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# Modelling Electricity Generation and Capacity with $CO_2$ Emissions for Sub Saharan Africa

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## Abstract

In this investigation the electricity generation and the electricity capacity of energy mix for sub Saharan Africa from 2020 to 2040 including $CO_2$ emission from (coal, oil, gas) (Total Final Consumption, transport) and power generation were analyzed. These energy sources include conventional and renewable energy sources such as coal, oil, gas, hydro, nuclear, bioenergy, solar PV, and other renewables. We developed a linear regression equation based on the least-square method of estimation to forecast the value of energy and $CO_2$ emission. We fit a linear trend to the energy time series including $CO_2$ emission to show how simple linear regression analysis can be used to forecast future value. The predicted results from 2020 to 2040 show that the electricity capacity and the electricity generation from gas, hydro, solar PV and other renewables will dominate compared to nuclear and bioenergy. Some forms of energies contributions such as nuclear and bioenergy will remain insignificant. The gas will continue to emit a lot carbon dioxide compared to the emission from oil and coal. The emission of $CO_2$ from total final consumption (TFC) of oil will be high compared to its emission from power generation (PG) and transport. The least squares estimated regression equation adequately describes the relationship between Energy or $CO_2$ emission and time period with a high R-squared. This approach of modeling in a linear regression, the energy and $CO_2$ emission simplifies significantly the analysis to help policy makers underlying reasons for the trends to develop appropriate strategies for the future, may be useful to assess the sustained economic development and transformation that require a definition of electricity access in those countries.

## Keywords

$CO_2$ Emission, Conventional and Non-Conventional Resources, Sub-Sahara,

Africa Century Case

## 1. Introduction

African continent resources are not limited only to fossil fuels, but include renewable energy resources such as solar, wind, biomass, geothermal, and hydro. The resources are spread throughout the continent and are capable of providing affordable and secure supplies of energy. As a result of the abundant resources, Africa can be diversified and is likely to have a universal and sustainable energy access. The International Renewable Energy Agency (IRENA) Regional Action Agenda calls for countries and regional organizations to consider cost-effective renewable power options for optimizing investment in electricity generation [1]. Renewables need to be given first priority when planning for future sustainable energy as well as establishing long-term master plans by taking into account their costs, energy security, environmental and socio-economic benefits. Planning is critical to ensure effective energy infrastructural development and to achieve sustainable development goals [1]. This will create a predictable environment that will help sub-Saharan African countries to attract investment in energy infrastructure. A lot of obstacles like limited access to data on renewable sources and technologies stand in the way of putting up such master plans. In addition, a shortage of expertise, tools and methodologies are not also to be undermined as hindrances.

Sub-Sahara Africa (SSA) lies south of the Sahara desert with a total number of 49 countries. The Sahara Desert is located in the northern part of Africa which most people consider to belong to the Arab world [2]. With a total population of one billion, Sub-Sahara Africa has got a high population growth expected to double by 2050 and dominated by young people below 15 years except South Africa [2]. Sub-Saharan Africa is characterized by very old power infrastructures unable to meet the current power requirements. Compared to Spain with a population of 45 million, SSA generates approximately the same amount of power for its one billion people [2].

As Africa's economy continues to grow, its major challenge remains energy. More than two thirds of SSA's population lack access to modern clean energy services like electricity, though its potential remains the highest in the world [3]. The rising demand for energy in the industrial and transport sectors by 2030 will require at least a doubled supply [4]. More than triple of electricity will also be needed in an economically, environmentally and socially sustainable way [4]. This problem will be better solved through promotion of renewable energies. This will guarantee the continent energy access and security in an efficient, reliable and cost competitive way.

Compared to fossil fuels, renewables are environmentally sustainable. With inter-regional power integration, opportunities to exploit the economies of scale that come with renewable projects will be enhanced. This will save the continent billions of money in regard to development, operation and maintenance costs.

Electricity generation in Africa is mainly from hydro and fossil fuels (diesel). This has led to the power sector being centralized, thus the limited access. With the development of alternative sources from which electricity can be produced, this problem is nearly solved. Electricity generation from non-conventional renewable technology sources like solar, biogas, etc. will help in decentralization of the power sector which will in turn increase accessibility.

With an increased deployment in renewable technologies, there is a significant transformation opportunity for the power sector. By 2030, the generation mix energy maybe estimated to be 50% and probably will be dominated by renewables [5]. 100 GW capacity will be generated from each hydropower and wind. In addition, 90 GW from solar are expected to be installed [5]. This intense investment in renewables will also help reduce approximately 310 Megatons of carbondioxide compared to the baseline scenario [5]. Currently it's estimated that 70 GW generation capacity is installed in SSA out of which 44 GW are in South Africa alone [2]. Due to some technical problems and aging of the equipment, the capacity is not fully available.

Sub-Saharan countries have got different generation mixed energy from both convention and non-convention sources. South Africa alone comprises of 85% power generation from coal characterized with a lot of carbon emission [2]. Other countries in SSA generate their power mostly from hydro sources, coal, diesel fired turbines and gas plants. However due to climate change, hydropower has become unreliable in the past few years due to fall in water levels. Problems like frequent outages have proved that it's not sustainable to depend on hydro power since it is being threatened.

Nonetheless, the region's potential as regards hydro is high and it still remains the most dominant power source. However, the outages have resulted into increased use of power from other sources like coal and liquid fuel generation due to the increasing demand hence a rise in power prices [2]. Additionally other sources like nuclear are being utilized with Kenya in the process to set up a nuclear plant. Currently there is only one nuclear plant with an installed capacity of 1.8 GW and is located in South Africa [6].

Transformation from conventional energy sources to renewables and their diversifications encompasses a lot of things which include; more investment in research and development, technical human resource development, collection and interpretation of data. Before investments into renewable energies, it's important to project and analyze data. This will address the question of why this should be the right path for Sub-Saharan Africa which is energy poor. Efforts have been taken by certain organizations to provide data about the existing energy potential of the different renewable energy resources in the different countries. Examples of organizations include; Global Energy Atlas which provides solar and wind maps that can be accessed through their datasets on their website [7], IRENA and African Energy Outlook who do publish data on the energy status of Africa every year.

This manuscript sets out to analyse data based on an African Century Case about electricity generation, electricity capacity and $CO_2$ emissions in Sub-Saharan Africa. The purpose is to establish the trend of the resources' electricity generation and their electrical capacity based on the projections. Environmental pollution from power, total final consumption (TFC) and transport sectors that largely depends on fossil fuels is also looked at under the projections of an African Century case.

## 2. Methodology

Data on electrical capacity of resources, their gross electricity generation and carbondioxide emissions from fossil fuels based on Africa century case scenario was obtained from the Africa Energy Outlook Report in 2014 [8] [9]. In this investigation Microsoft Excel was used to carry out comparisons between convention and non-convention sources of energy according to the projections. For the analysis, all the data was treated in percentages. **Tables 1-4** below are expressed as percentages of the total electrical capacity, electricity generation, carbondioxide emission from different resources and different from sectors, respectively. A graphical representation of the data [8] from **Tables 1-4** are shown in **Figure 1(a)**, **Figure 2(a)**, **Figure 3(a)** and **Figure 4(a)**, **respectively**. Regression analysis was used to develop equation showing how variables are related. This statistical technique involving one independent variable (Time) and two dependent variable (Energy% and $CO_2$ emission%) for which the relationship between variables is approximated by a straight line based on the least-square method of estimation to forecast the value of these two dependent variables. For analysis, slopes and y-intercepts are extracted from each graph and plotted in **Figure 1(b)**, **Figure 2(b)**, **Figure 3(b)**, and **Figure 4(b)**.

**Table 1.** Electrical Capacity (GW); Source: Africa Energy Outlook, 2014 [8].

| | 2020 | | 2025 | | 2030 | | 2035 | | 2040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Resource** | **[GW]** | **%** | **[GW]** | **%** | **[GW]** | **%** | **[GW]** | **%** | **[GW]** | **%** |
| coal | 54 | 33.75 | 64 | 29.63 | 72 | 25.087 | 82 | 21.41 | 93 | 18.563 |
| Oil | 24 | 15 | 24 | 11.111 | 26 | 9.059 | 29 | 7.572 | 33 | 6.587 |
| Gas | 31 | 19.375 | 46 | 21.296 | 65 | 22.648 | 93 | 24.282 | 129 | 25.749 |
| Nuclear | 2 | 1.25 | 2 | 0.926 | 4 | 1.394 | 6 | 1.567 | 7 | 1.397 |
| Hydro | 36 | 22.5 | 52 | 24.074 | 76 | 26.481 | 107 | 27.937 | 143 | 28.543 |
| Bioenergy | 2 | 1.25 | 4 | 1.852 | 6 | 2.091 | 8 | 2.089 | 11 | 2.196 |
| Solar PV | 6 | 3.75 | 13 | 6.019 | 21 | 7.317 | 32 | 8.355 | 48 | 9.581 |
| Other renewables | 5 | 3.125 | 11 | 5.093 | 17 | 5.923 | 26 | 6.789 | 37 | 7.385 |
| **Total Capacity** | **160** | | **216** | | **287** | | **383** | | **501** | |

**Table 2.** Electricity Generation (TWh); Source: Africa Energy Outlook, 2014 [8].

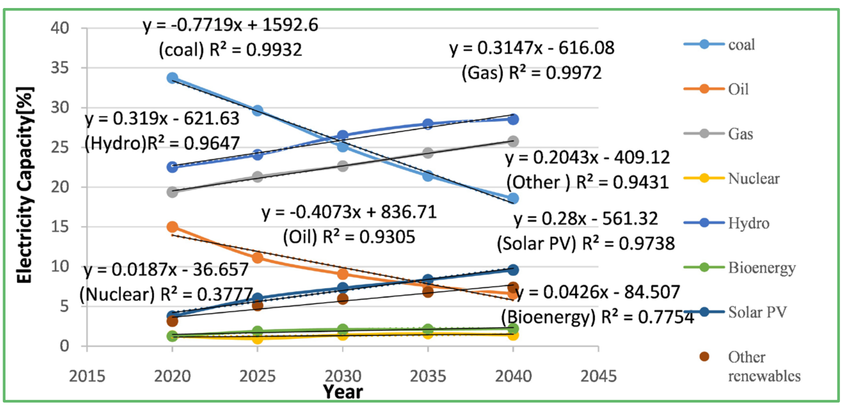
| | 2020 | | 2025 | | 2030 | | 2035 | | 2040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Resource** | **TWh** | **%** | **TWh** | **%** | **TWh** | **%** | **TWh** | **%** | **TWh** | **%** |
| coal | 288 | 44.444 | 327 | 38.335 | 359 | 31.996 | 407 | 27.097 | 464 | 23.131 |
| Oil | 38 | 5.864 | 40 | 4.689 | 44 | 3.922 | 52 | 3.462 | 71 | 3.539 |
| Gas | 101 | 15.586 | 160 | 18.757 | 233 | 20.766 | 352 | 23.435 | 534 | 26.62 |
| Nuclear | 13 | 2.006 | 13 | 1.524 | 25 | 2.228 | 40 | 2.663 | 54 | 2.692 |
| Hydro | 169 | 26.08 | 237 | 27.784 | 337 | 30.036 | 466 | 31.025 | 620 | 30.907 |
| Bioenergy | 11 | 1.698 | 20 | 2.345 | 30 | 2.674 | 40 | 2.663 | 51 | 2.542 |
| Solar PV | 10 | 1.543 | 21 | 2.462 | 35 | 3.119 | 53 | 3.529 | 79 | 3.938 |
| Other renewables | 18 | 2.778 | 35 | 4.103 | 59 | 5.258 | 92 | 6.125 | 133 | 6.63 |
| **Total generation** | **648** | | **853** | | **1122** | | **1502** | | **2006** | |

**Table 3.** Carbondioxide Emissions from resources (Mt); Source: Africa Energy Outlook, 2014 [8].

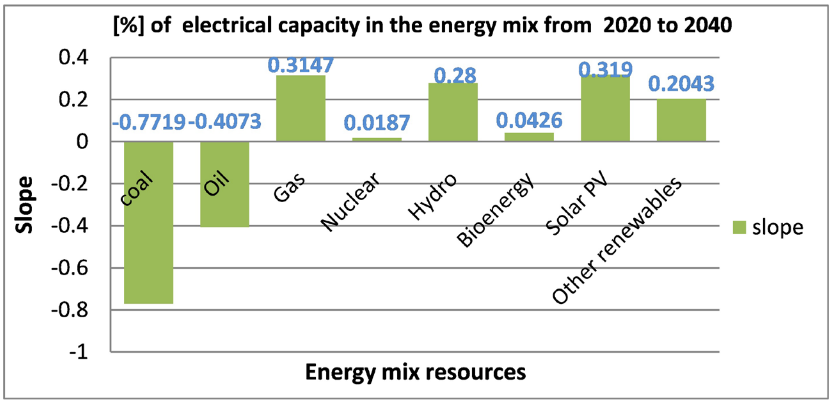
| | 2020 | | 2025 | | 2030 | | 2035 | | 2040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Resource** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** |
| coal | 358 | 46.313 | 398 | 43.593 | 420 | 40.191 | 462 | 37.108 | 517 | 33.703 |
| Oil | 330 | 42.691 | 392 | 42.935 | 461 | 44.115 | 555 | 44.578 | 684 | 44.589 |
| Gas | 85 | 10.996 | 123 | 13.472 | 164 | 15.694 | 228 | 18.313 | 333 | 21.708 |
| **Total $CO_2$** | **773** | | **913** | | **1045** | | **1245** | | **1534** | |

**Table 4.** Carbondioxide Emissions sector wise (Mt); Source: Africa Energy Outlook, 2014 [8].

| | 2020 | | 2025 | | 2030 | | 2035 | | 2040 | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Sector** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** | **Mt** | **%** |
| Power generation | 344 | 36.87 | 397 | 35.96 | 437 | 34.194 | 513 | 33.442 | 625 | 33.086 |
| TFC | 404 | 43.301 | 482 | 43.659 | 572 | 44.757 | 694 | 45.241 | 860 | 45.527 |
| Transport | 185 | 19.829 | 225 | 20.38 | 269 | 21.049 | 327 | 21.317 | 404 | 21.387 |
| **Total $CO_2$** | **933** | | **1104** | | **1278** | | **1534** | | **1889** | |

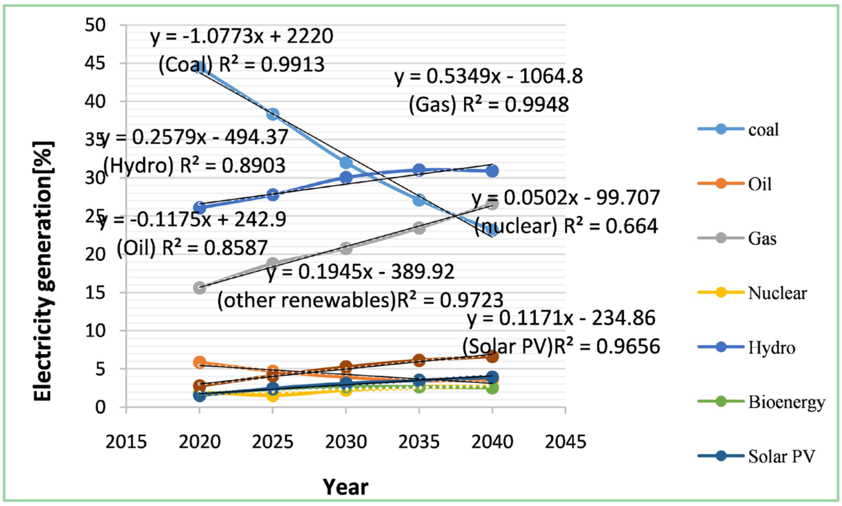



(a)




(b)

Figure 1. (a) Percentage of electrical capacity of each resource in the energy mix from 2020 to 2040. International Energy Agency [2014]; (b) Slope for resource in the energy mix. Slope obtained from the equation in Figure 1(a).

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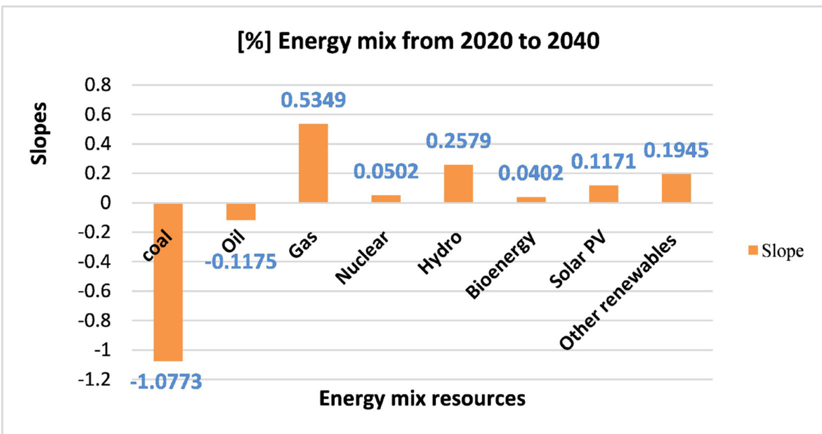
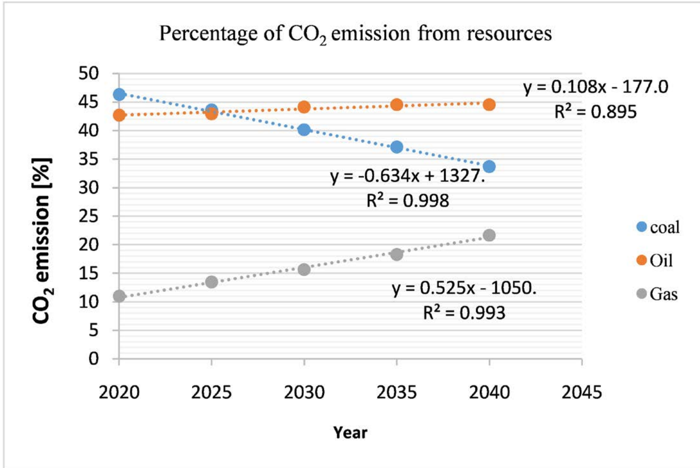



(b)

Figure 2. (a) Percentage of electricity generation of each resource in the energy mix from 2020 to 2040. International Energy Agency [2014]; (b) Slope for each resource in the energy mix obtained from the equation in Figure 2(a).

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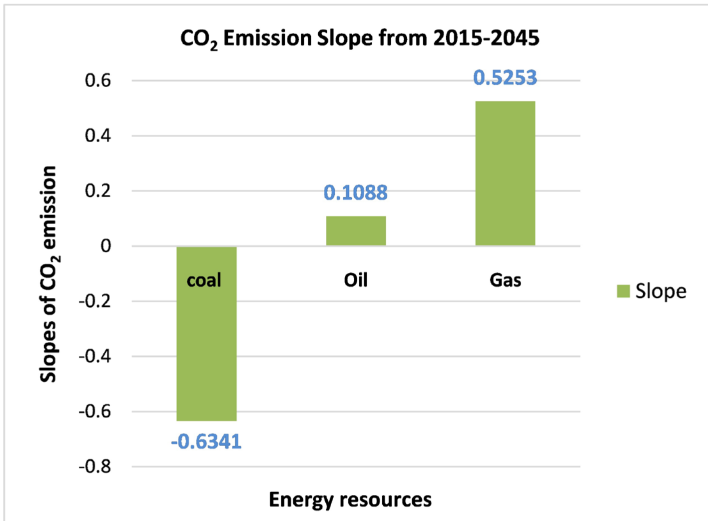
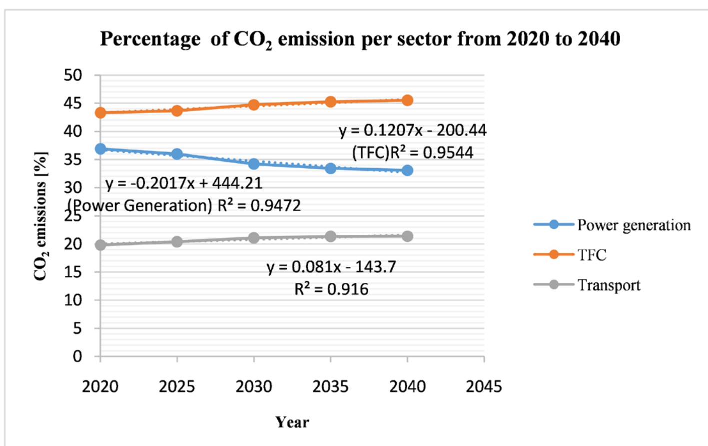
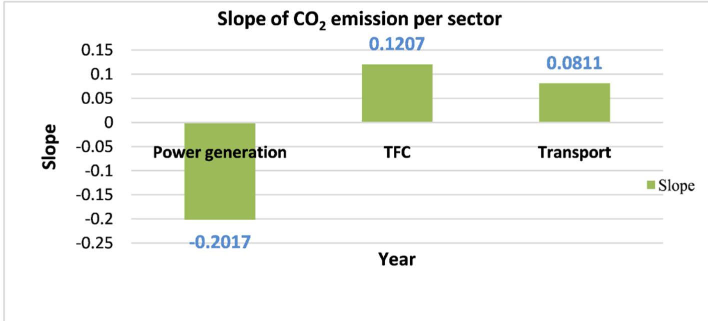



(b)

**Figure 3.** (a) percentage of $CO_2$ emission from coal, oil and gas.International Energy Agency [2014]; (b) Slopes for $CO_2$ emission from coal, oil and gas. Slopes obtained from the equation in **Figure 3(a)**.




(a)




(b)

**Figure 4.** (a) percentage of $CO_2$ emission power generation, TFC and transport. International Energy Agency [2014]; (b) slope of $CO_2$ emission from power generation, TFC and transport. Slope obtained from the equation in Figure 4(a).

The goal of this investigation was to establish the future of sub-Sahara's energy sector as well as the underlying reasons for the trends. The performance of each resource or technology was fully assessed through graphical representation. $CO_2$ emissions are also looked into in depth both resource wise and sector wise. The most polluting resources and sector were established based on the analyzed data.

## 3. Results and Discussion

Figures 1-4 show graphically the data [8] presented in Tables 1-4. The variation in percentage of electricity capacity and electricity generation of each resource in the energy mix are illustrated in Figure 1(a) and Figure 2(a), respectively. The slopes of the linear regression of these forms of energy are shown in Figure 1(b) and Figure 2(b), respectively with a high R-squared. The energy model in Figure 1(a) and Figure 2(a) shows that gas, nuclear, hydro, bioenergy, solar PV and others resources continue to increase at different rate from 2020 to 2040. Gas, Hydro, Solar PV, other resources with high rate will play a big role in electricity capacity and generation and will continue to increase rapidly compared to other forms of energies. While the share of coal and oil in energy generation will decrease significantly (negative slope) compared to other resources.

Comparing Figure 1(b) and Figure 2(b), the results show there is full exploitation of resources as regards generation of electricity. Nuclear and bioenergy will be the least famous renewable resources to be used. This may be because of nuclear energy's safety issues after the Fukushima incidence accompanied with need for high expertise. Bioenergy's food security threat will contribute much to its underdevelopment.

According to the projected scenario, the percentage use of coal and oil in electricity generation shows a negative rate (Figure 2(b)). This means dependence on these two resources for electricity generation will drop continuously, may be due to the diverse negative effects (emissions) to the environment caused by coal and oil. Therefore, in order to avoid charges of carbon capture, transformation to renewables is preferred. Nuclear, hydro, bioenergy, solar PV and other renewables will continuously increase as shown by the positive rate in the graphs (**Figures 2(a)** and **Figure 2(b)**). Bioenergy and nuclear will increase at a low pace compared to solar PV and hydro (**Figure 2(b)**). Gas as one of the conventional resources will continue to be used most probably due to its low carbon-dioxide emission per joule of energy produced in comparison to its price.

From 2020 to 2040 the linear regressions of $CO_2$ emissions from coil, oil and gas are indicated in **Figure 3(a)**. The emission of carbon dioxide from Gas will probably dominate other emissions from coal and gas. While the share of coal and oil in energy generation will decrease significantly (negative slope) compared to other resources

The oil will emit less compared with gas and their emissions continue to increase at different rate (oil $a_{gas} = 0.5253$, $a_{gas} = 0.1088$). While the emission of $CO_2$ from of coal with negative slope ($a_{oil} = -0.6341$) will decrease significantly.

This high emissions is due to more usage of gas than oil. Day to day, the oil is transformed in many forms which are mainly necessary energy need. Gas is used for electricity generation, transport and lighting that why emissions from oil will continue to dominate emissions from coal and gas.

In **Figure 3(b)**, $CO_2$ emission from gas increases more than that of oil. As for coal it decreases at a faster rate. This is most probably because in Sub-Saharan Africa, coal is mostly used in South Africa (SA). With SSA's shift to renewable technologies, the reduction in emissions due to coal is expected to happen as seen in **Figure 3(b)**. In addition, the use of coal yields less energy per ton of carbondioxide produced, so its use will most probably be limited. Commitments were made by different countries in the 21st meeting of Conference of Parties held in Paris (CoP) 21 [10]. These included reducing the global temperatures by 2˚C. In order to achieve above condition, measures are being put in place so as to meet their pledges. Reduction in use of polluting resources like coal and oil is one of the measures that countries are to adopt. The quest for industrialization and economic development of Sub-Sahara, explains the continued use of oil and gas since they are already established and cheap. Furthermore more reserves are still being discovered for oil and gas therefore with an increase in the prices, these resources will still be of much use in the region hence the increase in emission due to them. Continued subsidization of oil and gas due to fears of unrests that can be caused when subsidies are withdrawn and prices go high will also make these resources emissions persist in the region.

In **Figure 4(a)**, $CO_2$ emissions from TFC, transport and power are represented by linear regressions of generation with a high R-squared ($R^2 > 0.89$). The transport with lower rate ($a_t = 0.0811$) will emit less compared with TFC ($a_{TFC} = 0.1207$) and their emissions continue to increase at different lower rate from 2020 to 2040. While the emission of $CO_2$ from of coal with negative slope ($a_{coal} = -0.6341$) will decrease significantly compared to TFC, transport and gas.

From Figure 4(b), Total Final Consumption (TFC) contributes more to emissions followed by transport. $CO_2$ emissions from power generation will keep reducing with time. This might be mainly due to the transformation of the sector to clean energy technologies like solar PV. Currently this is one of the widely used technology in Sub-Sahara as regards renewables. The transport sector's emissions are less compared to TFC's most probably due to adoption of more effective and efficient cars. TFC's emissions are mainly due to the inefficient methods that will continue to be used e.g. production methods in the industrial setups. High share of the rural population of the region who can't afford modern technologies is another factor [10]. The culture of sub-Sahara being more concerned about the outcome than the methods used in achieving it, is more to blame as well. Also the abundance of resources in the region leads to extravagance and less concern about the efficiencies

The advantage of scatter diagram shown in Figures 1-4 is that it provides an overview of the data and enables us to draw preliminary conclusions about a possible relationship between the variables, namely dependent variables (Energy or $CO_2$) and independent variable (Time). It appears that the relationship between two variables can be approximated by straight line; indeed, the time and the energy or $CO_2$ appear to be positively or negatively related. In Figure 1(a), Figure 2(a), Figure 3(a) and Figure 4(a), we can draw a straight line through the data that appears to provide a good linear approximation of the relationship between the data.

Using the least-square method of estimation, the estimated regression equation is

$$y = ax + b \tag{1}$$

where

$y$ = is the estimated value of the dependent variable (Energy or $CO_2$)

$b$ = Intercept of the estimated regression equation

$a$ = slope of the estimated regression equation

$x$ = value of the independent variable (Time)

$$a = \frac{\sum x_i y_i - \left(\sum x_i \sum y_i\right)/n}{\sum x_i^2 - \left(\sum x_i\right)^2/n} \tag{2}$$

$$b = \bar{y} - a\bar{x} \tag{3}$$

$x_i$ = the i^th^ value of the independent variable

$x_i$ = the i^th^ value of the independent variable

$\bar{x}$ = mean value for independent variable

$\bar{y}$ = mean value for dependent variable

$n$ = total number of pair of observations

Sub Sahara Africa is undergoing unprecedented sustained period of economic growth and transformation. Starting from 2020, other forms of energies will appear and continue to increase at different rate. The international trade of electricity in this region will appear in 2020 and continue to increase as predicted by the data. Up to 2040, hydro will play a big role in electricity generation with other renewable energy sources, such as Gas, solar PV that will continue to increase at different rate. The share of solar PV in energy generation will increase compared to bioenergy and nuclear energy. Coal and oil in energy generation will decrease significantly (negative correlation). The capacity of hydro, Gas and solar PV will be high compared with other sources of energy such as bioenergy, nuclear and other renewables. Coal and oil for electricity generation will drop continuously. The results show also that bioenergy will increase slowly in electricity generation and capacity in comparison with other source of energies.

The results show also that Gas and Oil will continue to emit a lot carbon dioxide under different rate compared to coal. The emission of $CO_2$ from total final consumption (TFC) of oil and transport will continue to be high in comparing with $CO_2$ emission from power generation (PG) of oil. The emission of carbon dioxide from power generation of TFC from 2025 until 2040 will be high compared with emission of $CO_2$ generated from transport. In this period, the emission from TFC and transport will remain insignificant. The $CO_2$ emission from gas in general will dominate other emissions from both coal and gas. Due to this high emission of $CO_2$, new technologies should be introduced in order to reduce gas pollution from TFC. This study demonstrates that the electricity generation and electricity capacity and $CO_2$ emissions, which are an indicator of the economic growth can be described by a linear regression. The magnitude of the extracted parameters maybe useful to assess the sustained economic development and transformation that require a definition of electricity access in those countries.

## 4. Conclusions

Sub-Saharan Africa's industrial revolution should be based on clean non-conventional energy sources. Wild fires that normally destroy vegetation and forests in the region would have been solved. According to the Africa century case, this will reduce the current carbon dioxide emissions by 4%. Renewable energy technologies should be heavily invested. Manufacturing the equipment should be put in place instead of just importing them. This will see a greater adaptation to renewable energy as the capital investment will go down and favorably compete with fossil fuels.

As another way to make renewables cheap and affordable, subsidies to conventional energy sources can be shifted to renewables. Integrating SSA's energy with fossils should be done efficiently and with a less polluting source (gas). A total ban on importation of inefficient and used vehicles can also help reducing the emissions from the transport sector.

Renewable energy policies and a clear understanding of energy performance should be developed to differentiate success from failure and to identify what must be avoided to improve this performance. The main goal in this investigation is to become familiar with the theories of energies and policies developed over the past years that make possible this performance. To set the path towards this goal, we take a first look at energy growth, and learn why these energy phenomena merit intention.

The present results show that the relationship between the projections of energy mix and $CO_2$ emissions that can be described by a linear regression. The magnitude of extracted parameters namely the slope and y-intercept may be used as guideline to access and evaluate the generation electricity and $CO_2$ emissions in simplified way to establish the future of sub-Sahara's energy sector as well as the underlying reasons for the trends. The performance of each resource or technology was fully assessed through graphical representation. This approach of modeling the Energy or $CO_2$ in linear form significantly simplifies the analysis.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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