Some Economic Implications of Deploying Gas Turbine in Natural Gas Pipeline Networks

A. Nasir, P. Pilidis, S. Ogaji, and W. Mohamed

***Abstract*—The development of a natural gas pipeline system requires important data such as appropriate pipe sizes, gas rate and required delivery pressure. The investment for the pipeline and compressor station is capital intensive and therefore the techno-economic study that will minimize the cost becomes imperative. A techno-economic module which performs the pipelines and compressor station analysis and the economics of a selected gas turbine has been developed. This module is integrated with a thermodynamic performance module of a 34MW gas turbine. The design point and off design simulation was carried out using an in-house performance simulation software called Turbomatch (a Cranfield University specially developed gas turbine performance simulation software). As a case study for this analysis, a 24 inch 512km pipeline with a throughput of 4.54 Mm^3 per day (160.3 MMscfd) requiring about a 34MW drive power was employed in order to demonstrate the effects of under and over sizing of pipes and gas turbines. The results presented illustrate the potentials in cost-effectiveness that can be made by correct pipe sizing and gas turbine selection. The results also shows that the gas power required increases with pipe under sizing and reduces with over sizing and this consequently affects the capital investment. Establishing the economics of this important aspect of a gas pipeline will guide the selection of an economic pipe size and appropriate gas turbine which will ultimately lead to an overall cost effective pipeline system.**

***Index Terms*—Gas turbine, natural gas pipeline, performance, techno-economic module.**

I. INTRODUCTION

The increase in world's energy demand combined with the on-going concern about emissions, energy utilization efficiency and reliability has made natural gas a fossil fuel of choice for the foreseeable future and consequently gas turbine fired by natural gas a predominant prime mover for pipeline transportation. The development of gas fields and its transportation modes are growing by the day and natural gas wells are usually located in remote areas far from the consumers. This makes its transportation procedure very important. One of the major means of transporting natural gas is through a pipeline system which requires compressors in order to sustain the flow and deliver at a set pressure.

Designing a natural gas pipeline system which will give steady supply to consumers involves, among other considerations, appropriate pipe sizing, compressor and gas turbine selection for any particular throughput, as well as meeting technical needs, and also very importantly cost effectiveness.

The development of a gas pipeline network is capital intensive and the major component that contributes to the initial capital costs are the compressor stations, pipeline, mainline valve and metering stations, control and telecommunications [1]. Other cost that may also contribute to the initial capital investment includes right of way (ROW), environmental and permitting cost, engineering and construction management and contingency.

Generally two major cost, capital and annual operating costs are the cost related to pipeline system. The recurring annual operating cost which is a major cost relates to the operation and maintenance of the system. In order to minimize these costs, it is important to analyse the technical requirements which lead to a reduced cost for transporting natural gas. This invariably defines the operational effectiveness of the system. The techno-economic module developed determines the economic pipe diameter based on the input pressure and the required delivery pressure, compressor power required for a particular gas flow rate and calculates the life cycle cost for the entire pipeline system.

II. GAS TURBINE AS A DRIVER OF CHOICE

Traditionally, gas turbines fired with natural gas have been chosen as the main driver for pipeline compressors;, because such systems do not need additional infrastructure (fuel is tapped from the transported gas) [2]. It also lacks reciprocating and rubbing members which could result in a balancing problem, with exceptionally low lubricating oil consumption and high reliability [3]. In the family of the prime mover of choice in the oil and gas industry, there exist different configurations and cycles. The gas turbine configuration mostly employed is a single spool with power turbine to drive the pipeline compressor (Fig. 1).

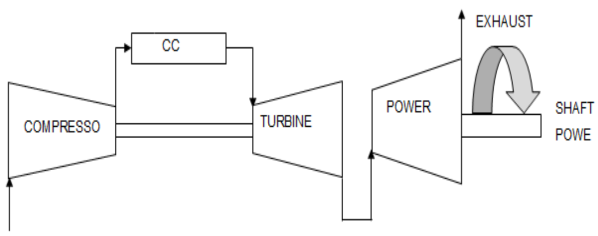

Fig. 1. Gas turbine configuration for natural gas pipeline.

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III. Gas Turbine Performance Simulation

Gas turbine performance simulation was carried out using turbomatch, a fortran based code. The code reads the data for each of the major parts of the gas turbine, relates the data thermodynamically and conduct design and off-design calculations of the necessary performance parameters. Parameters that affacts the performance of the gas turbine such as ambient temperature, turbine entry temperature(TET), mass flow and pressure ratio were actually investigated. One of the important results that is required from the performance simulation is the fuel flow which strongly influences the operating cost of the gas turbine. The configuration used is as in Fig. 1.The gas turbine simulation gave the following result at design point (Table I).

TABLE 1: Engine Performance Parameter at Design Point

Parameters	Value
Power Output	34.08MW
Pressure ratio	23:1
Thermal Efficiency	41.1
Turbine Entry Temperature	1510 K

IV. Natural Gas Flow in Pipeline

The ability to transport natural gas has always been an important factor in the successful development of a gas field, both off-shore and on-shore. Historically, pipelines have been the most common means used to transport this product in most countries. The flow of natural gas in pipelines is characterized by pressure drop along the length of the pipeline.

Flow equations have been developed over the years by considering the basic energy equation and applying the gas laws to predict the performance of a pipeline transporting gas [4]. These formulae are intended to show the relationship between the gas properties, such as gravity and compressibility factor, with the flow rate, pipe diameter and length, and the pressures along the pipeline. Simplifications are sometimes introduced, such as uniform gas temperature and no heat transfer between the gas and the surrounding soil in a buried pipeline, in order to adopt these equations for manual calculations. Although transient situations are experienced in gas flow in pipelines, for most practical purposes, the assumption of isothermal flow is sufficient, since in long transmission line the gas temperature reaches steady state or constant values, anyway.

Weymouth equation was used for the pipe flow analysis since the case study considered falls into the class of large diameter pipeline, high pressure, and high flow rate.

$$Q = 3.7435 \times 10^{-3} E \left(\frac{T_B}{P_B}\right) \left[\frac{P_1^2 - e^s P_2^2}{G T_f L_e Z}\right]^{0.5} D^{2.667} \quad (1)$$

where L_e is given in 2

$$L_e = \frac{L(e^s - 1)}{s} \quad (2)$$

The parameter s which depends upon the gas gravity, gas compressibility factor, the flowing temperature and the elevation difference can be expressed as shown in 3 [1].

$$s = 0.0684 G \left(\frac{H_2 - H_1}{T_f Z}\right) \quad (3)$$

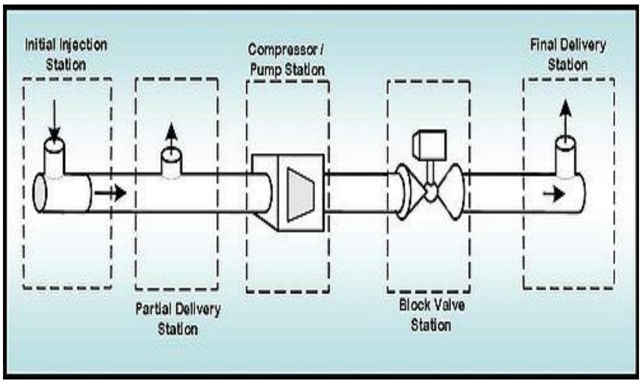

Fig. 2. A pipeline schematic [5].

V. Pipeline and Compressor Station Modules

This module analyses the natural gas flow in the pipeline, calculating for a given pipe size and length the flow rate possible through it based upon an inlet pressure and an outlet pressure of a pipe segment. It also predicts the standard pipe diameter necessary to transport a particular gas throughput. The optimum pipe diameter can be determined based on technical and economic considerations. Using the pipe size below the optimum will obviously reduce the pipe capital cost but will require a high compression system to compress same flow through same pressure difference. This will invariably increase the cost of compression. This model linked with the compressor station model also predicts the effect of gas temperature on the required compression power and consequently selects a suitable gas turbine as a driver.

The continuous flow of natural gas in a pipeline is made possible by the help of compressor stations which boost the pressure at a predetermined interval along a pipeline. These stations are generally made up of basic components such as compressor and driver units, scrubber/filters, cooling facilities, emergency shutdown systems, and an on-site computerized flow control-Supervisory Control and Data Acquisition (SCADA) and dispatch system that maintains the operational integrity of the station [5].

This module computes the required compressor power to compress a certain flow through a specified pressure ratio. It is made robust enough to establish the optimum compressor station position along a pipeline, calculate the number of main valve station all depending on the length of pipeline.

VI. Economic Issues

Cost is an important element in the design, construction and operation of a natural gas pipeline system [6]. The development of a gas transmission pipeline network consumes a huge investment. The two main cost components are those related to the pipeline system and the cost related to compressor system [7]. The diameter and length of the pipeline controls the material cost of pipe, this increase with increase in these parameters. The pipe material cost can be obtained from 4.

$$PMC = 0.0246(D - t)tLC \quad (4)$$

The compressor station cost includes the cost of right of way (ROW), main valve and meter stations and telecommunication and SCADA. The most significant cost pertains to the operation of the pipeline system, this consist primarily of annual energy cost of running the system. The fuel consumed by the gas turbine is an output data from the performance simulation of the gas turbine. This is used to calculate in energy terms the annual energy required to run the gas turbine.

VII. Module Development and Integration

The gas turbine performance simulation, compressor station, pipeline and economic modules are integrated as shown in Fig. 3. The economic module which is the heart of the present study was developed in subroutines of FORTRAN code.

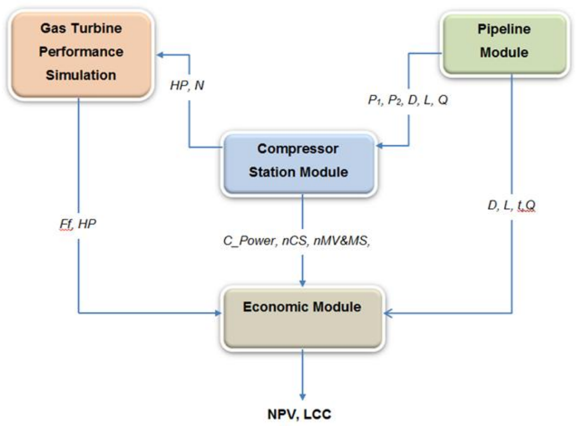

Fig. 3. Integrated techno-economic modules for gas pipeline

Receiving important data from the pipeline, compressor station and a gas turbine simulation models as shown in Fig. 3, the economic module computes the capital cost as it relates to all the equipment, operating and maintenance cost for the entire life of the project. The module takes into accounts the degradation of gas turbine which could affect its fuel consumption as the years roll by. The module computes the LCC of the system by establishing the present values of all the costs associated with the project over its useful life. It finally presents the net present values of the cash flow all through the life of the project. The results are presented in the results and discussion section of this paper. The economic assumptions made in this paper are also presented in TABLE II.

TABLE II: Economic Assumptions

Parameters	Value
Interest rate on Loan	10%
Production Life	20 years
Equity	20% of capital
Discount rate	10%
Federal Income tax rate	30%
Year to commission	3 years

VIII. Results and Discussions

The effect of varying pipe sizes and gas temperature at inlet into the compressor station on drive power is presented in Fig. 4. The drive power increases with increase gas inlet temperature to maintain a constant throughput. The efficiency of the overall compression process is reduced; an improvement in the efficiency of compression could be achieved by cooling the gas before a stage of compression [8]. A drive power of 34.04 MW is required for a throughput of 4.5 Mm3/day through a 24 inch (609.6 mm) pipe size. A gradual reduction in drive power is noticed with increase pipe size until a pipe size above 1000 mm where the drive power seems constant. This suggests ane economic pipe size of 609.6 (24”) for a throughput of 4.5 Mm3/day. A conclusive statement or result of economic pipe size for a particular flow can only be established through the results from the economic module.

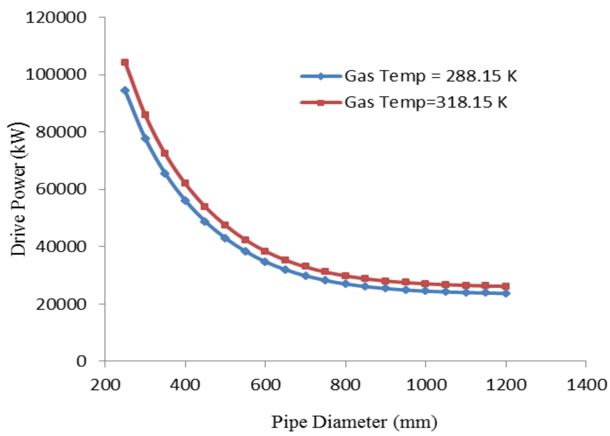

Fig. 4. Graph of drive power versus pipe diameter

Fig. 5 shows the effect of pipe sizes on the two main cost components viz pipe material cost and the operating cost and the comparative effect on the economics of the entire project. For a pipe size of 1219.2 mm (48 inch) the pipe material cost is $109 million and the operating cost is $420 million for gas price of $5.0/GJ. Reducing the pipe size for the project to 609.6 mm will give a saving of $55.1 million in pipe material cost but an increase in operating cost of approximately $188 million for a gas price of $5.0/GJ or $301.5 million for a gas price of $8.0/GJ is incurred. This shows that although a saving in pipe material is obtained by reducing the pipe size, this saving is far less than the increase in operating cost which makes the under sizing of pipe economically unviable and negates the profitability of the entire project.

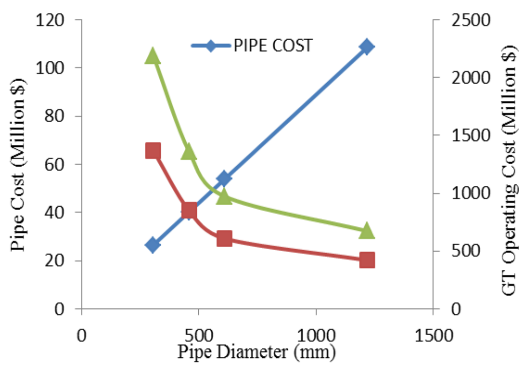

Fig. 5. GT operating cost and pipe cost variation with pipe diameter

Fig. 6 and Fig. 7 presents the effect of throughput on the Net Present Value (NPV) which is the appraisal technique used in this research. The NPV indicates whether a project is economically viable or profitable over a period of time or not. For a throughput of 4.5 Mm^3/day the NPV is $1548.1, $1663.5, $1675.4 million employing 304.8 mm, 609.6 mm and 1219.2 mm pipe sizes respectively. For an increase in throughput to 6.5 Mm^3/day, the NPV is $2191.4, $2390.4, $2438.5 million using 304.8 mm, 609.6 mm and 1219.2 mm pipe sizes respectively. It is seen that generally the NPV increases with increase in throughput. An increase of 2 Mm^3/day gave rise to $726.9 million increase in NPV.

Fig. 7 shows that for any increase in throughput there is a corresponding increase in drive power required which consequently means an increase in the operating and capital

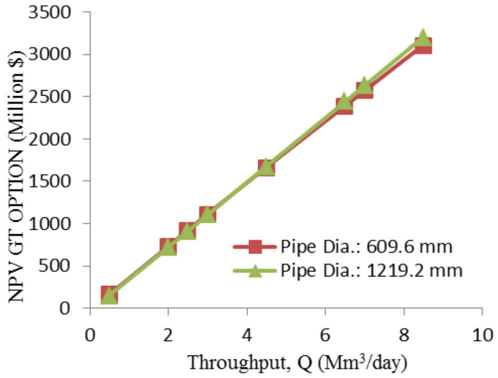

Fig. 6. NPV against gas flow rate for varying pipe sizes.

investment. The huge increase in NPV, despite the increase in capital and operating costs, is due to large economies of scale attributed to the natural gas pipeline system [9]. The NPV also increases with increase in pipe sizes for the same throughput. This is because any increase in pipe size gives a reduction in the drive power required and, consequently, lower capital and operating costs.

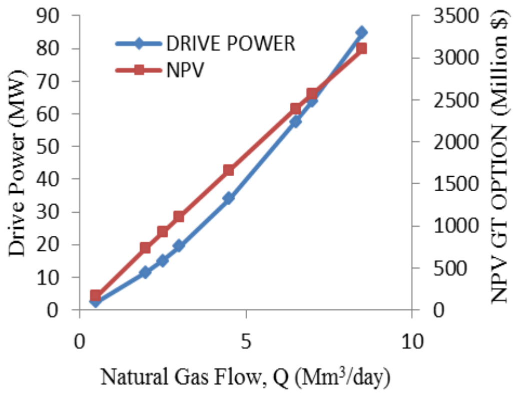

Fig. 7. Drive power and NPV against gas throughput

Fig. 8 shows the effect of varying discount rate on NPV for different throughput. For a throughput of 4.5 Mm^3/day, the NPV is $3.09 Billion at a discount rate of 5 % and 1.03 billion at a discount rate of 15 %. At a discount rate of 5%, the NPV is $291 million and $4.44 billion for 0.5 Mm^3/day and 6.5 Mm^3/day respectively. This huge difference of $4.15 billion is reduced to $491 million at a discount rate of 30%. Since discount rate is the rate at which future value is discounted, it follows that an increase in discount rate will obviously reduce the NPV.

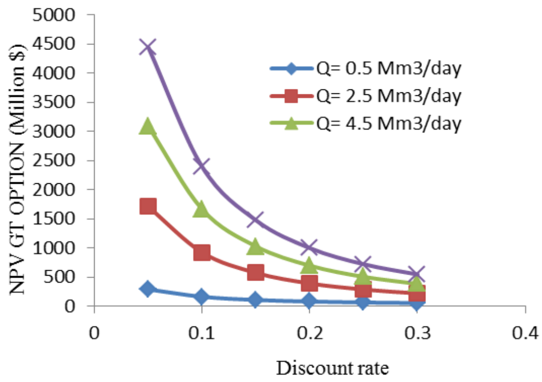

Fig. 8. NPV against discount rate for varying throughput

Fig. 9 presents the operating cost of the gas turbine against the natural gas throughput for two pipeline sizes. The operating cost increases with increase throughput, this is as a result of increased gas turbine power required to maintain the pressure under varying throughput. For a throughput of 4.5 Mm^3/day, the gas turbine operating cost is $608.2 million and $419.7 million for 609.6 mm and 1219.2 mm pipe sizes respectively. This is about 30% rise in operating cost.

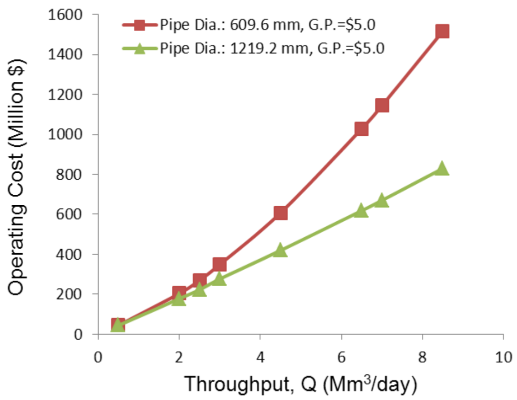

Fig. 9. Operating cost natural gas throughput.

Fig. 10 shows the total cost for the power plant against throughput. The total cost comprise operating cost and capital cost

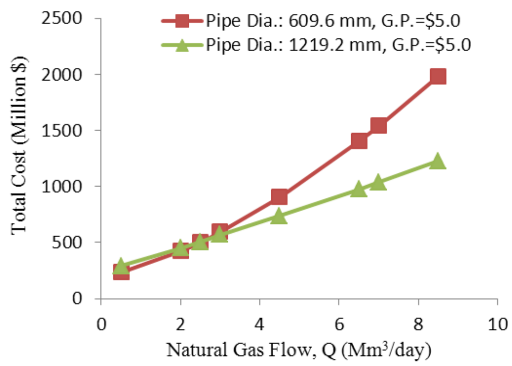

Fig. 10. Total cost against natural gas throughput.

Fig. 11 presents the effect of throughput on gas transportation cost for varying pipe sizes. The transportation cost is $0.10/$m^3$, $0.11/$m^3$ and $0.15/$m^3$ at $5.0/GJ gas price for 0.5 Mm^3/day through 304.8 mm, 609.6 mm and 1219.2

mm pipe sizes respectively. The Fig depicts the optimum natural gas flow for each pipe sizes and this defines the economic pipe size.

The economic pipe size for 0.5 Mm^3/day is 304.8 mm (12”), as shown in Fig. 9, this is because the huge pipe cost for large pipe sizes control the overall cost at this point. For a 2.5 Mm^3/day throughput, the transportation cost is \$0.048/m^3, \$0.035/m^3, and \$0.039/m^3 at \$5.0 gas price and through pipe sizes of 304.8 mm (12”), 609.6 mm (24”) and 1219.2 mm (48”) respectively.

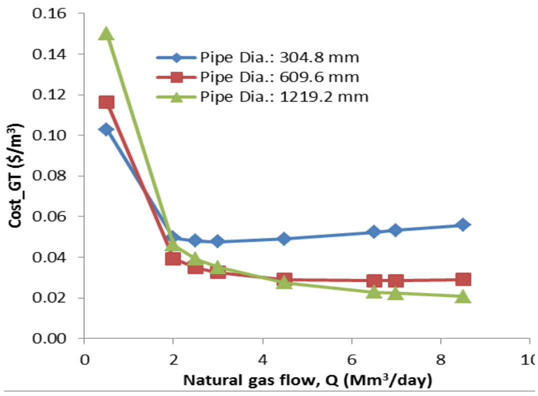

Fig. 11. Transportation cost per unit of gas against throughput for varying pipe sizes

As the flow increase the trend of the effect changes and small pipe sizes become less economical, and large pipe sizes become more profitable. There exist a changing point in the inter-play between pipe material cost and the compression cost. At very high throughput such as 7.0 Mm^3/day, it is noted that a 1219.2 mm (48”) pipe size continue to take the lead in economic profitability as it presents the lowest transportation cost. For each of the pipe sizes a point is noted which is the flow where they present least cost and beyond this point there is noticeable rise in the transportation cost. Although this result has not reached the minimum of 1219.2 mm pipe sizes, it is believed that beyond 8.5 Mm^3/day, a point exist where the transportation cost will increase.

IX. Conclusion

A Techno-economic model which performs the analyses of natural gas pipelines and compressor stations and the economics of the system has been presented. The model has been applied to a case study, and the results presented show the huge economic impact of pipe under sizing on the system, because pipe under sizing implies increase in driver power (GT Power requirement). The results from the model also gave large increase in NPV with expansion due to increase in throughput. This confirms the large economies of scale ascribed to the pipeline system in literature and other research findings. The economic pipe size for a 3.0Mm^3/day of natural gas was established to be 24 inch pipe because it yielded the minimum gas transportation cost of \$0.03/m^3 which is equivalent to \$0.9/GJ.

X. Nomenclature

C Cost per unit length
CC Combustion chamber
D Pipe diameter (mm)
e. Base of natural logarithms (e=2.718..)
E Pipe efficiency
F_f Fuel flow
G Gas gravity
GT Gas turbine
H_1 Upstream pipe elevation (m)
H_2 Downstream pipe elevation
L_e equivalent pipe length (km)
LCC Life cycle cost
Mm^3 Million cubic meter
MMscfd Million metric standard cubic feet per day
P_1 Upstream pressure (kPa)
P_2 Downstream pressure (kPa)
P_B Base pressure (kPa)
PMC Pipe material cost
Q Gas Throughput (m3/day)
Selevation adjustment parameter
t. Pipe thickness (mm)
T_B Base temperature (K)
T_f Average gas flow temperature (K)
Z Gas compressibility.

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