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Techno-Economic Analysis of Transportation of Sequestered Carbon (IV) Oxide from Afam IV Power Plant

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Abstract:
Carbon capture and storage (CCS) has been recognized as one major technology that could sustain a greener environment. Because of the constant use of fuel for power generation, which releases CO_2 that could be sequestered in geologic sites preventing their eventual release to the atmosphere. This study used Afam IV Gas Turbines in Nigeria as a case study and evaluated the emission of CO_2 from the plants and the techno-economic analysis of transporting captured CO_2 from this power plant to Jones Creek (the propoFsed sequestration site in this study). The CO_2 emission factor was determined from the daily energy generation from the gas consumption of the two turbines at the plant. Pipe Flo Professional 14 software was used for the pipeline design that was used for the transportation. The CO_2 emissions from the two turbines were found to have a flow rate of 0.68kg/s, requiring 4,416kW and 61.402kW of compressor power and pump power, respectively, each at 85% efficiency. This power requirement constitutes 3.44% of 130MW of the installed capacity of the two turbines at Afam IV. The capacity of Jones Creek was found to be $8.94x10^6m^3$, and the pipeline cost for the transportation of CO_2 was found to be ₦21.994Billion. The National Electricity Regulatory Commission (NERC) Multi-Year Tariff Order (MYTO) D3 billing rose to 600% during the construction period but dropped to 19% increment beyond the construction period as a result of the CO_2 compression and transportation. It is recommended that the Federal Government of Nigeria should start to implement policies that would propel oil and gas companies in Nigeria to start considering CCS as an emission mitigation option in Nigeria.

Keywords: carbon capture and storage, multi-year tariff order, Sequestration, CO_2, Pipeline

I. INTRODUCTION

Petroleum refining from upstream to downstream has been identified as one of the highest pollutant emissions [1-2]. Similarly, CO_2 has been acknowledged as one of the most significant contributors to global warming due to its large volume in the environment. There are so many sources through which CO_2 is being added to the atmosphere. In Nigeria, with 21 natural gas-fired power plants of different installed capacities, which are currently operating at different efficiencies because of reliability issues. This as a result of massive emissions from thermal power plants during operation. [3-6]

The continued emission of CO_2 to the atmosphere as a result of energy requirements is leading to global warming, and Nigeria is not an exception [7-9]. The influence of global warming is being felt even in Nigeria, already resulting in desertification and flooding. Sambo et al. [10] reported that 84% of power generation in Nigeria comes from fossil fuel. Tsaurai [11] outlined changes in temperature and the atmospheric imbalance. The recurrent droughts, floods, and cyclones decline in some plant and animal populations — the spread of disease vectors, including malaria, freezing, and breaking of ice on rivers or lakes. Reducing food productions, an increase in death rate and threats are some of the observed effects of global warming in Nigeria. There have been earlier projections that developing countries will account for 81% of the projected increase in the world carbon emission between 1990 and 2010, and 76% between 1990 and 2020, (IEA, 2001)

Carbon Capture and Storage (CCS) is the technology that removes CO_2 or carbon from flue gases for transportation and storage to geologic sites. Such as abandoned oil wells, un-mineable coal seams, aquifers, or oceans. Carbon emission has been on the rise even with increasing carbon taxing; carbon capture and storage is proving to be the only option that would allow the continued use of fossil fuels such as coal, natural gas, and oils without a detrimental effect to the environment. CCS is suitable for carbon-intensive sectors such as power generation, cement production, oil mining, and steel production. Several writers have advocated for CCS as the hope for continued use of fossil fuel in an environmentally sustainable form. Statoil of Norway rather than pay hefty carbon emission fine, which was reduced from $200 per ton of carbon (t C) to $140 per tC in 2000. Opted to be compressing and injecting the captured CO_2 into a deep saltwater aquifer below the ocean floor since 1996, [12]. CCS is welcomed as the technology for the future, as the perspective of non-conventional sources of energy, such as solar, wind, and geothermal energy will not substitute the conventional fossil fuel in the immediate future. The CCS site map as of 2016 is shown in Fig. 1. Only one pilot project is located in South Africa and is operational while another 'in planning' is still situated in South Africa.

Fig. 1: CCS project map (source: [13], p. 25)

In addition, IEA estimated that an effort to reduce halve the global CO_2 emission by half without CCS would increase the cost to more than 70% per year [14]

El-Suleiman et al. [15] presented the power requirements of compression of CO_2 using Peng-Robinson's equation of state without actually computing the energy cost. Lazic et al. [16] did an extensive study of the cost of installation of a CCS system in the Humber region of the UK. Adopting no specific method but instead exploring data from different sources. Steem (nd) estimated that 75% of CO_2 emissions come from fossil fuel combustion. A dense phase conditions, the liquid phase, and vapour pressure drop equation has been shown to give similar results for CO_2 transportation through pipelines [16].

II. EXPERIMENTAL

This study aims at carrying out a techno-economic analysis of transportation of sequestered carbon(iv)oxide from Afam (IV) Power Plant by evaluating the effects of compression and transportation of capturable CO_2 a component of CCS on NERC's MYTO.

Visits were made to the facilities of Afam Power (IV) Plant in Obigbo Local Government Area of Rivers State. The management of the plant provided the daily gas consumption data and daily energy generation between the period of 1st January 2012 and 31st December 2017. Two functional gas turbine units of the plant, gas turbine 17 (GT17) and gas turbine 18 (GT18), were evaluated. GT 17 and GT18 have installed a capacity of 65MW each. Neither of the turbine units was functional between the 30th of April 2014 and 31st of October 2017. The CO_2 emissions of the turbines were not available at the plant, and thus, the emission factor was used to obtain the CO_2 emissions from power generated. This study, while estimating the emission from thermal power plants, adopted the method developed by [17-18]. This method uses the emission factor to evaluate the flue gases of the power plants.

II.I. Determination of fossil fuel power plant emission

To be able to analyze the emission of power plants, mathematical models have been developed to predict the radiation at different conditions.

This study used the emission factor in determining the CO_2 emission [19].

$$E_t = \sum \left(F_{C,t} * \rho_{i * H_u * EF_{iCO_2}} \right) \tag{1}$$

Where $F_{C,t}$ = Fuel consumption for the t period of time;
ρ_i = fuel density at 15^0C of fuel type i (kg/m^3)
Hu = lower heating value of fuel (fuel oil or natural gas) (MJ/kg)
EF_{iCO2} = national emission factor of CO_2 of ith fuel(g/MJ)
The national emission factor EF_t is evaluated as:

$$EF_t = \frac{E_t}{EG_t} \tag{2}$$

Where E_t is the total CO_2 emission and EG_t is the total electricity generation (MW)

Another approach to using emission factors to determine the emission of the power plant was adopted by and is presented here. The emission factor facilitates the estimation of emission from various sources of air pollution, including power generation plants, thermal power plants or cogeneration power plants that use fossil fuel. The emission factor is expressed in the unit of mass per unit of energy consumed or produced. The emission factor is expressed in g/GJ. For the determination of specified CO_2 emission factors, the following general equations can be used:

$$EF_{CO_2} = \frac{44}{12} c_{fuel} * \varepsilon_C * \frac{1}{Hu} * 106 \left(\frac{g}{GJ} \right) \tag{3}$$

Where C_{cfuel} = carbon content of fuel (in mass of C/mass of fuel) (kg/kg), ε_c = fraction of carbon oxidized (defined as the main part of carbon oxidized to CO_2)

$$\text{The value of } CO_2 \text{ in the flue gas } = C_{CO_2} * E_{fuel} \left(\frac{g}{m^3}\right) \quad (4)$$

The efficiency of the power plant can as well be used to determine the emission of the plant

$$\eta_e = \frac{EG_t}{F_{c,t}} \quad (5)$$

$$\eta_t = \frac{Q_Y}{F_{c,t}} \quad (6)$$

Where η_e = electrical efficiency; η_t = thermal efficiency
EG_t = total electricity generation (MW); Q_y = useful heat produced by the plant

The emission factor is determined as follows:

$$EF_{CO_2} = \frac{3.6 * 10^{-3}}{\eta_t} \left(\frac{kg}{MW}\right) \quad (7)$$

Improvement inefficiency of the power plant results in less emission for the same power output. The bigger the installed capacity, the more the emissions from the plant.

II.II. Modeling of the Compressors and Pumps in Pipe Flo® Professional 14

The transportation of the capturable CO_2 via pipelines is analyzed in Pipe Flo Professional software, a pipeline analytical tool. The modeling is achieved by the use of the design points in Table 1.

Table 1: The CO_2 and pipeline design parameters

Parameters	Values
Pressure, P_1 before compression	1bar
Pressure, P_2 after compression	200bar
Temperature T	35^0C
Viscosity before compression	0.00007344[kg/m-s]
Viscosity after compression	0.00009174 [kg/m-s]
Density before compression, ρ	1.725kg/m^3
Density after compression	901.2 kg/m^3
The hydraulic gradient between the turbine exhaust and capture point	950m
Distance between exhaust and capture point	0.5km
Hydraulic gradient between capture point and sequestration site	950m
Distance between capture point and sequestration site	225km
Compressor efficiency	0.85
Pump efficiency	0.85

The compression process was achieved using two-stage compression and the compression ratio obtained using equation (8)

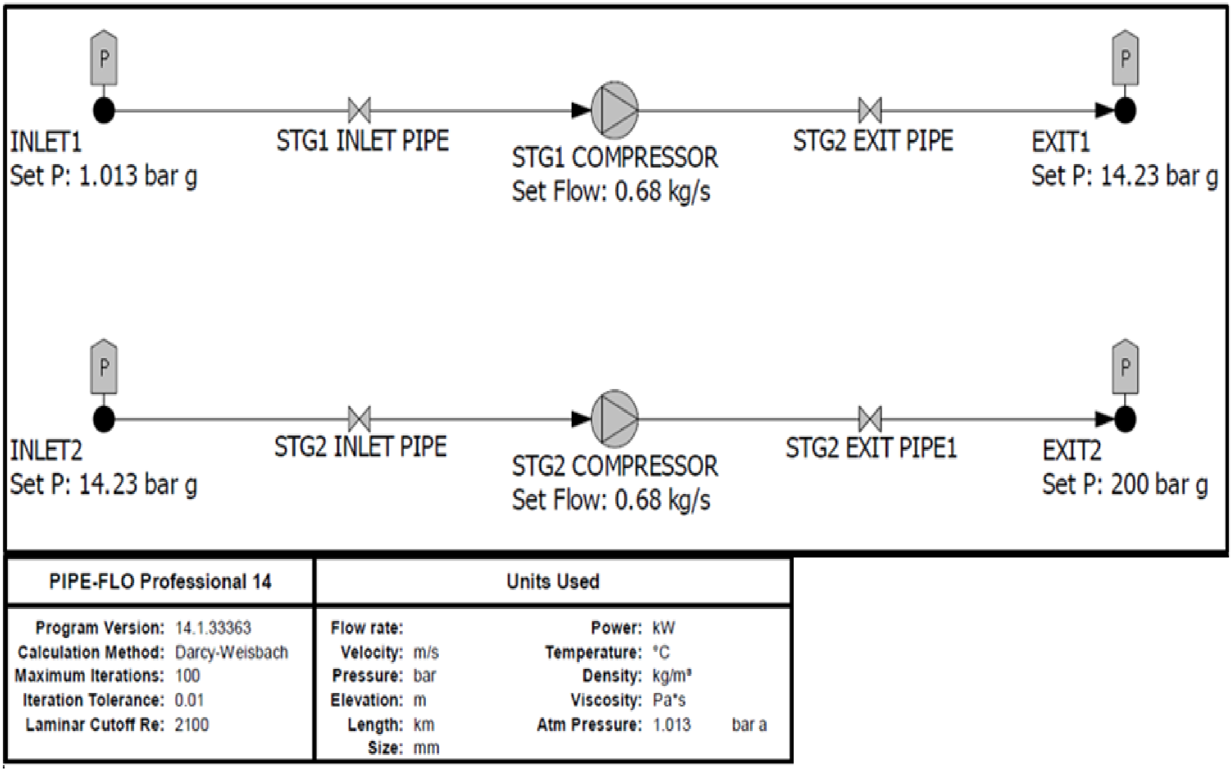
$$CR = = \left(\frac{P_{cut-off}}{P_{initial}}\right)^{\frac{1}{N_{stage}}} \quad (8)$$

Where: $P_{cut-off}$ = cut off pressure (MPa), $P_{initial}$ = initial pressure (MPa)
N_{stage}= the number of compression stages
The combination of two series-connected pumps achieves the use of pumps for the long-distance transportation of the compressed CO2 in condensed phase form. The pipe flow professional was able to compute the total heads of all the compressors and pumps. Thus saving them time and power consumed on manual iterations and computation of the Darcy-Weisbach equation. The pipeline flow model for the compression and pumping stages are shown in Fig. 2 and Fig. 3. The two compressors and the stage one pump were installed at the point of capture. The stage two pump is a booster pump located midway between the point of capture and the sequestration site. The compression ratio calculated for the compression is 14.05, and the pressure ratio for the pumping stages is 1.072. The simulation software evaluates the total head of the compressors and the pumps, and this can now be applied in equations (9) and (10) to evaluate the power consumed by the compressors and the pumps.

$$P_{comp} = \frac{\dot{m} * g * H_T}{\eta_T} \quad (9)$$

$$P_{pump} = \frac{\dot{m} * g * H_P}{\eta_P} \quad (10)$$

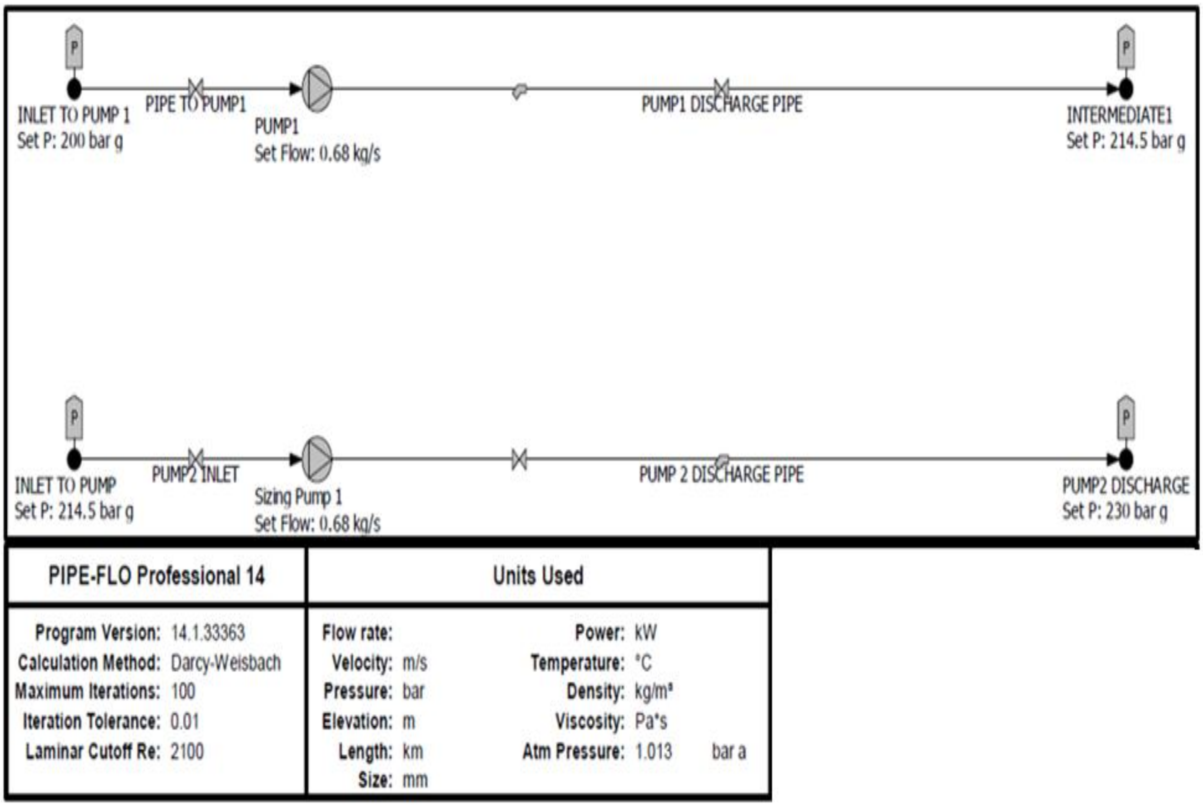
The flowsheet for the compression and pumping as set up in the Pipe Flo Professional is shown in Fig. 2 and Fig. 3, respectively.



Program Version: 14.1.33363
Calculation Method: Darcy-Weisbach
Maximum Iterations: 100
Iteration Tolerance: 0.01
Laminar Cutoff Re: 2100

Flow rate:
Velocity: m/s
Pressure: bar
Elevation: m
Length: km
Size: mm
Power: kW
Temperature: °C
Density: kg/m^3
Viscosity: Pa*s
Atm Pressure: 1.013 bar a

Fig. 2: The flowsheet for the compression stages of CO_2.



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Calculation Method: Darcy-Weisbach
Maximum Iterations: 100
Iteration Tolerance: 0.01
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Velocity: m/s
Pressure: bar
Elevation: m
Length: km
Size: mm
Power: kW
Temperature: °C
Density: kg/m^3
Viscosity: Pa*s
Atm Pressure: 1.013 bar a

Fig. 3: The flowsheet for the pumping stages of CO_2 in the condensed phase.

III. RESULTS AND DISCUSSION

The phase transformation of CO_2 shows that it is easy to transport CO_2 in a dense liquid phase if it is compressed to suitable temperature and pressure. It has been established that beyond the critical temperature and pressure, CO_2 can be safely transported in the dense phase form. The processes of transportation are in two stages; stage one is the compression of CO_2 to the appropriate temperature and pressure from the sequestration plant. The average flow rate of emitted CO_2 from Afam IV turbines is 0.68kg/s. This captured CO_2 is compressed to a pressure of 200bar. After compression, a pump is used for long-distance transportation from the plant to the sequestration site. The parametric values for viscosity and density for the design of the pipeline in the Pipe Flo Professional 14 software were determined by deploying the EES software.

The DOE/NETL model was adopted in this work and is used to compute the pipeline cost for CO_2 sequestration in Nigeria. To develop a costing model for the pipeline, there is a need for combination of the studies by the United States Department of Energy's and National Energy Technology Laboratory (NETL) on carbon dioxide transport with storage costs published in 2013 was adopted. CO_2 transport costs are broken down into three categories: pipeline capital costs, related capital expenditures, and operation and maintenance (O&M) costs. A regression analysis was used to generate the cost curves as a function of pipe diameter (in inches) and length (in miles). These costs are: (1) Pipeline Materials cost, (2) Direct Labour cost, (3) Miscellaneous Costs, and (4) Right-of-way acquisition cost [20], [21].

CO_2 Emission from GT17 and GT18: There is instability in the amount of CO_2 emitted for the periods considered, as depicted in Fig. 3. This instability is because of the erratic nature of energy generation. At periods of shut-downs, there were no emissions in the system at all. At periods when both GT17 and GT18 were operational, the amount of CO_2 emissions becomes large comparably. In the pipeline, the design allowance is provided for the breakdown within the interconnections. Such that when one plant shuts down, other plants remain operational to keep the loop functional and profitable. The interconnectivity of all the power plants along the route keeps the pipeline functional at all the time though the allowance is created for breakdowns and maintenance. The accumulated monthly energy generated used to compute the monthly CO_2 emission shown in Fig. 4.

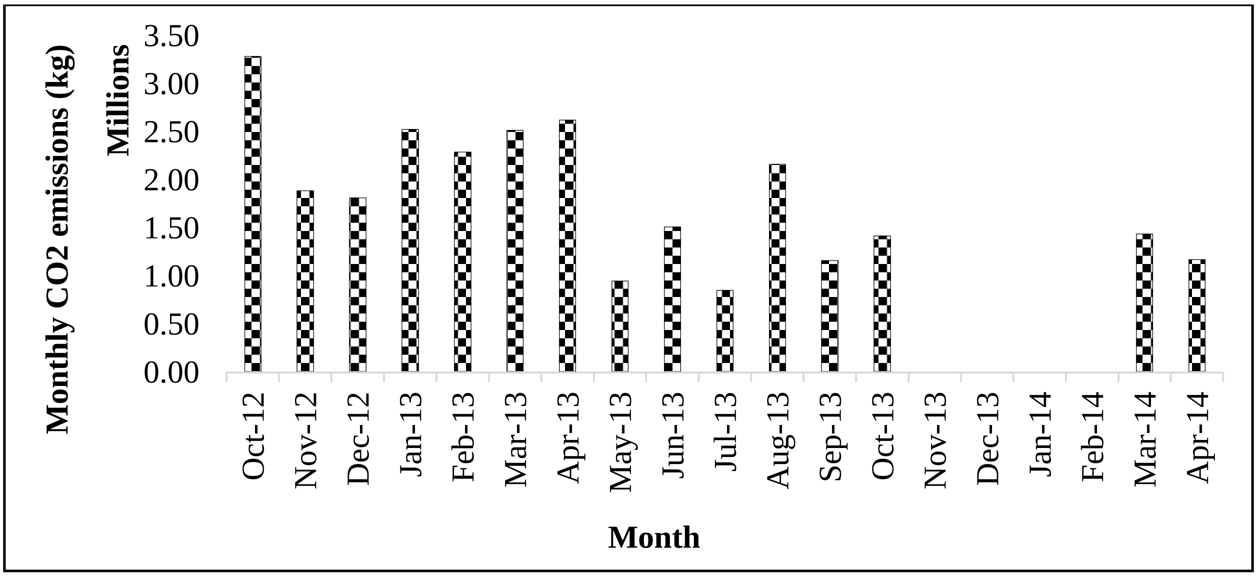

Fig. 4: CO_2 emissions per months for GT17 and GT18

III.I. The Analysis of the Cost Components of the Pipeline
The pipeline cost is broken down into five categories, the material cost, the labour cost, the miscellaneous cost, right-of-way cost, CO_2 surge tank cost, pipeline control system cost, and total O&M cost. Labour cost is the major cost of pipeline gulping 69.57% of the total pipeline cost. Thus, it is right to conclude that one major constraint to the pipeline is more technical than material. The right of way cost is 7.83% of the total cost of the pipeline. The material cost and miscellaneous costs are significant components part of the pipeline cost, gulping 11.39% and 5.71% of the pipeline cost, respectively. The pipeline control system cost and CO_2 surge tank cost are the least component cost of the pipeline cost with CO_2 surge tank costing only 3.51% of the entire pipeline cost, and the pipeline control system costing a relatively insignificant 0.32%. Total O&M cost, which is an annual cost that is associated with the entire project life, is low compared with other costs. This favours the establishment of the pipeline system as the major cost are included in the fixed capital costs. This is presented in the chart of Fig. 5. These costs are dependent on the prevailing inflation rate and interest rate. The overall pipeline cost at an exchange rate of $1 to N310 is Twenty-One Billion, Nine Hundred and Ninety-Four Million, Seven Hundred and Twenty Thousand, Three Hundred, and Sixty Billion Naira. (₦21,994,720,360).

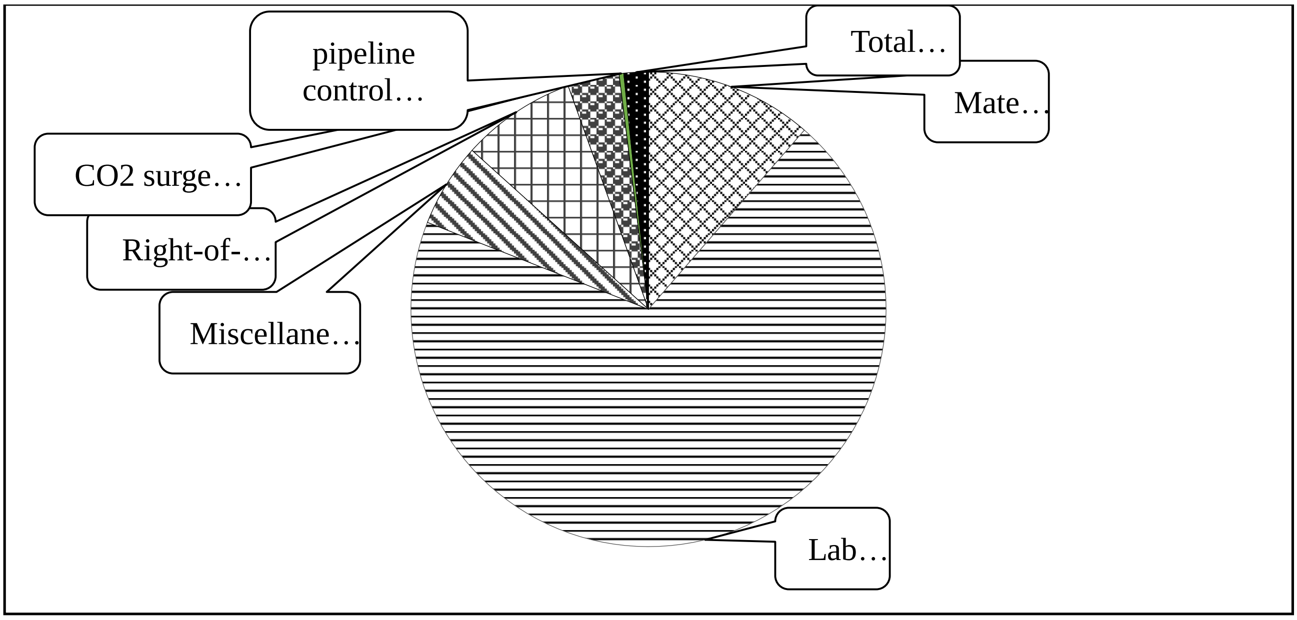

Fig. 5: Total CO_2 pipeline component costs

Energy Cost Analysis: The energy cost of compression and pumping the captured CO_2 was analyzed by using the power requirement of the compressors and pumps. To determine the yearly cost of running these pumps, the average energy cost for all the distribution companies for the years under consideration were used. The cost of pumping is minimal compared to the compression cost despite the distance that the pumped fluid will flow through. This is expected as less amount of energy is required to pump the same amount of fluid than to compress the same amount of liquid. This is presented in Fig. 6, where we observed the variations in the cost of energy based on the NERC's MYTO for each year. The initial rise and subsequent fall in the price of the energy is occasioned by an equally rising and falling MYTO of NERC. Thus with improvement in power supply and subsequent fall in energy charges, the amount required for the operation of captured CO_2 pipelines will fall. The major cost is in the compression, as pumping is a small fraction of the cost of compression.

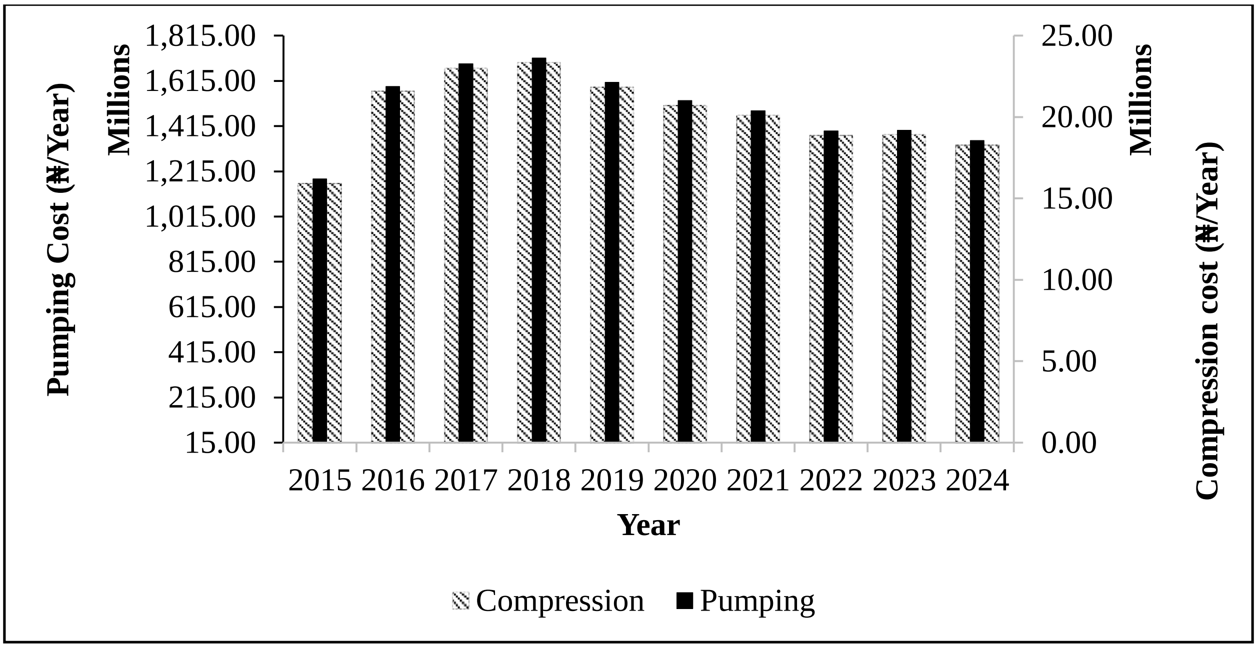

Fig. 6: The compression and pumping costs of CO_2 for the years under consideration.

The total cost is now summed up by adding the compression cost and the pipeline cost. The total cost is summed up into capital cost; include the pipeline material cost, labour cost, miscellaneous cost, right-of-way cost, CO_2 surge tank cost, and pipeline control system,
O&M cost (which provides for energy cost)

Energy costs and O&M costs are annual payments that are affected by policy changes and inflation. Thus inflation and currency devaluation are accounted for as a percentage of the total cost. The capital cost is spread for five years, which is assumed to be the period of construction. An annual interest rate of 10% is compounded on the capital cost for the period of development. Then the yearly charge of 10% on operation and maintenance cost is charged on the O&M cost for the years preceding the construction period, while a 5% inflation rate is assumed. We observe that the cost within the first five years is very high because of the cost of construction which has been factored into the construction cost. Beyond 2021, the price drops to a significantly lower value owing to the completion of construction. The cost associated with the pipeline is now the O&M costs, as shown in Fig. 7.

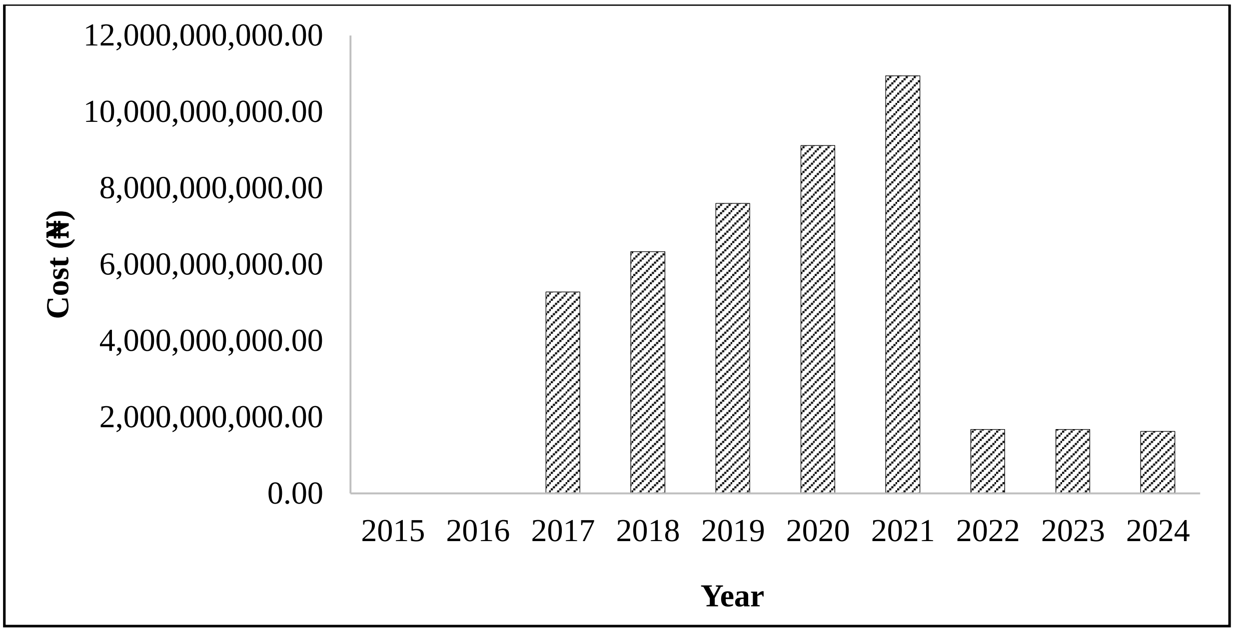

Fig. 7: Construction and operation costs for the periods 2016 to 2024 NERC MYTO

III.II. The Impact of CO_2 Compression and Transportation on NERC's MYTO

The NERC's MYTO rises significantly above 600% for the first five years, and this covers the period of construction of the CO_2 pipeline. In the subsequent years, the cost of energy for the consumer of electricity drops significantly to 19% of the pre – CCS years. This 19% increment in the price of power as a result of CO_2 compression and transportation is very significant because the cost of capture and sequestration has not been included in the cost. But with efficient operation of the power plant and services at high capacity factor, this cost will significantly fall. This scenario is presented in Fig. 8.

The cost of energy with capture is compared with the cost of energy without capture and is presented in Fig. 9. From the figure, we see a wide margin between the cost of energy with the capture and the cost of energy without capture. This is highly pronounced in the first five years which is a result of the cost associated with the construction of the plant. In the following years, where the price is limited to the cost of operation and maintenance of the pipeline, there is a significant reduction in the cost of electricity. This significant reduction is still higher than the price of energy without capture.

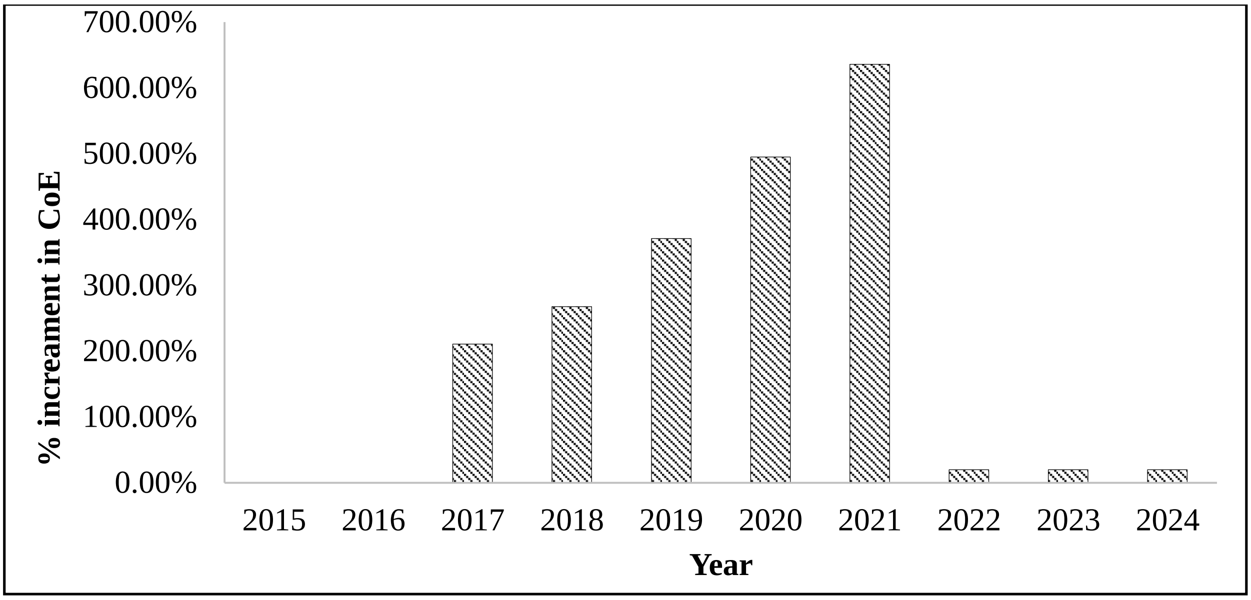

Fig. 8: Percentage increment in the cost of electricity attributable to CO_2 transportation

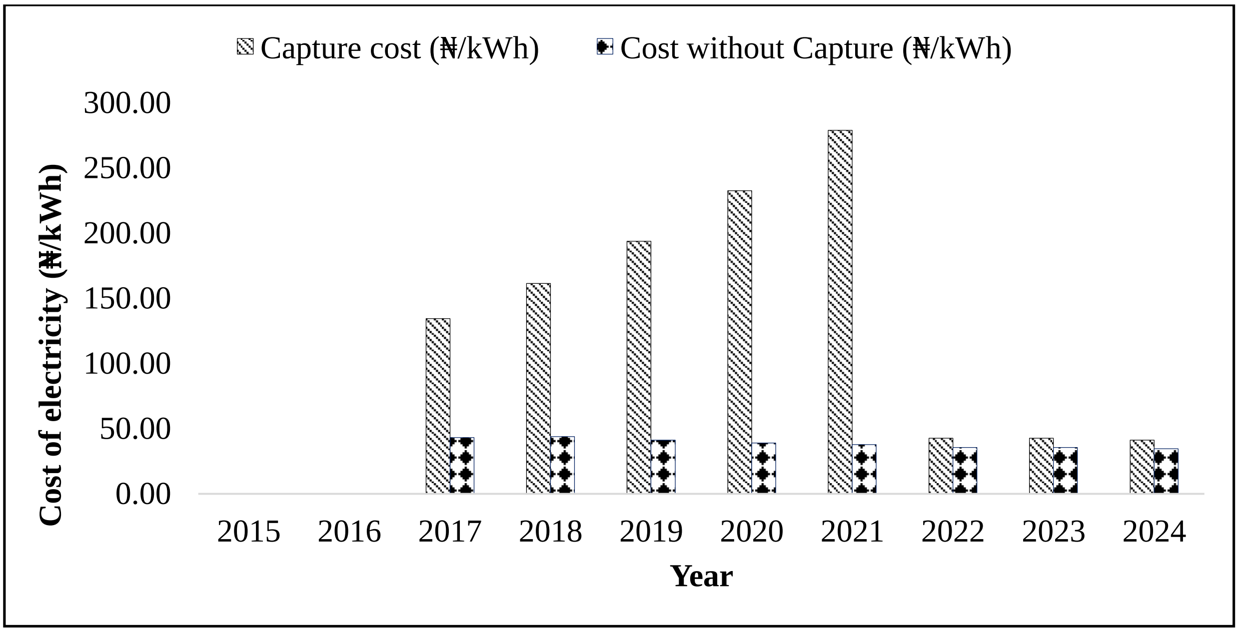

Fig. 9: The influence of CO_2 compression and transportation on energy cost.

IV. CONCLUSION

This study carried out a comprehensive investigation of the techno-economic analysis of transportation of sequestered CO_2 from Afam IV plants to Jones Creek. With CCS, the incremental cost of energy associated with capturing, compressing, and transporting sequestered CO_2 though very significant but with improvement in the mode of operation of the plants and retrofitting as many plants as possible will improve the capture rate and lower the energy cost. The policymakers should give the possibility of deploying CCS for the continued use of fossil fuels in power generation in Nigeria. Nigeria is yet to invest significantly in energy diversification. For a country seeking ways to mitigate against global warming while continuing to deploy fossil-fueled power plants for power generation. The development of a comprehensive CCS implementation plan is of great importance.

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