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TECHNO-ECONOMIC EVALUATION OF PIPELINE COMPRESSION SYSTEM: ECONOMIC EVALUATION OF THE NATURAL GAS PIPELINE COMPRESSION SYSTEM-PART 3

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ABSTRACT

This paper presents the evaluation of the life cycle cost (LCC) of the natural gas pipeline investment using ''techno-economic and environmental risk assessment'' (TERA) technique. The significance of this paper is to evaluate the cost implication of all the parts of this research work. The selected engines models for the gas compressor drive were developed based on public domain specification, using an in-house engine performance simulation software: TURBOMATCH. The gas turbine engines were modelled to run at constant power amid high ambient temperature. The performance results were further used for the economic investigation using a developed model in MATLAB. These were investigated with respect to three seasons (winter, dry and hot season) of the years based on the location of this project (Trans-Saharan gas pipeline with 18 compression stations). Three economic conditions of 0%, 2% and 4% escalation rate of fuel and maintenance cost were investigated to analyse the LCC. The results obtained shows that the total LCC for the 0% escalation rate was approximately $32.01 billion. The fuel cost was 39.60% of the total LCC for the entire project. The operating and maintenance (O&M) costs, gas turbine, gas compressor, the pipeline with all accessories costs and emission tax attracted 10.1%, 6.89%, 9.95%, 28.89%, and 4.57%, respectively of the total life cost. The result also depicted that 2% and 4% escalation rate of fuel and O&M cost on the LCC result in 19.5% and 47.8% increased, respectively when compared with the 0% escalation rate at the end of project life. The result of the overall life-cycle cost of the pipeline investment represents the operational cost of the system. The proposed approach will help operators on the real potential cost of pipeline investment, taking into account the different cost element and ambient condition of the natural gas pipeline system. Importantly, this model can be applied or adapted to any natural gas pipeline transportation business.

Keywords: TURBOMATCH; TERA, Investment; Performance; Inflation; Capital cost

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NOMENCLATURE	
C- cost of material ($/ton)	OD-Off-design
CS-Compressor station	&M-Operation and Maintenance cost
CAPEX- Capital Expenditure	NGT (N_{GT})= Number of GT in a station
COF-cost of fuel	P_{INSTC}, - pipe installation cost
DP- Design point	PIPC-Pipeline initial project cost
C_{CI},-depicts the cost of coating or insulation.	PL/AC-Pipeline and accessories
C_{PK} -Cost per Kilowatt ($/kW);	PL_c, -denotes the pipeline cost;
E_Tax-Emission tax	PMC- Pipe material cost
D- diameter of pipe (mm)	SRV- Shiping and regional Variation cost
ER-Escalation rate	T- Pipe thickness (mm)
Fcost/FC- Fuel cost	Tamb- Ambient temperature
FP-fuel price (($/kg),	TM- TURBOMATCH
FF- Fuel flow (kg/s)	TET-Turbine entry temperature
GC-Gas compressor	t-Time of the season (hours)
GT-Gas turbine	PR-Pressure ratio
GT_{CC} -Gas turbine capital cost	TET-Turbine entry temperature
GTE -Gas turbine Engine Power (MW);	2S-Two shaft
IC-Installation Cost	3S-Three shaft
L- pipe length (km)	TERA-Techno-economic and environmental risk assessment
LCC- Life cycle cost	Vcost-Variable cost
M-cost-Maintenance cost	X-(diameter/mm)
MF-Mass flow	Y- Cost in ($/km)

1. INTRODUCTION

The increasingly-stringent financial budget makes it more imperative for natural gas pipeline investors to quantify capital intensive project and the factors that influence such a project. Natural gas pipeline transportation network which accommodates two or more compressor stations has been known to be a capital intensive project. The economic success of a natural gas transportation business is hinged to a greater extent on the cost of machinery that makes up the system and its maintenance schedule. The main equipment in the natural gas pipeline business involves, the pipeline, gas compressor (GC), gas turbine (GT) and several accessories that aid in the gas transportation business[1,2]. The cost component besides the capital expenditure (CAPEX) is the operating and maintenance (O&M) and the fuel cost. Bejan et al. [3] affirmed that economic analysis of a gas turbine project after some relevant assumptions and predictions covers some major costs such as the total capital expenditure (CAPEX) for the project, the operating and maintenance (O&M), and fuel costs. However, they did not consider the emission tax, which is an integral part of the operating cost of a gas turbine engine. However, this paper takes into account the emission tax in addition to the above-itemised costs.

Cost is the fundament factor in the design, construction, operation, and maintenance of a natural gas pipeline system[4]. The investment costs and operating expenses of natural gas pipeline networks are significantly substantial that even little improvements in system utilisation can involve significant amounts of money. It is therefore imperative for natural gas pipeline investors to evaluate technical viability and cost implications of investing in such a project. Thus, the techno-economic and environmental risk assessment (TERA) technique to rapidly evaluate the entire natural gas pipeline project becomes vital.

The idea, emergence, and application of TERA tool was discovered by Ogaji et al [5] at Cranfield University in the United Kingdom. TERA was implemented as a result of research work carried out in areas of multi-disciplinary optimisation and management of power plant; and the environmental impact on the plant at both design stage and in operation. TERA is an investment decision tool that looks into the available excellent option for engine performance, the impact of the environment and its associated emissions cost, the engine availability and reliability[6]. The multi-discipline modules of TERA framework focus on performance modelling, cost, noise, the environmental impact of gas turbine and aircraft weight, as shown in Figure 1. In its holistic form, TERA modules comprise of performance, economics, environmental, emission, weight, noise, and lifing modules. Each of these modules solves different problems, and the result is condensed into the TERA framework. The performance module occupies the centrality of this tool. This is because it explains the thermodynamics of the component parameters and simulating the design point and off-design point of the gas turbine engines. This implies that result obtained from these modules are being fed by another module which includes emission, economics, risk and environmental. These are all analysed from the performance module. Evidently, according to Ogaji et al. [5], TERA is a veritable tool to select and rank an excellent option for investment and to identify any risk involve and efficiently manage the resources allocation. Summarily, the main aim of TERA is to thoroughly explore the given design space and minimise computational time and costs. It also enables the definition of a project's aims and channels the research in a way that it takes into consideration all the major areas of interest.

Figure 1. TERA philosophy and framework for aircraft optimisation [5].

TERA tool was initially implemented for aero engines and was recommended to be applied in industrial application. Mucino[7] established a techno-economic performance simulation and diagnostics computational system model based on TERA concept for the performance optimisation and risk management of a combined cycle gas turbine (CCGT) power station using the same route as Gayraud [8].

TERA has been explored both for marine[9] and industrial application. Gayraud [8,10,11] investigated industrial gas turbine for power application and using TERA and established the basis for a decision support system for combined cycle systems. Maccapani et al. [12] detailed their investigations into a TERA where they created a TERA based tool to help the choice of suitable driver for LNG. They concluded that among the four GT engines considered in the analysis, the one with the highest power rating serves as the best solution while the lifing and risk issue depends on the firing temperature.

Considering the above application of TERA, literature is silence on the application of TERA for natural gas pipeline transportation system that will take into account the driver (GT) operating in a time-based ambient temperature, driven, pipeline, and some fundamental pipeline accessories. Therefore, this paper aims to apply the concept of TERA in evaluating the life cycle cost of the natural gas pipeline having 18 compressor station (CS) in a time-based system. This was done in addition to the impacts of economic inflation on the LCC of the project. In the process of evaluating the LCC, the paper also established a novel method of estimating the capital cost of the various pipeline accessories for natural gas transportation.

In the previous work, the GC power requirement and the number of GC in each of the CS and the pipeline have been evaluated. The connection between the previous work and this paper is in the area of selecting the appropriate GT engines based on the evaluated GC power and generally calculate the cost of the GT, GC, pipeline and the addition of some necessary pipeline accessories including the operating cost. The addition of all these cost component will constitute the LCC.

Generally, in the pipeline transportation system, the costs of pipe and compressor stations dominate the initial capital cost. For instance, Menon [2] stated that the gas compressor and pipeline took about 96percent of the construction materials. Similarly, the significant operating cost for pipeline investment is the fuel cost that system utilised both yearly and throughout the project life. It is important to state that without the accuracy of the technical content of the various module of the pipeline system, the economic analysis cannot be ascertained. Hence, the need to use the TURBOMATCH software and incorporate the TERA framework that will encapsulate the various modules in order to actualise the economic result of the natural gas pipeline investment.

2. GAS TURBINE SELECTION BASED ON GAS COMPRESSOR POWER

There are many prime movers or drivers used in the pipeline system. These include; steam turbine, motor, gas turbine and reciprocating engines.[14]. Wash and Fletcher[15] explained that the selections of these drivers depend on some consideration which includes; fuel or energy cost, life cycle cost, reliability, excellent thermal efficiency, availability, low weight, and realistic part power torque. Smalley et al. [16] finalised that gas turbine engines are widely used in gas pipeline transmission since they are suitable for driving centrifugal compressors, especially in terms of reliability and availability. Also, the gas turbine operating range matches that of the centrifugal compressor, which is between 50 -105% of the compressor rated speed [17]. Again, Horowitz[18] investigated the operating comparison between steam turbine, gas turbine and electric motor and confirmed that GT has a wide operating range as compared to other drivers which make it suitable to drive centrifugal compressors. One of the considering factors which are economic-based in selecting between the prime mover is the available energy to power the installation. gas turbines utilise 3–5% of pipeline gas flow for their operation [19,20] and don’t need any electric supply like the use of electric motors as CS drivers [16,21]. Therefore, the present study considered the gas turbine engine for the pipeline compression of natural gas, especially since the areas of the CS are impoverished of electricity.

The choice of the type of GTs to be used was based on the calculated gas compressor power in all compressor stations, as shown in the previous work. Four GTs that are inspired by SGT-400, SGT-500, GT35 and LM1600, referred to as IGTA, IGTB, IGTC and IGTD respectively were chosen based on some performance criteria. The selected engines are represented in Figure 2 with their respective design point shaft power. These engines were chosen based on the following criteria,

- Adequate power to meet up the gas compressor power requirement
- Engine configuration was considered as each configuration has different part-load performance, reliability and maintainability aspects
- Sufficient data available in the public domain, useful during the modelling process
- Proven experience

It is worthy of note that a 10% margin on the power of the gas turbine selected for the compressor drive as required by API 616 was considered[22]. Meanwhile, all GTs selected are multiple shaft engines consisting of a gas generator and a free power turbine. Studies have shown that multiple shaft machines such as the selected types are better than single shaft engines for mechanical drive applications. The primary reason is that the gas generator speed of two or three-shaft engines is not tied to that of the driven load when compared with a single shaft. Therefore, it is more appropriate to handle power demand fluctuation and speed variability[23].

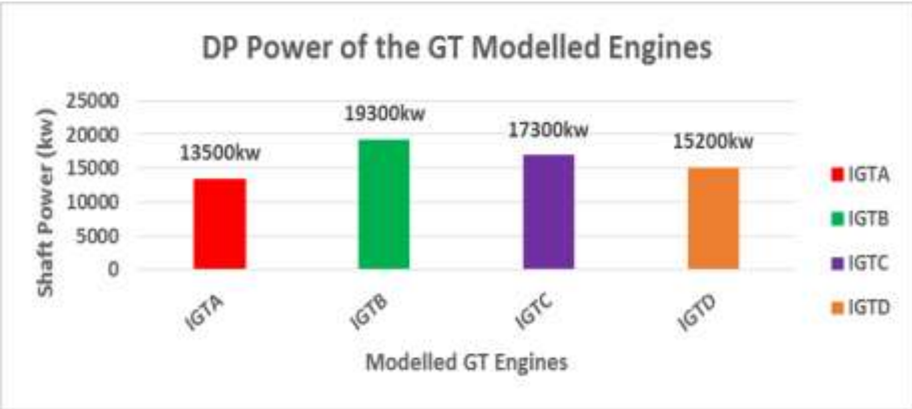

Figure 2 DP power of the selected GT modelled engines

3. COMPOSITION AND ESTIMATION OF THE CAPITAL COST OF THE GAS PIPELINE UNDER CONSIDERATION

The capital cost for the natural gas pipeline is essential when analysing the economics of the investment. Vaibhav et al. [24] stated that equipment capital investment cost comprises of initial costs of equipment, installation cost, electrical instrumentation and control costs, project management fees and contingencies. They calculated the equipment cost using the thermo-economic cost functions that were modified by Traverso et al.[25]. However, their analysis did not apply to the natural gas transportation system. Also, gas turbine world handbook [26] presented the trend for a simple cycle gas turbine to evaluate the cost/kW of GT. The trend shows the relationship between the price ($/kW) and shaft power (MW). According to the handbook, it is an intention to make the analysis a helpful guide for project planning and cost estimation. Based on this report, Brinckherhoff & Zealand[27] expressed that using this relation correctly and for a basic application, its accuracy can reach ± 10%. This relationship was used by the authors of this paper and further developed a trend line correlation that was used to predict the cost of the selected engine. Furthermore, according to Menon [28], the cost of the pipeline accessories is a function of the pipeline initial project cost (PIPC). Therefore, this paper adopted the PIPC costs as the costs of pipelines, GCs and GTs.

The capital expenditure (CAPEX) for this paper did not only based on the initial cost of gas compressors and prime movers (drivers) but also on necessary system accessories for the proper operation of the compressor stations. Achieving the number of mixed fleets of engines for the entire 18 CS, the number of gas compressors in each compressor stations, all necessary accessories and operational necessities of natural gas pipeline investment will enhance accurate evaluation of the CAPEX. It is worth noting that this paper takes into account the following major components as the capital costs of the gas pipeline under consideration (TSGP): Pipeline (PL), gas compressor (GC) and gas turbine (GT). Its accessories which are an integral part of the CAPEX include SCADA and telecommunication, mainline vale (MLV), right of ways (ROW), engineering construction and management (ECM), environmental and permitting (E&P) and contingencies (C&T). The cost associated with the above-itemised components constitutes the CAPEX in this paper.

4. VARIABLE OPERATING COSTS

The variable cost associated with the natural gas pipeline under consideration comprises of the operation and maintenance (O&M) costs, the fuel costs and the cost associated with emission from the engines.

4.1. Operation and Maintenance

The O&M cost is one of the significant cost elements when analysing the economics of investing in a natural gas pipeline project. In this case, the O&M cost was based on the costs of labour and the costs of keeping the GT working at the desired power setting to keep the gas pipeline in an excellent operating condition. This will help meets the desired gas supply constant. The O&M costs usually consist of two components: fixed costs and variable costs[29,30]. However, this research shall include TET based costs (major maintenance costs) as the third components of O&M cost. As used by Obhuo [31] in his PhD work to analyse the maintenance costs of GT engines. This is because the shaft power was fixed during operation at the expense of the engine TET and fuel consumption.

Considering the major maintenance costs (TET-based maintenance costs), it is crucial to establish that the operation of the GT engine in this research was such that, the shaft power was fixed irrespective of the ambient conditions. Fixing the shaft power and addition to the harsh time-based ambient temperature will affect the engine TET and by extension, the fuel consumption. Hence, the need to look into this as major maintenance. Major maintenance cost, which incorporates the engine life evaluation in its calculation, is also regarded as the TET based maintenance cost[31].

4.2. Fuel Cost

Fuel cost is the most dominant cost in the economic investigation of a project involving a prime mover. When considering the gas turbine on natural gas transportation. Based on the project under consideration, the vital performance parameter for the economic evaluation of each of the compression station operation is the efficiency and operating range. Efficiency has to do with the amount of fuel utilised to deliver a certain amount of gas from suction pressure to discharge pressure. The high thermal efficiency of the driver (GT) and high isentropic efficiency of the driven (GC) are good packages for the cost-effective system. Meanwhile, the operating range describes the range of likely operating conditions in terms of flow and head at an acceptable efficiency, within the capability of the power of the gas turbine. It is worth noting that fuel consumption increases when the pipeline operates at maximum transport capacity. This is because the pressure loss increases at maximum transport capacity due to friction and consequentially fuel consumption. Fuel consumption of GT on pipeline application can be observed in the work of Sekirnjak[32], Wu et al. [33]. Santos et al. [34] and Fabio et al. [19]. They aim to optimise fuel consumption during gas compression. Also, Kurz and Bruns [35][21] showed that fuel cost constitutes more than 50% of GT operational life cost. In this paper, the result of the fuel flow from the developed performance model in each of the 18 CS was further used in the developed economic model to evaluate the real fuel cost of operating the engine with the time-based ambient temperature.

4.3. Emission Tax

An additional economic indicator for the calculation of the natural gas pipeline investment is the emission tax. This is the cost associated with the amount of CO_2 generated during the engine operation on the natural gas pipeline. An emission model to quantify the amount of Nox, CO, and CO_2 on the TSGP project has been developed [1]. The developed model assumed that **CO_2** emission calculation was hinged on the genuine assumption that complete combustion of the fuel injected into the engine occurred in the presence of excess air. Based on this research work as represented in Figure (3), the authors evaluated the emission tax associated with this generated CO_2

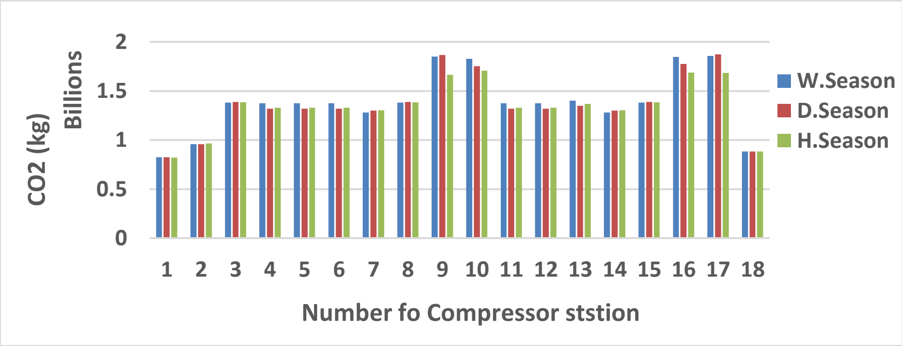

Figure 3. CO_2 Emission generated at each season of the year[1]

5. METHODOLOGY

Much research has not been expended on evaluating the true cost of pipeline investment for a natural gas transportation network, using a concept that can capture all variables involved in the LCC. The authors have developed a concept that enhanced the evaluation of the LCC of the gas transportation system based on TERA technique.

5.1. The Developed TERA Framework for the Natural Gas Pipeline Application

Considering the operation of each of the compressor station in the midst of harsh ambient temperature with respect to the overall investment cost of this project, this research has given rise to several variables. These variables include an integrated CAPEX of the project, the time-based fuel cost of the plants, time-based O&M costs of the engines and all necessary pipeline accessories. They are vital on a natural gas transportation project, as earlier discussed. This gave rise to the use of TERA concept. Figure 4 illustrates the pipeline investment model created by the authors to evaluate the investment cost (life-cycle costs) of the natural gas pipeline project using the TERA approach. The authors employed the TERA tool to investigate the techno-economic of the natural gas transportation network. Various modules such as pipeline, gas compressor, engine performance, emission, lifing, and the economic module are been utilised by the developed TERA framework. The framework also illustrates the various performance parameters that are required by the economic model in order to calculate the LCC.

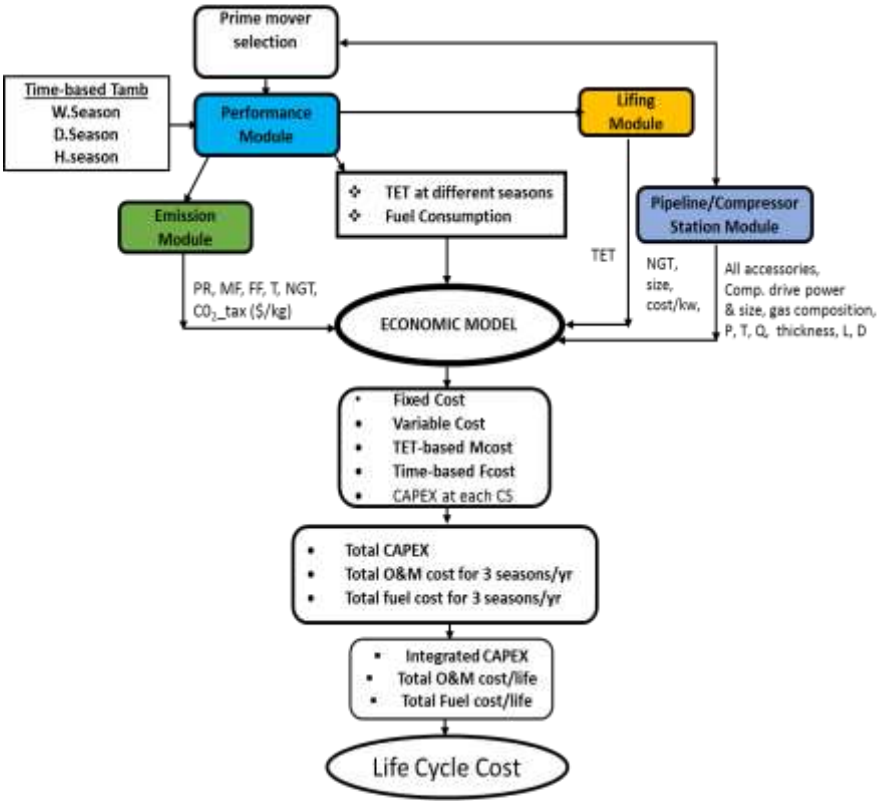

Figure 4 Developed TERA framework for the pipeline project

Because of this adapted concept of TERA, each module has been evaluated as discussed subsequently

5.2. Performance Module

The performance module serves as the fundamental of TERA framework. TURBOMATCH simulation software was used to simulate the engine thermodynamic behaviour at both DP and OD point conditions. TURBOMATCH is an advance intramural software of Cranfield University at the United Kingdom used to model and simulate gas turbine engine at both design and Off-design performance using a modified Newton-Raphson method as the convergence technique. The program was developed in FORTRAN and has continuously been improved upon over the years. DP calculation was carried out with initial user specification of component efficiency, ambient condition, pressure loss, EGT, to mention but a few.

The result of the performance model was linked with another module such as emission, lifing and pipeline/compressor station module. This is the reason why the performance module is the key element in the TERA concept. During the simulation process, both the compressor and turbine map of the input file is been scaled by TURBOMATCH while the OD points have been calculated based on the environmental conditions. In this paper, the effects of ambient temperature in all the CS have been simulated. The results of all performance parameters are been supplied by the performance module to the economic model

5.3. Pipeline/ Compressor Station Module

The pipeline/compressor station module comprises of the GT, GC, pipeline and all its accessories. The cost associated with these constitutes the CAPEX. This is one the component for evaluating the investment of the natural gas pipeline under investigation. The pipeline route and performance data have been discussed in the previous work. To evaluate the capital expenditure of this project, Figure 5 shows the flow chart developed by the authors to calculate the cost of the component that constitutes the CAPEX.

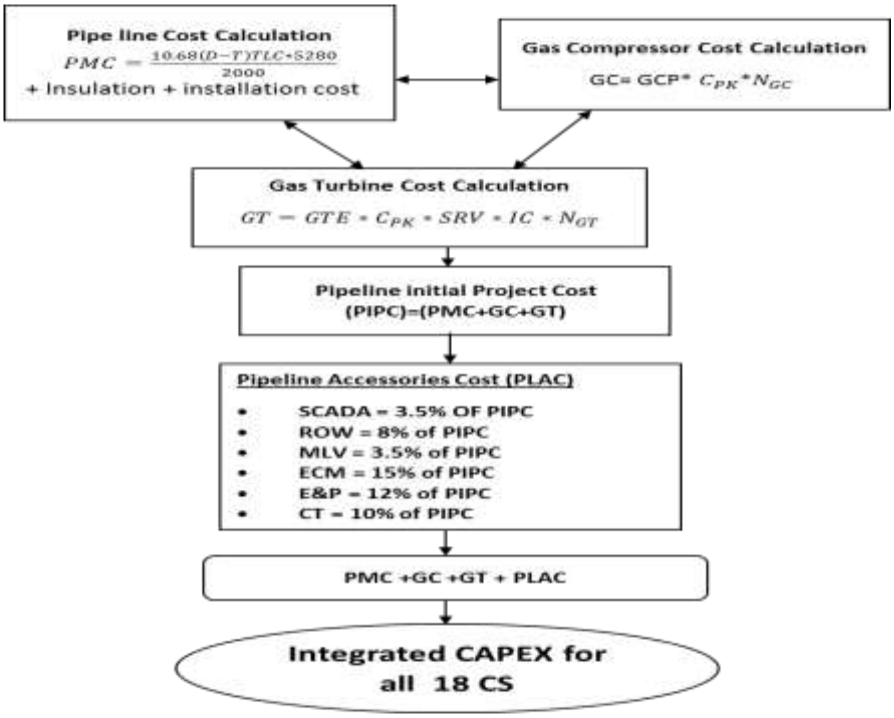

Figure 5. Method to calculate the capital cost

The pipeline-related costs comprise of the cost of material, cost of installation, coating, and insulation. cost evaluation for pipe generally depends on the material used, the diameter of the pipe, wall thickness and the pipe length. This is given in Equation (1)

$$PMC = \frac{10.68(D-T)TLC\ X\ 5280}{2000} \qquad (1)$$

The categorization of welded and seamless pipeline used for gas pipeline and petroleum industries is given by the American petroleum institute (API). This research used AP1 51 and X70 steel grade, which is appropriate for transporting natural gas. It is important to state that the actual cost of the pipeline is the combination of the cost of pipe material, installation and insulation. Equation (2) was used to actualise the installation cost for a given diameter and length of the pipe.

$$Y = 343.21X^2 + 2073.9X + 170013 \qquad (2)$$

The cost for the pipeline installation is a function of the topography, length, and diameter of the pipe. Coating and insulation are valued in ($/feet). In this paper, $5/foot was utilised for coating[28]. Therefore, Equation (3) was used to calculate the actual cost of the pipeline

$$PL_c = PMC + P_{INSTC} + C_{CI} \qquad (3)$$

5.4. Gas Compressor and Gas turbine Cost Calculation

It was assumed in this paper that each compressor station accommodates four GCs and the required number of GTs was based on the influence of site ambient temperature with respect to the control on the engine TET in each compressor station. The initial cost of the GC was calculated using Equation (4)

$$C_c = cost\ per\ \left(\frac{\$}{kW}\right) * Number\ of\ GC\ (KW)\ installed \qquad (4)$$

$3000 was used as the cost per kilowatt of the GC [36]. In evaluating the cost for GT engines, the gas turbine handbook has provided a guide on the cost calculation of GTs engines, as shown in Figure 6, the price ($/kW) of the engine decreases as the engine capacity increases[26].

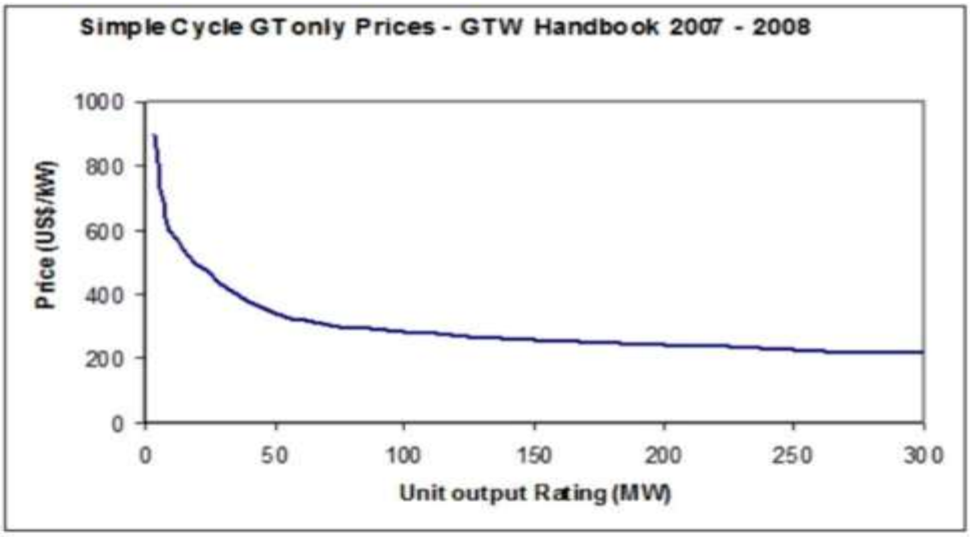

Figure 6. Price of gas turbine engine [26]

Based on Figure 6, web plot digitiser was used to retrieve the original values. From there, a trend line polynomial function was produced using a curve-fitting approach. This was done to accommodate the capacity of the selected engines. After that, the actual cost per kilowatt of the engines was derived based on the polynomial function. the capital cost of GT was calculated using Equation (5) having known the cost per kilowatt,

$$GT_{CC} = GTE * C_{PK} * SRV * IC * N_{GT} \quad (5)$$

The following assumptions were utilised in calculating the GT capital cost[36];

- The GT costs were increased per kW by multiplying by 2 to accommodate the installation cost
- Multiply by a factor of 1.38 to cater for shipping and regional variation cost

5.5. Pipeline Accessories Calculation

All the pipeline accessories were calculated based on the recommendation of Menon [28]. Based on the recommendation, supervisory control and data acquisition (SCADA) was calculated using 3.5% of the pipe PIPC. Mainline valve was calculated using **3.**5% of the PIPC with the assumption of the installation after every 33 km. Right of ways (ROW) was calculated using 8% of PIPC. Engineering Construction and Management (ECM) was calculated using 15% of the PIPC. Environmental and Permitting (E&P) were calculated using 12% of the PIPC. Finally, 10% of the PIPC was used to account for contingency costs.

5.6. Fuel and O&M Cost Calculation

To evaluate the fuel and O&M cost of the engines used on each of the compressor stations, the performance result obtained from the TM code becomes important in the evaluation process. Figure 7 illustrates fuel and O&M costs concepts, showing the performance data flow from simulation result to estimate the fuel and O&M costs at different seasons. This means that the TET and their corresponding fuel flow from the engines will be different from each other since the ambient temperature varies from one season to another. Hence the need to produce the performance data from the different season that will serve as the best data for the economic evaluation.

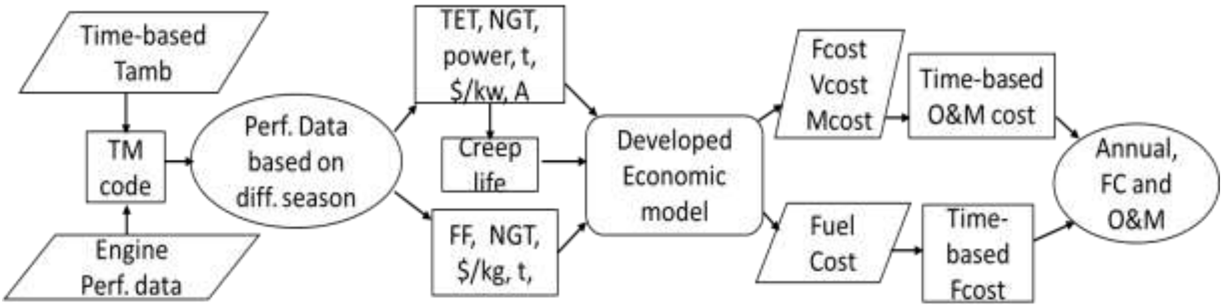

Figure 7. Method of calculating Fuel and O&M costs

Equation (6), (7) and (8) were used in the developed model to calculate the fixed, variable and major maintenance cost respectively in each season of the year. These three costs constitute the total O&M costs.

$$Fixed\ Cost = \left(\frac{\$}{Kw}\right) * GT_{shaft\ power}(kw) * NGT * 1000 \quad (6)$$

$$Variable\ Cost = \left(\frac{\$}{kw}\right) * GT_{shaft\ power}(kw) * T\ (hours) * Availabilty * NGT * 1000 \quad (7)$$

$$Major_{maintenance\ factor} = \left[\left(\frac{\$}{kw}\right) * \frac{Baseline\ Life}{Creep\ Life}\right] * GT_{shaft\ power}(kw) * T\ (hours) * Availablity * NGT * 1000 \quad (8)$$

The baseline life of the engines used in the Equation was the assumed creep life of the GTs engine at DP (25,000 hours). 5.8 $/kW and 0.23 $/kW were used for variable and fixed cost calculation[37]. Also, engine availability was assumed to be 100%

For fuel cost calculation, daily ambient temperature variation for each CS was segmented into three seasons and hours of the day for 24 hours as conducted in the previous works. The time taken were segmented into three hours different (0:00, 3:00, 6:00, 9:00, 12:00, 15:00, 18:00 and 21:00 hours of day). The ambient temperatures that correspond with this time of day in each of the CS were used to simulate the various GTs engine throughout the 18-CS. The time-based performance result obtained from TM was used for economic analysis. Each season was assumed to have an equal number of days. The sum of the result obtained from each season gives the annual fuel cost, and this was also applicable to the O&M cost.

Equations (9) and (10) were used in the developed economic model to calculate the cost of fuel for the pipeline project

$$COF = FP * FF * T * NGT * 3600 \quad (9)$$

$$COF = \sum_{n=1}^{n=30} FP * FF * T * NGT * 3600 \quad (10)$$

The time (T) was measured in seconds, and the unit cost for fuel consumed by the GT was assumed to be 0.168 ($/kg) [36]. The performance parameters such as fuel flow, TET, and shaft power from TM result including the number of GTs in each compressor station were loaded in the developed economic model to calculate the O$M and fuel costs. Project life was assumed to be 30 years.

5.7. Economic Sensitivity Analysis

Sensitivity analysis here referred to the effect of inflation on the overall O&M and fuel costs. In this paper, 0%, 3%, and 5% escalation rates were implemented annually. The main aim was to check the effects of inflation on the overall O&M and fuels costs and by extension, see how this inflation affects the life cycle cost of the pipeline project.

5.8. Lifing and CO_2 Tax Evaluation

Considering the lifing module, the factors that limit the working cycle of an engine are the disks and high-pressure turbine and are been influenced by the operating TET of the engine. In this paper, a simple creep life model was developed. This model uses a simple relationship between the engine creep life and the TET. The simple developed model assumed that for every 20K rise in the operational TET, the engine life reduces by half and uses the DP TET as the reference TET with the corresponding assumed creep life. This relationship was used to produce trend line polynomial function with an RMS value of 0.998. This was further connected to the developed economic model to estimate the creep life of the engines in a time-based system at various seasons of the year throughout the project life. This technique was adopted based on the work of Gad-Griggs[38], that for every 20K increase in the engine TET, the HPT blades lifetime reduces by half. It is important to state that as the engine operational TETs increases, the creep life reduces, while the creep life increases with reducing TETs. The estimated creep life was used to calculate the major maintenance cost at various seasons of the year throughout the project life and at all compressor stations.

The CO_2 tax was calculated based on the result presented in Figure 3 using Equation 11 in each season of engine operation and further sum up to an annual emission tax. The emission tax goes into the economic module as presented in Figure 4 where it constitutes an essential cost element in evaluating the life cycle cost of the natural gas pipeline.

$$Cost\ of\ \frac{CO_2}{(yr)} = \frac{CO_2}{(kg)} * \frac{CO_{2tax}}{1000} * NGT \quad (11)$$

5.9. Gas Turbine and GC Allocation at each CS

It should be noted here that the outcome of the total number of GT used was based on the highest temperature of the year, which is the hot season due to the control of the engine TET. The number of GT engines in each CS with their respective power and the GC power at each season is shown in table 1. The economic evaluation of the GC and GTs including the performance parameter based on engine operation were calculated with respect to Table 1

Table 1. GT Engines attached to their respective Compressor's station

No. of CS	GT Used	Power (KW)	No. of GT Used	GC Power(kW)
1	IGTA-2S	13400	5	9323
2	IGTB-3S	15200	5	12606
3	IGTC-3S	17000	5	14802
4	IGTC-3S	17000	5	14411
5	IGTC-3S	17000	5	14461
6	IGTC-3S	17000	5	14467
7	IGTC-3S	17000	5	13966
8	IGTD-3S	19300	5	15968
9	IGTD-3S	19300	5	14897
10	IGTD-3S	19300	5	15046
11	IGTC-3S	17000	5	13311
12	IGTC-3S	17000	5	13412
13	IGTC-3S	17000	5	14763
14	IGTB-3S	15200	5	11252
15	IGTC-3S	17000	5	13739
16	IGTD-3S	19300	5	15118
17	IGTD-3S	19300	5	14975
18	IGTA-2S	13400	5	10292

6. RESULT AND DISCUSSION

The effects of time-based ambient temperature on the performance parameters at different fixed power setting are discussed. Also, the result of the CAPEX, fuel cost, O&M cost, and the life-cycle cost of the project are also presented.

6.1. Effects of Time-based Ambient Temperature on the Performance Parameters

Figure 8 shows the variation of TETs as a result of different power settings with respect to time of day. The time taken for the ambient temperatures were segmented into three hours different (0:00, 3:00, 6:00, 9:00, 12:00, 15:00, 18:00 and 21:00 hours of the day). The result obtained shows that at a particular power setting, the TET increases with increasing ambient temperature. The result also shows that at a fixed power setting of engine capacity (19.3MW), every 1% increase in ambient temperature, result in a 0.05% increase in TET. Figure 9 shows the time-based fuel flow at different power setting. The result also shows that at a fixed power setting, the fuel flow increases with increasing ambient temperature. The further result depicts that for every 1% increase in ambient temperature, the fuel flow increases by 0.04%, while the thermal efficiency in Figure 10 decreases with increasing ambient temperature at a fixed power setting. The thermal efficiency also decreases by 0.04% at every 1% increase in ambient temperature. This analysis was done in all the CS with respect to the three seasons under investigation. The result of the time-based performance parameters was used to evaluate the pipeline investment cost.

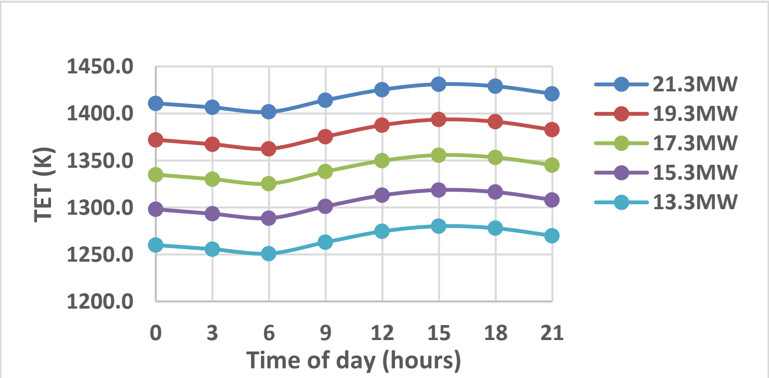

Figure 8. Time-based TET at different power settings

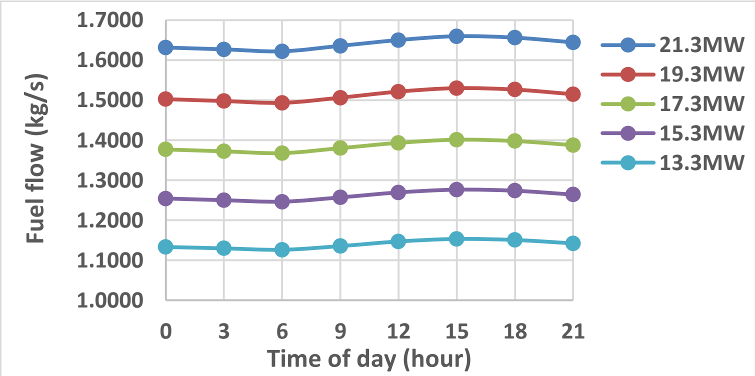

Figure 9. Time-based fuel flow at the different power setting

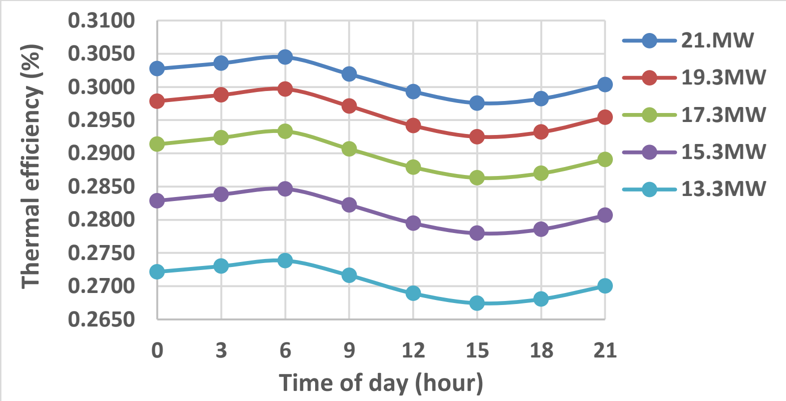

Figure 10. Thermal efficiency at different power settings.

6.2. Evaluation of the Project CAPEX

Figure 11 shows the cost of various pipeline accessories used for the natural gas pipeline transportation in this paper. It should be recalled that the pipeline accessories depends on the PIPC. It was observed that ECM has the highest cost, followed by E&P and thirdly CT. The SCADA and MLV have the list costs when compared with ROW, as indicated in Figure 11. Figure 12 represents all the components that constitute the total CAPEX. It should be noted here that the auxiliary cost consists of the costs of SCADA, ROW, MLV, and CT. The result obtained shows that the 4,180km pipeline of 56'' diameter constitute 28.1% of the total CAPEX. This is the highest cost, followed by the cost of GC, Auxiliaries, GT, ECM, and E&P with 21.5%, 16.4%, 16.1%, 10.5%, and 7.2% of the CAPEX respectively. The result strongly agreed with literature that the cost of a long distance pipeline is always a major cost when constructing a gas pipeline. It also agreed with literature that the cost of GC is higher than the GT cost when both are within the same power rating.

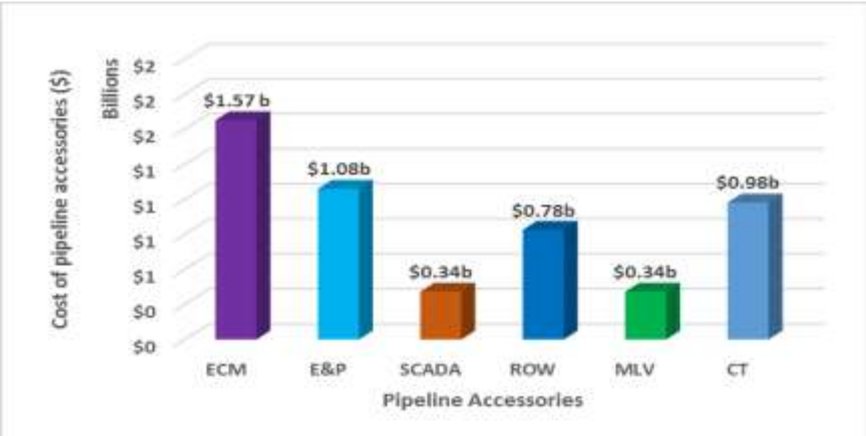

Figure 11. Cost of pipeline accessories.

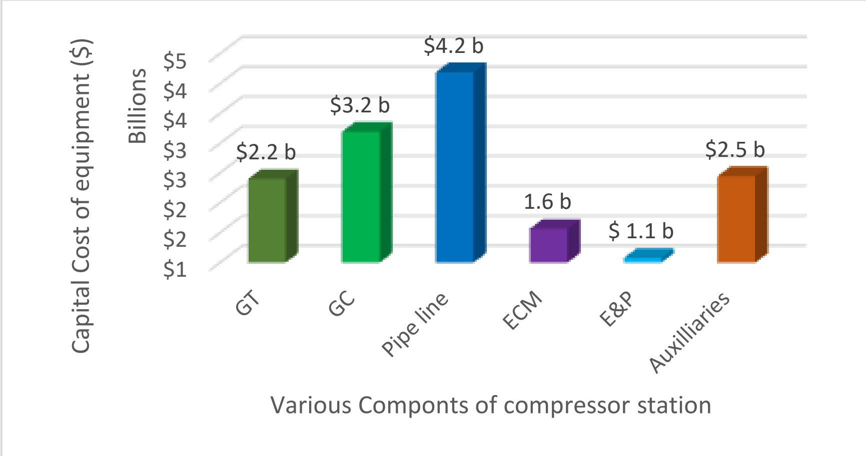

Figure 12. The capital cost of all pipeline component for the 18-CS

6.3. Evaluation of Fuel Cost and the impacts of Escalation rate

The shaft power of GT was fixed with respect to the GC power requirement for constant operation for natural gas business; the TET increases with a corresponding increase in fuel flow as the ambient temperature increases. The increase in the fuel flow, especially in the hot season when the ambient temperature was the highest directly affects the fuel cost. The result in Figure 13 shows the summation of the cost of fuel consumed by the GTs engine in the three seasons of the years from all the 18-CS under consideration. The operation of the engine was assumed clean throughout the period. This is the reason why the cost of fuel for clean condition remains constant each year with an approximate annual cost of $0.425billion throughout the life of the project. Escalation rate (inflation rate) of 2% and 4% were implemented in the cost model to see the effect of inflation on the fuel cost. The result obtained shows that the fuel cost increases annually due to the impact of annual inflation when compared with the 0% escalation rate (ER).

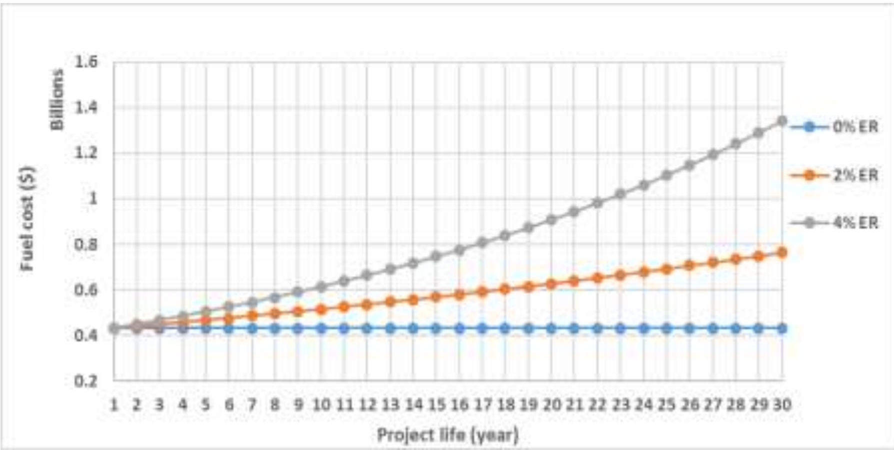

Figure 13 Annual escalated fuel cost for project life

6.4. Evaluation of Operation and Maintenance Cost and the Impacts of Escalation Rate

O&M cost is essential in determining the life-cycle cost in this paper. The maintenance cost was hinged on the TET as the power of the gas turbine was fixed throughout the operation in each season of the year. The addition of the O&M cost of the three seasons, taking into account the time-based ambient temperature of the 18-CS resulted in the annual O&M costs for 30 years, as depicted in Figure 14. From the result, O&M cost for the 0% escalation rate remains constant with an approximate annual cost of $0.11b throughout the life of the project. This is because the engine was assumed clean throughout the operation. The further result revealed that 2% and 4% escalation rate have an increasing trend as the year progresses. The increase in the annual cost indicates the influence of annual inflation on the maintenance cost. This will directly affect the life cycle cost of the project. Generally, as the ambient temperature increases based on the time of day, the engine TET increases also. The increase in TET results in lower creep life of the engine. This directly affects the maintenance cost of the engine. So, an increase in ambient temperature results in high O&M cost.

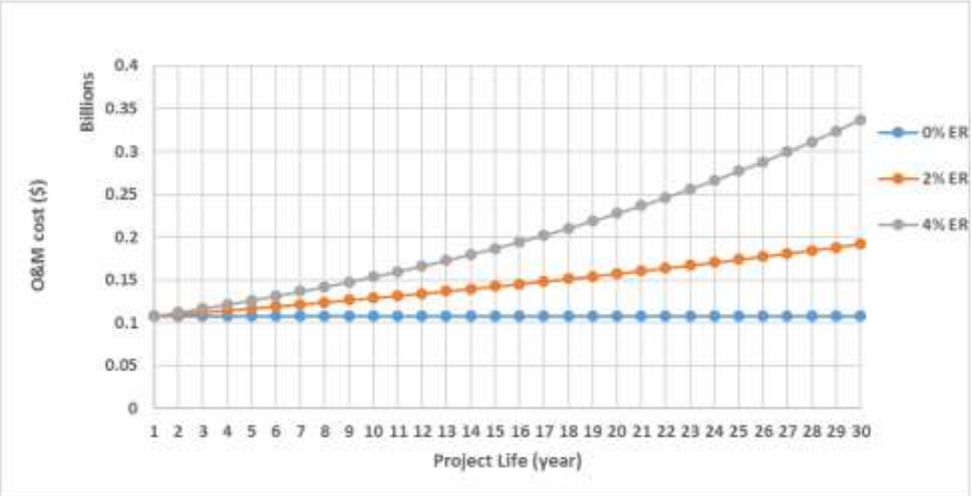

Figure 14 Annual escalated O&M Cost for project life

6.5. Emission Tax

The summation of the three seasons per CS in each year throughout the project life for the emission tax is shown in Figure 15. The result obtained shows that the emission tax for the 0% escalation remains the same in all the years of operation at an approximate annual cost of $0.05 billion. The reason has been that it was assumed the engines remain clean throughout the operation of project life. The result also shows that the emission tax for 2% and 4% escalation rate increases as the year increases, indicating the effects of inflation on investment cost. emission tax increases with an increasing ambient temperature of the engine when the engine operates on fixed shaft power

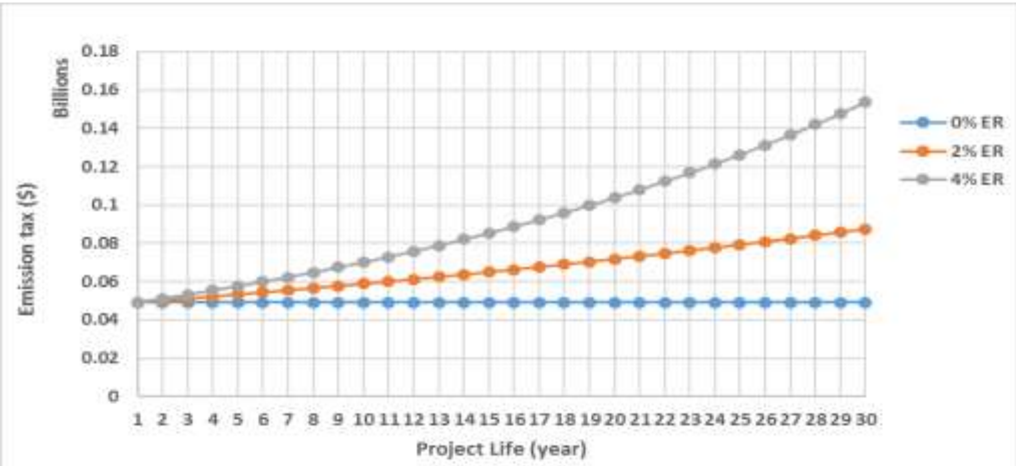

Figure 15 Annual escalated emission tax for the project

6.6. Life Cycle Costs for the Pipeline Project

The LCC of the natural gas pipeline investment is represented in Figure (16) to (18). The LCC consists of the total cost of fuel consumed throughout the operation, O&M cost which includes the fixed, variable and major maintenance based on TET, cost of GTs, GC, and the pipeline with all its accessories as well as the emission tax from the total number of GT engines used for this investigation. The sum of these costs components made up of the LCC. The life cost result in Figure 16 depicts that the fuel component in each escalation rate which is the total fuel cost for the 18CS throughout the project life has the highest cost when compared with all the cost component under investigation. The result also shows that the pipeline with all the additional considered accessories (PL/Acess) was the second dominant cost next to the fuel cost. The result further shows that the cost of the gas compressor was higher than the GT. Summarily, the result in Figure 17 shows the breakdown of the cost at 0% escalation rate. This shows that the fuel cost dominates the total life cost of the project with 39.60% of the total LCC. While M-cost, GT, GC, PL/AC, and E_Tax has 10.1%, 6.89%, 9.95%, 28.89%, and 4.57%, respectively of the total life cost. It is important to state that implementing an annual escalation rate (inflation rate) shows the impact of inflation on the LCC of the pipeline project

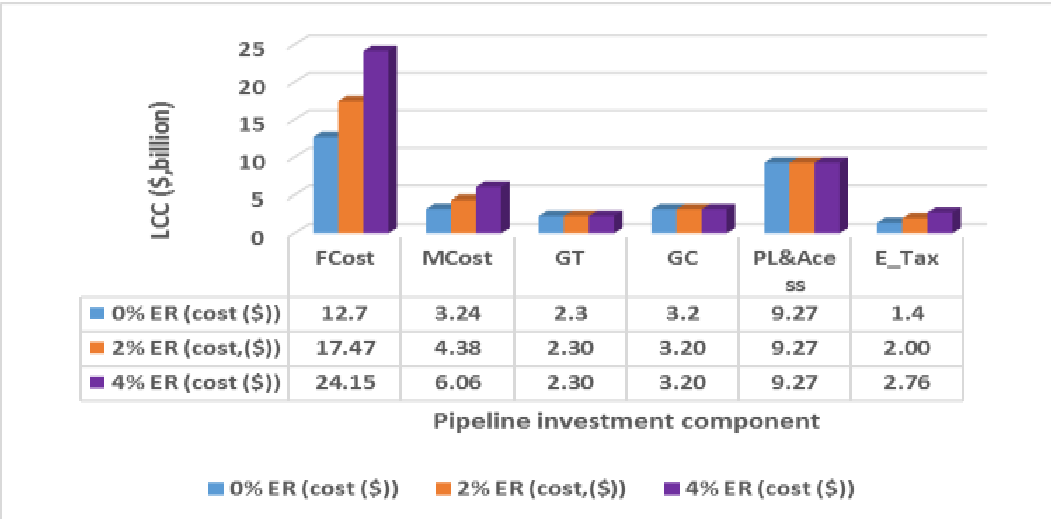

Figure 16. Life cycle cost for pipeline investment

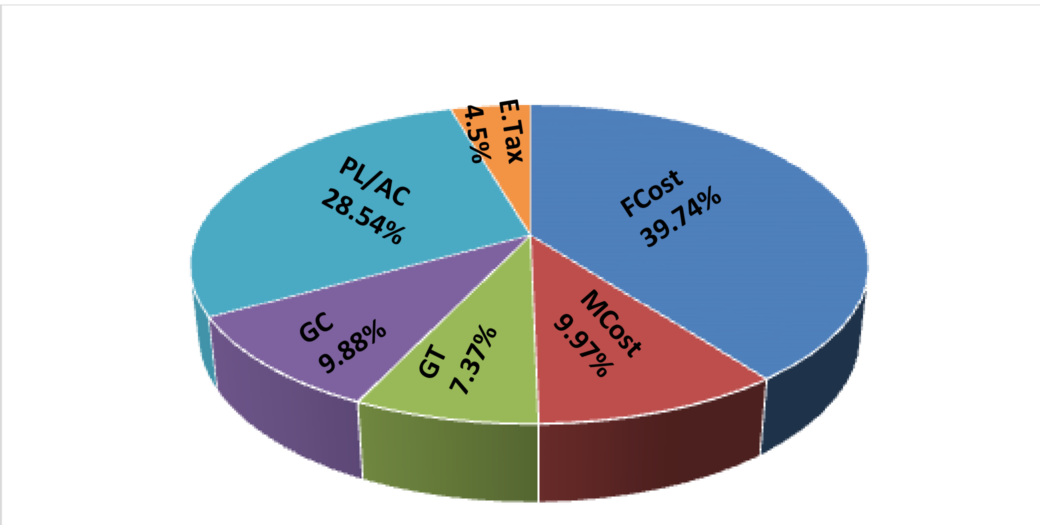

Figure 17 Break down of project cost at 0% ER

Furthermore, the result in Figure 18 shows the total life cost of investment. The total LCC costs for the 0% escalation rate was approximately $32.31 billion. The 2% and 4% escalation rates have 19.5% and 47.8% increase, respectively when compared with the 0% escalation rate at the end of project life. This clearly shows the impact of inflation on the LCC for the natural gas pipeline project.

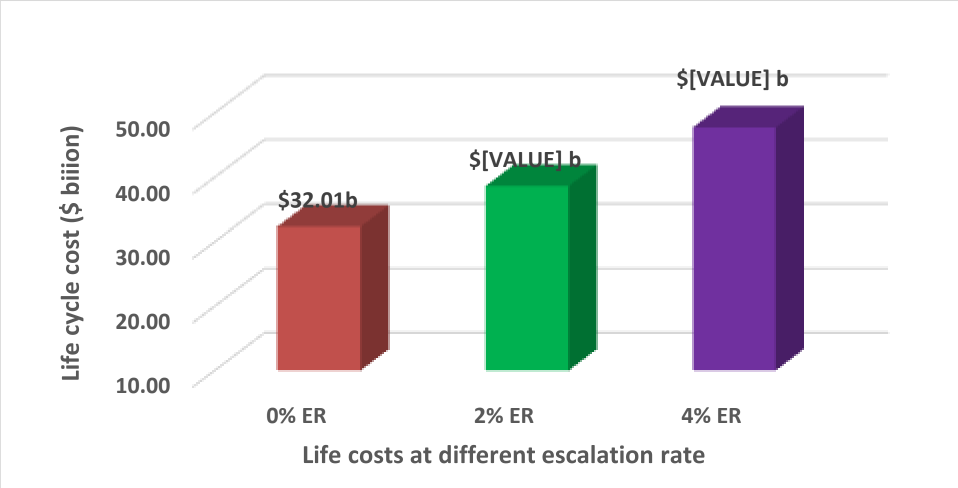

Figure 18. Total life cycle cost of the pipeline investment

7. CONCLUSION

Knowing the necessary equipment, in addition to the cost of investment, is very important for any project to be executed. Also, the performance of the equipment to be involved, in addition to the economics of operation becomes a concern in any scientific and economic investments. In this paper, the time-based performance of the modelled engines at fixed shaft power operation for the pipeline project has been presented as shown in figure (8) to (10). The economics of investment has been elucidated. Also, necessary equipment that can aid the smooth operation of the natural gas transportation business has been identified and evaluated, as shown in Figure (11) and (12). A technique (TERA concept), which considered all the cost components of the pipeline project had been produced and utilised in this paper. The components for the LCC include the total cost of fuel consumed throughout the operation, O&M cost which includes the fixed, variable and major maintenance based on TET, cost of GTs, GC, the pipeline with all its accessories and the emission tax from the 90 GT engines used for this investigation. The sum of these cost components made up of the life cycle cost. The LCC of the natural gas pipeline investment has been evaluated as presented in Figure (16), (17) and (18). Three economic operational conditions were examined in evaluating the LCC of the project; the 0% ER, 2% ER and 4% ER condition (sensitivity analysis). These conditions investigated the impact of inflation on fuel cost, O&M costs and emission tax in order to analyse their impacts on the LCC of the natural gas pipeline project. This is necessary to safeguard investors on the potential impacts of increasing inflation in modern investment. The pipeline under consideration is a 56 inches pipe diameter with a distance of 4180km from the Niger Delta region of Nigeria to Benisaf in Algeria. The pipeline is expected to convey 30 billion cubic meters of gas per year with 18-CS (booster station) along the pipeline. The use of the TERA module, which incorporates all the investigated modules in this paper enhanced the LCC of the natural gas pipeline that was investigated.

Importantly, the proposed approach and methodology in this present study will help investors understand both the technical as well as the economic implications of pipeline investment, taking into account the different cost elements, the impacts of inflation in investment cost and the impact of time-based ambient temperature on the GT operation. This can be applied to any natural gas pipeline transportation business.

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