International Journal Of Humanities Education And Social Sciences ***(IJHESS)*** *E-ISSN:* **2808-1765**
Volume 4, Number 2, October, *Page. 718 – 725*
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System Dynamics Model of CO2 Pollution Stocks Changes Due to Emissions and Absorbent in Indonesia

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Abstract
Air pollution, including CO2 pollution, is a serious issue worldwide, including in Indonesia. This CO2 pollution can impact public health and the environment. In the context of economic development, activities in Indonesia are increasing, leading to higher CO2 emissions. The highest CO2 emissions come from deforestation, large-scale peatland fires, and, to a lesser extent, burning fossil fuels for energy. This research focuses on a simple System Dynamics model approach to understand the cause-and-effect relationship of changes in CO2 pollution stocks concerning emissions and absorption in Indonesia. The method used in this study is qualitative based on system dynamics. System dynamics is a method that can be used to create structures, predict behavior, and provide feedback. The System Dynamics model uses Powersim Studio 10 Express, covering the research period from 2020 to 2040. The results of the system dynamics model show two structures related to CO2 pollution stocks: a positive feedback (reinforcing loop) from CO2 emissions and a negative feedback (balancing loop) from CO2 absorbent. The behavior of the model is exponential growth, it's also considered valid due to simulation results based on real data processing and statistical analysis, yielding an Average Means Error (AME) of 0.56%.

Keywords: System Dynamics, Pollution, Emission, Absorbent, CO2.

INTRODUCTION

Indonesia was ranked as the seventh-largest emitter of greenhouse gases globally in 2022 (Cindy, 2023). It is also the 16th largest economy worldwide and the largest in Southeast Asia. With economic activities on the rise, Indonesia's operations have increased, leading to higher emissions. The most significant emissions stem from deforestation and extensive peatland fires, with a lower level attributed to the combustion of fossil fuels for energy. The current government has pledged to reduce emissions by 29-41% by 2030. This commitment was conveyed to the United Nations Framework Convention on Climate Change (UNFCCC) as part of the preparations for the Paris climate conference (Paris Agreement). Indonesia ratified the Paris Agreement in 2016, aiming to gradually decarbonize its economy through enhanced land use and spatial planning policies, energy conservation, promotion of clean and renewable energy sources, and improved waste management.

The pressing issue at hand is the escalating CO2 pollution in Indonesia. Beyond causing environmental degradation, pollution also poses health risks to the population. This condition has a profoundly adverse impact on society since air pollution is a leading cause of various diseases, such as respiratory problems, eye irritation, coughing, lung cancer, cardiovascular issues, among others. In 2022, Indonesia's carbon output surged by 18.3% from the previous year, marking the highest increase among nations. There is a critical need for a counterbalance to these CO2 emissions, namely CO2 Absorbents. The blue carbon ecosystem is particularly vital for Indonesia due to its capacity to absorb and store large amounts of organic carbon, surpassing the capability of forests in performing the same function. Data from Our World in Data indicates that from 1990 to 2022, Indonesia's CO2 emissions grew at an approximate rate of 9.13% per year.

Considering the carbon absorption potential in Indonesia, there are 2,661,281 hectares of effective mangrove land with a carbon absorption capacity of 197.36 tons per hectare. Regrettably, approximately 637,824.31 hectares of mangrove land in Indonesia are in critical condition. Additionally, there are 875,957 hectares of effective seagrass beds with an absorption capacity of 119.5 tons per hectare, and the Indonesian seas are estimated to absorb up to 138 million tons per year. However, this only accounts for 4.08% of the total CO2 accumulation, indicating that CO2 emissions are increasing at a rate greater than their absorption capacity (Forest Digest, 2021).

The growing threat caused by pollution has emphasized the urgent need for natural CO2 absorbents, such as forests and other vegetation areas, to play a more prominent role in carbon sequestration. Existing research suggests that expanding vegetation areas and rehabilitating degraded lands are crucial strategies for increasing the capacity of natural CO2 absorbents (Griscom et al., 2017). However, these efforts will be insufficient without robust environmental policies aimed at protecting existing carbon sinks. As reported by Friedlingstein et al. (2020), the continuous loss of critical ecosystems, such as rainforests and wetlands, significantly hampers global carbon sequestration efforts, contributing to the alarming pace of climate change. Without efforts to reduce emissions, there is a 50% chance that the temperature increase of 1.5ºC above pre-industrial levels will be exceeded within seven years—several years earlier than projections in the Intergovernmental Panel on Climate Change Report (IPCC, 2021).

In utilizing the system dynamics methodology, defining the problem in dynamic terms is the initial step. It involves conceptualizing a tangible system with interrelated variables that influence each other, demonstrating the efficacy of modeling systems where these variables interact dynamically over time (Sterman, 2000). This conceptualization is depicted through a Causal Loop Diagram (CLD). Following the completion of the CLD, the subsequent phase involves pinpointing the system's independent accumulations or stocks and discerning the respective inputs and outputs (Wen Keat & Musa, 2014). These insights are pivotal in crafting a behavioral model capable of emulating the dynamic issue within a set boundary. Typically, this model is executed as a Stock and Flow Diagram (SFD) on a computer system. Recent studies have increasingly applied system dynamics to model the effects of emissions and land-use changes on carbon stocks. For instance, Jia et al. (2022) applied similar methodologies to examine land-use and climate dynamics in agricultural regions, highlighting how shifts in land management practices and policy interventions can significantly affect CO2 stocks.

Hence, this study centers on a straightforward dynamic systems modeling technique to grasp the cause-and-effect dynamics of the alterations in CO2 pollution stocks resulting from emissions and absorption in Indonesia. Through this approach, we can pinpoint the elements that drive the variations in changes of the CO2 pollution stocks and represent these factors using a Causal Loop Diagram (CLD) and Stock and Flow Diagram (SFD).

RESEARCH METHODS

The research employs system dynamics modeling. Modeling is the process of creating a representation based on observations of real-world phenomena within the cognitive framework of the modeler. System Dynamics is the application of feedback control principles and systems techniques to managerial, organizational, and socio-economic issues (Roberts, 1978). It serves as a critical method for aiding in the conceptualization, visualization, sharing, and communication of the complex evolution of organizational issues and challenges over time (Maani et al., 2000).

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Numerous software applications are available to facilitate the construction of system dynamics models. This research utilized the academic trial version of Powersim Studio 10 Express. Employing such software tools simplifies the researcher's tasks in conducting analysis, running simulations, and generating processed data from the model. This study leverages authentic data from the Global Carbon Budget (2023), focusing on CO2 and Greenhouse Gas Emissions, with a time series dataset spanning from 2020 to 2022.

Data processing entails the development of a program or simulation model utilizing Causal Loop Diagrams (CLD) and Stock and Flow Diagrams (SFD). These models incorporate linear equations and are operationalized through computer execution. Subsequently, a verification phase is conducted to ascertain the congruence of the data employed in the model with the observed system. This is followed by validation to assess the degree to which the constructed model accurately represents the observed reality or system.

Broadly, System Dynamics modeling is depicted as follows: (1) undertaking a literature review to comprehend the theoretical underpinnings of the study; (2) gathering reference data via prior literature surveys; (3) processing data by crafting a Causal Loop Diagram (CLD) simulation to elucidate the interrelations among pertinent variables, and devising a simulation model employing Stock and Flow Diagram (SFD) with linear equations facilitated by computer execution; (4) validating to confirm that the system or model adheres to pre-established standards and criteria; (5) analyzing the diagram to scrutinize the interplay among the variables it contains; and finally, (6) drawing conclusions predicated on the research findings and proffering recommendations.

RESULT AND DISCUSSION

The reference data amassed were analyzed by the researcher to construct a simulation model predicated on the interrelated variables within the cause-and-effect framework of CO2 pollution stock changes due to emissions and absorbents in Indonesia. The formulation of the CLD was contingent upon the needs analysis identified in the preceding stage. The observational data revealed five variables that significantly influence the CO2 pollution stock changes due to emissions and absorbents in Indonesia, namely: (1) CO2 Pollution; (2) CO2 Emissions; (3) CO2 Absorbents; (4) Rate of Increase in Gross CO2 Emissions; (5) Rate of Gross CO2 Absorption. There are two behavioral relation patterns: the first is a positive feedback loop (reinforcing loop) occurring between CO2 pollution and CO2 emissions, and the second is a negative feedback loop (balancing loop) between CO2 pollution and CO2 absorbents. The visualization of this pattern is depicted in Figure 1 below:

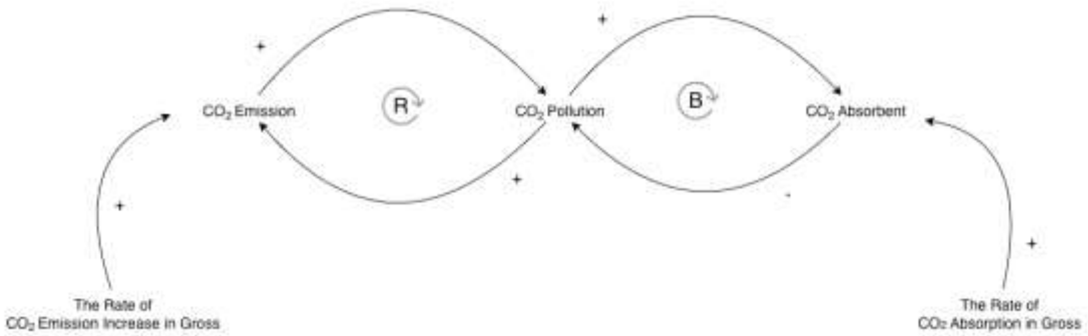

Figure 1. Causal Loop Diagram of CO2 Pollution Stocks Changes Due to Emissions and Absorbent
Source: Data Processing (2024)

In reference to the CLD depicted above, it is observable that several factors can influence the alterations in CO2 pollution stock in Indonesia. Examining the reinforcing loop, CO2 emissions directly augment the total CO2 pollution through various emission sources released into the atmosphere, such as human activities (industry, motor vehicles, and fossil fuel combustion) and natural processes (increased temperatures leading to polar ice and glacier melt, releasing more trapped CO2, and drying of peatlands, which emits more CO2). Conversely, the balancing loop directly facilitates the reduction of total CO2 pollution through the capacity to absorb CO2, thereby diminishing overall pollution levels. The data and information inputs from each component are processed using a computer with the Powersim Studio 10 Express application to generate a Stock Flow Diagram (SFD), as illustrated in Figure 2 below:

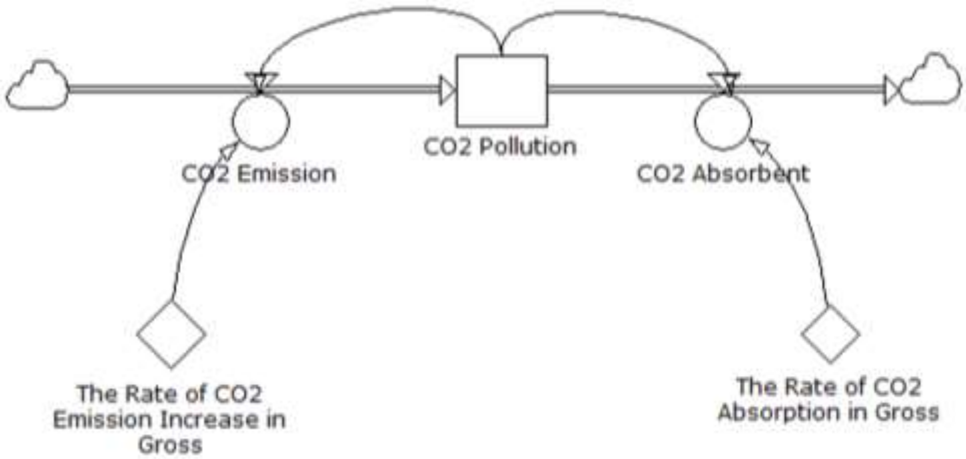

Figure 2. Stock Flow Diagram of CO2 Pollution Stocks Changes Due to Emissions and Absorbent
Source: Data Processing (2024)

The system dynamics process concerning the changes in CO2 Pollution Stocks resulting from Emissions and Absorption in Indonesia was executed using the Powersim Studio 10 Express software tool. The simulation was based on data with specified simulation times (start-time and stop-time). This study employed time specifications spanning from 2020 to 2040, yielding results depicted in time-series graphs as illustrated in Figure 3 and tabular data as presented in Table 1 below:

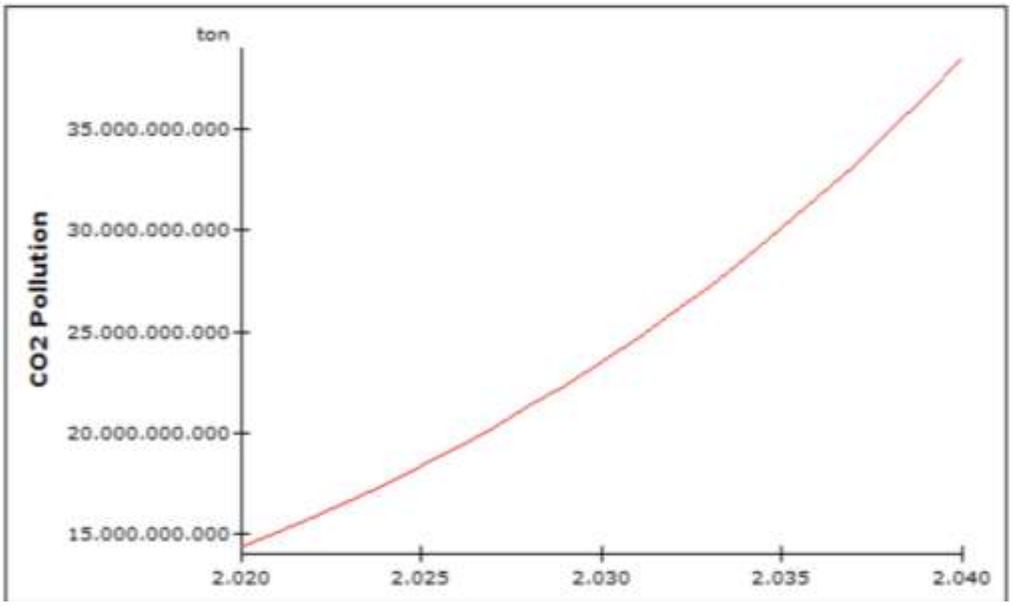

Figure 3. Simulation Time Chart of CO2 Pollution Stocks Changes Due to Emissions and Absorbent
Source: Data Processing (2024)

Table 1. Simulation Time Chart of CO2 Pollution Stocks Changes Due to Emissions and Absorbent

year	CO2 Pollution (ton)
2.020	14.367.307.000,00
2.021	15.092.856.003,50
2.022	15.855.045.231,68
2.023	16.655.725.015,88
2.024	17.496.839.129,18
2.025	18.380.429.505,20
2.026	19.308.641.195,21
2.027	20.283.727.575,57
2.028	21.308.055.818,14
2.029	22.384.112.636,96
2.030	23.514.510.325,12
2.031	24.701.993.096,54
2.032	25.949.443.747,92
2.033	27.259.890.657,19
2.034	28.636.515.135,37
2.035	30.082.659.149,71
2.036	31.601.833.436,77
2.037	33.197.726.025,33
2.038	34.874.211.189,61
2.039	36.635.358.854,68
2.040	38.485.444.476,84

Source: Data Processing (2024)

The simulation outcomes of the constructed model revealed that the predominant structure is Positive Feedback (Reinforcing Loop) with Exponential Growth behavior. The simulation data indicate that the annual total CO2 pollution has escalated by 9.13%. The actual total CO2 pollution in 2020 was recorded at 14,367,307,000 tons and is projected to perpetually rise each year to 38,485,444,476.46 tons in 2040 as per the simulation.

Subsequently, the model validation process necessitates the selection of a statistical technique. In this case, the author employed the Absolute Means Error (AME) statistical technique, with validation results expressed as a percentage (%) of error by comparing and processing original data with simulation data. The validation of the constructed model yielded the following results:

$$AME = \frac{[\bar{S} - \bar{A}]}{\bar{A}} \times 100\% = \frac{|15.105.069.412 - 15.020.883.333|}{15.020.883.333} \times 100\% = 0{,}56\%$$

$\bar{S}$ = average value of simulation results
$\bar{A}$ = average value of the reference/ real data

The Average Means Error (AME) test yielded a value of 0,56%, thereby categorizing the model as valid. This is because the model is predicated on a real scale, where the AME test value threshold for models based on a real scale is 30%.

Based on the validated simulation results, an ongoing increase in CO2 pollution is anticipated due to the rate of CO2 emissions exceeding the capacity for CO2 absorption. If the issue of CO2 pollution is not promptly addressed, it will have significant implications for climate change and the environment. There is a pressing need for stricter measures to regulate CO2 emission sources resulting from human activities and to expand conservation areas for CO2-absorbing vegetation. One potential CO2 absorbent, blue carbon, has yet to receive adequate attention from policymakers, unlike terrestrial forest carbon, which is included in one of the emission reduction schemes through deforestation and land degradation prevention. The blue carbon ecosystem is crucial for Indonesia due to its ability to absorb and store large amounts of organic carbon, surpassing the capacity of forests to perform the same function. The vast potential of Indonesia's blue carbon ecosystem has not been fully supported by comprehensive research. Existing studies are still partial and necessitate further steps. Transitioning to clean energy also presents a solution, promoting the use of renewable energy sources. Initiatives could start with investments in solar, wind, and hydro energy to reduce reliance on fossil fuels, all of which should be fully supported by the government and the community.

CONCLUSION

The model of CO2 Pollution Stocks changes resulting from Emissions and Absorption in Indonesia can be said to be valid, where the dominant structure formed is Positive Feedback (Reinforcing Loop) with Exponential Growth behaviour. This is in accordance with the fact that the annual total CO2 pollution has escalated by 9.13% every year. The actual total CO2 pollution in 2020 was recorded at 14,367,307,000 tons and is projected to perpetually rise each year to 38,485,444,476.46 tons in 2040 as per the simulation. There is a pressing need for stricter measures to regulate CO2 emission sources resulting from human activities and to expand conservation areas for CO2-absorbing vegetation. Transitioning to clean energy also presents a solution, promoting the use of renewable energy sources. Initiatives could start with investments in solar, wind, and hydro energy to reduce reliance on fossil fuels, all of which should be fully supported by the government and the community.

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