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The Possibility of Achieving Zero CO_2 Emission in the Indonesian Cement Industry by 2050: A Stakeholder System Dynamic Perspective

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Abstract: According to the SDG on climate change, Indonesia is expected to achieve net-zero emissions by 2060 or sooner, as outlined in the long-term low-carbon and climate resilience strategies implemented by the country's president. Therefore, this research aims to apply the system dynamic model to simulate sustainable targets for CO_2 emission reductions until 2050. The simulation was limited to factors influencing the cement industry's CO_2, as described in the IEA's recommendations, and the scenarios were based on the AHP (analytical hierarchy process) results from the stakeholders. The simulation results showed that the realistic target for sustainable CO_2 emission reduction in Indonesia by 2050 was the scenario from the combined stakeholders with 450 $kgCO_2eq$/ton cement, corresponding to a 27% decrease in emissions from the 2020 baseline. This serves as input for interested parties to showcase the efforts of reducing CO_2 emissions, and provides recommendations for the achievements by (1) determining carbon taxes and revising cement product standards to further increase the clinker substitution rate; (2) developing an RDF (refused derived fuel) waste-processing plant independently to increase alternative fuel use; (3) ensuring the efficiency of electrical energy by increasing renewable energy sources; (4) integrating carbon capture and storage technology in cement plants.

Keywords: system dynamic; CO_2 reduction; AHP; SDG; cement industry

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1. Introduction

Cement is the main ingredient in concrete and the world's most widely used manufacturing material. The recent increase in global population and urbanization patterns, coupled with the need for infrastructure development, are driving the demand for cement and concrete. According to estimates, [1] global cement production is expected to increase from the current level by approximately 12–23% by 2050. In Indonesia, the demand was recorded at 76.4 million tons in 2019, but there was a reduction of 12.3% in 2020 due to the COVID-19 pandemic, causing delays in most construction and infrastructure projects [1]. Therefore, it can be concluded that the increase in demand for cement has effects on the environment.

One of the main cement industry effects on the environment is caused by enormous energy usage, namely gas emissions—particularly CO_2—which causes climate change [2]. According to a previous report [3], the cement production process requires a large amount of thermal energy [4]. Meanwhile, its operational cost is around 30% to 40%, which is the same as the energy procurement cost. It was also discovered that fossil fuels such as coal and industrial diesel are generally used as an energy source in the cement industry.

The cement industry is the world's third-largest consumer of industrial energy, accounting for 7% of global industrial energy use (10.7 exajoules CO_2eq). Cement production involves limestone (calcium carbonate) decomposition, representing about 60% of the total CO_2 emissions produced in the process, while the remaining emissions are caused by burning fuels and other energy uses [5]. According to the Reference Technology Scenario (RTS) of the International Energy Agency (IEA), direct CO_2 emissions from the cement industry are expected to increase by 4% globally in 2050, although production is predicted to improve by 12% over the same period [6].

To reduce Greenhouse Gas (GHG) from the cement industry, the government issued a regulation through the Minister of Industry concerning a roadmap for reducing CO_2 emissions in Indonesia. In the regulation, cement industries are expected to voluntarily reduce CO_2 emissions by 2% from 2011 to 2015 and obligatorily by 3% between 2016 and 2020. This led to a reduction in total emitted CO_2 by 5% from the established baseline [7]. In 2021, President of the Republic of Indonesia, Mr. Joko Widodo, published a commitment to realize zero emissions, especially in the cement industry, by 2060 or sooner [8]. This commitment aims to review and quarry whether Indonesian cement industries can achieve this target by 2050. The system dynamic is useful to simulate the policy scenarios from its stakeholders.

It has been observed that the current cement industry's condition contributed to direct CO_2 emissions of 3083.2 kgCO_2eq in 2018 [9] or produced approximately 641 kg CO_2eq/ton of cement in 2020 [10]. According to the comparative data on CO_2 emissions in Indonesia [11], cement factories reduced CO_2 emission intensities by 11.7% on average from 725 kg CO_2eq/ton to 641 kgCO_2eq/ton of cement in 2010 and 2020, respectively. Moreover, this emission level is still above those recorded in developing countries such as South America, Central America, India, etc., having below 600 kgCO_2eq/ton of cement [11]. This indicates that the emissions in Indonesia must be reduced to a range of 100–90 kg CO_2eq/ton cement to hold the earth's temperature below 2 °C (2DS) by 2050 [12].

Several studies have examined the potential efforts for reducing cement industry emissions [13–17]. Apart from the different scenarios, baseline emissions, and methods considered, these studies analyzed the four main options for reducing emissions, as contained in the IEA technology roadmap, which includes [18]: (1) improving thermal and electrical efficiency by applying the latest or old technology in cement plants; (2) clinker substitution, which involves the carbon-intensive substitution of clinker with low-carbon materials such as fly ash, plaster, and clay; (3) the use of alternative fuels, including low-carbon or carbon-neutral fuels, such as biomass or those derived from waste; (4) the use of new and innovative technologies, including the application of Carbon Capture Storage (CSS) technology in the cement manufacturing process.

Based on the background above, this research aims to determine the ability of the Indonesian cement industry to reduce CO_2 emissions in line with the reference provided by the IEA. This criterion is suitable to be applied in cement industries to restrain the rate of increase in the earth's temperature below 2 °C by 2050.

This paper is organized as follows: Section 2 describes the methodology of the Analytical Hierarchy Process (AHP) to determine the criteria for the stakeholder's effort in the cement industry; Section 3 discusses the system dynamic model of cement industries according to IEA's reference and its comparison with real system behavior using AME (Average Mean Error) simulation [19] with actual data from reliable formal sources; Section 4 explains the system dynamic approach for simulating the achievable results of the Indonesian cement industry in the given scenarios.

2. Materials and Methods

The stages of the AHP method begin with the definition of the goals and steps as a hierarchy [20]. According to the scenario and the predetermined criteria, the AHP matrix is described in a hierarchical chart as follows (see Figure 1):

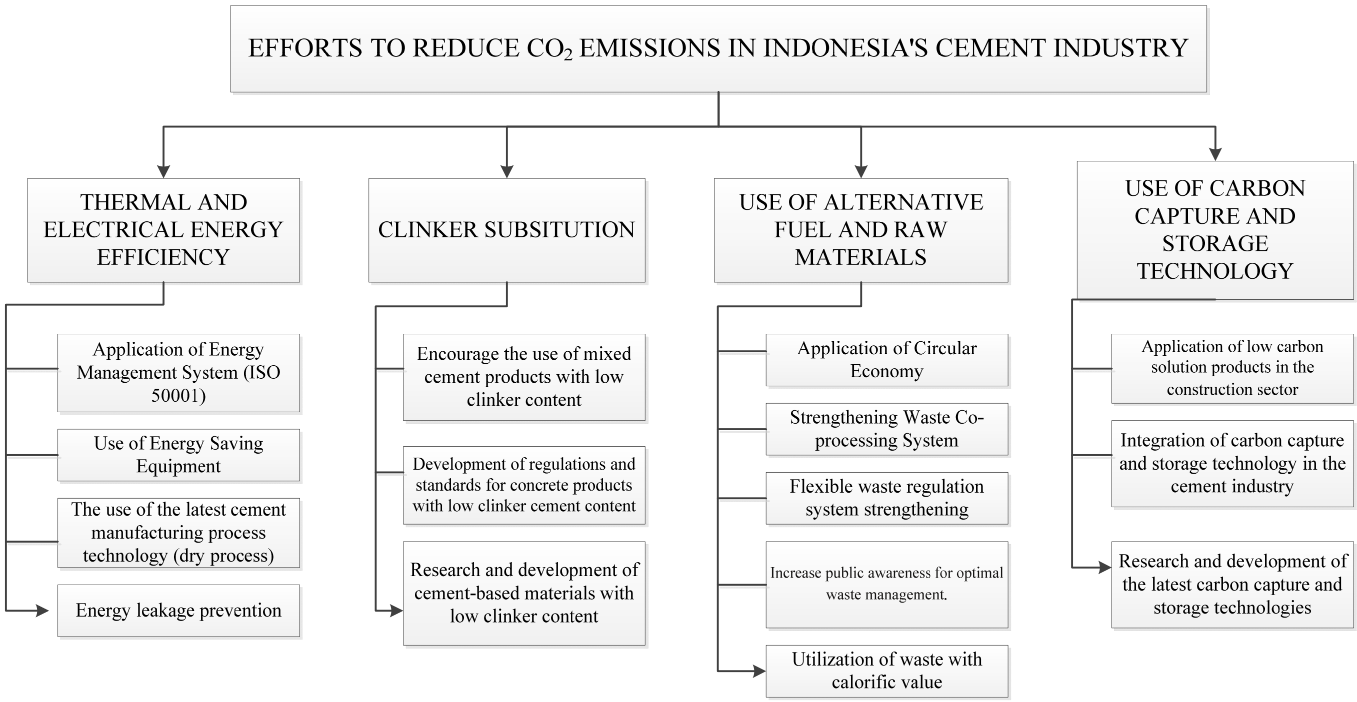

Figure 1. Hierarchical chart of CO_2 emission in the Indonesian cement industry [21,22].

The questionnaire was administered to 26 respondents from the cement industry's stakeholders in Indonesia. Meanwhile, the data were collected through random sampling of their efforts in CO_2 reduction, as categorized below (see Table 1).

Table 1. A sampling of questionnaire data and stakeholder interviews for CO_2 reduction measures in the cement industry.

Stakeholder	Interest Focus
Ministry of Industry	Policy/Regulator
Ministry of Forestry and Environment	Policy/Regulator
Cement Industry	Implementation of reduction efforts
Cement Association	Coordination of cement industry members as an effort to reduce CO_2 emissions
Research Institute	R&D new technology
Environmental NGOs	Control over policies and implementation of CO_2 reduction efforts

The results of the AHP calculation were checked for inconsistency ratio [21] and generated as input to the system dynamic scenario policy. Subsequently, questionnaire data were processed using expert choice software, which produced the results that will be discussed in the next section.

As qualitative data for policy implementation and recommendation, all efforts were discussed with cement industry stakeholders.

2.1. AHP's Priority Calculation

Based on expert choice software calculation, the respective results of respondents from the questionnaire are shown in the Table 2.

Table 2. Priority effort from stakeholders (expert choice results).

Stakeholder	Goal	Efforts	Values	Priorities
Cement Industry Association (1 respondent)	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.166	III
		Clinker Substitution	0.545	I
		Alternative Fuel	0.174	II
		CCS Technology	0.114	IV
Stakeholder	**GOAL**	**Efforts**	**Values**	**Priorities**
Research Institute (3 respondents)	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.098	IV
		Clinker Substitution	0.130	III
		Alternative Fuel	0.344	II
		CCS Technology	0.429	I
Stakeholder	**GOAL**	**Efforts**	**Values**	**Priorities**
Govt ministry (2 respondents)	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.475	I
		Clinker Substitution	0.210	II
		Alternative Fuel	0.161	III
		CCS Technology	0.154	IV
Stakeholder	**GOAL**	**Efforts**	**Values**	**Priorities**
Environmental NGO's (2 respondents)	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.177	III
		Clinker Substitution	0.124	IV
		Alternative Fuel	0.453	I
		CCS Technology	0.246	II
Stakeholders	**GOAL**	**Efforts**	**Value**	**Priorities**
Cement Industry (16 respondents)	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.166	III
		Clinker Substitution	0.545	I
		Alternative Fuel	0.174	II
		CCS Technology	0.114	IV

Each respondent showed a different effort priority regarding the setup goal. Based on the respondents' perspectives and expertise, the results in Table 2 are summarized as follows:

1. Respondents from the cement industry association considered clinker substitution the priority, with a value of 0.545.
2. Those from the research institute ranked CCS technology first, with a value of 0.429.
3. Stakeholders from the government ministry set energy efficiency as the priority, with a score of 0.475.
4. Environmental NGO's respondents set alternative fuel as a top priority, with a value of 0.453.

Based on Table 3, all respondents were pooled and re-calculated using expert choice application software, and the result showed that clinker substitution was the priority, with a value of 0.405.

Table 3. Priority effort from the combined stakeholders (expert choice result).

Stakeholder	Goal	Efforts	Values	Priorities
Combined	To reduce CO_2 emissions in the Indonesian cement industry	Energy Efficiency	0.206	III
		Clinker Substitution	0.405	I
		Alternative Fuel	0.225	II
		CCS Technology	0.165	IV

2.2. Consistency Ratio

The decisions made depend on stakeholders' knowledge and expertise, while the prioritization using the AHP method relies on their perceptions. The respondents' entries showed inconsistencies in their perception compared to the given criteria. Therefore, consistent measurements need to be performed to measure the inconsistencies using the CR (Consistency Ratio) value. The CR value for paired matrices is declared consistent when it is less than 0.1 (i.e., CR < 0.1) or 10%. However, when it exceeds 0.1, the process must be repeated [20].

3. System Dynamic Model for CO_2 Emission in Cement Production

After identifying the system, a conceptual model was built to provide an overview of the system dynamic and all data from the AHP result will be used for input calculation in system dynamic Powersim software. The modeling begins with the creation of a causal input–output diagram (casual loop diagram), followed by a stock–flow diagram.

3.1. Causal Loop Diagram

The diagram shows the relationship between one process and another connected by a line indicating a causal relationship. It also reveals a positive or negative increase between variables, which is qualitatively illustrated by a positive or negative sign in the diagram [23]. According to the input, there are four efforts for realizing the sustainable goals of reducing CO_2 emissions in the cement industries. This leads to five cause-and-effect parts, which are shown in the self-explanatory figure below (see Figure 2).

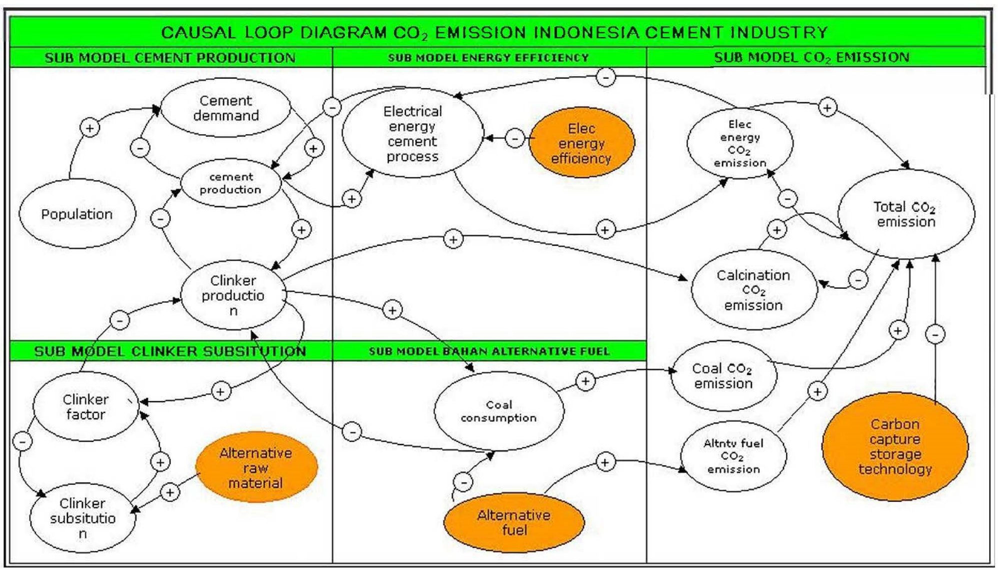

Figure 2. Causal loop diagram for CO_2 emission from the Indonesian cement industry [24].

3.2. Stock–Flow Diagram

After creating a causal loop diagram model, namely causal relationships and interactions between the variables defined in Table 4, the stock–flow diagram was drawn according to the system dynamic requirements in form of a stock–flow auxiliary level or constant. Consequently, the variables affecting the system were formulated in form of a simple mathematical relationship, indicated by a connecting symbol. The stock–flow model for each sub model is shown in the diagram below (see Figure 3).

Table 4. Consistency ratio for each hierarchy process.

Pairwise Comparison	CR	Remarks
Between Criteria (level 1)	0.04	Consistent
Between subcriteria energy	0.09	Consistent
Between subcriteria raw material	0.07	Consistent
Between subcriteria waste	0.07	Consistent
Between subcriteria technology	0.07	Consistent
Between subcriteria energy management	0.07	Consistent
Between subcriteria low energy equipment	0.05	Consistent
Between subcriteria recent cement technology	0.07	Consistent
Between subcriteria energy leaking prevention	0.07	Consistent
Between subcriteria utilization of low clinker cement product	0.07	Consistent
Between subcriteria regulation and standardization for low-carbon concrete	0.07	Consistent
Between subcriteria R&D for low clinker cement product	0.07	Consistent
Between subcriteria circular economy	0.07	Consistent
Between subcriteria waste co-processing	0.07	Consistent
Between subcriteria flexible waste regulation	0.07	Consistent
Between subcriteria community education for waste management	0.07	Consistent
Between subcriteria caloric value waste	0.05	Consistent
Between subcriteria low carbon cement product	0.06	Consistent
Between subcriteria CCS technology integration with the cement process	0.06	Consistent
Between subcriteria R&D for CCS technology	0.06	Consistent

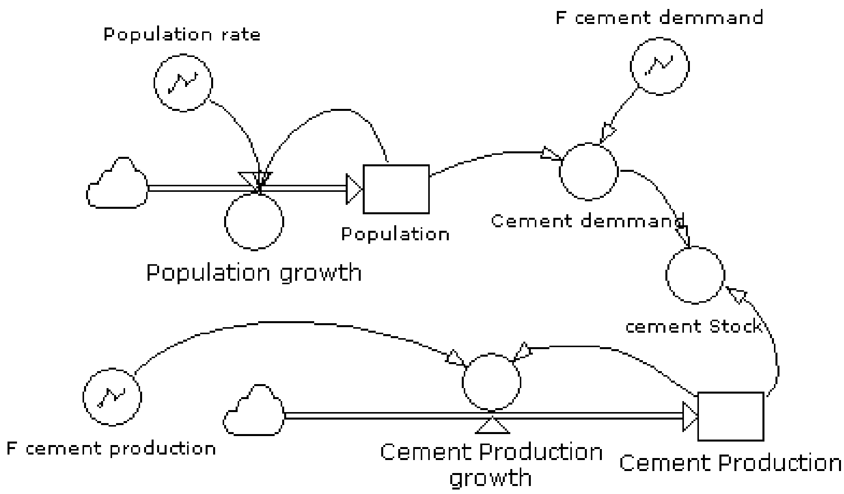

Figure 3. Population and cement production stock–flow diagram [25].

The first stock–flow of cement production was affected by population growth, which increases demand. Therefore, population growth and cement production are represented with stock symbols that rise or fall, as shown above in the Figure 3. The population rate is the key to the initial stock–flow diagram, as described in the following graphical equations [26].

$$\text{Population} = \text{Population} + \text{dt} \times (\text{Population growth}) \quad (1)$$

where

- Population growth = Population rate × Population
- Population rate = GRAPH (TIME; 2015; 1; {1.138; 1.106; 1.074; 1.041; 1.008//Min: −1; Max: 11//}<<%/year>>)

$$\text{Cement demand} = \text{F cement demand} \times \text{Population} \quad (2)$$

where

- auxiliary of F cement demand is cement demand (tons) per person from 2015–2020 [27].
- F cement demand = GRAPH (TIME; 2015; 1; {0.24189; 0.23766; 0.25820; 0.26909; 0.26682; 0.23593//Min: −1; Max: 11//}<<Ton/person>>)

$$\text{Cement production} = \text{cement production} + dt \times \text{cement production growth} \quad (3)$$

where

- Cement production growth = F cement production × cement production
- F cement production = GRAPH (TIME; 2015; 1; {1535; 11,516; 5191; 1667; −9888; 2468 //Min: −1; Max:11//}<<%/year>>)

The second sub-model was the clinker substitution model, where the cement composition was affected by the clinker ratio, the amount of other inorganic raw materials replacing the clinker. Moreover, the raw materials for clinker replacement include limestone ($CaCO_3$) and gypsum as cement retardant [5]. The clinker substitution constant marked with brown in the model was used as a system dynamic scenario (see Figure 4).

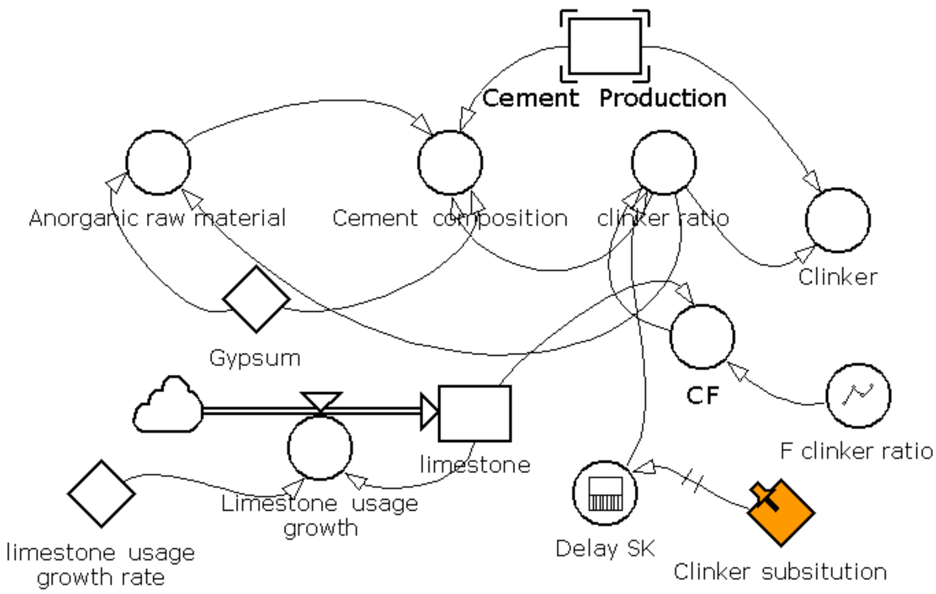

Figure 4. Clinker substitution stock–flow diagram [25].

Auxiliary Clinker was responsible for CO_2 emission based on the cement composition in the formula below

$$\text{Cement composition} = (\text{'Cement Production'} \times \text{'clinker ratio'}) + (\text{'Cement Production'} \times \text{Gypsum}) + (\text{'Inorganic raw material'} \times \text{'Cement Production'}) \quad (4)$$

where:

- Clinker = 'Cement Production' × 'clinker ratio', while clinker ratio and CF depend on the cement composition.
- Clinker Ratio = GRAPH (TIME; 2015; 1; {77.0642094990512; 78.7065471441271; 77.6899699349955; 74.5685259262785; 72.024; 70.6; 70.3; 69.68; 66.7; 65.8; 65.2; 64.6; 64.3; 63.7; 63; 62.5; 62.2; 61.6; 61.3; 61; 60.7; 60.7; 60.35; 59.8; 59.5; 59; 58.6; 58.3; 58; 57.4; 57.4; 57; 56.5; 56;55.3; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55; 55//Min:55; Max:100//}<<%>>)

  While Gypsum = 4% as the constant and
- Inorganic raw material = 100 <<%>>-(Gypsum + Clinker Ratio)

The third model is energy efficiency, showing that the energy required during the manufacturing of cement affected the stock and caused a decrease in the electrical energy. Based on the diagram, brown represents the electrical energy efficiency constant used for the scenario (see Figure 5).

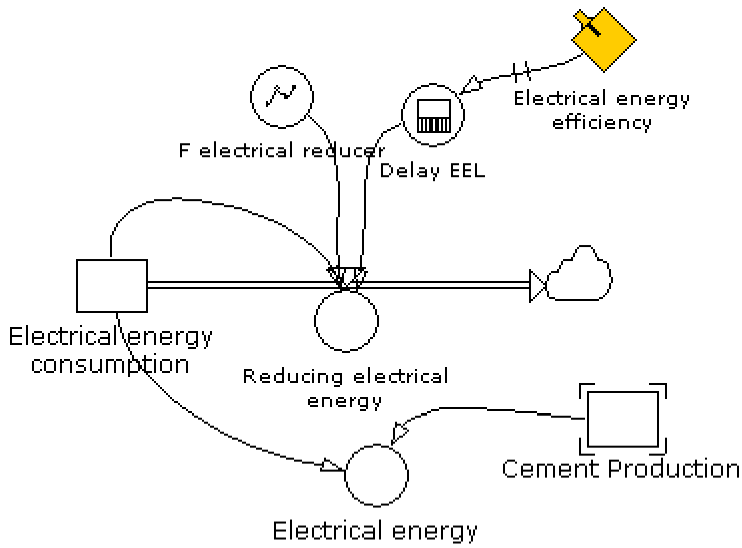

Figure 5. Energy Efficiency stock–flow diagram [25].

The constant F electrical reducer led to the use of electrical energy responsible for CO_2 emission contribution in the following equation.

$$\text{Electrical energy consumption} = \text{Electrical energy consumption} - dt \times \text{Reducing electrical energy} \quad (5)$$

where

- Reducing electrical energy = IF (Electrical energy consumption > 'Delay EEL'; Electrical energy consumption' × 'F electrical reducer')
- Delay EEL = DELAYINF ('Electrical energy effiency'; 10; 1; 83 <<Kwh/Ton>>)
- Electrical energy efficiency = 83 Kwh/Ton (as Constanta)
- F electrical reducer = GRAPH (TIME; 2015; 1; {1.9762; 3.662; 0.9415; 1.2531; 3.8860; 0.5//Min: −1; Max: 11//}<<%>>)

The municipal waste was assumed as an alternative fuel and was converted into a Revised Derived Fuel (RDF) to replace coal as the traditional fuel (Figure 6). According to the Indonesian statistic office, the country's GDP waste was 0.26 tonnes/people/day and the RDF waste conversion factor was 20%. The equation is described as follows.

$$\text{Coal} = (\text{Clinker} \times \text{'F Coal}) - ((\text{Clinker} \times \text{'F Coal}) \times \text{TSR}) \quad (6)$$

$$AF = Coal \times TSR \quad (7)$$

where

- F Coal = GRAPH (TIME; 2015; 1; {0.363346040669620; 0.370608580457636; 0.381539050451196; 0.388524288490419; 0.403115388984129; 0.423331998151721; 0.424249486175100; 0.475369759565820//Min: −1; Max: 11//})
- TSR = IF (‘Delay BBA’ = 0<<%>>; RDF; ’Delay BBA’)
- RDF = GRAPH (‘RDF raw material; 0 <<Ton>>; 13290570.80<<Ton>>;{20; 27; 33; 37; 42; 88; 54; 59; 65; 70; 76; 82; 93; 106; 115; 123; 132; 139; 147; 154; 160; 166; 169; 173; 177; 181; 186; 190; 195; 199; 203; 207; 214; 220; 227; 233; 238; 242; 248; 250; 253; 259; 263; 266; 270; 274; 276; 283; 287; 293; 298; 300; 300; 300; 300; 300; 300; 300; 300; 300; 300//Min: 20; Max: 300//}<<%>>)
- Delay BBA = DELAYINF (Alternative fuel; 10; 1; 0<<%>>)
- Alternative fuel = 0
- F Waste = 0.26
- Waste = F Waste × Population
- RDF raw material = 0.2× Waste

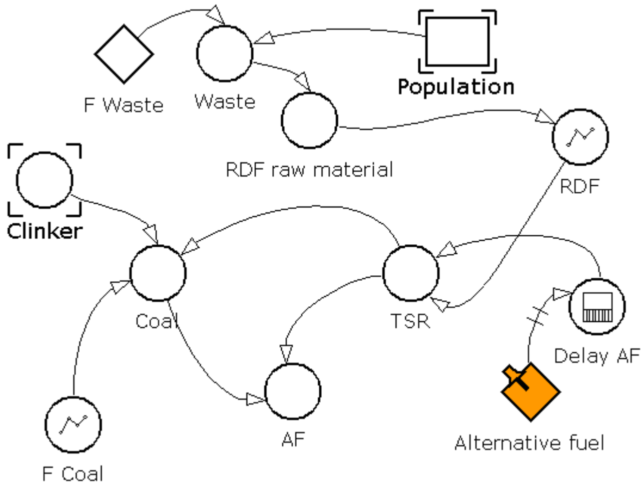

Figure 6. Alternative fuel stock–flow diagram [25].

All sub-model CO_2 emissions (Figure 7) were expressed with the following equation.

Total CO_2 emission = ((‘Calcination CO_2 emission’ + ‘Electrical CO_2 emission’ + ‘TSR CO_2 emission’ + ‘Coal CO_2 emission’)—((‘Calcination CO_2 emission’ + ‘Electrical CO_2 emission’ + ‘TSR CO_2 emission’ + ‘Coal CO_2 emission’) × ‘Delay CCS’))/’Cement Production’ (8)

where:

Calcination CO_2 emission = Clinker × F Calcination CO_2 emission
F Calcination CO_2 emission = 678.9640823 $kgCO_2$/ton (as Constanta)
Electrical CO_2 emission = Electrical energy × F CO_2 electrical
F CO_2 electrical = 1.05 $kgCO_2$/Kwh (as Constanta)
TSR CO_2 emission = AF × F TSR CO_2 emission
F TSR CO_2 emission = 13.12 $kgCO_2$/ton (as Constanta)
Coal CO_2 emission = Coal × F Coal thermal capacity
F Coal thermal capacity = 234.75 $kgCO_2$/ton (as Constanta)
Delay CCS = DELAYINF(CCS; 20; 1; 0<<%>>)

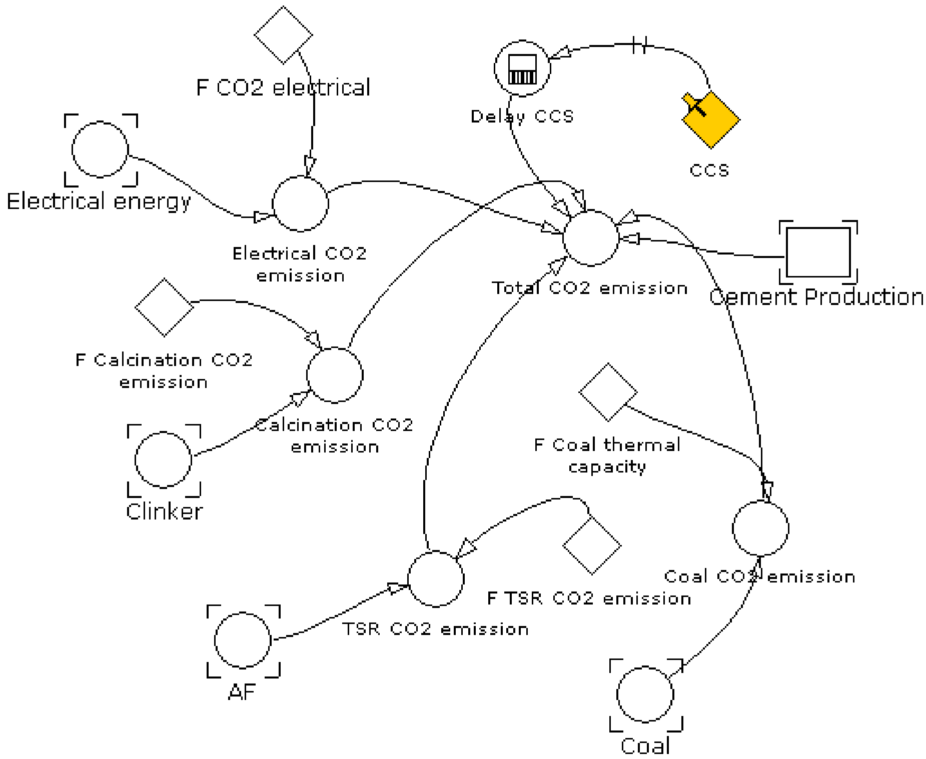

Figure 7. Total CO_2 contribution stock–flow diagram [25].

Auxiliary CCS technology indicated with brown color acts as a variable for the scenario.

3.3. Scenario Generation

Scenarios were determined from the AHP results of each stakeholder and the combination of all respondents. The baseline was set to 620 kg CO_2eq/ton of cement from 2020 data, and seven scenarios were defined. The first scenario was considered as Business As Usual (BAU) with no modified efforts, while the remaining six were those introduced from 2020 to 2050, as shown in the table below (Table 5).

1. Scenario 1 (BAU) was generated from the existing data of the Indonesian cement industry from 2015 to 2020 and was projected up to 2050 using a system dynamic.
2. Scenario 2 from the cement industry association has the following parameters:

Table 5. Scenario 2 from cement industry association.

Stakeholder	Efforts	Values	Priorities	Scenario 2
Cement industry association	Energy Efficiency	0.166	III	92 Kwh/Ton cement
	Clinker Substitution	0.545	I	54.5%
	Alternative Fuel	0.174	II	17.4%
	CCS Technology	0.114	IV	11.4%

3. Scenario 3 from the research institute has the following parameters (Table 6):

Table 6. Scenario 3 from research institute.

Stakeholder	Efforts	Values	Priorities	Scenario 3
Research Institute	Energy Efficiency	0.098	IV	86.7 Kwh/ton cement
	Clinker Substitution	0.130	III	63%
	Alternative Fuel	0.344	II	34%
	CCS Technology	0.429	I	43%

4. Scenario 4 from the government and related ministry has the following parameters (Table 7):

Table 7. Scenario 4 from the government and related ministry.

Stakeholder	Efforts	Values	Priorities	Scenario 4
Govt ministry	Energy Efficiency	0.475	I	41.5 Kwh/ton cement
	Clinker Substitution	0.210	II	71%
	Alternative Fuel	0.161	III	16%
	CCS Technology	0.154	IV	15%

5. Scenario 5 from Environmental NGOs has the following parameters (Table 8):

Table 8. Scenario 5 from environmental NGOs.

Stakeholder	Effort	Value	Priority	Scenario 5
Environmental NGOs	Energy Efficiency	0.177	III	93 Kwh/Ton cement
	Clinker Substitution	0.124	IV	62.4%
	Alternative Fuel	0.453	I	45.3%
	CCS Technology	0.246	II	24.6%

6. Scenario 6 is the combination of all respondents' parameters (Table 9).

Table 9. Scenario 6 from the combination of all respondents' parameters.

Stakeholder	Efforts	Values	Priorities	Scenario 6
Combine	Energy Efficiency	0.206	III	95 Kwh/Ton cement
	Clinker Substitution	0.405	I	59.5%
	Alternative Fuel	0.225	II	22.5%
	CCS Technology	0.165	IV	16.5%

7. Scenario 7 is the parameters referenced from IEA and Paris agreement trackers (Table 10).

Table 10. Scenario 7 from IEA and Paris agreement trackers reference.

Stakeholder	Efforts	Values	Priorities	Scenario 7
IEA reference	Energy Efficiency	0.177	III	79 Kwh/Ton cement
	Clinker Substitution	0.124	IV	50%
	Alternative Fuel	0.453	I	65%
	CCS Technology	0.246	II	60%

3.4. Model Validation

This validation was used to verify that the model behaved the same as the actual system when reproducing the data. Specifically, the 2015–2020 CO_2 emission data from the official publication of the Indonesian Ministry of Industry was validated using Absolute Mean Error (AME). The result was compared with the simulation data having a standard tolerance of 10% see (Table 11), as described in the formula below.

$$\text{AME} = [(\text{Si} - \text{Ai})/\text{Ai}] \tag{9}$$

where

Si = Si N, where S = simulation result
Ai = Ai N, where A = actual data
N = time interval

Table 11. The AME validation report of CO_2 emissions below tolerable standards.

Year	Emission (kg CO_2/ton Cement)		AME (%)
	Ministry of Industry Data	Simulation Data	
2015	674.89	672.15	0.41
2016	687.87	683.31	0.66
2017	691.02	673.58	2.52
2018	668.16	659.29	1.33
2019	646.09	631.91	2.20
2020	641.46	620.08	3.33
Mean	666.92	653.63	2.01

4. Result and Discussion

The results of the different scenarios developed in the system dynamic model were discussed to determine the impact of various policy options on the CO_2 emissions from the cement industry in Indonesia. Furthermore, the trends over approximately 30 years were evaluated starting from 2020 to 2050.

4.1. Baseline or Business as Usual (BAU) Scenario

The baseline scenario was simulated using formal standard data from the Ministry of Industry [9] and was developed into the following results under normal conditions (Table 12).

Table 12. Indonesian ministry of industry cement data 2015–2020.

Year	Net Specific kg CO_2 Emission per ton Cementitious Total	Specific Power Consumption (kwh/ton Cement)	Specific Heat Consumption (MJ/ton Clinker)	Clinker Ratio (%)	Alternative Fuel Usage (%)
2015	674.89	95.43	3506.58	77.06	3.43
2016	687.87	97.32	3460.95	78.71	3.53
2017	691.02	93.75	3465.22	77.69	2.50
2018	668.16	92.87	3447.32	74.57	3.16
2019	646.09	94.03	3436.23	72.02	3.47
2020	641.46	90.38	3428.54	70.23	3.70

There is a continuous increase in cement production due to high demand and population growth. This is projected from the initial production of 64 million tons to 135 million tons in 2020 and 2050, respectively. Specifically, CO_2 emissions are expected to decrease to 506 kgCO_2 eq/ton of cement by approximately 27% without the influence of other parameters. The figure below (Figure 8) shows that the increase in cement and clinker production, due to the clinker ratio as well as the use of alternative fuel as the thermal substitution rate (TSR), reduced CO_2 emission.

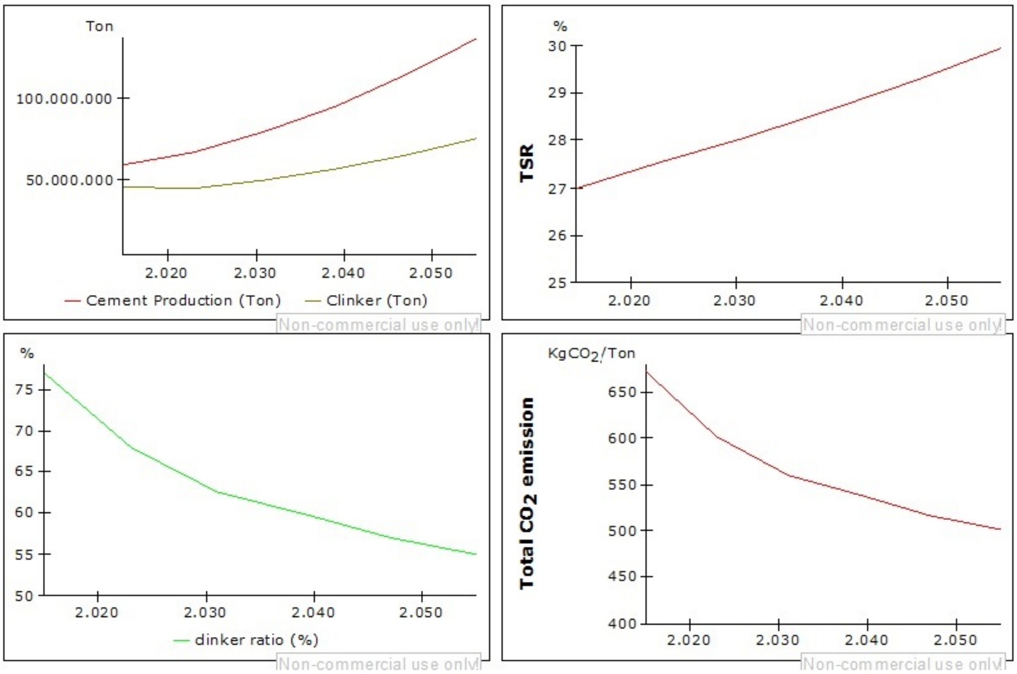

Figure 8. Relation of cement production, TSR, and clinker ratio to CO_2 emission [25].

4.2. Modified Scenarios

The proposed model was executed with possible combination efforts determined from AHP results using Powersim software. All scenarios were run under the same cement production conditions till 2050. Table 13 shows the results of all scenarios implemented in 2020.

Table 13. Simulation results of CO_2 emissions in 2050.

No	Respondents	Scenarios	CO_2 Emissions in 2050 (kg CO_2eq/ton Cement)	A Reduced Percentage from Baseline by 2050
1	BAU	1	506	21%
2	Cement Industry association	2	470	24%
3	Research Institute	3	350	43%
4	Govt ministry	4	510	18%
5	Environmental NGOs	5	420	32%
6	Combine	6	450	27%
7	Reference	7	255	75%

Gross CO_2 emission is increasing along with annual population growth of approximately 1.008% [26]. This is expected to foster more cement production and consumption, thereby causing an increase in clinker production as an intermediate raw material for cement. Conceptually, the clinker production process or calcination is a means of burning the most limes ($CaCO_3$) in the kiln to release CO_2, while the water became a hydrated lime.

It is important to note that the CO_2 emitted from the calcination process formed the biggest emission source in the cement industry, with approximately 60–75% [6]. The results showed that clinker production was responsible for CO_2 emission. Therefore, reducing its amount in the cement composition by replacing it with other materials that have similar characteristics was one of the efforts of reducing CO_2 emission; one of efforts is using hemp-lime that had lower emissions [28].

Scenario 2 from the cement industry association has the highest option of clinker substitution, with up to 54% compared to other scenarios. The replacement was almost the same as the reference from IEA in scenario 7.

According to a previous report [26], the most effective means of reducing CO_2 emission was carbon capture and storage (CCS) technology, which directly captures the CO_2 physically, chemically, or biologically. Although this technology has not been proven for complete removal [29], it was capable of removing up to 65% and continues to develop for higher efficiency by 2030 [18,30]. Scenario number 3 from the research institute showed that CSS technology has the highest percentage of CO_2 emission removal at 43%, while the IEA reference was 65%.

Scenario 4 from the government ministry showed the lowest achievement of CO_2 reduction due to the limited energy efficiency threshold [5,29], and scenario 5 having the second-best yield of CO_2 reduction by utilizing alternative fuel is limited by high investment cost [2,31].

Although scenario 3 yielded the best results in reducing CO_2 emission, the interviews with stakeholders showed that higher CO_2 removal using CCS technology is currently not feasible in Indonesia, unlike the scenario of the cement industry association.

5. Conclusions and Policy Implementation

A system dynamic simulation for CO_2 emissions in the cement industry was developed. The model was applied to make a forecast until 2050 to achieve the best practical implementation based on stakeholders' expertise. The results showed that CO_2 emissions from cement industries in Indonesia depend on many interrelated variables, namely population growth, cement demand and production, clinker production, electrical energy, and traditional fuels, as well as the applied CCS technology. The scenarios' combination and scenario 2 from the cement industry association seem realistic to be implemented, with the possibility of realizing a 27% reduction by 2050.

Further recommendations for realizing the efforts stated in the scenarios have to be achieved by implementing several steps from qualitative data based on expert opinion. These include: (a) The provision of a carbon tax mechanism for emitters with specified quality standards and a domestic carbon trading mechanism, which serves as a means of obliging the factories to regulate their emissions with the issuance of a new government carbon tax regulation. (b) Establishing a new green standard for the cement industry by providing a reference for achievement that supports the 2050 emission target, including reference factors for clinker, thermal and electrical energy, use of alternative fuels, and CO_2 emissions. (c) Revision of the reference standard of Indonesian national products for mixed, hydraulic, and pozzolanic cement by reducing the clinker factor to a significant level. During this process, the compressive strength standards of cement and its application in the construction sector are considered. (d) Increasing the use of alternative fuels in each cement company to replace fossil fuels by installing an RDF plant independently to use the urban waste where the cement factory is located. (e) Ensuring electrical energy efficiency by using Renewable Energy (RE), solar panels, and wind turbines. This is achievable by situating the cement factory location in open areas and limestone mountains, with abundant solar and wind energy potential. (f) Integrate CCS technology in proven cement plants, such as calcium looping and hydrogen–oxygen combustion, to gradually capture carbon emissions based on investment considerations. Furthermore, investigations need to be conducted regarding CCS technology, such as biological and chemical carbon sequestration.

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