumption and electricity needs. The increase in raw material processing emissions is reduced by the use of alternative raw materials. Increased thermal consumption will increase emissions due to the use of fossil fuels. This is mitigated by using alternative fuels. Meanwhile, the increase in electricity needs is reduced by alternative electricity purchases such as the use of solar panels and Advanced Process Control (APC). The total emissions of the cement factory after the mitigation scenario are further mitigated by carbon sequestration. CLD of PT X process and emissions the processed to make stock and flow diagram.

The stock and flow diagram (SFD) of the dynamic system model is created based on CLD in Vensim software. The decarbonization scenario in the cement industry of PT X is modeled with business-as-usual (BAU) conditions.

Model testing is carried out by validating data to ensure that the dynamic system model can represent the actual conditions of the system. Cement and clinker production data along with quantification of PT X emissions from 2021 to 2023 are compared with simulation results using Mean Absolute Percentage Error (MAPE). MAPE measures the relative amount of error or bias in a particular time series. The MAPE equation (6) sums all percentage errors at each time point and divides it by the number of time points so that the model time series is evaluated comparatively (Yaffee & McGee, 2000). The MAPE value represents the modeling results. A value of ≤10% means high accuracy, good modeling results at 11–20%, fair modeling results at 21–50%, and inaccurate modeling results at ≥51% (Lewis, 1982). In this study, MAPE used <20%.

$$\text{MAPE} = \frac{1}{n}\sum\frac{|A_t - F_t|}{A_t} \times 100\% \qquad (6)$$

where: At = Actual value; Ft = Modeled data value; n = Number of data points.

Results and Discussion

Cement is produced by a calcination process that produces clinker, which is then mixed with additives with a certain composition to become cement. In cement production, the calcination process, heat energy generation, and the acquisition of electrical energy from external sources produce emissions that are quantified and further analyzed in this study to explore decarbonization scenarios. This section will discuss the existing conditions and the amount of emissions produced by the company, as well as predictions of emission decarbonization from dynamic system modeling for policy making that companies need to do in achieving zero carbon emission conditions in 2050.

Existing conditions of cement production and emission emitted

The main production process of the cement industry produces cement and clinker. Shown in Figure 2, the cement company recorded cement and clinker production in 2021 of 13.45 million tons which increased sharply in 2023 to 13.86 million tons. In 2022, there was a decrease in cement production which was possibly influenced by the factor of decreasing demand. Despite the decrease, overall cement and clinker production in the company increased annually.

Clinker, as the main composition of cement making, comes from the calcination process that converts limestone into calcium oxide and CO_2. Figure 2 shows the increase in emissions with increasing cement and clinker production. In 2022, there was an increase in emissions even though there was a decrease in production due to the increase in the clinker factor, shown in Figure 3, which is the percentage of clinker originating from non-renewable raw materials in cement.

Based on Cavalett et al. (2024), it is estimated that the calcination process contributes 60% of the total emissions of the cement production process. One of the decarbonization steps that can be taken is to use alternative raw materials to reduce the clinker factor. The clinker factor that the company has successfully achieved in 2023 reached 70.30%, as shown in Figure 3. The reduction in the clinker factor was achieved by using alternative raw materials such as fly ash and bottom ash (FABA).

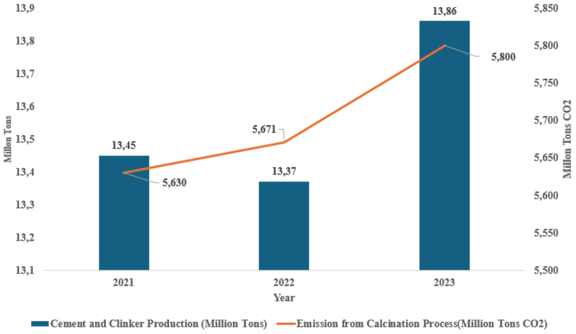

Figure 2. Cement production and calcination process emissions of PT X

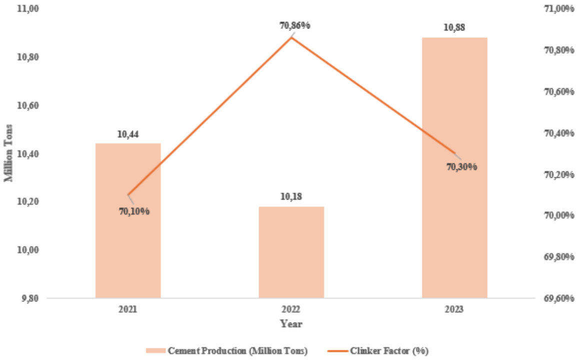

Figure 3. Clinker factors in PT X cement production

Clinker substitution using alternative raw materials up to a ratio of 60% in 2050 is estimated to mitigate emissions by 0.3 $GtCO_2$ (Supriya et al., 2023). The company's plan to reduce the clinker factor by 68% in 2025 to 62% in 2030, and reach 52% in 2050 according to GCCA projections (2021) estimated to reduce emissions.

The cement industry is categorized as an emission-intensive industry originating from the production process and energy acquisition, both from on-site energy generation and from external parties. The on-site energy generation process is included in scope 1 emissions, which are direct emissions produced by the company. The main process in a cement plant, namely the calcination process to produce clinker, occurs at a temperature of 1450°C, will decarbonize limestone which contains a high amount of carbonate and releases CO_2. Increasing clinker production in cement production will increase the need for heat energy, thereby increasing emissions. This is consistent with what is shown in Figure 4.

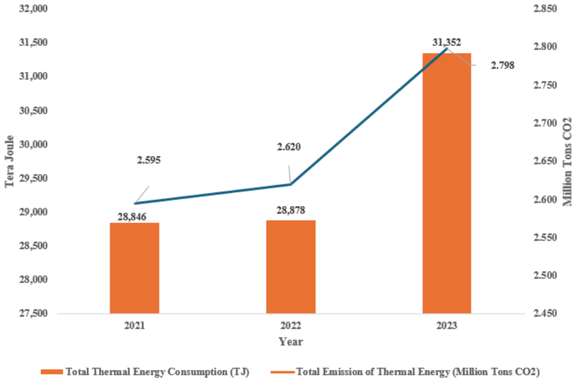

Figure 4. PT X thermal energy consumption and emissions

The provision of heat energy by PT X uses a combination of renewable and non-renewable fuels. Non-renewable fuels come from fossils such as coal and industrial diesel oil. Meanwhile, alternative fuels use refused-derived fuels derived from industrial waste and domestic waste, as well as biomass in the form of rice husks. In proportion of heat energy consumption 87% is generated by coal, 0.6–0.7% is generated by industrial diesel oil, 7–9% comes from refused-derived fuel and the remaining 2–4% comes from biomass combustion.

Total heat energy consumption and the percentage of alternative fuel use as a substitute for heat supply are shown in Figure 5. Based on the figure, the increase in the proportion of alternative fuels in heat energy generation increased from 11.43% in 2021 to 12.17% in 2023, with an increase of around 0.7% in 3 years. This shows the company's commitment to reducing dependence on fossil fuels and adopting more environmentally friendly energy sources. Although there is an increase in heat substitution with alternative fuels, there is also an increase in total heat energy due to increased production.

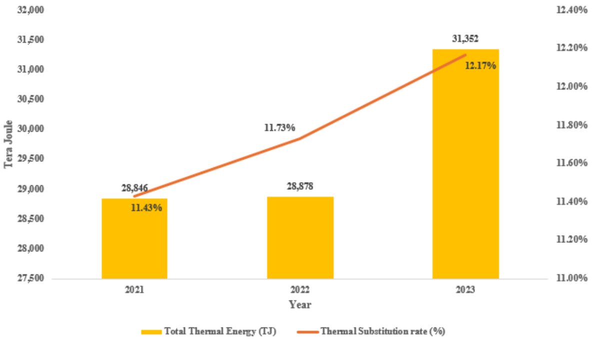

Figure 5. PT X thermal energy consumption rate of thermal substitution energy

To reduce emissions from the use of fossil fuels, it is necessary to increase the use of RDF and biomass as alternative fuels. The selection of RDF as an alternative fuel is due to its high calorific value ranging from 15 to 20 MJ/kg and biomass has a calorific value of 14 to 21 MJ/kg. Biomass is considered CO_2 neutral, because during its growth, biomass absorbs CO_2 from the atmosphere in almost the same amount as the CO_2 released during its combustion. However, RDF and biomass have limitations due to their uncertain supply. Thermal energy consumption contributes 35-40% of total cement production emissions, while alternative fuels only reduce 10% of total cement production CO_2 emissions (Antunes, et al., 2021). Therefore, it is necessary to increase the rate of thermal substitution higher, implement other decarbonization measures such as increasing combustion efficiency by adding hydrogen to coal combustion and utilizing exhaust gas heat using waste heat recovery.

The electrical energy obtained from external sources of the company is a scope two emission or indirect emission produced by the company. The amount of electrical energy consumed by the company is shown in Figure 6. From 2021 to

2023, it is known that the increase in electrical energy consumption increases along with the increase in cement production.

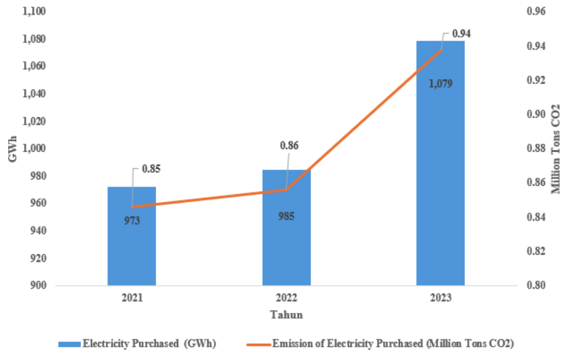

Figure 6. PT X electrical energy consumption and emissions

The electrical energy used in cement production is divided into several uses. 28% of electrical energy is used to process raw materials, 39% for cement grinding and 5% for other operations (Cantini, et al., 2021). The emission factor for the Java and Bali power plants is provided by the Directorate General of Electricity, with a value of 0.87 tons of CO_2/MWh. Based on this emission factor, the calculated value of electricity consumption emissions is obtained. Figure 6 shows that increasing electricity consumption will increase the emissions produced by the company. This is because emissions from electricity consumption contribute 10% of total cement production emissions (Khaiyum, et al., 2023).

In a sustainable process, the company carries out energy efficiency using the implementation of a sophisticated process control system or Advanced Process Control (APC) and the use of renewable solar energy. The use of APC reduces specific electricity consumption by 88kWh/ton of cement, with an increase of 1 kWh/ton of cement each year. PT X has an installed solar panel capacity of 30.96 KWp which produces 21.86 MWh of electricity/year in 2023.

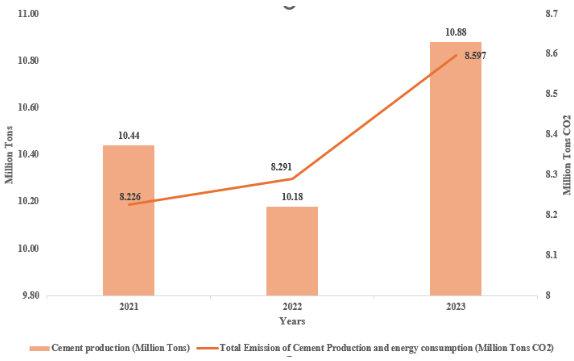

Figure 7. Cement production and total emissions emitted of PT X

Figure 7 shows the total emission of PT X from the calcination process, thermal and electrical energy consumption in 2021 reached 8.2 $MtCO_2$, and increased to 8.6 $MtCO_2$ in 2023.

System Dynamic Modeling of BAU conditions and Emission Reduction conditions

Company activity data is used to project emissions generated in 2050 with the parameters in table 1.

Table 1. Decarbonization strategies for system dynamic model scenarios

Variable	Unit	***Business as usual***
Clinker Factor	% Total Cement	70.1
Alternatif Raw Material	%Raw Material	7.6
Refused-derived Fuel	% total fuel	7.54
Biomass	% total fuel	3.89
APC	Kwh/ ton cement	88
Solar Panel	kWp	30.96
Waste Heat Recovery	MW	0
Carbon Sequestration	Ton CO_2	371.24

Cement and clinker production are each influenced by the rate of demand obtained from the company's historical production trends. Increasing cement and clinker production will increase the need for raw materials, electricity needs and thermal energy consumption, which increases emissions from the production process. To reduce emissions, several decarbonization steps are taken. In BAU conditions, the decarbonization scenario uses the decarbonization conditions that have been achieved by the company and are projected from 2021 to 2050. Figures 8, 20, 12 and 14 show stock and flow diagrams of the system dynamics decarbonization strategy of PT X.

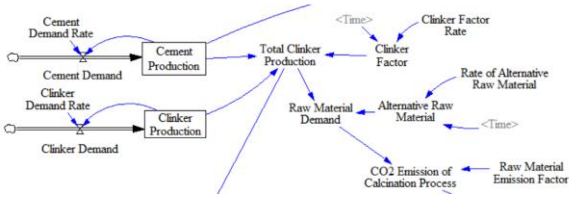

Figure 8. Stock and flow of PT X calcination process and emissions

The equation in Figure 8 system dynamics for the calcination process is shown in Equation (7) – (13).

Cement Demand = Cement Demand Rate × Cement Production (7)

Cement Production = INTEG(MIN (Cement Demand, 14.86 − Cement Production), 10.44) (8)

Clinker Demand = Clinker Demand Rate × Clinker Production (9)

Clinker Production = INTEG(Cement Demand,3.01) (10)

Raw Material Demand = 1.341 × (1−Alternative Raw Material)×Total Clinker Production (11)

Clinker Factor=0.701×(1−(Clinker Factor Reduction Rate×Time)) (12)

Alternative Raw Material=0.099×(1+(Alternative Raw Material Rate×Time)) (13)

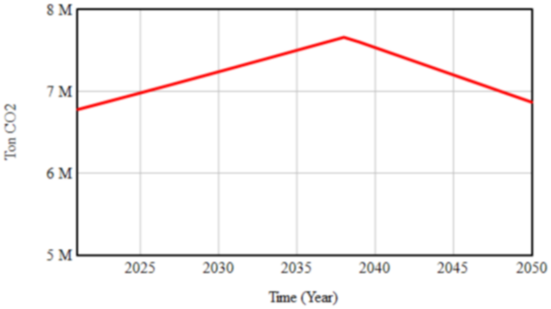

Figure 9. Projection of PT X calcination emissions

Cement production is modeled with a production increase rate of reaching the company's maximum production capacity of 14.86 million tons from 2039 to 2050, at a rate of 2.09%, with a MAPE value of 1.5%. The proportion of clinker in cement (clinker factor) in 2021 reached 70.1% and is targeted by PT X to decrease to 68% in 2025 and 62% in 2030. While the GCCA target, the clinker factor decreases to 52% in 2050. In modeling, the clinker factor uses historical data from 2021 to 2023 with a target reduction in 2025, 2030 and 2050 achieved at a rate of 0.89%/year.

Under BAU conditions, CO_2 emissions are mitigated using alternative raw materials. The projection of emissions generated by raw material processing is shown in Figure 9, emissions increase until 2038, reaching 7.66 $MtCO_2$ and decrease starting in 2039 until 2050, reaching 6.87 $MtCO_2$. The decrease occurs because the production value reaches a maximum and is constant starting in 2039, but the increase in raw material substitution is still carried out. In the cement production projection, decarbonization steps using alternative raw materials are known to be insufficient to reduce CO_2 emissions from the calcination process.

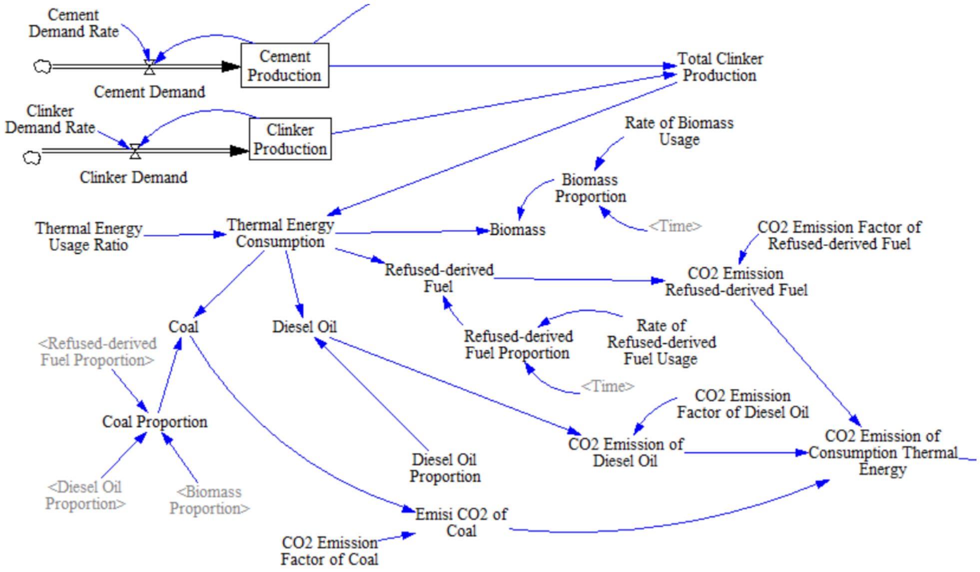

Figure 10. Stock and flow of PT X thermal energy consumption and emissions

The equation in Figure 10 system dynamics for energy consumption and emissions is shown in equation (14) – (21).

Thermal Energy Consumption =
Thermal Energy Ratio×Total Clinker Production (14)

Coal= Thermal Energy Consumption ×
Coal Proportion (15)

Coal Proportion=1 − Diesel Oil Proportion
−Refused-derived Fuel Proportion
− Biomass Proportion (16)

Diesel Oil = Thermal Energy Consumption ×
Diesel Oil Proportion (17)

Refused-derived Fuel =
Thermal Energy Consumption × Refused-derived Fuel Proportion (18)

Refused-derived Fuel Proportion = MIN(0.5, 0.0754 × (1 + Refused-derived Fuel Increase Rate × Time)) (19)

Biomass = Thermal Energy Consumption ×
Biomass Proportion (20)

Biomass Proportion = MIN(0.2, 0.0389 × (1 + Biomass Usage Rate×Time)) (21)

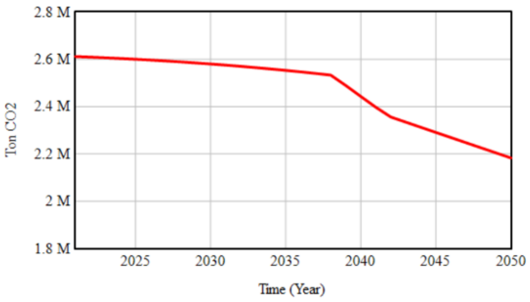

Figure 11. Projection of PT X thermal energy emissions

The increase in cement production affects the consumption of thermal energy. Thermal energy consumption is provided by coal, diesel oil, RDF and biomass. PT X in 2021 has a proportion of coal usage of 87.92%, diesel oil 0.66%, RDF 7.54% and biomass 3.89%. The projection of the use of alternative raw materials in the modeling uses the rate of increase that has been achieved by the company from 2021 to 2023. The increase in the rate of RDF use is 1.2%/year to reach a proportion of 10.16% in 2050. Biomass use increases at a rate of 19.88%, projected to reach 20% of the fuel proportion in 2042. The proportion value is maintained at 20% until 2050, in accordance with the maximum use of biomass as a fuel substitute in the kiln. Increasing the proportion of RDF and biomass reduces the proportion of coal use, reaching a thermal substitution rate (TSR) value of 62.86% in 2050, while the proportion of diesel oil remains at 0.66%. The projection of emissions resulting from thermal energy consumption in Figure 11, increases until 2038 reaching 2.53 $MtCO_2$ and decreases with constant cement production, reaching 2.18 $MtCO_2$ in 2050.

In the modeling, emissions from biomass consumption are not included in the calculation because they are considered carbon neutral, adjusting to the quantification carried out.

Currently, PT X has achieved 12% TSR with the use of RDF and biomass. The TSR value is targeted by PT X to achieve 15% in 2025 and 25% in 2030. Projections using modeling, in 2025 to achieve TSR 14.88% and 19.20% in 2030. TSR in 2030 was not achieved because the value of the increase in the proportion of RDF was only 1.2% per year which needs to be increased to achieve the target.

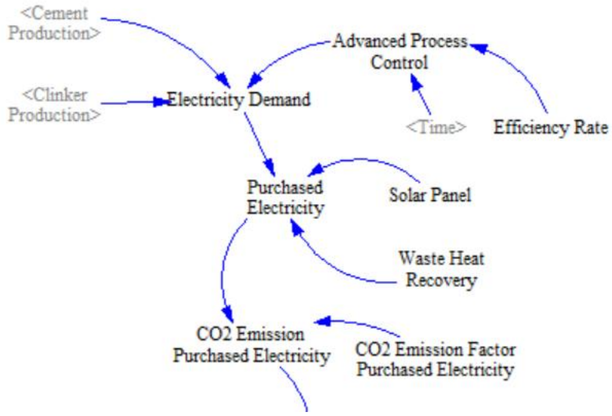

Figure 12. Stock and flow of PT X electric energy consumption and emissions

The equation in Figure 12 system dynamics for electric energy consumption and emissions is shown in equation (22) – (19).

$$\text{Electricity Demand} = (\text{Clinker Production} + \text{Cement Production}) \times \text{Advanced Process Control} \qquad (22)$$

$$\text{Advanced Process Control} = \text{MAX}(70000, 88000 \times (1 - \text{Efficiency Increase Rate} \times \text{Time})) \qquad (23)$$

$$\text{Purchased Electricity} = \text{Electricity Demand} - \text{Solar Panel} - \text{Waste Heat Recovery} \qquad (24)$$

$$\text{Solar Panel} = \text{DELAY FIXED}(21.86,2,0) \qquad (25)$$

The electrical energy used to produce cement and clinker at PT X in 2021 reached 88 kWh/ton of cement, and decreased by 1 kWh/ton of cement-year using Advanced Process Control (APC). The APC value reached a maximum of 62.48 kWh/ton of cement in 2050. The need for electrical energy is provided by external parties and solar panels with a capacity of 30.96 kWp (kilowatt-peak) generate electricity of 21.86 kWh.

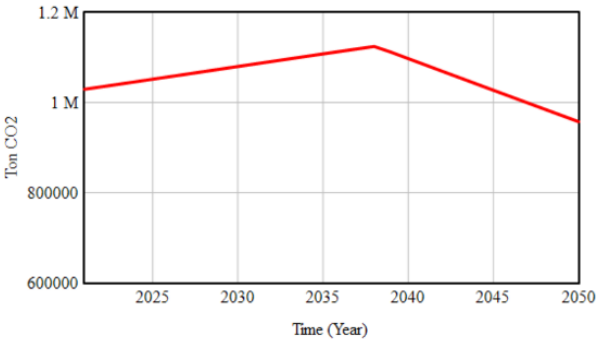

Figure 13. Projection of PT X electric energy consumption and emissions

Figure 13 shows that the emission of purchasing electrical energy reaches 957.7 thousand tons of CO_2 in 2050. The use of APC and solar panels is less significant in reducing the increase in the need for electrical energy, which increases CO_2 emissions from purchasing electrical energy. The need for other decarbonization steps such as WHR which utilizes excess heat in the kiln as an alternative to electrical energy.

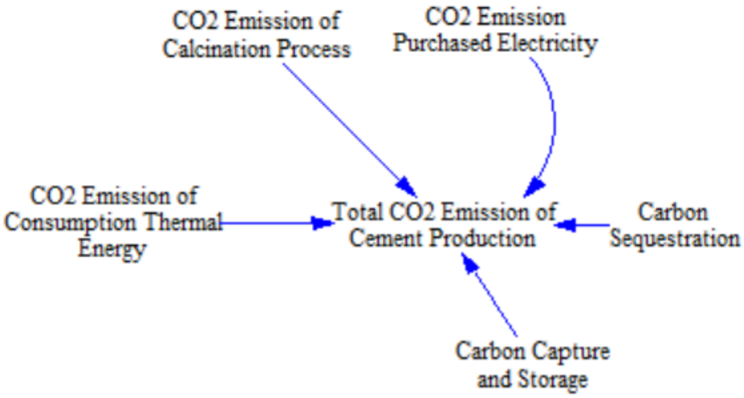

Figure 14. Stock and flow of PT X total emission

The equation in Figure 14 system dynamics for energy consumption and emissions is shown in Equation (26) – (32).

$$CO_2 \text{ Emissions from Coal} = \text{Coal} \times \text{Coal } CO_2 \text{ Emission Factor} \quad (26)$$

$$CO_2 \text{ Emissions from Diesel Oil} = \text{Diesel Oil} \times \text{Diesel Oil } CO_2 \text{ Emission Factor} \quad (27)$$

$$CO_2 \text{ Emissions from Refused-derived Fuel} = \text{Refused-derived Fuel} \times \text{Refused-derived Fuel } CO_2 \text{ Emission Factor} \quad (28)$$

$$\text{Total Fuel } CO_2 \text{ Emissions} = CO_2 \text{ Emissions from Coal} + CO_2 \text{ Emissions from Diesel Oil} + CO_2 \text{ Emissions from Refused-derived Fuel} \quad (29)$$

$$CO_2 \text{ Emissions from Calcination Process} = \text{Raw Material Demand} \times \text{Raw Material } CO_2 \text{ Emission Factor} \quad (30)$$

$$CO_2 \text{ Emissions from Purchased Electricity} = \text{Purchased Electricity} \times \text{Purchased Electricity } CO_2 \text{ Emission Factor} \quad (31)$$

$$\text{Total } CO_2 \text{ Emissions from Cement Plant} = CO_2 \text{ Emissions from Calcination Process} + (CO_2 \text{ Emissions from Coal} + CO_2 \text{ Emissions from Diesel Oil} + CO_2 \text{ Emissions from Refused-derived Fuel}) + CO_2 \text{ Emissions from Purchased Electricity} - \text{Carbon Sequestration} \quad (32)$$

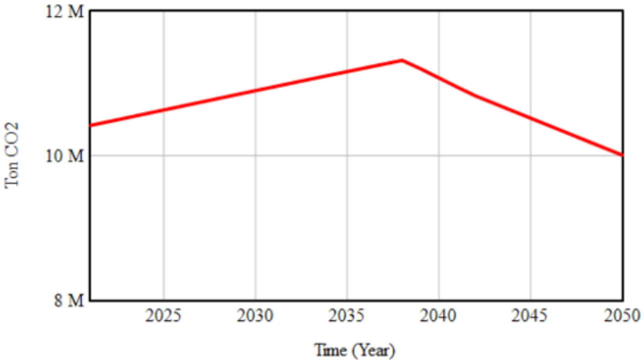

Figure 15. Projection of PT X total emission

Total CO_2 emissions of cement production are affected by increasing emissions from the calcination process, thermal energy consumption and electricity purchases and carbon sequestration that has been carried out. Sequestration that has been carried out by PT X is in the form of using microalgae and planting eucalyptus trees with a total sequestration capacity of 371.24 tons of CO_2. So with the increase in each emission minus the sequestration carried out, it will decrease the total CO_2 emissions of cement production shown in Figure 15. The decarbonization scenario under BAU conditions reaches a peak emission of 11.32 $MtCO_2$ in 2038 and reaches 10.01 $MtCO_2$ in 2050. This value is far from the target of zero net emissions in 2050, so more massive decarbonization steps are needed to reduce emissions from PT.X cement production.

Conclusions

The cement industry emits significant emissions due to the high carbon content of raw materials and the use of fossil fuels. In 2023, emissions of cement production reach 8.597 $MtCO_2$, and projected to reach 10.01 $MtCO_2$ in 2050 with mitigation strategies implemented.

Increasing demand in the cement industry leads to higher raw material processing, thermal energy consumption, and electricity usage, resulting in increased CO_2 emissions. To mitigate these emissions, energy efficiency, substitution of raw materials, and reduced fossil fuel usage are essential. Simulation results indicate that while decarbonization scenarios can significantly reduce emissions, achieving net-zero emissions (NZE) by 2050 remains unattainable without additional measures. Achieving NZE by 2050 requires the implementation of advanced decarbonization technologies, research into process optimization, and government policy interventions, such as carbon taxes and carbon trading.

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