Findings on Modelling Carbon Dioxide Concentration Scenarios in the Nairobi Metropolitan Region before and during COVID-19

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Abstract – The increasing concentration of GHG in the atmosphere has been verified as the most important cause of global warming. Carbon (IV) oxide (CO_2) is the most important of them all and is the greatest contributor to global warming. CO_2 is emitted majorly from fossil fuel combustion and industrial production. The sources, of interest, of CO_2 in the study area are mining activities, transport system, and industrial processes. This study is aimed at building models that will help in monitoring the emissions within the study area. A statistical modelling approach was applied. The Orbiting Carbon Observatory-2 (OCO-2) and the Orbiting Carbon Observatory-3 (OCO-3) secondary data were used. Three scenarios were discussed, namely: pessimistic scenario; business-as-usual scenario; and the optimistic scenario. The result showed that there was a reduction in CO_2 concentration by about 50.3 ppm between March 2020 and January 2021 inclusive. From the models, the pessimistic, business-as-usual, and the optimistic scenarios gives CO_2 concentration of about 545.9 ppm, 415.0 ppm, and 360.1 ppm respectively on December 31st 2021. Also, the CO_2 concentration trend follows the business-as-usual scenario (BAU) path. This research helps paint the picture, to the policy makers, of the relationship between energy sources and CO_2 emissions. This research recommends investment in solar energy by energy-intensive companies, equipment and machine maintenance, investment in electric vehicles, and doubling tree planting efforts to achieve the 10% cover.

Keywords – economic recovery, forecasting, greenhouse gas, green energy, energy-intensive.

I. INTRODUCTION

The increasing concentration of greenhouse gases (GHG) in the atmosphere has been verified as the most important cause of global warming, which is a major environmental concern [1]. Carbon (IV) oxide (CO_2) is the most important of the GHGs and is the greatest contributor to global warming[2]. The principal anthropogenic sources of CO_2 are fossil fuel combustion and industrial production, which are largely concentrated in urban areas [3][4]. Ice core and instrumental measurements show that atmospheric CO_2 levels have risen by almost 40% in the last 150 years. Because greenhouse gases trap outgoing radiation from Earth's surface, the rising CO_2 level has led to global warming [5]. Global warming has adverse effects on natural resources such as biodiversity, forests and water resources. High temperatures cause heat stress, which affects the productivity of economic activities such as agriculture and other activities that involve hard field labour, artisanal mining included [6].

Kenya's successive climate change impacts over the past 10 years have resulted to socio-economic losses estimated at 3 – 5% of the GDP annually despite having negligible global GHG emissions (<0.1% in 2018). This has an impedance to realization of Kenya's Vision 2030. As Kenya realises its development aspirations, there will be gains and risks. A growing population and economy with urbanization will mean increase in greenhouse gas emissions. The largest absolute growth in emissions is expected in energy and transport, with energy emissions increasing from 10 $MtCO_2eq$ in 2010 to 33 $MtCO_2eq$ in 2030 and transport emissions increasing from 6 $MtCO_2eq$ in 2010 to almost 18 $MtCO_2eq$ in 2030. The industrial sector is relatively small in Kenya. It is estimated that 95% of industrial process emissions in Kenya are created by two industries: cement manufacturing (1.7 $MtCO_2eq$ in 2010) and charcoal production (0.8 $MtCO_2eq$ in 2010) (The Ministry of Environment and Forestry, 2013). Transition to a low carbon climate resilient development pathway can, therefore, address future risks, thereby improving Kenya's ability to prosper under a changing climate while reducing the emissions intensity of a growing economy [7].

Kenya has put up ambitious policies and measures to pursue her low emission climate resilient development pathway to realise Vision 2030. Her INDC which was submitted in 2015 aimed to reduce emissions by **30%** relative to the BAU scenario by 2030. This target was taken as half of the potential emission reduction by 2030, i.e., 100 $MtCO_2eq$ emission reduction by 2030. On the other hand, her updated NDC (2020-2030) targets to reduce emissions by **32%** relative to the BAU scenario by 2030. Some of the priority mitigation activities relevant to this study according to the Kenya updated Nationally Determined Contribution (NDC) to the Paris Agreement [8] include:

- Increasing of renewables in the electricity generation mix of the national grid;
- Enhancement of energy and resource efficiency across the different sectors;

- Make progress towards achieving a tree cover of at least 10% of the land area of Kenya;
- Clean, efficient and sustainable energy technologies to reduce over-reliance on fossil and non-sustainable biomass fuels.
- Low carbon transport systems

This research, therefore, will be part of decision support system for the stakeholders involved in the Kenya's NDC and Long Term Strategy (LTS) development. This is because there are no near real-time mechanisms to monitor the CO_2 concentrations within the study area and in Kenya at large, hence CO_2 concentration trends in the study area are not known. It is, therefore, hard to timely evaluating the policies put in place to reduce the CO_2 emissions, since the procedure used to estimate emissions for the NDCs is tedious and one that cannot be carried out monthly. With the models in this study, it will be easy for policymakers to track the performance of policies they put in place hence improve decisions made.

The occurrence of COVID-19 pandemic caused by the new Coronavirus that appeared in December 2019, prompted this research. Many countries adopted measures to control the quick widespread of this virus by applying curfew, lockdown, and social distancing measures, Kenya included. As a result, industrial production and energy consumption in some countries were reported to decline by up to 30% in just a few weeks as lockdowns were imposed to protect public health [9]. Taking the COVID-19-driven changes in energy markets, industrial production, and transportation behaviour, as well as building use and agricultural production, [10] estimate that US GHG emissions were 18% lower, on average, between March 15 and June 15 2020 compared to the same period in 2019. Transportation having the largest decline at 28%, followed by electric power and industrial production. Initial estimates of emissions changes based on a limited sample of power plants and indirect satellite observations of atmospheric pollutants have suggested that we may be witnessing the largest drop of emissions since the end of the Second World War[9]. Reference [11] predicted a drop of about 8% (1687 million tons CO_2 eq.), almost six times the last record, set in 2009 (1.3% - 274 million tons CO_2 eq.) that occurred due to the effects of the economic crisis and an overall fall in GDP. Less clear is how the crisis will shape emissions in the years ahead.

The main objective of this research, therefore, is to monitor CO_2 concentrations trends in the study area by analysing the changes in the CO_2 concentrations due to COVID-19 containment measures and predicting the possible future concentrations through modelling and forecasting. Pre-and-during COVID-19 CO_2 concentration were obtained, and models developed in MS Excel from which possible future trends were established and analysed.

This study answers questions such as:

i) What is the trend of CO_2 concentrations within the study area pre-and-during COVID-19?

ii) What is the drop in CO_2 concentrations due to COVID-19 mitigation measures? and

iii) What are the possible future CO_2 concentrations trends within the study area?

These research questions were answered with the aid of satellite data and through modelling and forecasting.

II. MATERIALS AND METHODS

A. The Study Area

This study focuses on the Nairobi Metropolitan Region (NMR) comprising four out of the forty-seven counties in Kenya namely: Nairobi, Kiambu, Machakos, and Kajiado as depicted in Fig. 1. The area is a highly urbanizing region with 24 urban centres. Nairobi city is the most dominant of the metropolis. The region extends over an area of approximately 32514km^2 that substantially depends on Nairobi city for employment and social facilities [12]. In the NMR, the main anthropogenic sources of CO_2 are mining activities (quarry, mining, and mineral exploration), industrial processes, and transport activities. From the mining cadastre map, the study area has about 74 mining activities (Kajiado county 44, Machakos county 27, Nairobi county 1, and Kiambu county 2). Mining is a heavy industry that uses fuel and infrastructure services intensively and as such leads to carbon emissions along the value chain [6]. Kenya's transport sector is dominated by road transport. In Nairobi and other major cities, severe traffic congestion, contributes to local air pollution.

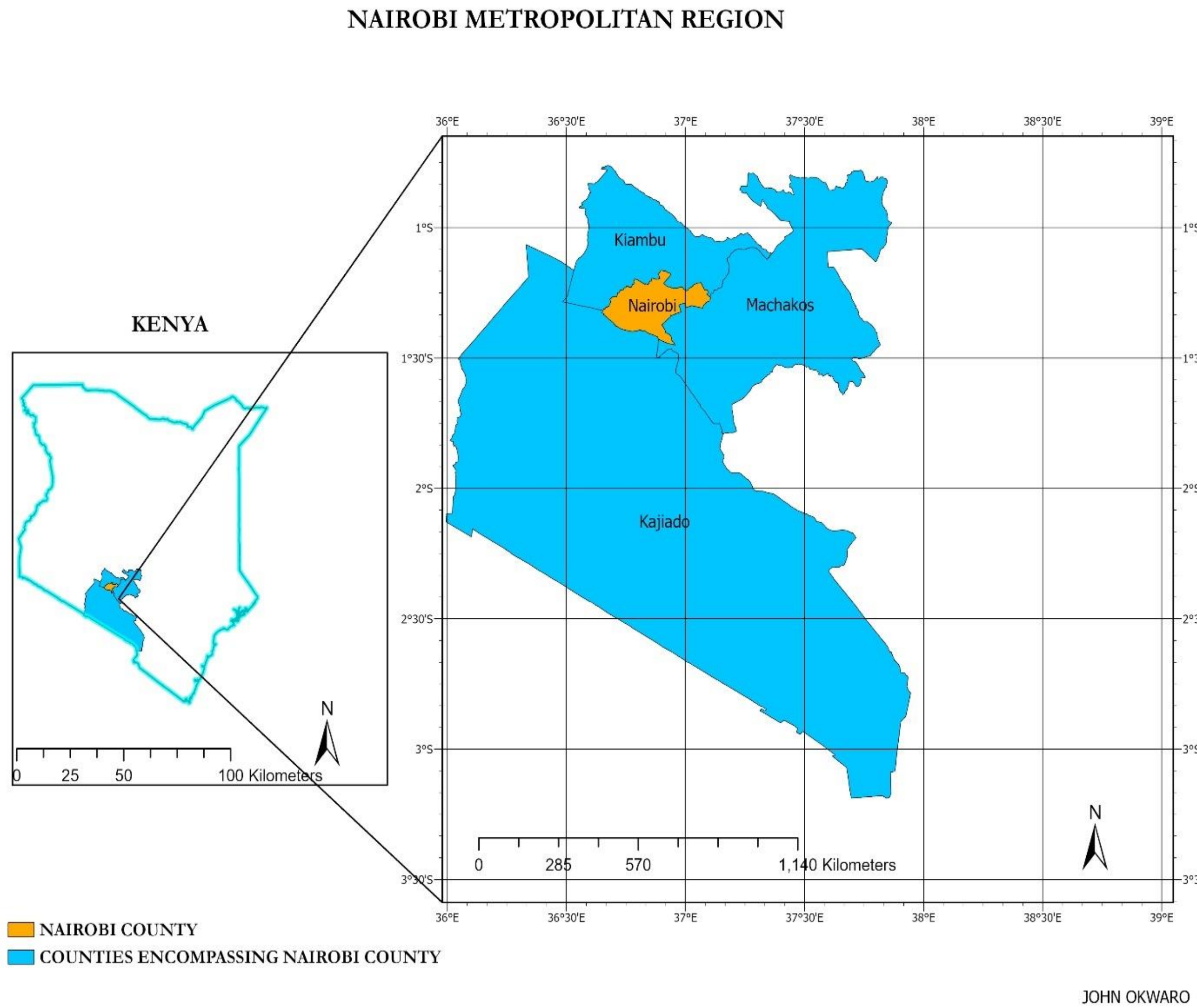

Fig. 1 Study Area

B. Data

In this study, Arc GIS pro was used to create the map of the study area, the mining activities were obtained from the mining cadastre map on the Ministry of Petroleum and Mining website. Also, the OCO-2 and OCO-3 XCO_2 data from 15th January 2019 to 31st May 2021 were used. The data were downloaded from the OCO-2 and OCO-3 data centers on 4th June 2021. These data were chosen because of their improved spatial-temporal coverage with small footprints of 0.1^0 (1.3km), which makes studying CO_2 concentrations at city scale possible from 2014 to date. The level 2 (L2) products downloaded were in Hierarchical Data Format (HDF) hence HDFView software was used to view the data. The data reported from 15th January to 31st May 2021 were used to test the predictive power of the models. The outliers on 31/01/2019 and 15/10/2019 reporting dates were removed before forecasting was done. This is because outliers are likely to affect the data distribution.

C. Methods

Data analysis was carried out in the MS Excel environment. The data were used to plot line graphs, which forms the models in this study.

To predict the possible future CO_2 concentrations, the pre-and-during COVID-19 CO_2 concentration model was used as the baseline. Trend lines/best-fit curves were then introduced to show the possible path the CO_2 concentrations are likely to follow in future. Trend lines have equations that will help in predicting CO_2 concentrations beyond 2021. Three scenarios were discussed, namely: The Pessimistic scenario, the Business-as-usual scenario, and the Optimistic scenario.

The pessimistic scenario describes a situation where Kenya over-relies on fossil fuel as the energy source to recover the economy, hence, it describes the highest level of emissions that can be reached. In this case, this research considered the part of the baseline curve that reported high rise in CO_2 concentrations trend. The period 15/01/2019 to 15/03/2019 inclusive was considered because these data sets describe an instance where the rise in CO_2 concentration was highest. The pessimistic scenario is described by the linear equation below.

$$y = 0.127x + 408.21 \quad (1)$$

The value of the $R^2 = 0.7621$. This means that 76.21% of the data used in the forecasting was represented.

The business-as-usual scenario describes the status quo. This was described by the data set from 15/08/202 to 15/10/2020 inclusive because these data sets describe instances where the rise/drop in CO_2 concentration was moderate. It, therefore, describes the current state of emissions. The business-as-usual scenario is therefore described by the linear equation below.

$$y = 0.0375x + 408.19 \qquad (2)$$

The value of $R^2 = 0.7027$.

The optimistic scenario describes lower future concentrations. This scenario is forecasted using data from 15/06/2020 to 15/08/2020 inclusive because this period describes a period where there was a higher drop in CO_2 concentration. The optimistic scenario is described by the linear equation below.

$$y = -0.0474x + 411.31 \qquad (3)$$

The $R^2 = 0.8452$. This shows a good representation of the data used in the regression.

Since the empirical data points follow the BAU scenario path, BAU model was calibrated using the empirical data. The least square method was used in the calibration. The slope was M = 0.003x while the Y-intercept was 411.8. The resulting equation was as below.

$$y = 0.003x + 411.8 \qquad (4)$$

D. *Assumptions*

a) Since weather conditions such as wind and sunshine are likely to affect the dispersion of CO_2 gas, the research assumes that the weather conditions remained the same during data capture.
b) Secondly, this research assumes that the study area is a closed system with boundaries being the administrative boundaries, hence CO_2 concentrations measured are due to the emissions that occurred within the boundaries.
c) The research assumes that the decrease in CO_2 concentrations was brought about solely by the COVID-19 containment measures.

III. RESULTS AND DISCUSSION

A. *Pre-and-during COVID-19 CO_2 concentrations*

The twenty-four-month model that covers the period from 15th January 2019 to 31st December 2020, as depicted in figure 3-1, shows the changes that occurred in CO_2 concentrations due to COVID19. The low CO_2 concentrations from March to December 2020 are attributed to COVID-19 containment measures. These measures included partial lockdown that was in force from 6th April to 6th July 2020, grounding of aeroplanes that lasted up to 1st August 2020, and the curfew that is still in force to date.

A. *Drop in CO_2 Concentration*

Table I shows CO_2 concentration drop due to COVID-19 containment measures. The drop is about 50.3 ppm.

TABLE I
CO_2 CONCENTRATION DROP DUE TO COVID-19

	"2020/2021	"2019/2020	Diff. (ppm)
January	420.0	414.7	5.3
February	414.1	412.9	1.2
March	411.1	415.2	-4.1
April	412.5	414.0	-1.5
May	410.3	414.7	-4.4
June	410.8	414.3	-3.5
July	409.8	412.6	-2.8
August	408.8	414.7	-5.9
September	409.1	414.0	-4.9
October	410.8	419.4	-8.6
November	410.2	413.8	-3.6
December	412.3	414.2	-1.9
January	410.9	420.0	-9.1
February	414.9	414.1	0.8
March	412.6	411.1	1.5
April	416.5	412.5	4.0
May	413.1	410.3	2.8
Average	412.2	414.3	
		Sum	-34.7
		Sum (negative)	-50.3
		Diff. Average periods	-2.0
		Average	-2.0
		Diff. Start date (J-2019) - end date (M-2021)	1.6

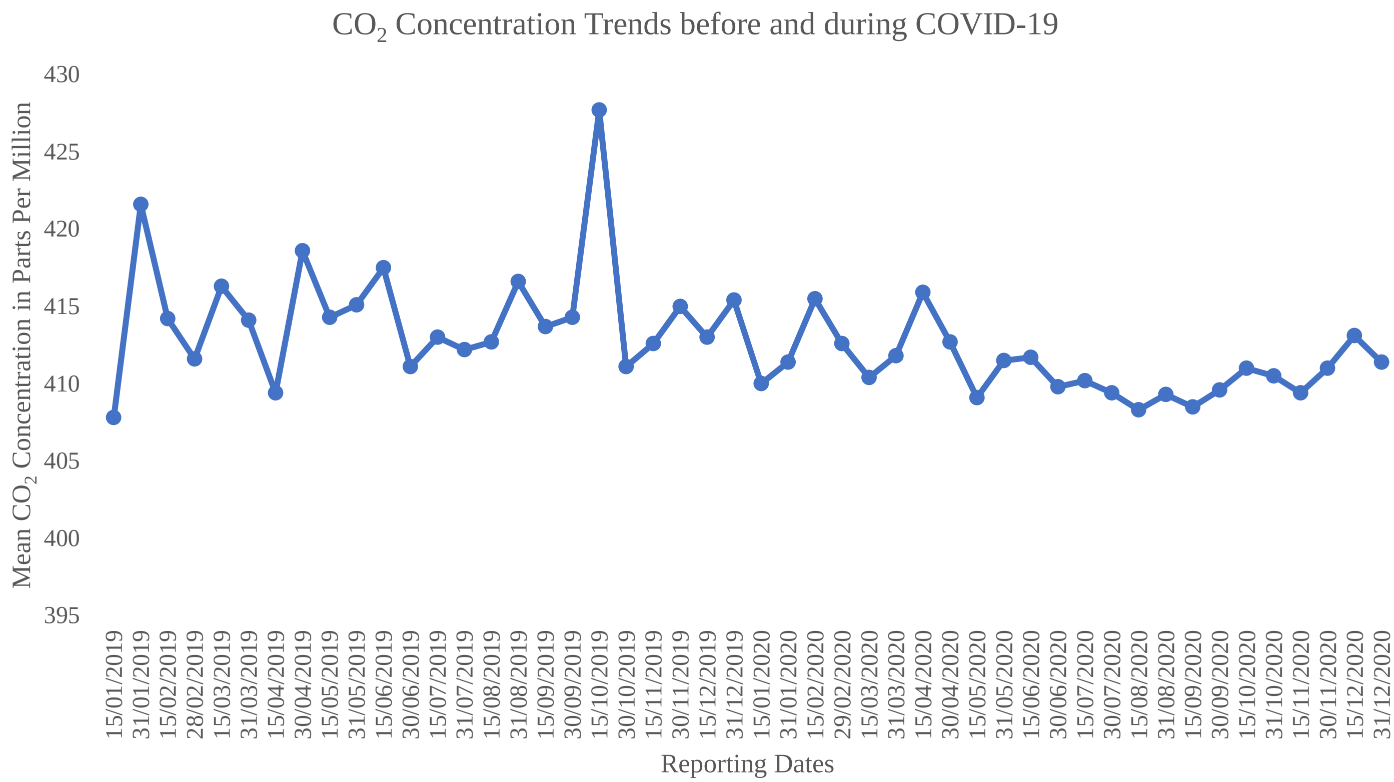

Fig. 2 Pre-and-during COVID-19 Concentration Model.

B. Modelling

The equations that were developed for the three scenarios were used to model the possible future CO_2 concentrations. Fig. 3 shows the path that each scenario takes. From the models, it was noted that the pessimistic, the BAU, and the optimistic scenarios are giving 501.3 ppm, 412. 8 ppm, and 377.4 ppm respectively at the end of the year 2020. Also, from the model, it can be seen that the empirical values are following the BAU scenario path.

After the BAU scenario model was calibrated and concentrations projected for the year 2021, the results were as shown in Fig. 4. The BAU scenario gives 415.0 ppm at the end of the year 2021. This shows an increasing trend of CO_2 concentrations.

When the models were tested, it was noted that the empirical values still follow the BAU scenario path with a deviation of about 0.05% as shown in Fig. 5. This tells us that by the end of the year 2021, the CO_2 Concentrations will be about 415.0 ppm, give or take. This value is very high hence, mitigation measures need to be put in place to reduce emissions.

The models in this research have several limitations. Some of these limitations include:

i. The data points are obtained by averaging a large sum of individual readings which is likely to cause errors.
ii. The daily and weekly variations in CO_2 concentrations cannot be determined from the model.

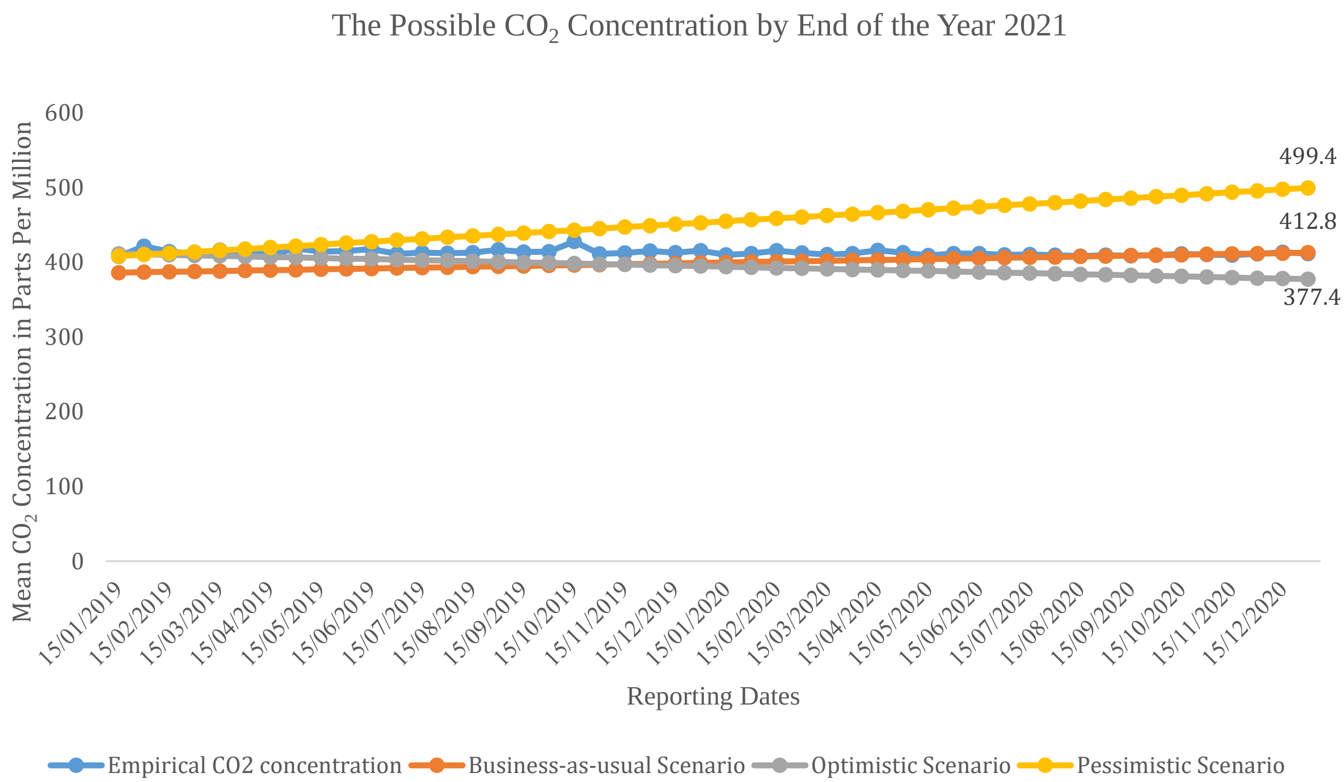

Fig. **Error! No text of specified style in document.** Model Showing Possible Concentrations by End of the year 2020

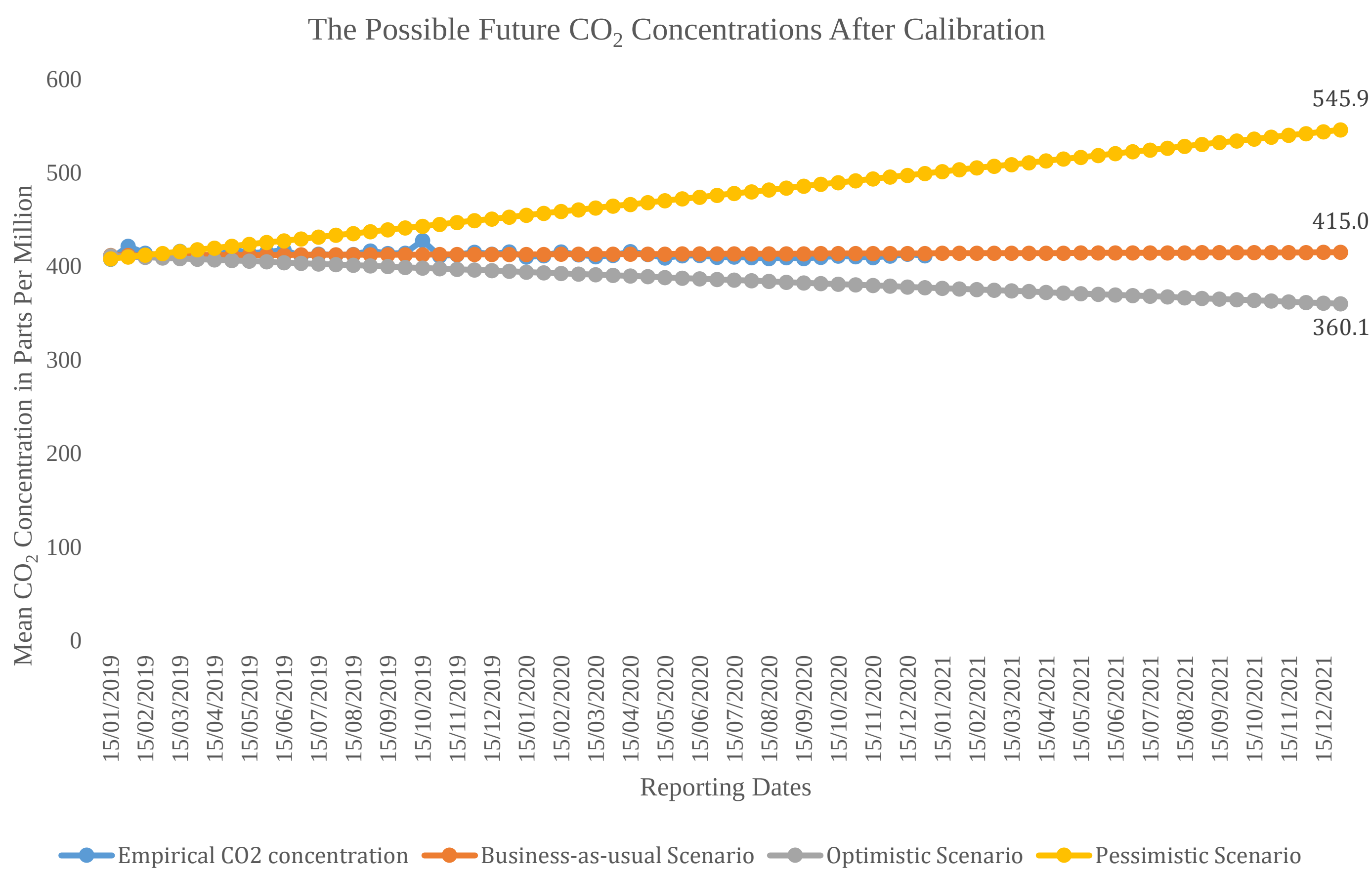

Fig. 4 Models Showing the Result of Calibration

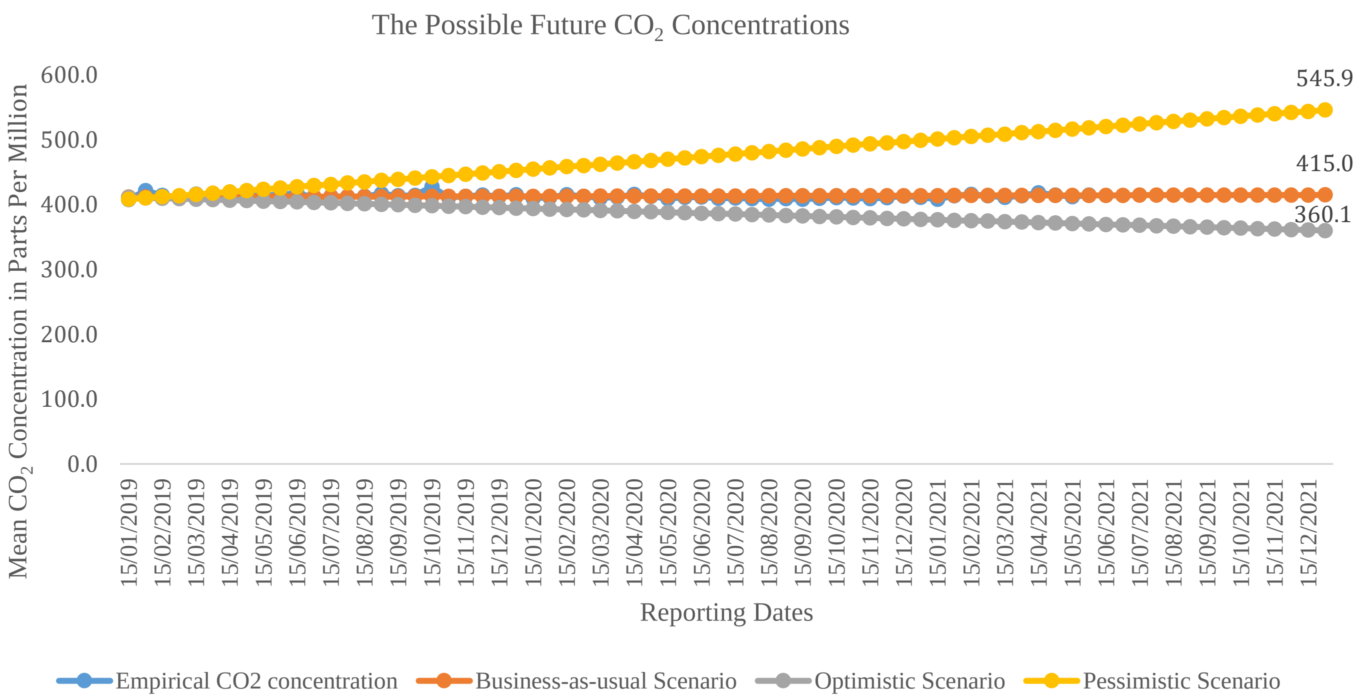

Fig. 5 Models Showing the Concentration Path Followed by the Empirical Data

C. *Findings*

From table I, it is clear that the containment measures put in place by the government caused a reduction in CO_2 concentrations. Secondly, from the models, it is clear that the CO_2 concentrations are high, well above 400 ppm. This should be a reason enough for policymakers to worry. Further, the models show that the concentrations within the study area are rising. This means that mitigation measures put in place are not doing enough to combat CO_2 emissions. More mitigation measures, therefore, should be put in place. It is, however, important to note that emission reduction due to COVID-19 has very little effect on global CO_2 concentration.

Also, it is clear that currently, CO_2 concentrations in the study area are following the business-as-usual scenario path. If the country builds the gas and coal power generation facilities and no mitigation measures are put in place to capture the CO_2 emitted, then the CO_2 concentrations are likely to follow the pessimistic scenario path in future. Therefore, as the country prepare to build these facilities, the consequences should be considered.

D. *Recommendation*

To realise the optimistic scenario path, this research recommends the following mitigation measures: First, the mining and other high energy-intensive companies should install the solar PV system for electricity back-up instead of using the diesel generators. Secondly, the equipment, machines, and vehicles used in the mining site be well maintained to reduce emissions. Thirdly, the cement manufacturing companies should replace clinker in the cement mix with alternative low carbon materials or use carbon-capture technologies to cut on the CO_2 emitted. Fourth, the government should support the idea of electrifying motor vehicles where diesel/petrol engines are converted to electric engines, an idea that already exist in Nairobi city. This will reduce the reliance on fossil fuel by motor vehicles hence lower CO_2 emissions. Finally, tree planting efforts should be doubled so as to achieve the 10% tree cover sooner. This is because trees are natural sinks for CO_2 gas, hence, the more the trees, the more the uptake of CO_2 gas from the atmosphere which in turn reduce its concentration in the atmosphere.

Since the reduction in CO_2 emission was due to decreased use of fossil fuel as there was decrease in economic activities, it means that if Kenya replace fossil fuels with green energy in post COVID-19 period, there will be more CO_2 emission reduction. It is, therefore, prudence for Kenya to consider the measures discussed in this paper to ensure that the CO_2 concentrations follow the optimistic scenario path if she is to have any hope of achieving the target contained in her updated NDC. This means a reduction in CO_2 emissions of about 48 ppm by the end of the year 2021.

III. CONCLUSIONS

Globally, countries have embraced green energy technology in an effort to reduce emissions. Developed countries, for instance, are investing in solar, wind, and hydrogen energy. Some countries have put in place policies that discourage the use of fossil fuels while others have put in place carbon-capture technologies all in the effort to reduce emissions. In addition, in many developed countries, there is population awareness about the importance of reducing emissions, hence emission reduction is a collective responsibility. The developing countries can pick some of these mitigation efforts so as to reduce on their emissions.

Since countries are aiming at recovering economies within the shortest time possible, more energy will be needed. This, for the countries that depend more on fossil fuel, like Kenya, means that more emissions are expected. This may see a rise in CO_2 concentration above pre-COVID-19 levels. Therefore, CO_2 concentration trend may begin to move towards the pessimistic scenario path.

More study of this kind, therefore, should be done to correctly asses the carbon dioxide and other GHGs situations in countries and help in policy formulations and discard of policies that are not effective. Further, to win the war against the rise in GHG emission, the government should partner with the private sector and the civil society.

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