

CRANFIELD UNIVERSITY

OJO OLUWATAYO BABATOPE

INTRODUCTION OF SOCIAL BENEFITS TO THE TERA - GAS
TURBINES AND PIPELINES

SCHOOL OF AEROSPACE, TRANSPORT AND
MANUFACTURING
Centre for Propulsion and Thermal Power Engineering

DOCTOR OF PHILOSOPHY
Academic Year: 2022 - 2023

Supervisor: Professor Pericles Pilidis
Associate Supervisor: Dr Uyioghosa Igie
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ABSTRACT

The aim of this work is the techno-economic and environmental risk analysis (TERA) of the Trans-Saharan Gas Pipeline on gas turbine compressor stations. A pipeline project encompasses many aspects, viz., choice of compressor station location, power of each compressor station, compressor station availability, pipeline sizing, and it includes socioeconomic impacts. Therefore, this research considered the impacts of engine availability, compressor station location, and socioeconomic impact in the TERA for pipelines while optimising for the lowest lifecycle cost.

The pipeline and gas compressor modules were evaluated considering segmented pipe length, elevation, and station location ambient temperature variation at varying flow conditions. The design and off-design points performance of the selected gas turbine models were simulated using Turbomatch to obtain essential performance data required for the techno socio-economic analysis. The unit availability was evaluated based on a developed local maintenance schedule and failure rate retrieved from literature studies. The analysis considered the social impacts and benefits of compressor station locations. A scenario-based techno socio-economic analysis was performed to show the sensitivities of the compressor station and pipeline systems to social and technical aspects of the project in terms of social benefits and availabilities. The economic model was developed based on social benefit algorithms and the variation in compressor station location ambient temperatures at varying flow conditions.

Results show compressor station system availabilities of 0.2542, 0.4657, and 0.9926 with corresponding lifecycle costs of \$22.22 billion, \$23.05 billion, and \$24.11 billion assuming a 15% discount rate for scenarios 1, 2, and 3, respectively. An increase in availability leads to a corresponding increase in the lifecycle cost estimate. The employment and road benefit ratios would increase by a factor of 10 and reciprocal of new locations. This ratio is for every 10 km decrease in the distance at each station location. Results show the significance of the modelling and optimisation approaches utilised in this research for

compressor station locations optimisation of the integrated pipeline TERA. This will guide decision-makers on the ultimate selection of engine configurations that will give the optimum lifecycle cost and socio-economic benefits at the optimised station locations.

Keywords: Compressor Station, Location Optimisation, Availability, Social Impact, Techno socio-economic, Ambient Condition, Lifecycle Cost, Gas Compressor, Employment Benefit, Road Benefit, Algorithm

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NOMENCLATURE

Symbols

a_{act}	Actual sound speed	m/s
a_{ref}	Sound speed at Reference condition	m/s
A	Pipeline cross sectional area	m ²
A	Vine presence factor	
A_C	Compressor station land-use area	km ²
A_f	Adjustment factor	
A_G	Gas compressor land-use area	km ²
A_K	Availability of compressor station K, K = 1, 2 ...18	
A_o	Operational Availability	
A_O	Other land-use area	km ²
A_p	Transmission pipeline land-use area	km ²
A_R	Road infrastructure land-use area, Travel area	km ²
A_s	System Availability	
A_s	Social influence area	km ²
A_t	Total CS and pipeline system land-use area	km ²
A_T	Gas turbine land use area	km ²
A_{t_n}	Turbo-compressor unit availability, no standby unit	
A_{t_s}	Turbo-compressor unit availability, standby unit	
A_u	Unit Availability	
A_{u_n}	Unit Availability, no standby unit	
A_{u_s}	Unit Availability, standby unit	
A_{ugc_n}	Gas compressor unit availability, no standby unit	
A_{ugc_s}	Gas compressor unit availability, standby unit	
A_{ugt_n}	Gas turbine unit availability, no standby unit	
A_{ugt_s}	Gas turbine unit availability, standby unit	
B	Base time	minute/hectare
bhp	Gas compressor power	horsepower
c	Non-wage labour cost	
C	Pipe material cost	\$/metric ton
C	Engine creep life	hours
C_{dp}	Expected engine life	hours
C_i	Climatic index	
c_p	Specific heat at constant pressure	KJ kg ⁻¹ K ⁻¹
CF	Annual net cash flow	\$
CF_a	Annual cash outflow	\$

CF _j	Net cash flow for year j	
C ₀	Initial Capital Investment	\$
D	Pipeline diameter, <i>travel distance</i>	mm, km
D	Sum of diameter of trees per hectare > 180 cm	
D _a	Total annual downtime	hours
D _c	Drainage unit cost	\$/km
D _n	Downtime per unit failure, no standby unit	hour/failure
D _s	Downtime per unit failure, standby unit	hour/failure
D _s	Population density	Person/km ²
D _{t_n}	Unit total downtime, no standby	hour
D _{t_s}	Unit total downtime, standby	hour
e	Pipeline internal roughness, <i>Euler's number</i>	mm, 2.7183
E	Pipeline efficiency	%
E _c	Job index construction and installation, job cost	job-yr./MW, \$
E _{cf}	Earthwork unit cost for flat terrain	\$/km
E _{ci}	Earthwork unit cost	\$/km
E _{cm}	Earthwork unit cost for mountainous terrain	\$/km
E _{cr}	Earthwork unit cost for rolling terrain	\$/km
E _f	Earthwork volume for flat terrain	m ³ /km
E _j	Employment cost	\$
E _m	Earthwork volume for mountainous terrain	m ³ /km
E _M	Employment index operation and maintenance	job/MW
E _r	Earthwork volume for rolling terrain	m ³ /km
EX _f	Excavation rate for flat terrain	km/hour
EX _m	Excavation rate for mountainous terrain	km/hour
EX _r	Excavation rate for rolling terrain	km/hour
f	Pipeline friction factor	
f _o	Frequency of overhauls	
F	Failure rate	failure/hour
F	Minutes per 30 cm diameter for trees > 180 cm diameter	
F _{ac}	Annual fuel consumption cost	\$
F _c	Correction factor for gas turbine driven compressor	
F _f	Fuel flow	kg/s
F _{lc}	Lifecycle fuel consumption cost	\$
F _u	Fuel cost per kg of fuel	\$/kg
G	Gas gravity	
G _p	Gas price	\$/MMBtu
GC _t	Total gas compressor cost	\$
GT _c	Gas turbine capital cost	\$

GT_{eq}	Gas turbine equipment cost	\$
h	Heat transfer coefficient	
H_1	Upstream elevation	m
H_2	Downstream elevation	m
H_{DP}	Polytropic head at the design point	
H_{OEM_DP}	Polytropic head at design point from OEM	
H_p	Polytropic head	kJ/kg
H_{SF}	Scaling factor for polytropic head	
H_v	Gas higher heating value	Btu/m ³
I_s	Income tax rate	%
j	Year of project cash flow	
J	Job	
J_C	Annual jobs in construction and installation	job
J_I	Compressor station unit lifecycle job	job
J_{local}	Local jobs	job
J_M	Annual jobs in operation and maintenance	job
J_s	Compressor station and pipeline system lifecycle	job job
J_t	Total annual jobs per 10000 population	job/person
k	Isentropic exponent	
k_{act}	Actual polytropic exponent	
k_{ref}	Polytropic exponent at Reference condition	
K	Number of units shut down	
L	Pipe length	km
L_A	Road infrastructure area per km of road length	km ² /km
L_c	Techno-economic lifecycle cost	\$
L_c	Pipe culvert length per km of road length	m/km
L_e	Pipeline equivalent length	km
L_s	Location characteristics	
L_T	Techno socio-economic lifecycle cost	\$
LU_C	CS and pipeline component land-use impact area	km ² /MW
LU_R	Road infrastructure impact area	km ² /MW
m	Establishing alignments	\$/mile
$m, \dot{m}$	Mass flow rate	kg/s
M	Gas compressor and gas turbine power margin	
M	Minutes per tree	
$\dot{m}_{act}$	Actual mass flow rate	kg/s
M_{ac}	Annual maintenance cost	\$
M_{afc}	Annual fixed maintenance cost	\$
M_{amc}	Annual availability-based major maintenance cost	\$
M_{avc}	Annual availability-based variable maintenance cost	\$

$\dot{m}_c$	Corrected mass flow	
$\dot{m}_{c_DP}$	Corrected mass flow at the design point	
$\dot{m}_{c_SF}$	Scaling factor for corrected mass flow	
$\dot{m}_{c_OEM_DP}$	Corrected mass flow at design point from OEM	
M_f	Fixed maintenance cost factor	\$/kW-year
m_i	Coefficient for flat, rolling, or mountainous terrain	
M_{lc}	Lifecycle maintenance cost	\$
M_{lfc}	Lifecycle fixed maintenance cost	\$
M_{lmc}	Lifecycle availability-based major maintenance cost	\$
M_{lvc}	Lifecycle availability-based variable maintenance cost	\$
M_v	Variable maintenance cost factor	\$/MWh
M_{v1}	Maintenance cost factor 1	\$/MWh
M_{v2}	Maintenance cost factor 2	\$/MWh
$M\&S$	Marshall and Swift cost index	
n	Establishing cross-section limits	\$/mile
n	Polytropic exponent, project duration	
n_i	Constants for flat, rolling, or mountainous terrain	
N	Total number of installed units	
N	Number of trees per hectare	
N_c	Number of culverts per road length	culverts/km
N_t	Number of road trips	trips
η_{DP}	Polytropic efficiency at design point	
η_{OEM_DP}	Polytropic efficiency at design point from OEM	
η_{SF}	Scaling factor for polytropic efficiency	
O_f	Operational period	hours
P_{aux}	Auxiliaries cost	\$
P_m	Annual preventive maintenance downtime	hour
p	Travel time saved at expense of work done while travelling	
P	Total pressure	kPa
P_{act}	Actual pressure	kPa
P_{avg}	Average pipeline pressure	kPa
P_b	Base pressure	kPa
P_c	Critical pressure	kPa
P_c	Pavement unit cost	\$/km
P_{c_w}	Pipe coatings and wrapping cost	\$/feet
P_1, P_d	Pipe inlet pressure, GC discharge pressure	kPa
P_2, P_s	Pipe outlet pressure, GC suction pressure	kPa
P_g	Annual gas production	MMm ³
P_G, P_{GC}	Gas compressor power	kW

P_{GT}, P_T	Gas turbine power	MW
P_i	Gas compressor installation cost	\$
P_i	Pipeline project initial cost	\$
P_{mat}	Pipeline material cost	\$
P_p	Gas compressor purchased cost	\$
P_r	Production rate	m ³ /hour
P_s	Population	Persons
P_t	Total pipeline cost	\$
P_{to}	Total project capital expenditure	\$
$P(K)$	Station availability	
P_{ref}	Reference pressure	kPa
PR_{DP}	Pressure ratio at design point	
PR_{OEM_DP}	Pressure ratio at design point from OEM	
PR_{SF}	Scaling factor for pressure ratio	
ΔP	Pipeline pressure drop	kPa
q	productivity of work done while travelling to the workplace	
q	Cost per linear metre of culvert	\$/m
$Q, \dot{Q}$	Volumetric flow rate, heat transfer rate	m ³ /day, KJ/s
Q_{act}	Actual volume flow rate	m ³ /hour
r	Discount rate, travel time saved used for leisure	
r_l	Estimated lost revenue per hour	\$/hour
r_s	Social discount rate	
R	Gas constant	KJ kg ⁻¹ K ⁻¹
R_{act}	Actual gas constant	KJ kg ⁻¹ K ⁻¹
R_B	Road benefit	
R_c	Road construction cost	\$
Re	Reynolds number	
R_g	Road gradient	
R_g	Gross annual revenue	\$
R_l	Lost annual revenue	\$
R_n	Overhaul and replacement times, no standby unit	hour
R_{net}	Net annual revenue	\$
R_s	Overhaul and replacement times, standby unit	hour
R_o	Universal gas constant	KJ kg ⁻¹ K ⁻¹
R_{ref}	Gas constant at reference condition	KJ kg ⁻¹ K ⁻¹
R_t	Lifecycle road tax revenue	\$
R_t	Total annual revenue	\$
R_{uc}	Road construction unit cost	\$/km
s	Elevation adjustment parameter	

shp	Shaft horsepower	horsepower
S	Annual salary per job, income level	\$/job
S _c	Socio-economic lifecycle cost	\$
S _c	Surveying and staking unit cost	\$/km
S _E	Existing level of wealth	\$
S _N	Employment Benefit	\$
S _p	Site preparation unit cost	\$/km
S _t	Compressor station and pipeline system job benefit	\$
S _t	Staking unit cost	\$/km
S _u	Surveying unit cost	\$/km
SA _G	Gas compressor percentage share of area	%
SA _O	Other percentage share of area	%
SA _p	Transmission pipeline percentage share of area	%
SA _R	Road infrastructure percentage share of area	%
SA _t	Percentage share of the total land-use equivalent area	%
SA _T	Gas turbine percentage share of area	%
SU _c	Surfacing cost	\$/m ²
t, l	Project lifecycle	year
t _e	Travel time for existing road	hour
t _n	Travel time for new road	hour
t _s	Lifecycle downtime	hour
T	Total temperature, <i>pipe wall thickness</i>	K, mm
T	Total tractor time	hour/km
T _A	Ambient temperature at CS location A	K
T _{act}	Actual temperature	K
T _{amb}	Ambient temperature	K
T _{avg} , T _{av}	Average gas flow temperature	K
T _b	Base temperature	K
T _B	Ambient temperature at CS location B	K
T _c	Clearing time	minutes/hectares
T _c	Critical temperature	K
T _C	Construction and installation duration	years
T _{C,a}	Ambient temperature at actual CS location C	K
T _{C,h}	Ambient temperature at hypothetical CS location C	K
T _D	Ambient temperature at CS location D	K
T _{DP}	Discharge temperature at the design point	
T _e	Travel time cost for existing road	\$
T _E	Ambient temperature at CS location E	K
T _f	Gas flow temperature	K

T_F	Ambient temperature at CS location F	K
T_{1f}	Inlet gas flow temperature	K
T_{2f}	Outlet gas flow temperature	K
T_i	Terrain index	
T_n	Travel time cost for new road	\$
T_n	Overhaul and replacement times, no standby unit	hour
T_{OEM_DP}	Discharge temperature at the design point from OEM	
T_p	Piling time	minutes/hectare
T_r	Real station ambient temperature	K
T_{ref}	Reference temperature	K
T_s	Overhaul and replacement times, standby unit	hour
T_{SF}	Scaling factor for discharge temperature	
ΔT	Average temperature difference	K
u, v	Distance between compressor station location	km
U_e	Travel speed for existing road	km/hour
U_n	Travel speed for new road	km/hour
U_n	Unit running period, no standby	hour
U_o	Operating period	hour
U_s	Unit running period, standby	hour
v	Specific molar Volume	m ³ /kmol
v	Number of registered vehicles	
V	Tractor owning and operating cost	\$/hour
w	Gross wage rate, first-year tax rate	\$
W	Road width	km
W_p	Transmission pipeline land-use width	km
w_s	Social benefit width	km
x	Outer diameter, <i>road location cost</i> , <i>Altitude</i>	inches, \$/mile, <i>m</i>
X	Hard wood or density factor	
y	Volume fraction, pipeline installation cost	-, \$/mile
y	Traverse, profile, x-section costs, <i>Altitude</i>	\$/mile, <i>m</i>
z	Annual tax rate, <i>Altitude</i>	\$, <i>m</i>
Z	Compressibility factor	
Z_{act}	Actual compressibility factor	
Z_{ref}	Compressibility factor at reference condition	

Greek Symbols

μ	Gas dynamic viscosity	Poise
ρ	Gas density	kg/m ³
η	Polytropic efficiency	

ϵ Relative pipe roughness

Subscripts

1	Inlet, upstream, discharge
2	Outlet, downstream, suction
a	Annual, average, actual
A	Area
ac	Annual cost
act	Actual
afc	Annual fixed cost
amb	Ambient
amc	Annual maintenance cost
av	Average
avc	Annual variable cost
avg	Average
b	Base
B	Benefit
C	Critical, corrected, compressor, cost, component, clearing
c	culvert
C	Construction and installation
cf	Cost flat
cm	Cost mountainous
cr	Cost rolling
C_DP	Corrected design point
C_OEM_DP	Corrected original equipment manufacturer design point
C_SF	Corrected scaling factor
c_w	Coating and wrapping
d	Discharge
e	Equivalent, existing
eq	Equivalent
E	Existing
f	Flow, factor, flat
1f	Inlet flow
2f	Outlet flow
g	Gas, gradient
G	Gas compressor
h	hypothetical
i	Component, installation, index
j	Year of project cash flow, component

l	Lifecycle, lost
lc	Lifecycle cost
lfc	Lifecycle fixed cost
lmc	Lifecycle maintenance cost
lvc	Lifecycle variable cost
M	Operation and maintenance
M, m	Maintenance
m	mountainous
mat	material
n	No standby, new
N	Benefit
o	Operation, Initial, universal, other
p	Polytropic, price, pressure, purchased, pipeline
p	Piling, preparation
r	rolling
R	Road
ref	Reference
s	Suction, inlet, social, standby, station
SF	Scaling factor
t	Total, tax, topography
to	Total
T	Turbine, total
u	Unit
uc	Unit cost
v	Value, variable

Abbreviations

aux	Auxiliary
CF	Cash flow
CSA	Cost savings approach
DP, dp	Design point
EBR	Employment benefit ratio
MDT	Mean maintenance downtime
max	Maximum
min	Minimum
MPF	Value of extra output due to reduce travel fatigue
MPL	Marginal product of labour
MTBM	Mean time between maintenance
MW	Molecular weight
OEM	Original equipment manufacturer

SF	Scaling factor
GC	Gas compressor
NPV	Net present value
PR	Pressure ratio
RBR	Road benefit ratio
TERA	Techno-economic and Environmental Risk Analysis
TET	Turbine entry temperature
VL	Value to the employee of leisure time relative to travel time
VTTS	Value of travel time savings
VW	Value to the employee of worktime at the workplace relative to travel time
WTP	Willingness-to-pay

1 INTRODUCTION

1.1 Background of the Research

According to [1], Nigeria proved natural gas reserves were estimated at 193.3 Trillion cubic feet. The statistics showed that Nigeria is the tenth and largest holder of proven natural gas reserves globally and in Africa, respectively. Europe consumed more than it produced with the difference imported from other countries with enough supplies. It is believed that the demand for natural gas in Europe is expected to increase in the coming years [2][3] despite the current attention being given to renewable energy. Natural gas is the preferred choice to other fossil fuels due to its cleanliness, low emission, low environmental pollution, and continuous application in the industrial, transportation, residential, electrical power, and commercial sectors. Thus, a feasible scheme needs to be implemented to improve natural gas supply to Europe and other parts of the world with increased demand for this product through an executable infrastructural project. The proposed Trans-Saharan Gas Pipeline project is anticipated at improving this supply of natural gas.

Nigeria and Algeria have proposed plans to construct the Trans-Saharan Gas Pipeline. The 4180 km pipeline would carry natural gas from the Niger Delta region, run north through Niger to Algeria's export terminal on the Mediterranean Sea and eventually supply natural gas to Europe [4]; [5]; [6]. The Trans-Saharan Gas Pipeline will minimise gas flaring and contributes to the World bank target of zero routine flaring by 2030 [7] since most of the natural gas produced in Nigeria is being flared due to lack of infrastructure to export the gas. Presently, Nigeria ranks among the top ten gas flaring countries in the world and data from [8] showed that about 7.4 billion cubic feet of gas was flared in 2018 and about 425.9 billion standard cubic feet of gas with an estimated value of about \$1.1 billion was flared in 2019 [9]. Natural gas estimated at \$1.24 billion, which could produce the annual electricity use of 804 million Nigerian citizens, was flared in 2020 alone [10]. Recently, the Trans-Saharan Gas Pipeline was mentioned in planning documents [11]; [12]; [13]. The Nigerian National Petroleum Cooperation affirmed

its commitment to the project to continue the ongoing Trans Nigeria Gas Pipeline, which has already reached an advanced stage of its development.

The global energy demand will grow by 30-40% by 2040 [14]. With the increase in the world energy demand for natural gas, compressor stations are needed for natural gas transportation in pipelines from the production site to the end-users. These compressor stations require prime movers as mechanical drivers for an efficient operation. A gas turbine engine is the promising prime mover option for this study. Given their small size and reliability, gas turbine engines are extensively used in pipeline installations. A particular challenge that arises is the selection of the power plants and the distance between compressor stations. These are profoundly affected by the design and environment in which the pipeline is laid. Nigeria is classified as a developing country. Thus, the impact of investments on the country's growth and development including the social context is important. A pipeline investment presents many challenges and opportunities, and much work has been devoted to the economic challenge.

Nasir et al. [15] looked at the economic implications of gas turbine deployment in the natural gas pipeline networks. They show that the gas power required is a function of pipe sizing that consequently affects the capital investment. Nasir [16] looked at the techno-economics of the gas turbine or electric motor drives in pipeline application. His study concluded that electric motor drives might initially seem better in terms of environmental pollution. But from the generation of electricity today and in the future, the use of electric motor contributes more to environmental pollution than the gas turbine. It may not be a feasible option for the interstate pipeline in locations with inadequate electricity supply. El-Suleiman [17] investigated TERA on CO₂ compression power requirements for gas turbine-driven pumps and compressors. The economic model was developed based on net present value. Tukur [18] investigated the techno-economics of gas turbine compressor stations in natural gas pipelines. His economic model was performed based on the lifecycle cost by assuming an availability of 100% and considering station local conditions. Aziaka [19] investigated the techno-economics of degraded gas turbines on pipeline application in given compressor station

locations. These studies are the only known work on TERA application in pipelines.

El-Shiekh [20] optimised the decision variables of natural gas transmission pipelines, including compressor stations, using the software Lingo to select the optimum decision variables to minimise the total capital cost. Olsen et al. [21] evaluated economic models for various drivers and driven equipment technologies in gas compression application for a project life of 20 years. The lifecycle cost of one large gas turbine was estimated as \$62.3 billion, \$68.3 billion for three smaller gas turbines and \$74.4 billion for three reciprocating engines at a 12% discount rate. However, it is pertinent to note that none of these studies examined by adapting TERA for pipelines:

1. The opportunities that arise in the social context
2. The impact of engine availability on the investment
3. An economic analysis using compressor station location as a decision variable

Thus, there exist knowledge gaps in the literature that this research intends to accomplish. To fill these identified gaps in knowledge, this research presents a successful application of pipeline TERA incorporating availability and social benefits models for the first time. The developed pipeline TERA framework is integrated with an optimiser that enables an economic analysis using the compressor station location as a decision variable to be performed for the first time. It sheds light on the sensitivity of compressor station location optimisation to the proposed project economic costs. It could help in forecasting for the first time the impact of availability on the life cycle cost, social benefits and economic performance of the compressor stations and pipeline systems.

The installation and operation of gas turbine compressor stations may experience acceptance or resistance by the local community stakeholders who oppose or support the negative or positive social impacts. Some negative social impacts are accident fatalities, the potential death of employees, and displacement of local communities from the compressor station locations. The positive social impacts are employment impact, road infrastructure impact, water infrastructure impact,

and provision of electricity. Thus, stakeholders' inclusion and impact on the project's planning process are essential. It is imperative to balance the main organisational goal with other social goals that soothe stakeholders' objectives while maximising profits with respect to the shareholders' objectives. Consequently, this study proposes a new approach to any compressor stations and pipeline projects design, development and management integrating techno-economic and socio-economic goals. The developed methods can guide the quantification of social impacts and socio-economic benefits during any compressor station's design and development stage for pipeline application and other related projects. The adopted scenarios could give policymakers insights and help select the best project alternative that will maximise the net positive social impacts and socio-economic benefits brought about by the gas turbine compressor station locations. It also guides the final decision on the techno socio-economic blueprint of the proposed Trans-Saharan Gas Pipeline project. The developed social benefits algorithms could play an essential role in the industry for stakeholders' goal evaluation.

A considerable component of the life cycle cost goes to the compressor stations and pipelines. It has been estimated that the compressor stations operating cost could constitute between 25% and 50% of the total company's operating budget [22]; [23]. Considering this, the lifecycle cost of the compressor stations and pipelines could represent values greater than 50% to 85% of the total company's operating budget. Thus, a slight enhancement of the compressor station availability could increase the project profitability by decreasing downtime, thus minimising the loss of revenue. Compressor station system availability analysis will help minimise the downtime costs while ensuring a continuous supply of natural gas to end-users. The developed availability methods will help minimise the loss in revenue and establish the installation of standby turbo-compressor units at some or all compressor station locations to minimise these losses arising from engine downtime. The adopted method could identify the subsystem's availabilities, which greatly impacts the overall compressor station system's availability. This will help decision-makers better understand the importance of the individual gas turbine and gas compressor subsystems on the overall

availability of the compressor station system, thus leading to practical resource and financial management.

This research presents a new analysis in terms of compressor station location optimisation. This study does quantify some social costs and benefits arising at the optimal compressor station location.

The outcome of this research can be easily applied in the industry, serve as a benchmark for policy analysis, and guide decision-making while improving the social benefits and cost effectiveness of the proposed Trans-Saharan Gas Pipeline and any pipeline projects.

1.2 Research Aim

This research aims to investigate the impact of the social context opportunities and engine availability on the specification, socio- and techno-economics of natural gas transportation in pipelines while focusing on compressor station location optimisation. The compressor stations are needed to be effectively placed at locations where they will deliver social benefits. This is one of the essential criteria required for stakeholders' goal evaluation and policy analysis to minimise economic cost and maximise profit.

1.3 Research Objectives

1. To model the pressure drops in the proposed Trans-Saharan Gas Pipeline and estimate gas compressor drive power requirement at design and off-design conditions by selecting suitable gas turbines as drivers for the gas compressors.
2. To determine the compressor station power requirement based on isothermal, intermediate and non-isothermal flow of natural gas in pipelines.
3. To analyse the design and off-design performance of selected gas turbines as prime movers for natural gas transportation in pipelines.
4. To analyse the concept and implication of availability on gas turbine operation and economics.

5. To determine the potential social impacts and social benefits of the compressor station locations along the pipeline routes.
6. Techno-economic and techno socio-economic optimisation of the distance and equipment used in the compressor stations as a function of the compressor station location, pipeline characteristics, availability, and social context. In this case, techno-economic integrates technical and economic aspects of the project, while techno socio-economic integrates the technical, social, and economic aspects of the project.

1.4 Problem Statement

The uneven distribution of natural gas has made it imperative to develop means of transportation from locations with abundant reserves to other areas. The increase in world natural gas consumption will require a considerable investment in new natural gas infrastructure that is efficient and safe. Natural gas transportation in pipelines over long distances is considered a cheaper and safer mode of gas transportation [2]. The proposed Trans-Saharan Gas Pipeline project is the motivation for this research. An efficient and reliable natural gas transportation will require the following conditions to be satisfied:

- ❖ Sufficient proved reserves of natural gas able to meet the demand requirements
- ❖ Lowest possible capital expenditure, operating expenditure, and lifecycle cost
- ❖ Availability of the equipment used in the compressor stations, including the gas compressors and gas turbines
- ❖ Positive social impact and social uplifts from the installation and operation of the system
- ❖ Able to meet organisational goals encompassing stakeholders

To meet these conditions, the following questions need to be answered:

- ❖ What gas compressor and gas turbine sizes are required at varying flow conditions dependent on the location ambient conditions at each compressor station location?

- ❖ What are the implications of availability on gas turbine operation and economics?
- ❖ How many compressor stations are needed along the pipeline routes? Where is their optimised location, and at what pipeline segments along the pipelines?
- ❖ What are the social impacts and social benefits of compressor station location along the pipeline routes? Are they positive and beneficial?
- ❖ Which turbo-compressor configuration has the lowest lifecycle cost and highest net present value?

1.5 Contributions to Knowledge

This research contributions to knowledge are:

1. TERA for pipeline application on gas compressor stations considering the first introduction of the social context opportunities and engine availability while optimising with compressor station location for the lowest lifecycle cost.
2. Development of a model and methodology for evaluating the social impacts and benefits of compressor stations along the pipeline routes.
3. Development of a model and methodology for evaluating the impact of engine availability on the techno-economics of natural gas transportation in pipelines.
4. Development of the techno-economic model and station location optimisation using SIMULINK.
5. Development of models leading to faster and more economical pipeline system specification, an improvement on the social and economic performance of the compressor stations leading to the best decision of selecting the most cost-effective engine configuration.
6. Models and methodology developed will serve as useful decision-making tools for the Nigerian government to design and develop the proposed Trans-Saharan Gas Pipeline project.

1.6 Thesis Structure

Chapter One presents an overview of the research background, aim and objectives, problem statement, contribution to knowledge, and thesis structure.

Chapter Two presents a detailed literature review on the compressor station and pipeline systems. The review focus on natural gas and transmission system, the design of gas transmission pipeline, centrifugal compressor, gas turbine and their availability, economic analysis, TERA and optimisation scheme, social impact analysis. Finally, the review is concluded by identifying research gaps and contributions to knowledge.

Chapter Three presents the research methodology based on the TERA framework. The methods utilised in the pipeline TERA for gas turbine compressor stations are described. The different modules that make up the adapted TERA framework and the approaches used by the optimiser for the optimisation studies are discussed.

Chapter Four presents the pipeline and gas compressor power estimation at isothermal, intermediate, and non-isothermal flow conditions. The impact of environmental conditions on gas compressor performance is described. Gas compressor performance maps are illustrated. Finally, gas compressor and gas turbine selection are discussed.

Chapter Five looks at the design and off-design performance simulation of the selected gas turbine models.

Chapter Six presents the impact of turbo-compressor availability on the techno-economics of natural gas pipeline transportation. The developed local maintenance schedules are shown. The units, station, and system availability are presented. The Chapter described the SIMULINK model of the TERA framework and explored the subsequent results obtained from the analysis.

Chapter Seven presents social benefits analysis and the integrated techno socio-economic scenarios. Job creation and Road infrastructure are explored.

Non-dimensional social uplifts are illustrated. Results are presented and discussed.

Chapter Eight presents techno-economic and techno socio-economic optimisation with compressor station location as the decision variable. SIMULINK and genetic algorithm optimisation procedures are described. The optimisation problem is formulated. Decision variable, objective function, and constraint are identified. Results are presented and discussed.

Chapter Nine presents the conclusions of the whole research and highlights some recommendations for future work.

2 RESEARCH BACKGROUND

2.1 Natural Gas and Transmission System

Natural gas is frequently being utilised for residential heating and cooking, electric power generation, transportation, and industrial application due to its low carbon dioxide emission and low environmental pollution compared to other fossil fuels. The share of natural gas in primary energy demand continues to rise, accounting for 24.7% in 2020 [1]. Consequently, the demand for natural gas will continue to increase despite the present attention being given to renewable energy. Thus, an efficient and reliable transmission system is needed to meet this demand from locations with abundant reserves to other areas.

2.1.1 Natural Gas Properties

Natural gas is classified into conventional and unconventional gas. Associated and non-associated gases are the two forms of conventional natural gas. Unconventional natural gas derived from coal, gas hydrates and gas shales contain a high proportion of natural gas, but its production process is more complex than conventional gas. Natural gas consists of hydrocarbon and non-hydrocarbon mixtures. The main constituent is methane, ethane, propane, butane, pentane, and traces of heavier hydrocarbons are other components. Nitrogen, carbon dioxide and hydrogen sulphide are among the non-hydrocarbon components.

Natural gas, an odourless, tasteless, and colourless gas is usually sold to the end-users within specified pressure limits and heating values. The natural gas heating value varies and is dependent on the constituent mixtures and the degree of impurities present in the gas. Table 2-1 shows the typical properties of natural gas.

Table 2-1 Typical Composition of Natural Gas (Adapted from [24]; [25])

Natural Gas Constituents	Volume Fraction (%)
Methane	70-99
Ethane	0-5
Propane	0-5
Butane	0-5
Pentane	0-5
Hexane	Trace-5
Heptane	Trace-5
Carbon dioxide	0-8
Oxygen	0-0.2
Nitrogen	0-15
Hydrogen Sulphide	0-5
Water	Trace-5

Pipelines operating conditions are significantly influenced by the natural gas properties and composition, which depend on the extraction period during the year, the production source, and treatment level [26]. Any change in the natural gas composition will ultimately affect its thermophysical properties. The properties of interest in this review are specific gravity, density, compressibility factor, viscosity, and specific heat.

2.1.2 Natural Gas Transmission System

Natural gas needs to be transported from locations with abundant reserves to other areas with high demand for this commodity. These locations may be thousands of kilometres apart. Thus, it is imperative to design an efficient transportation system able to ensure a continuous supply of natural gas that meet demands from the end-users under all conditions. Several methods of natural gas transportation from the location source to areas with high demands include pipelines, Liquefied Natural Gas, Compressed Natural Gas, Gas to Liquid, Gas to Commodity, Gas to Solids, and Gas to Wire [27]; [28].

A convenient method of transporting natural gas over long distances is by pipeline networks or by tankers in the form of Liquefied Natural Gas [29]; [30]. Liquefaction costs are the extra cost incurred by the Liquefied Natural Gas transportation mode no matter how far or near it is being transported. Thus, the pipeline

transportation network has been identified as one of the most efficient and economical methods of transporting natural gas to areas with high demands [31]. The European gas market gas-on-gas competition has taken the form of pipeline imports competing against Liquefied Natural Gas imports [1]; [32]. The world trade movement by pipeline accounted for 60.8% in 2020, representing about 755.8 billion cubic meters of natural gas transportation in pipelines [1]. The following information is needed to understand the context of a gas pipeline and compressor station system, including the models I have developed or adapted considering the scope of this research work.

2.1.3 Natural Gas Transmission Pipeline

It has been understood that transmission pipelines are one of the safest and most economical modes of natural gas transportation over long distances [23]; [33]; [34]; [35]. Natural gas transmission pipelines link the production source and the end-users. Thus, the operation of the various components is vital for the continuous availability of supply to meet variable demands.

The gathering, transmission and distribution pipelines are the three standard pipelines for natural gas transportation. The small diameter, low-pressure gathering pipelines are used for natural gas transportation from the production source to the processing facility or transmission system. The transmission pipelines vary in size and usually range from 4 to 56 inches in diameter [16]; [36] depending on their application. They are used to transport natural gas over long distances and are usually made of carbon steel to withstand the high pressure required for gas transportation. These pipelines require the installation of compressor stations at appropriate distances along the pipeline to ensure the pressure do not drop below the specified limit. The low-pressure distribution pipelines are typically made of plastic materials and used to transport natural gas to end-users through other storage facilities.

The major components of the natural gas transmission pipeline are transmission pipelines and compressor stations. Other components are metering stations, pressure regulators, valves, supervisory control, and data acquisition. Figure 2-1 shows a typical natural gas transmission pipeline system layout schematic

diagram showing compressor stations represented by CS and transmission pipelines as the major components.

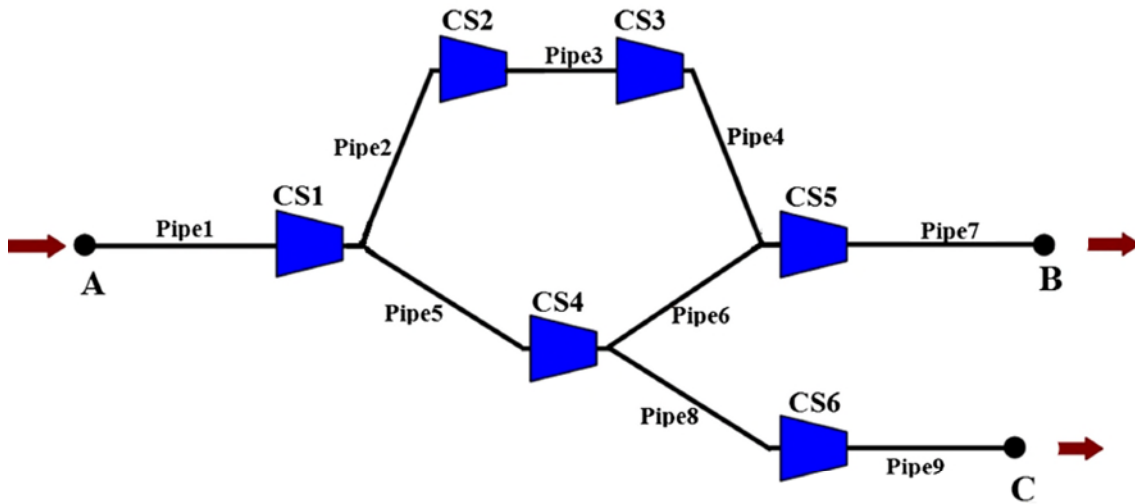


Figure 2-1 Typical Natural Gas Transmission System Layout [37]

2.1.4 Compressor Stations

Compressor stations are needed to transport a given amount of gas through long distances in pipelines due to pipeline pressures constraint. The locations of the compressor station and operating pressures are regulated by the available power, allowable pipe pressures, and environmental and geotechnical factors [38]. They are installed at different locations on the transmission pipelines to ensure the required pressure is maintained for gas transportation.

Compressor stations are one of the essential components of the transmission pipeline system. They are placed at strategic intervals along the pipeline to supply the pressure energy needed for constant gas flow and require between 10 to 40 acres of land [39]. Compressor stations consume about 3-5% of the total gas transported [30]; [40] and are usually installed within 150 to 200 km apart along the pipelines [18]; [41]. They accommodate compressors driven by prime movers. The prime mover options are electric motors or gas turbines. Nasir [16] has looked at the techno-economics of using an electric motor or a gas turbine as the prime mover on a natural gas pipeline. Other components include scrubbers and

filters, cooling systems, supervisory control and data acquisition, compressor station housing and lubrication system.



Figure 2-2 Typical Compressor Station [42]

Figure 2-2 shows a typical compressor station with three gas compressors arranged in parallel. Figure 2-3 shows compressor stations layout and pipe segments schematic diagram with five compressor units arranged in parallel at each station, including a gas plant supply node and a delivery terminal at the demand node.

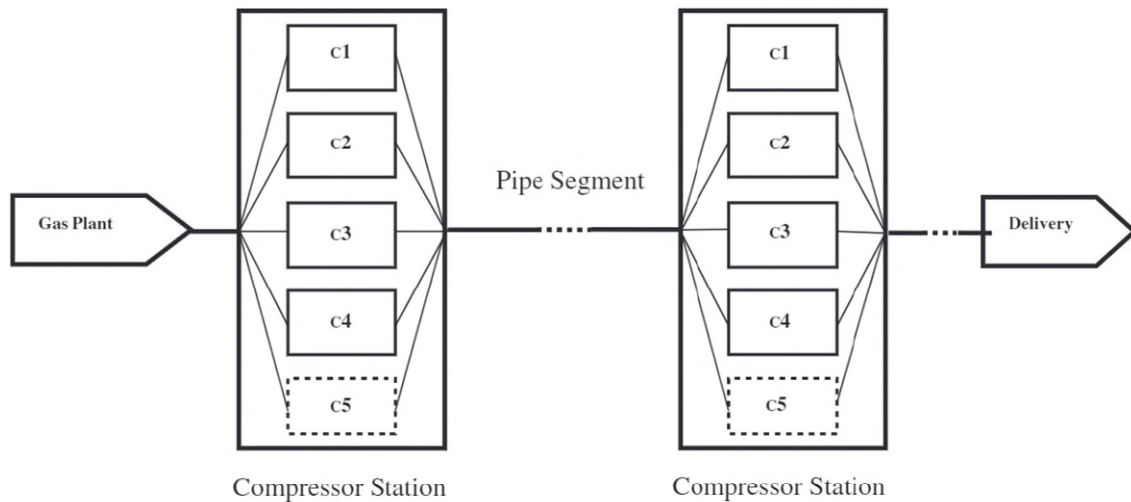


Figure 2-3 Compressor Stations and Pipe Segments Schematic [33]

2.1.5 Meter Stations and Regulators

The essential components of meter stations are fittings, meters, instrumentation, valves, and controls. They measure the natural gas flow rate through the transmission pipeline [38]. Pressure regulators are installed to regulate or control the pressure of the natural gas pipeline adequate for delivery to end-users.

2.1.6 Mainline Valve Stations

Valves are installed at specific intervals for operational and safety purposes within the transmission pipeline network [43]. They are valuable for maintenance and repair operations as they can shut down the flow of natural gas through faulty pipeline sections. These sections can be isolated by closing the mainline valves at that section.

2.1.7 Supervisory Control and Data Acquisition Systems

Supervisory control and data acquisition control the temperatures, pressures, and flow rates along the transmission pipeline. They can monitor and operate the compressor station and transmission pipeline systems remotely from a central control centre [38]. Supervisory control and data acquisition systems are also used to generate operational data, check device status and collect gas consumption information from the compressor station and natural gas pipeline network systems [43].

2.2 Design of Gas Transmission Pipeline

The effective design of a gas transmission pipeline system will be dependent on the joint efforts of the multidisciplinary team in engineering and allied disciplines. An efficient gas transmission network can save at least 20% of the natural gas consumed by the compressor stations [40]. Thus, designing an efficient and effective natural gas pipeline network is vital for meeting end-users demand and minimising transportation costs. The size and complexity of natural gas pipeline networks have increased with increasing demand. Consequently, it is essential that decisions regarding the design of a new natural gas transmission network or the expansion of an existing one are made about their long-term benefits [44]. Marcoulaki et al. [45] have presented a framework for designing pipeline systems intended for fluid transmission, including natural gas by integrating optimisation technologies with geographical information, process simulators and equipment databases. Their proposed approach was applied to designing a pipeline traversing mountainous terrain. They observed that the use of different geographical data affects pipeline design and investment.

It is essential to consider parameters such as pipe diameter, length, elevation, and the properties of the natural gas being transported in pipeline design. An optimisation is efficient if a slight improvement in the system can result in significant savings. Thus, optimisation for the design of the gas transmission pipeline system will be efficient if a slight improvement in the pipeline system results in significant savings. Sanaye and Mahmoudimehr [46] have proposed an efficient optimisation program for the optimal design of a natural gas transmission network. In the optimisation study, they considered various design parameters, including the network layout, pipe diameters, supply and delivery pressures, number, and location of compressor stations on each pipeline. Nasir [16] stated that the pipeline flow rates are dependent on the pipe diameter, length, pressure drop due to friction, gas suction temperature, gas suction pressure and gas properties.

2.2.1 Weymouth Equation

Many equations have been developed to predict natural gas transmission pipeline performance. These equations show the gas flow rate, pipeline diameter, length, gas properties, suction, and discharge pressures. Among these equations, the Weymouth equation has been shown to be the most conservative equation that predicts the highest pressure drop at any flow rate with a given pipeline efficiency [38]. Due to its simplicity and accuracy, it is usually used for high gas flow rate, high pressure, and large diameter pipelines.

The Weymouth gas flow equation in S.I units is stated as follows:

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

Where:

Q = Volumetric flow rate, (m³/day)

E = Pipeline efficiency, %

T_b = Base temperature, K

P_b = Base Pressure, kPa

P₁ = Inlet Pressure, kPa

P₂ = Outlet Pressure, kPa

T_f = Gas flow temperature, K

L_e = Pipeline equivalent length, km

G = Gas gravity, dimensionless

Z = Compressibility factor, dimensionless

D = Pipeline diameter, mm

e = 2.71828 (Euler's number)

s = Elevation adjustment parameter

Equation (2-1) defines the basic relationship between the gas flow rate and the pressure drop through a pipeline segment with upstream and downstream endpoints. The elevation adjustment parameter s , considers the difference in elevation between each pipe segment. It is expressed as follows:

$$s = 0.0684G \left(\frac{H_2 - H_1}{T_f Z} \right) \quad (2-2)$$

Where:

H_1 = Upstream elevation, m

H_2 = Downstream elevation, m

The equivalent length L_e , is expressed in terms of the elevation adjustment parameter and is given by:

$$L_e = \frac{L(e^s - 1)}{s} \quad (2-3)$$

Where:

L = Pipe length, km

Further details of the parameters in Equation (2-1) will be discussed in chapter four.

2.3 Centrifugal Compressor

Compressors are used for gas transmission in pipelines to increase gas pressure. Centrifugal and reciprocating compressors are the two major types of compressors. Both compressors utilize electric motors as drivers. However, reciprocating compressors can also use reciprocating gas engines as drivers. Moreover, centrifugal compressors are usually driven by gas turbines. The major difference is that reciprocating gas engines convert pressure into rotating motion using pistons driven by crankshafts. In contrast, gas turbines utilise the pressure from fuel combustion to rotate a turbine and produce power. Centrifugal compressors can be used for discharge pressures of up to 70 MPa and varying operating speeds of about 14 000 rpm for 3.7 MW units and 8 000 rpm for 15 MW

units [25]. Figure 2-4 shows the application ranges for reciprocating and centrifugal compressors.

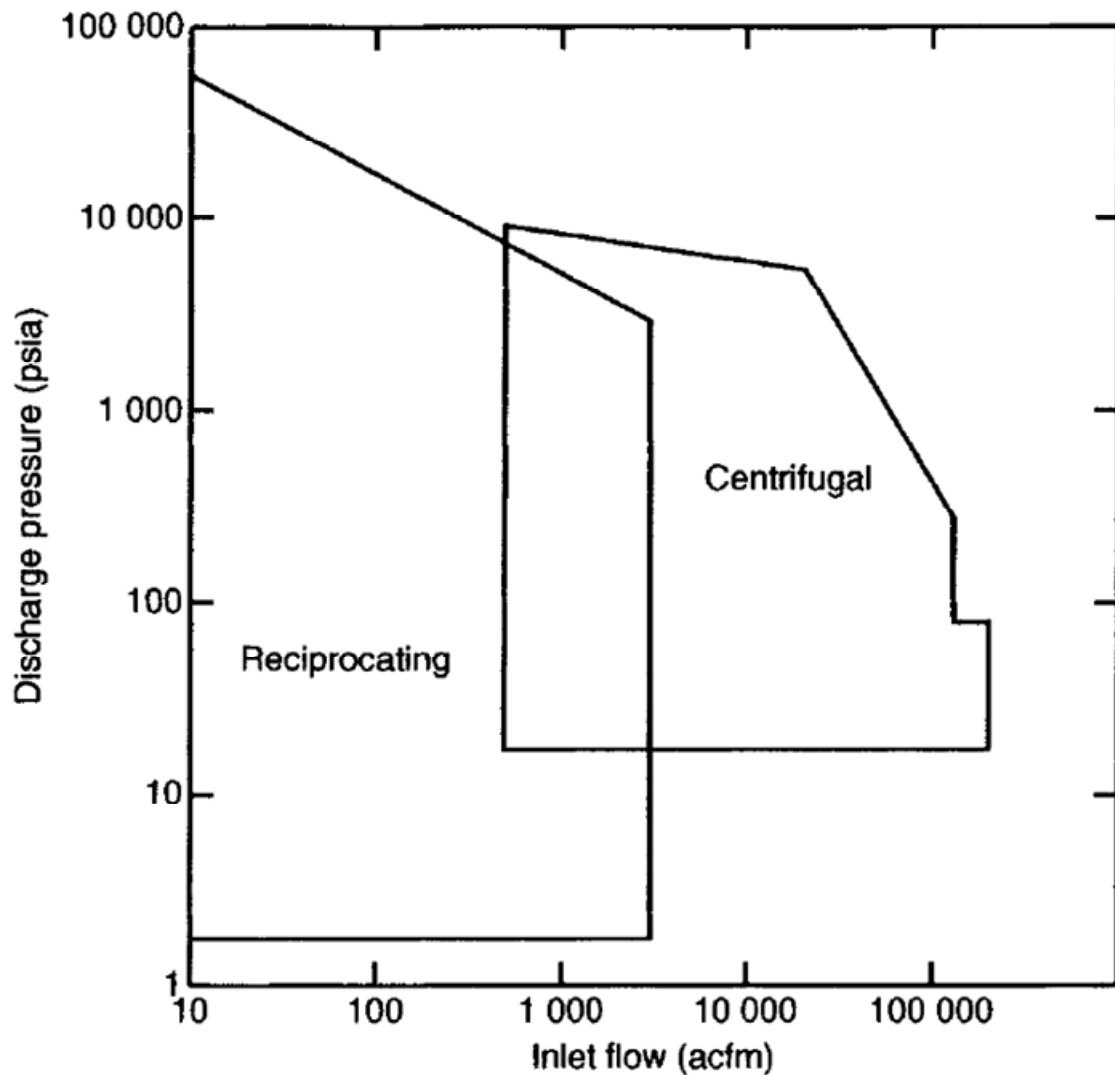


Figure 2-4 Application ranges for reciprocating and centrifugal compressors [47]

Since most long-distance transmission pipelines operate at pressures between 60 to 100 bar, natural gas must be compressed to pipeline pressures [48]. Natural gas compression is achieved by converting the driver's mechanical energy to kinetic energy in the gas. Figure 2-5 shows a typical centrifugal compressor and its components.

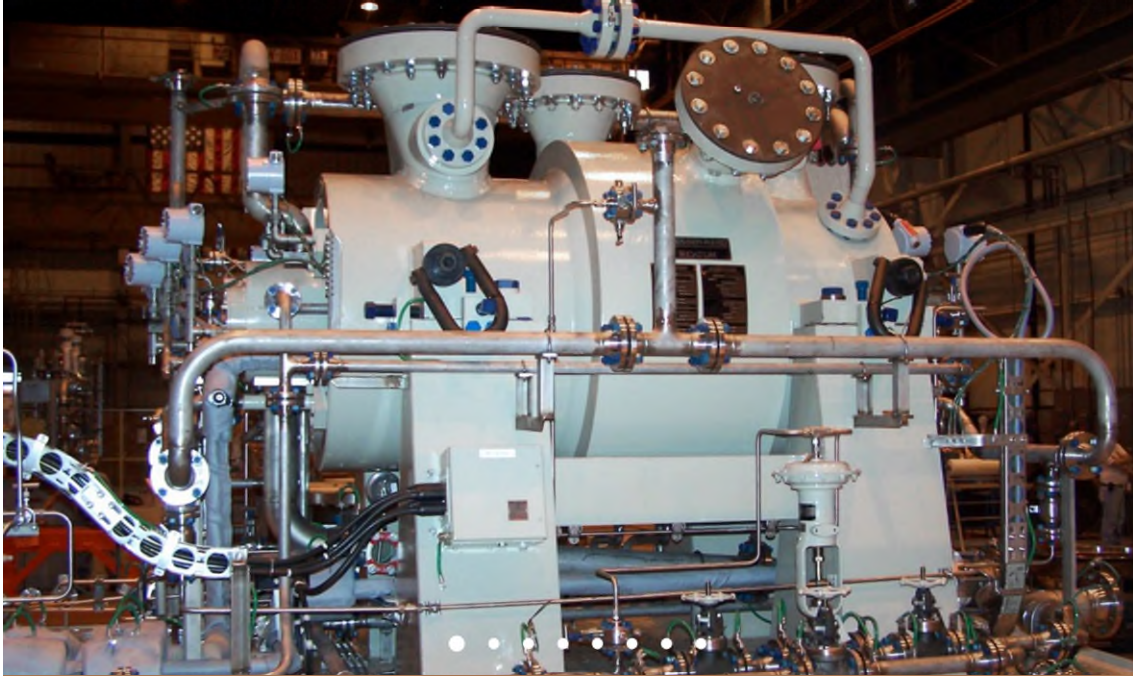


Figure 2-6 Siemens Barrel-Type STC-SV Compressor [49]

The different working principles cause variation in the operating characteristics of the centrifugal compressors. Its operating point is determined by the compressor map, the driver's power, and the head-flow characteristics [48]. The compressor performance map is created based on the selection and from hydraulic analysis and is utilised to determine its operating conditions by evaluating its head-flow characteristics. Centrifugal compressor performance is a function of inlet volume flowrate, speed, isentropic head, and isentropic efficiency [50]. The interrelationship between these parameters is shown with performance characteristic maps. The original equipment manufacturer can supply the compressor's power requirement, efficiency, and speed after performing the selection. The compressor's drivers are sized based on the above information and the prevailing ambient conditions.

The compressor operating speed is usually varied to control the flow through it. This can be achieved through its drivers: variable speed electric motors or multi-shaft gas turbines, which allow for compressor speed variation over a wide operating range. The parameters affecting the centrifugal compressor operating range are the surge flow, choke, driver power, and maximum and minimum

speeds. Surge flow occurs when the compressor is operated at lower flow leading to flow reversal and fluctuating load on the bearings. It is an unstable condition that causes pressure oscillation resulting in damage to the compressor and associated piping system [51]. Control systems are designed to detect and avoid surge to protect the compressor from damage. They must maintain the compressor's operating point within its safe operating range by avoiding instabilities that may cause breakdown and lead to downtimes [52]. The stonewall line occurs when the gas velocity inside the compressor reaches the speed of sound producing shockwaves that cause vibration in the component parts [53]. The acceptable operating range will be between the surge line and the stonewall line considering safety, stability, and anti-surge protection line. Figure 2-7 shows a typical centrifugal compressor performance map of head as a function of inlet volume flowrate and speed.

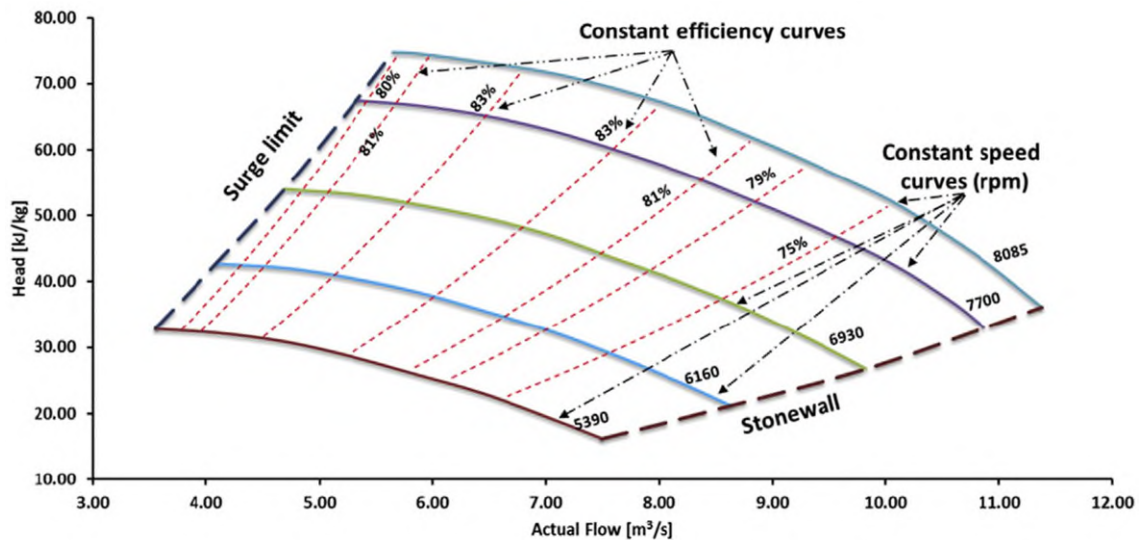


Figure 2-7 Centrifugal compressor map [54]

Meira et al. [53] have proposed an approach to performance modelling of compressor maps for natural gas pipelines. Their work extends the National Aeronautics and Space Administration loss theory to estimate energy losses and accurately obtain the compressor characteristic curves, including the surge and choke lines. The results showed the significance of the proposed modelling approach on the compressor map compared to the conventional model and have an essential role in the reduction of operational cost of compressor stations.

2.4 Gas Turbine

This study looks at gas turbines for mechanical drive applications in transmission pipeline compressors. Multi-shaft gas turbines are used to drive pipeline compressors where the compressor's speed varies with the load depending on the power requirement. The essential components of a simple cycle gas turbine are the compressor, combustor, and turbine. In most cases, the gas turbine usually utilises the natural gas being transported through the transmission pipelines as fuel consuming about 7-10% of the required throughput for compression purposes [55].

The design point performance of the gas turbine shows the performance of the whole gas turbine unit when it is running at the specific speed, mass flow and pressure ratio for which the essential gas turbine components were designed. The designer selects these parameters to achieve the required engine performance. However, gas turbines are needed to operate for long period at off-design conditions. These conditions arise due to variation in the ambient conditions, namely temperature and pressure, which have a great impact on the performance of the gas turbine. The off-design performance analysis of the gas turbine shows the variation of performance of the gas turbine over the entire operating range of speed and power output. Thus, it is vital to consider the effect of the ambient conditions on the power output during the off-design performance analysis. Hosseinimaab and Tousi [56] have investigated the off-design performance of a double-shaft gas turbine utilising a centrifugal compressor with different design speeds as the load. They showed the performance map and running line and evaluated the effect of environmental changes on the engine performance. According to Lubomirsky et al. [57], gas turbines power output and efficiency are significantly influenced by the ambient conditions, namely temperature and pressure. Thus, compressor stations should be designed to consider this variation in ambient conditions. However, a review of literature studies has shown that ambient temperature is the most important factor among all these conditions [58]; [59]; [60]. Moreover, the compressor pressure ratio, turbine entry temperature, and component efficiencies also have a significant impact on gas turbines performance.

Multi-shaft gas turbines for pipeline application are either the two-shaft gas turbine with a free power turbine or the three-shaft gas turbine with a free power turbine configuration. In the former arrangement, the high-pressure turbine drives the compressor, and both run at the same speed. This combination acts as a gas generator for the low-pressure power turbine, which is used to drive the load. The effect of mechanical load on the performance of a twin-shaft gas turbine engine in mechanical drive service was studied by Tahan et al. [61]. The engine operates as a mechanical driver for a process compressor in the gas compression service. Figure 2-8 shows the twin-shaft gas turbine arrangement with a free power turbine.

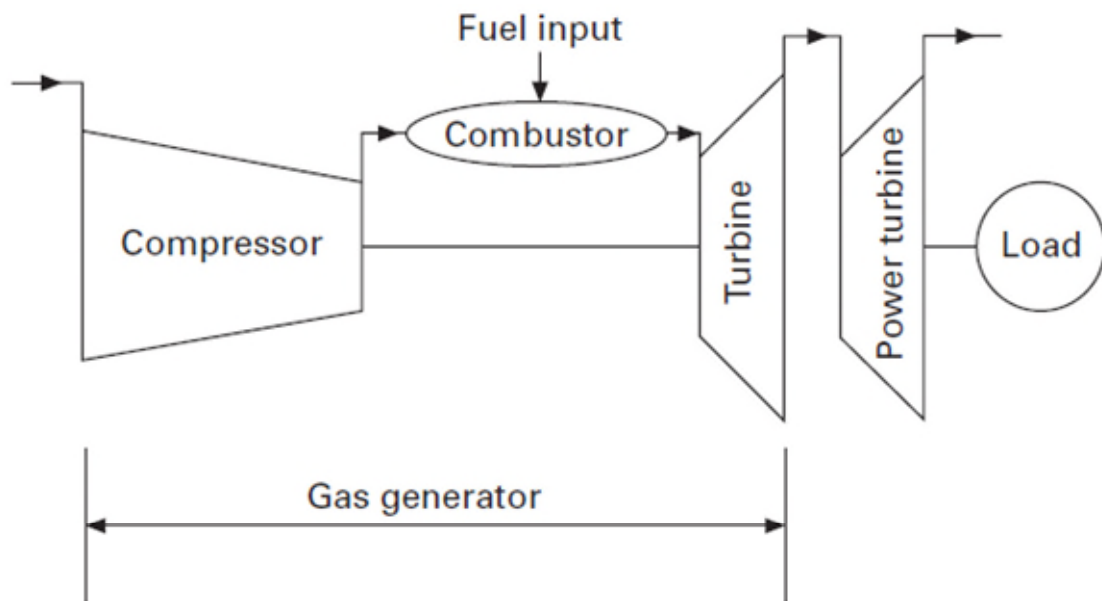


Figure 2-8 Twin-shaft gas turbine with a power turbine [62]

In the latter arrangement, the high-pressure turbine drives the high-pressure compressor, and the low-pressure turbine drives the low-pressure compressor. The power turbine installed in the arrangement will supply the required power to drive the load. They are often referred to as aero-derivatives because they are derived from the aircraft gas turbines, have small footprint, high performance, availability, maintainability [63] and have the advantage of higher thermal efficiencies, pressure ratio, and lower starting power than the twin-shaft gas turbine configuration. Although, two-shaft gas turbines have a higher speed range than single-shaft gas turbines [64]. The power variation is obtained by regulating

the fuel flow into the gas turbine. The turbine entry temperature and the pressure ratio decrease with reduction of the engine power from the design point with a consequent reduction in the engine thermal efficiency. Figure 2-9 shows the triple shaft gas turbine configuration with a free power turbine.

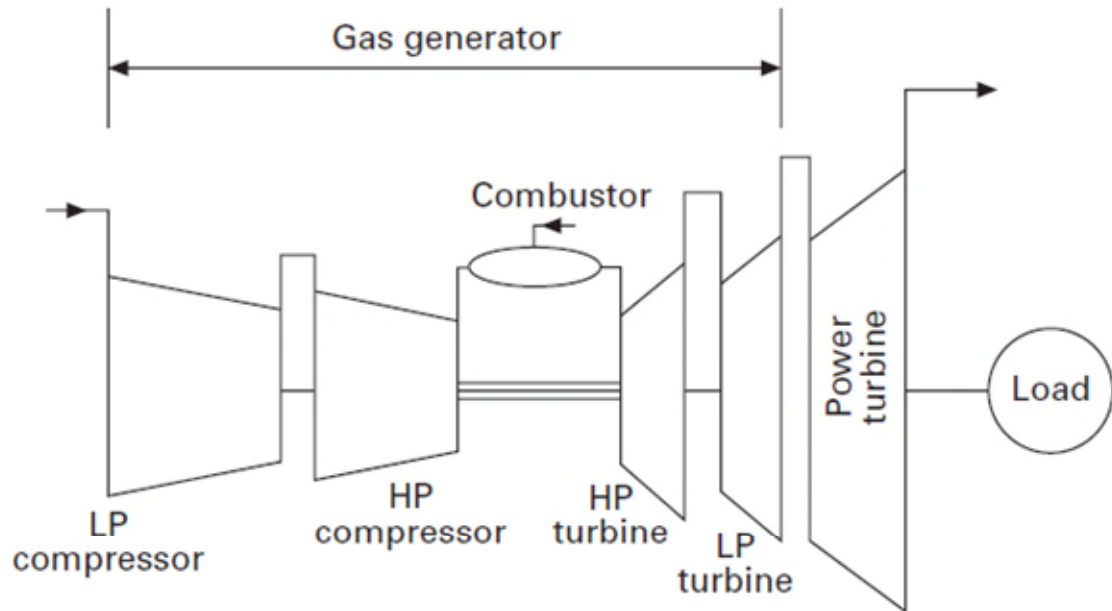


Figure 2-9 Triple-shaft gas turbine with a power turbine [62]

Atmospheric air enters the gas turbine's compressor, after which discharged air from the compressor enters the combustor, as shown in Figure 2-8. The fuel is burnt in the air to raise the combustor temperature, after which the high-temperature gases are expanded in the high-pressure turbine to produce the required power to drive the compressor. The high temperature gases leaving the high-pressure turbine enter the power turbine, expanding to produce the required power to drive the gas compressor [55]; [62].

2.5 Gas Turbine and Compressor Availability

The availability of a gas turbine, gas compressor or turbo-compressor unit is the percentage of time the unit is available to generate power or perform its required duty in any given period as a function of downtime. The operational availability A_o , is defined by [65]:

$$A_o = \frac{MTBM}{MTBM + MDT} \quad (2-4)$$

Where, *MTBM* is the mean time between maintenance and *MDT* is the mean maintenance downtime. It considers failures due to both scheduled and unscheduled outages. The increasing complexity of natural gas transmission pipeline networks with a consequent increase in the operation and maintenance costs have made it imperative to reduce the compression station system maintenance while improving the units' availability. Flow and pressure regulation in the gas transmission system depends on several compressor stations at which gas compressors operate either in series or parallel and the challenging nature of the failure of any one unit. Thus, analysing the impact of failures on gas transmission capability is a significant issue for gas operators [66]. Compressor station equipment failures arising from scheduled or unscheduled outages can lead to high economic costs in installing, operating, and maintaining associated components.

Compressor station system availability analysis has become an important topic among stakeholders. It is expected to remain the same over the coming years due to the increasing complexity of natural gas transmission networks arising from increased demand for natural gas by the consuming market. A typical value for smaller gas turbine unit availability is between 94-97% [67].

The availability of the compressor station system is greatly influenced by the operation and maintenance routine adopted, construction and installation of the various units that make up the system and the design layout. In many cases, maintenance policies are implemented to ensure the continuous availability of the components and to make sure it performs its required function in meeting end-users demand for natural gas. However, the quality of the maintenance policies and the actions taken to deal with environmental conditions have an important effect on the equipment's availability [42]. An effective maintenance policy will reduce the frequency of failures at any compressor station location, thus improving the station and overall system availability.

Engine availabilities are important in the compressor station and transmission pipeline system economics. The unavailability of the plant to generate power can be very costly in the operation of the compressor station. The cost is reduced if scheduled outages are planned for non-peak periods. The increase in plant efficiency of 7-10% from smaller capacity units to larger units has led to an equivalent reduction in plant availability due to larger plants taking more time to repair. This will have a major impact on the plant's economy. A 1% reduction in the engine availability could cost a yearly income loss of \$500,000 on a larger capacity plant [67]. The loss of income can be due to the unavailability of the commodity, penalties estimated because contractual agreements are not met, or the pipeline flowrate reduction [42].

The availability of a system can be determined either by performing a Monte-Carlo simulation or through an analytical method. Monte-Carlo simulation has the disadvantage of high computational time and the expenses involved in the model development and execution. Furthermore, analytical methods give more accurate results than Monte-Carlo simulation [68]. Few studies have been performed on compressor station availability analysis. In many cases, most focus on the compressor unit's availability, assuming that the compressor unit is equivalent to the turbo-compressor unit within the compressor station, while very few focus on the availability of the gas turbine unit. Santos et al. [69] calculated the Bolivia-Brazil gas pipeline compressor station's availability using binomial distribution and compared the results with the Monte Carlo method. They concluded that both methods are equivalent. This was also confirmed with the results obtained by [70]; [71]; [72]. Yasserli and Bahai [73] utilised the Design Structure Matrix mapping method to represent the system's components and dependencies. Additional reliability data were included in calculating availability. Availability of a single unit was obtained using the inherent availability approach by using the Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR) data obtained from the literature. The subsystems availability was calculated using the binomial distribution method. Carazas and De Souza [74] presents a method for availability analysis of gas turbines used in electric power station based on system reliability concepts. The method was applied to analyse two gas turbines installed in a

combined cycle power plant. The availability of the turbines was simulated based on a five-year failure database. The results show 99% and 96% availability for each turbine, indicating differences in their systems installation and operation.

2.6 Economic Analysis

Investment in any compressor station and pipeline project is capital intensive. Evaluation of the attractiveness of the investment is related to the economic benefits and feasibility of the proposed project. Economic decisions are usually based on the available data within the period decisions are made. In many cases, considerations are taken of the impact of the investment on the financial stability and project's profitability. Any economic analysis aims to provide a benchmark for making an effective economic decision with respect to any project. An effective economic analysis will help the decision-makers select the best alternative between competing projects where decisions are based on the variation between the considered alternatives. The cost of each alternative is compared with their benefits, considering the primary objective of making the best use of finite capital. Estimating project benefits in the form of revenue requires the determination of the volume of production and their component prices related through trading. Generally, a cash flow analysis is performed for each alternative, the outcome of the analysis is compared, and the decision is made to select the best alternative. However, it is imperative to note that concluding decisions should also consider the technical, environmental, and social aspects of the project in parallel with the economic decision.

Yuan et al. [75] created an economic evaluation model using the discounted cash flow method to explore the economic feasibility of shale gas development. The model provides the basis for investigating the effect of major policies available to improve shale gas production profitability. Discounted cash flow is the frequently used method for the technical and economic analysis of oil and gas development. Giacchetta et al. [76] have performed an economic analysis related to a hypothetical industrial-scale facility named LINK located in Alberta based on the discounted cash flow analysis. The results show that the plant is a profitable

investment, and the investment cost significantly affects the plant's competitiveness.

2.6.1 Time Value of Money

It is well-known that a dollar received today is more valuable than a dollar received at some future time [77]; [78]. An amount's economic value depends on the time value of money. The time value of money is usually considered when making an economic analysis to select the best alternative among competing projects. The value of money changes with time every day. The value of money today is not equivalent to the value of money in the future. This change might occur due to inflation or investment so that it earns money. Inflation is the loss in purchasing power, devaluing money since more money is needed to purchase the same quantity of goods. Investment in any compressor station and pipeline project over a long period requires considering the time value of money since the costs and benefits associated with the project can occur at different points. The interest rate enables the conversion of money from one point in time to another point in time.

For long-term projects, economic decisions are usually based on comparison or combination of cash flows occurring at different times over the project lifecycle. In most cases, comparisons or combinations are made at a reference point in time. The reference point could be time zero at the beginning of the project or any other point over the project lifecycle. Moreover, the project costs and benefits could be compared and the net present value estimated [78].

2.6.2 Net Present Value using a Discounted Cash Flow Analysis

The net present value (NPV) is the difference between the present values of benefits and costs over the project lifecycle [78]. The net present value using a discounted cash flow analysis is widely used because of its many advantages and easiness to interpret. It considers the time value of money over the project life cycle. It can also measure project profitability while recognising the difference between money's present and future value. Since a cash flow today is not equivalent to a similar cash flow in the future [79]. In the net present value

analysis, the present value of all cash inflows is compared with the cash outflows related to the project. The cash flow diagram could aid in the analysis of an investment opportunity. It accounts for all cash inflows and outflows to and from the project. The net cash flow is the difference between these inflows and outflows. The discount rate is the rate at which future cash flows are discounted to convert them to present values. The net present value is the difference between the present value of these cash flows and determines the proposed project's acceptability [77]. The net present value can be used to establish if a project will yield a net profit or loss [79]. It can guide the selection of projects among competing alternatives. The project that gives the highest positive net present value is usually selected. The net present value can be evaluated using the following equation:

$$NPV = \sum_{j=1}^n \frac{CF_j}{(1+r)^j} - C_o \quad (2-5)$$

Where:

CF_j = Net cash flow for year j

j = Year of project cash flow

r = Assumed discount rate

C_o = Initial Capital Investment

n = Total project duration

A discounted cash flow method based on the net present value approach is utilised as the economic appraisal method in this research work.

2.6.3 Life Cycle Cost Analysis

Life cycle cost analysis is a method of estimating the economic performance of projects comprising of varying cost components, including but not limited to the first cost, installed cost, operational cost, maintenance cost, direct cost, indirect cost, and other related costs acquired during the design and development of the project throughout its life cycle. Capital costs are incurred by purchasing assets,

while operational costs are incurred through the operation of the compressor station and its associated components. Installed cost is the equipment price specified from the original equipment manufacturer catalogues and include handling and shipping costs. In most economic evaluations, individual component's performance is utilised to assess the whole system effectiveness. The life cycle costs are disregarded because of the high total cost, making the project unfeasible. Although, operational effectiveness can only occur when the life cycle cost is considered [80]. The life cycle cost analysis enables the selection of a design alternative that considers all costs, present and future, over the project's life cycle. It allows decision-makers to make comparison among all possible alternatives given the constraint of finite resources. Therefore, economic decisions should be made considering the total cost of the whole project [77].

2.7 TERA and Optimisation Scheme

The idea of Techno-economic and Environmental Risk Assessment (TERA) was pioneered at Cranfield University based on various research work conducted over the years on power plants. Ogaji et al. [81] presented a description of the TERA tool for aircraft and engine asset management: TERA integrated with an optimiser comprises multi-disciplinary modules for modelling engine performance, environmental impact, economics, and others. It provides a method for evaluating engines' technological, economic, and environmental risks. Although TERA was initially conceived for aircraft engines, it has been applied to marine and industrial engines. Recently, it is now being employed for gas turbine application in pipelines [16]; [17]; [18]; [19].

2.7.1 Optimisation Scheme

An optimisation problem involves maximising or minimising a function called the objective function, subject to constraints imposed on the function's variables [16]. Optimisation establishes decision variables' values that maximise or minimise an objective function. Compressor station optimisation studies are needed due to the increasing complexity of natural gas transmission pipeline networks arising from increased demand for natural gas by end-users. This increase has led to a corresponding increase in economic cost from the construction, installation,

operation and maintenance of station units and associated components. So that an enhancement of the unit or whole system operation through optimisation studies can considerably reduce the life cycle cost and improve the system performance. Thus, efficient design of transmission pipeline networks able to meet various demands over its life cycle is essential. After all, a well-designed pipeline system could reduce the investment and operating cost.

There is an enormous amount of research work that has been done over the previous years on transmission pipeline network optimisation. Rios-Mercado and Borraz-Sanchez [43] present a review on optimising the natural gas transmission pipeline systems from an operations research perspective. They consider both steady-state and transient optimisation models assuming an existing pipeline network with the objective of minimising the operational cost. Üster and Dilaveroğlu [44] present an optimisation model for designing a new pipeline network or expanding an existing network while minimising the total investment and operating costs. However, these studies do not optimise compressor station location. The total operational cost of the transmission pipeline network system is primarily a function of the compressor station operating cost. The compressors operating cost could constitute between 25% and 50% of the total company's operating budget [23]; [43]. According to Zhang et al. [82], the balance between maximum allowable operating pressure, pressure ratio, pipe diameter, total horsepower and station number for a specified distance is important in reducing the initial capital cost of a new pipeline project. [20]; [21]; [83] have evaluated economic models for various drivers and driven equipment in gas compression application in natural gas transmission pipelines to minimise the total investment cost. However, they did not optimise station location. Thus, optimising the compressor station locations in the transmission pipeline network system can considerably reduce operating costs and bring huge economic benefits.

The genetic algorithm is an optimisation method based on the principles of genetics and natural selection. It allows an initial population to evolve under specified selection rules to a state that optimises the objective function [84]. Dao et al. [85] proposed a systematic approach based on Taguchi experimental

design for parameter tuning for maximising the performance of genetic algorithm solver in MATLAB. A two-dimensional problem was demonstrated with a success rate of 98.5% of finding the global optimal solution of the genetic algorithm solver with parameter tuned. Zhang and Wu [86] investigated the energy cost minimisation of a compressor station by modified genetic algorithms. Comparisons of the four devised genetic algorithms show that the coding sequence of a genetic algorithm influences its ability to find a feasible solution. Feasible solutions resulted from multiple runs of the same problem with standard error influenced by the coding sequence and no conclusion about the influence pattern. The common coding sequence of the real-coded genetic algorithm has the same best and average energy cost in Yuan per hour with the equal-distribution approach for the station equipped with identical compressors. Similar energy cost in Yuan per hour was observed for the genetic algorithm and the dynamic programming approach for the station equipped with compressors of different types. Results show that the best and average solutions of the genetic algorithms are comparable in Yuan per hour with the results of the equal-distribution and dynamic programming global optimisation methods in minimising the energy cost of a station. Knight et al. [87] developed and implemented an integrated through-life economic performance optimisation tool for gas turbine whole plant analysis using the software tool PSEconomy for the GTPOM project. PSEconomy is composed of three functional modules: process modelling module, economic analysis module and an optimisation module. The optimisation module utilises a genetic algorithm method to minimise the cost of electricity over the complete life cycle of the gas turbine power plant by varying the overall pressure ratio. The case study examples show an improvement in financial performance sufficient to justify the effort involved in the optimisation process. Nguyen et al. [88] compare three optimisation methods for compression selection: mixed-integer linear programming, genetic algorithms, and expert systems. Expert systems are methods that use human heuristics to produce the starting point for developing solutions to problems. They use specific knowledge of the domain coded in them to solve complex decision-making problems. Expert knowledge is obtained from specialists or other sources of expertise in the

literature and databases. The results identified the advantage of the genetic algorithm approach as not constrained by the assumption of linearity. Thus, a non-linear cost function can be utilised. Additionally, the genetic algorithm approach proves useful for larger-scaled problems due to its efficiency in traversing problem spaces. Their studies only focus on the behaviour of a compressor in a single compressor station and not the entire pipeline network. Sanaye and Mahmoudimehr [46] investigated the optimal design of a natural gas transmission network using a genetic algorithm. They considered the sum of investment and operating costs as the objective function while also considering a wide range of design parameters in the optimisation problem.

El-Sheikh [89] looked at optimising fuel consumption in compressor stations using genetic algorithms. The case study of compressor stations to obtain the minimum fuel consumption rate was solved using a genetic algorithm and the software program Lingo to compare the optimisation results. Lingo is computer software designed for building and solving non-linear optimisation models. The results show a fuel consumption rate of 17.011 lbm/s with the genetic algorithm and 17.231 lbm/s with Lingo. Furthermore, the fuel consumption rate was 18.3 lbm/s before optimisation. Thus, indicating that the genetic algorithm is effective since it shows a lower fuel consumption rate than Lingo after optimisation. The case study results showed the effectiveness of the developed and applied method. Fahimnia et al. [90] studied fuel consumption optimisation in compressor stations using a genetic algorithm. The best operational points with a minimum fuel consumption rate were generated for a typical compressor station case study. Habibvand and Behbahani [91] used a genetic algorithm for fuel consumption optimisation of a natural gas transmission compressor station. The results show that linear load sharing will be the most optimised choice in compressor stations with the same turbo-compressor packages. Mahmoudimehr and Sanaye [37] study and compare the results of three optimisation methods concerning the minimisation of fuel consumption of a natural gas compressor station. The results show the same solution for all methods for a station with similar turbo-compressor units, while the genetic algorithm and exhaustive search methods reveal a lower fuel consumption rate than that obtained by the

heuristic method. Exhaustive search method is optimisation method that determines the objective functions for all potential solutions and choose the solution with the best objective function as the global optimal solution.

The gradient descent optimisation algorithm uses a first-order iteration technique to find a local minimum of the objective function [92]. It iteratively takes steps in the opposite direction of the steepest descent of the gradient of the objective function. In most cases, an initial guess of the decision variable is made for a local minimum of the objective function. Subsequently, the algorithm evaluates values for the objective function based on the decision variable's specified lower and upper bounds. This process continues until a value is obtained that converges to the desired local minimum based on the specified tolerance limit. Convergence to a local minimum can be certified with the appropriate choice of the scaling factor and assumptions on the objective function. Gradient descent is based on a differentiable convex function. In a convex function, the line segment between any two points on the function's curve lies above or on its curve. For a convex objective function, the local minimum is also the global minimum solution. Thus, gradient descent can converge to the global solution [93].

The sequential quadratic programming (SQP) method can be used for evaluating nonlinearly constrained optimisation problems. Sequential quadratic programming converts a nonlinear problem into a sequence of quadratic programming sub-problems [94]. The sequential quadratic programming method utilises Newton's method to compute the optimal solution to constrained optimisation problems. Bazaraa et al. [95] showed that the determination of the iterative step in Newton's method equals the solution of a quadratic programming problem.

2.8 Social Impact Analysis

Many studies of the social impacts of energy technologies have been performed but have often focused on renewable energy technologies in many cases, and very few studies have focused on conventional energy technologies. Heavner and Churchill [96] estimated employment rates associated with some natural gas-fired power plants in the US based on existing and permit applications for

proposed power plants. Hartley et al. [97] investigated job creation from wind and unconventional oil and gas using an econometric model based on data from Texas over an eleven-year period. Their modelling results showed that unconventional gas has brought Texas high employment growth over the examined period.

A review of literature studies in energy technologies showed that future scenarios of potential employment have often been assessed using a common metric of jobs-year or job created per installed capacity [98]; [99]. Employments created in the construction and installation phase are temporary jobs measured in jobs-years. Employments created in operation and maintenance phase are permanent jobs measured in jobs. Barros et al. [100] assessed the direct employment generated by power plants throughout their lifecycles using a proposed probabilistic and analytical model. The direct job creation for non-renewable power plants was estimated using a normalisation process to vary from 0.1 to 2.4 job-years/GWh over the plant's lifetime. In most cases, employment benefits are defined in monetary terms based on the net income increase from the number of new jobs created. Tourkolias et al. [101] developed a framework using the input-output method to quantify the employment benefits associated with power generation technologies. The employment benefits were expressed in monetary terms using the opportunity cost of labour and public expenditure approaches. The opportunity cost of labour approach concentrated on the employment benefit of previously involuntarily unemployed new workers. In this concept, the income of a newly employed worker is equal to the opportunity cost of labour. The public expenditure approach was based on the government's readiness to pay for the extra employment created, reflecting public choices for job growth. In the basic scenario, they estimated the employment benefits for natural gas-fired power plants in Greece at 0.4-0.6 €/MWh.

Power plants land use are classified as direct impact due to physical infrastructure development and the total area associated with the complete power plant project [98]. The physical infrastructure includes the provision of social services expected to meet the local community's needs while enhancing their

quality of life. Very few studies have been performed on the land-use impact of power plants. Chatzimouratidis and Pilavachi [98] have presented the average land required by each type of power plant based on global data. They showed that the average land requirement for natural gas turbine power plant is about 0.0025 km²/MW of installed power capacity. Afgan and Carvalho [102] have evaluated the social aspects of energy systems using area and new job sub-indicators. They estimated the area requirement per kilowatt installed power for natural gas turbine energy systems as 2 m²/kW. Fthenakis and Kim [103] have reviewed the lifecycle land use for renewable and conventional fuel cycles based on literature studies and actual data. They estimated the direct land use of natural gas power plants as 128 m²/GWh for the power plant electricity generation stage based on a 30-year project lifetime. Klein and Whalley [104] have reported the direct maximum lifecycle land use for natural gas power plants as 0.31 m²/MWh based on a maximum capacity factor of 93% and a 30-year lifetime. The same land-use value was presented by Maxim [105] based on a capacity factor of 85%. Trainor et al. [106] have derived the range of land use efficiencies for a conventional natural gas energy source to be between 0.82-0.951 km²/TWh.

The direct land use impact of energy technologies can also be quantified in terms of power densities which is the reciprocal of land use impact or efficiency. The energy technology with the lowest power density will require the greatest amount of land per installed power capacity and vice versa. In their review of power densities and their application in the United States, van Zalk and Behrens [107] asserted that:

“Improved understanding of power densities may help examine trade-offs between different land-uses and their social implications”.

van Zalk and Behrens [107] have estimated the power densities for natural gas-powered systems to range from about 500-2000 MW/km² with a median of about 482.1 MW/km² based on a review of literature on power densities for different energy types and sub-types in the United States. The estimates were applied to National Renewable Energy Laboratory scenarios of future energy systems for state-specific assessments. They found that the largest land use growth occurred

in the southern United States. However, they did not show the impact of land use on the local communities where these energy systems were installed, nor did they show how the power densities estimates were applied for pipeline applications. Smil [108] has compared the power densities of fossil fuel extraction to renewable energy conversions. The power densities of thermal power plants were reported to be between 200-2000 W/m². However, no further information was given on the land-use related impact of the power plants.

2.8.1 The Value of Travel Time Savings

The value of travel time is the value of money people are willing to pay to earn one unit of travel time saving or to prevent one unit of time loss [109]; [110]. The value of travel time savings is one of the input variables in the cost-benefit analysis of road infrastructure projects [111]. It is generally used to estimate the costs and benefits of travel time changes resulting from improvements in road infrastructure or investment in public transport facilities [110]. The value of travel time savings has been subject to discussion in the literature because savings in travel time constitute the largest share of user benefits in the most cost-benefit analysis [112]; [113]. Thus, understanding the road user benefits derived through the valuation of travel time savings is essential to this current study in the socio-economic development of the social influence areas of the compressor station locations. In this study, social influence is the change in the population characteristics caused by the presence of other people within the population and other social factors. These social factors include population density, level of wealth, employment, and community safety. The community will be much safer with the creation of new road infrastructures. Employment provides income that influences the choice of housing, education, and healthcare.

The value of business travel time savings can be estimated using the cost-savings approach (CSA), the Hensher equation approach (HE), or the willingness-to-pay (WTP) approach. The value of travel time savings for work trips has been obtained primarily from the cost-savings approach. In the cost-savings approach, the travel time savings are valued at the marginal product of labour (MPL). The marginal product of labour is defined as the average wage rate plus

a marginal wage increment to allow for overhead costs [114]. The value of travel time savings using the cost-savings approach can be expressed as [113]:

$$VTTS = w + c \quad (2-6)$$

Where;

w = gross wage rate

c = non-wage labour cost

VTTS = value of travel time savings

The cost-savings approach is a theoretical method widely used to evaluate the value of travel time savings in the world practising the appraisal of transport infrastructures [113]; [115]. The United Kingdom Department for transport [116] stated that:

“Time spent travelling during the working day is a cost to the employer’s business. It is assumed that savings in travel time convert non-productive time to productive use and that, in a free labour market, the value of an individual’s working time to the economy is reflected in the wage rate paid.”

The Hensher equation approach [117] investigates the willingness to pay for travel time savings by recognising productive time spent travelling. However, not all saved time is used productively. It considers employer and employees’ interests. The Hensher equation is given by [113]:

$$VTTS = [(1 - r - pq)MPL + MPF] + \{(1 - r)VW + rVL\} \quad (2-7)$$

Where:

MPL = marginal product of labour

MPF = the value of extra output due to reduce travel fatigue

r = proportion of travel time saved used for leisure

p = proportion of travel time saved at the expense of work done while travelling

q = relative productivity of work done while travelling relative to the workplace

VW = the value to the employee of worktime at the workplace relative to travel time

VL = the value to the employee of leisure time relative to travel time

The terms r , p , q , in the Hensher equation are difficult to estimate with certainty and present practical difficulties. Although they can be quantified from survey observations.

The value of travel time savings could also be evaluated using the willingness-to-pay approach. This approach consists of the revealed preference method based on data obtained from actual observations. The other component is the stated preference method based on hypothetical choices [115]. The willingness-to-pay and Hensher equation approaches are outside the scope of this current study due to a lack of data. This study employs the cost-savings approach in the valuation of travel time savings and cost-benefit analysis of the road infrastructures. More so, Fayyaz et al. [111] established that only income had a statistically effect on route choice. Consequently, they summarise the value of travel time savings values assuming average income. It is reasonable to assume that this average income is equivalent to the wage rate. Therefore, the cost-savings approach utilised in this study in the valuation of travel time savings and cost-benefit analysis of the road infrastructures is acceptable. Given that the new road infrastructure to be assessed in this study benefits the entire population. This research assumes that the non-wage labour cost component of the wage rate is negligible. This is a reasonable assumption because it prevents an overestimation of the value of travel time savings using the cost-savings approach.

2.8.2 Cost Estimation Models for Road Construction Projects

Ghajar et al. [118] presented a model for cost estimation of forests roads based on standard engineering properties of cross sections and the location-specific parameters of terrain slope and vegetation information. Six main costs elements consisting of clearing operations, embankment, pavement, grading, culverts, and

ditch were assumed by the model for total construction cost estimation. The model outputs were compared with the experts' predictions for an existing forest road project in a mountainous condition. The results show that the model could estimate total cost of road construction by $\pm 6\%$ accuracy range. Stükelberger et al. [119] presented a model for estimating variability in road lifecycle costs based on terrain surface and geographical properties of the subsoil. The model comprises embankment, retaining structures, pavement, drainage, and stream-crossing structures linked to a geo-database allowing users to derive location-specific parameter value as input. They showed that variability in costs ranges widely for mountainous areas and strongly affects the optimal layout of a road network. Early cost estimation models for road construction projects using multiple regression techniques were developed by [120]; [121] based on a set of data collected in Palestine and Saudi Arabia. They showed that results are in good agreement with previous research since the mean absolute percentage error of the developed model are within the estimated accuracy in the early stages of a project. Markow and Aw [122] have developed models for estimating road construction costs for sector planning using data from various road projects in some developing countries in Asia, Africa and Central and South America. The developed models can yield predictions of the construction cost for a wide range of road design standards, terrain, and climate, assuming minimal available data. The predictions of construction quantities were based on engineering principles of road design and construction, while costs were related to construction quantities through unit prices. They asserted the usefulness of the developed models in isolating the individual impacts of road design standards, terrain, climate on road construction costs in developing countries.

2.9 Review of TERA Approach for Gas Turbine Application in Pipelines

There are minimal studies on the techno-economic and environmental risk analysis (TERA) approach for gas turbine application in natural gas transmission pipeline systems. The only known work on this area of research was done by Nasir [16], Tukur [18], and Aziaka [19] at Cranfield University, United Kingdom.

Nasir [16] looked at the techno-economics of the gas turbine or electric motor drives in pipeline applications. His study concluded that electric motor drives might initially seem better in terms of environmental pollution. But from the generation of electricity today and in the future, the use of electric motor contributes more to environmental pollution than the gas turbine. It may not be a feasible option for the interstate pipeline in locations with inadequate electricity supply. The study shows the reduction in compression cost with increase in pipe size due to pressure increase and reduction in compression power required. However, the study does not consider the impact of engine availability on investment.

Tukur [18] investigated the techno-economics of gas turbine compressor stations in natural gas pipelines. His economic model was performed based on the life cycle cost by assuming availability of 100%, constant annual values for maintenance and fuel cost and considering station local conditions. He performed power matching between the gas turbine and gas compressor based on ambient temperature variation and optimised for the project life cycle cost. The study concluded that the lifecycle cost reduces by varying the distance between each compressor station while using a bigger gas turbine. Nevertheless, turbo-compressor availability and their impact on the life cycle cost were not considered.

Aziaka [19] investigated the techno-economics of degraded gas turbine on pipeline application in given compressor stations locations. Nonetheless, he did not look at the social impact and benefit from the gas turbine compressor station operation. El-Suleiman [17] investigated TERA on CO₂ compression power requirements for gas turbine-driven pumps and compressors. The economic model was developed based on net present value. However, it was not applied to the natural gas pipeline, nor was compressor station location optimisation considered.

The four studies did not consider the opportunities that arise in the social context in terms of social benefits, the impact of engine availability on investment and compressor station location optimisation separately or simultaneously.

Thus, it is evident from the preceding that gaps in knowledge exist, which this present research intends to fill.

2.10 Research Gaps and Contributions to Knowledge

Three research gaps were identified from a comprehensive literature review on natural gas transmission pipeline networks and their associated components, including the compressor station, gas compressor and gas turbine.

Firstly, the research gap from the literature review is the lack of studies on the impact of engine availability on investment using the TERA approach. Although, there are studies on compressor station availability and economics [69]; [70]; [71]; [72]; [73]; [74]. The author could not find any public studies that have adapted TERA by applying a typical original equipment manufacturer maintenance schedule to determine the impact of turbo-compressor availability on the whole compressor station and pipeline system investments. For the first time, this research developed a model and methodology for evaluating the impact of gas turbine availability on pipeline TERA.

Secondly, previous studies have failed to quantify and incorporate the local community's social and socioeconomic values in terms of direct employment created and road infrastructure impacts into compressor stations and pipeline projects at the design and development phase. More so, some other studies [98]; [100]; [101]; [102]; [103]; [104]; [105]; [106] not related to compressor station and pipeline projects quantify social benefits purely as a function of the installed power capacities. The author did not find any study to examine by adapting TERA the social impacts on the local communities of compressor station's locations in terms of employment opportunities and the creation of new road infrastructures for natural gas-fired gas turbine power plants for pipeline applications as a function of compressor station location and the power required. For the first time, a model and methodology for evaluating the social impacts and social benefits of compressor station locations along the pipeline route has been developed.

Thirdly, although the literature is inundated with a vast number of studies on optimisation of natural gas transmission pipeline networks with several broad

assumptions to show the progress in the field. Surprisingly, no attention has been given to performing economic analysis using the compressor station location as decision variable. In fact, none of the literature studies examined this interesting aspect of economic optimisation of compressor station and pipeline systems. The set of compressor stations in any pipeline projects constitutes large cost element. Thus, compressor station location optimisation can have a great impact on the economic cost and is important in project life cycle cost minimisation. I highlighted that while the previous studies looked at this natural gas transmission pipeline system issue by using different approaches. In my research work, I propose an economic optimisation of the compressor station and pipeline system using the station location as a decision variable. This is based on the TERA framework able to determine the optimal compressor station locations with a first uncertain step in the socioeconomic benefits while optimising for the lowest life cycle cost. The compressor station location optimisation considers the influence of ambient conditions and altitude on the outcome of the results; hence it incorporates topography data. As evident in public domain, this is the first time this research aspect is done on optimisation of natural gas transmission pipeline system from a techno-economic and techno socioeconomic approach. Therefore, the main contributions to knowledge in this research work are:

1. TERA for pipeline application on gas compressor stations considering the impact of engine availability on investment
2. TERA for pipeline application on gas compressor stations considering the first introduction of the social context opportunities
3. An economic analysis using compressor station location as a decision variable

Consequently, this research work will:

1. lead to improved decision-making on the design and development of any pipeline project
2. benefit the Nigerian government on the design and development of the proposed Trans-Saharan gas pipeline project

3. show job creation, provision of road infrastructure thereby leading to improved quality of life of the society
4. opens a new field of research closely aligned to the evolution of organisational goals to encompass stakeholders and serve as an important platform for development.

3 RESEARCH METHODOLOGY

3.1 Introduction

This chapter looks at the methods utilised in the techno-economic and environmental risk analysis (TERA) for gas turbine compression stations in natural gas transmission pipeline applications. The adapted TERA framework is presented, and the different modules that make up the TERA framework are discussed. Finally, the approaches used by the optimiser for the optimisation studies are described.

3.2 The TERA Framework using Station Location as Decision Variable

The adapted TERA framework for pipeline application in this research work is composed of the following modules: pipeline/gas compressor modules, gas turbine performance module, maintenance/availability module, social module, and an economic module. It is integrated with an optimiser that facilitates an economic analysis of the complete TERA framework using the compressor station location as a decision variable. The inclusion of the optimisation method in the complete TERA framework will affect the results. This is the first time in the literature the TERA framework is incorporated with availability and social modules and further confirms the novelty of the methods used in this research. Figure 3-1 shows the adapted TERA framework for pipeline application using compressor station location as the decision variable. As shown in the figure, the whole calculation is triggered by compressor station location based on the local conditions at each station.

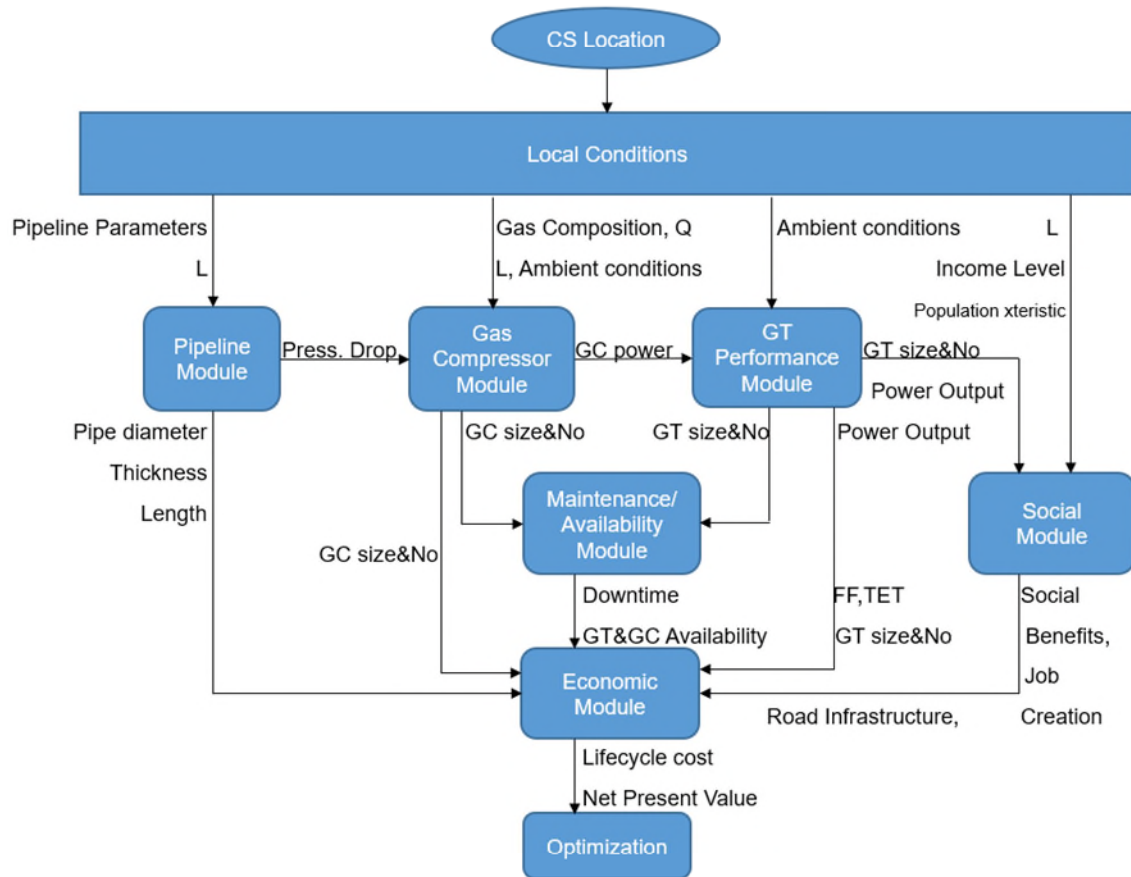


Figure 3-1 TERA Framework for Pipeline Application using Station Location as Decision Variable

3.3 Pipeline and Gas Compressor Modules

The pipeline module models the proposed Trans-Saharan Gas Pipeline's pipeline parameters and simulates the pressure drop along the pipeline. The pipeline module was developed in MATLAB using thermodynamic gas properties, the pipeline characteristics, and the Weymouth gas flow equation. The outputs from the pipeline module are fed into the gas compressor module and the economic module.

The gas compressor module estimates the gas compressor drive power requirement at design and off-design conditions needed to supply the required throughput through a specified pressure ratio. The gas compressor module was analysed using a developed code in a MATLAB environment, and the results were validated using ASPEN HYSYS software. The output from the gas

compressor module is the gas compressor drive power, which guides the selection of appropriate gas compressor size and numbers, including suitable gas turbine models from original equipment manufacturer catalogues. Additionally, the gas compressor power requirements were evaluated based on isothermal, intermediate, and non-isothermal flow conditions.

The developed models consider the variation in the ambient conditions based on the local conditions at each compressor station location along the pipeline. The data obtained from the initial report on Trans-Saharan Gas Pipeline [18] was utilised for the simulation. Figure 3-2 shows the pipeline elevation-distance profile used for this study. The pipeline and gas compressor modules require extensive adaptation of existing TERA models.

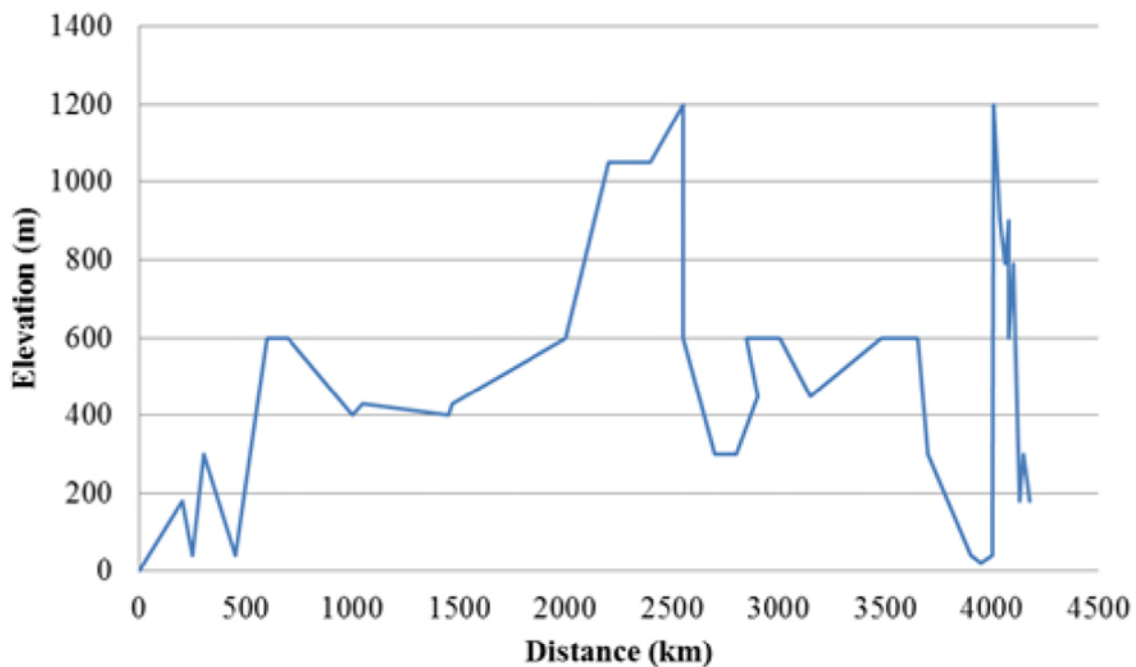


Figure 3-2 Pipeline Elevation-distance Profile [18]

3.4 Gas Turbine Performance Module

The gas turbine performance module simulates the design and off-design performance of the selected gas turbine. The engine performance model was done using TURBOMATCH, an in-house software developed at Cranfield University. Engine performance parameters at the design point used for the gas turbine performance modelling were obtained from the original equipment

manufacturer in the literature. The performance simulation results generated from the TURBOMATCH software were compared with the literature. The off-design performances of the selected gas turbine engines are simulated for varying ambient conditions (non-isothermal), isothermal and intermediate flow conditions. The data generated are inputted into the maintenance/availability, social, and economic modules. The gas turbine performance module was developed upon a straightforward application of the existing TERA model.

3.5 Maintenance/Availability Module

The maintenance module shows the effects of the maintenance schedule on engine availability as a function of the local condition. It uses the literature's failure rates to select the best maintenance pattern based on engine specification.

The availability module is developed in a MATLAB environment. It estimates the percentage of time the engine is available to generate power in each period as a function of downtime. This depends on replacing engine parts and the equipment used in the compressor stations. The inputs to the maintenance/availability module are the outputs from the gas compressor and gas turbine performance modules. The outputs from the maintenance/availability module are engine downtime, gas compressor, gas turbine and turbo-compressor availabilities. These are fed into the economic module to determine the impact of turbo-compressor availability on pipeline economics. The author could not find any public studies that have adapted TERA by applying a typical original equipment manufacturer maintenance schedule to determine the impact of turbo-compressor availability on the whole compressor station and pipeline system investments.

3.6 Social Module

The social module estimates the social impacts and benefits of compressor station locations along the pipeline route. This module consists of predicted job creation as a function of employment index and road infrastructure impacts as a function of land use impact areas. Land use impact areas are land areas directly

impacted for new road infrastructure creation due to the construction, installation, and operation of gas turbine compressor stations.

The predicted job creation was evaluated analytically using a developed code in MATLAB environment based on the employment index of natural gas power plant [123]; [124]; [125]; [126], population characteristics, income level and gas turbine installed capacities at each compressor station locations dependent on the gas compressor power requirement.

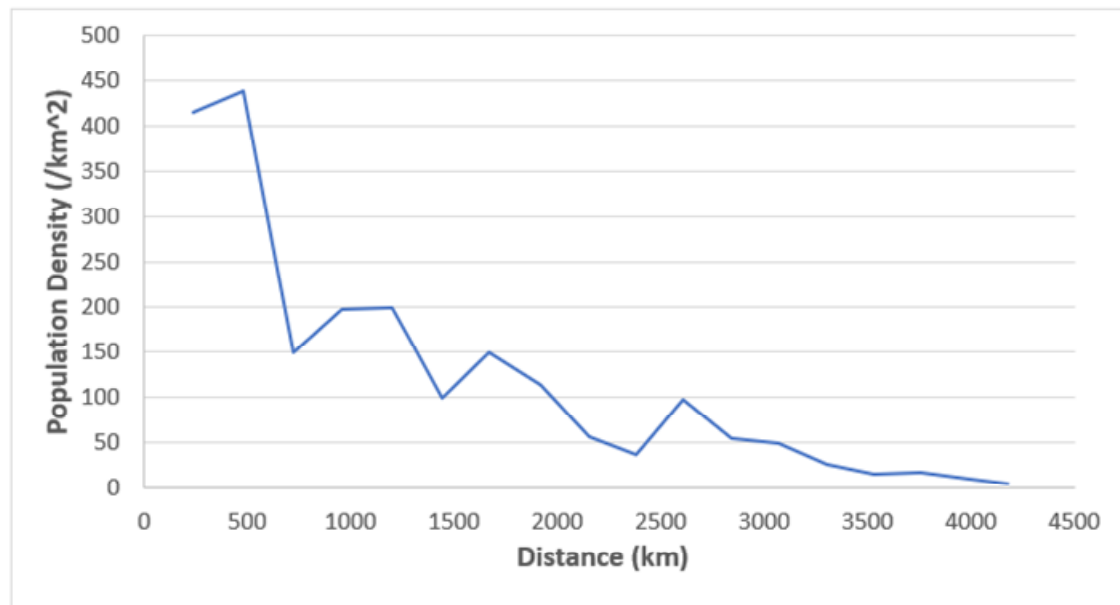


Figure 3-3 Population Map along the Trans-Saharan Gas Pipeline Route

Table 3-1 Wealth Map Information according to Income Groups

Station Number	Income Group
1	High-Income
2	High-Income
3	Middle-Income
4	Middle-Income
5	Middle-Income
6	Middle-Income
7	Middle-Income
8	Middle-Income
9	Low-Income
10	Low-Income
11	Middle-Income

Station Number	Income Group
12	Low-Income
13	Low-Income
14	Low-Income
15	Low-Income
16	Low-Income
17	Low-Income
18	Low-Income

The social impacts and benefits of a new road within the social influence area at each compressor station location were evaluated in terms of the travel time cost savings between the existing and new road infrastructures layout using a developed code in MATLAB environment. Figure 3-3 shows the population characteristics while Table 3-1 shows the wealth map information according to income group along the Trans-Saharan Gas Pipeline route developed by the author based on literature studies [127]; [128]; [129]; [130]; [131] of the social influence area along the pipeline route and utilised for this research. Figure 3-4 shows the Trans-Saharan Gas Pipeline route.



Figure 3-4 Trans-Saharan Gas Pipeline route [132]

The social module receives inputs from the gas turbine performance characteristics and the compressor station based on the local conditions experienced at each station location. The outputs from the social module are the social impacts and social benefits in terms of the jobs created and new road infrastructures. These are fed into the economic module to determine the socioeconomics of the compressor station and pipeline investment. The author did not find any study to examine the social impacts on the local communities of compressor station locations by adapting TERA. This social impact includes employment opportunities and new road infrastructures for natural gas-fired gas

turbine power plants for pipeline applications as a function of compressor station location and the power required.

3.7 Economic Module

The economic module estimates the capital and operating cost of the compressor stations' equipment that contributes to the natural gas pipeline transportation cost and the social costs and benefits of compressor station locations along the pipeline route. These costs are influenced by the engine's fuel consumption as a function of fuel cost, pipeline configuration and materials, number of gas compressors and gas turbines used in the compressor stations, compressor station auxiliaries, engine availability as a function of the maintenance cost, social costs, and social benefits as a function of road construction cost, taxes, road benefits and employment benefits. The economic module receives inputs from all other modules to evaluate the potential savings arising from using the gas turbine engines and their accessories in the compressor stations for natural gas transportation in pipelines and, consequently the feasibility of the proposed Trans-Saharan Gas Pipeline project. The economic module considers the variation in each compressor station location ambient temperature at varying flow conditions for the winter, dry, and hot seasons, respectively. The module is significantly impacted by the ambient and season conditions dependent on compressor station location. The ambient temperatures for the compressor station locations are segmented based on isothermal, intermediate, and non-isothermal flow conditions at the varying time of the day and seasons of the year. The gas compressor powers were evaluated at varying flow conditions. The gas turbines were selected based on the gas compressor power requirement, and the selected gas turbines were simulated using Turbomatch Software based on the compressor station location ambient temperature.

Figure 3-5 shows the economic model utilised in this research. The economic model is developed using SIMULINK block diagrams for the first time and a developed code in MATLAB environment. The input to the economic module consists of the pipeline cost, gas compressor cost, gas turbine cost, and auxiliaries' costs. These costs are the major components of the capital costs of

the compressor station and pipeline project. The pipeline cost consists of pipeline material cost, pipe installation cost, pipe coatings and wrapping cost. The gas compressor cost consists of the gas compressor purchased and installation costs. The gas turbine capital cost includes the gas turbine equipment cost, installation, and shipping costs. Auxiliaries' costs comprise the mainline valve stations, telecommunications, and supervisory control and data acquisition system, right of way, environmental and permitting, engineering and construction management, and contingencies. Additional input to the economic module includes the operation and maintenance costs which comprise the gas turbine fuel cost, fixed maintenance cost, engine availability based major and variable maintenance costs. The input to the economic module also consists of the social cost in terms of the employment and road construction costs. The social benefits include employment benefit and road benefit. The income tax and road tax are other components of the economic module. The total project capital expenditure for the techno-economic analysis is the sum of the pipeline cost, gas compressor cost, gas turbine cost, and auxiliaries' costs. These costs also include the road construction cost for the techno socio-economic analysis. The output from the economic module is the compressor station and pipeline project lifecycle cost. The lifecycle cost for the techno-economic analysis is made up of the pipeline cost, gas compressor cost, gas turbine cost, auxiliaries' costs, fuel cost, and maintenance cost. The employment and road costs are other components of the lifecycle cost for the techno socio-economic analysis. The economic model was evaluated based on the lifecycle cost and net present value analysis.

The economic model developed in chapter six requires extensive adaptation of existing models. The economic models developed in chapter seven are entirely new pieces of work.

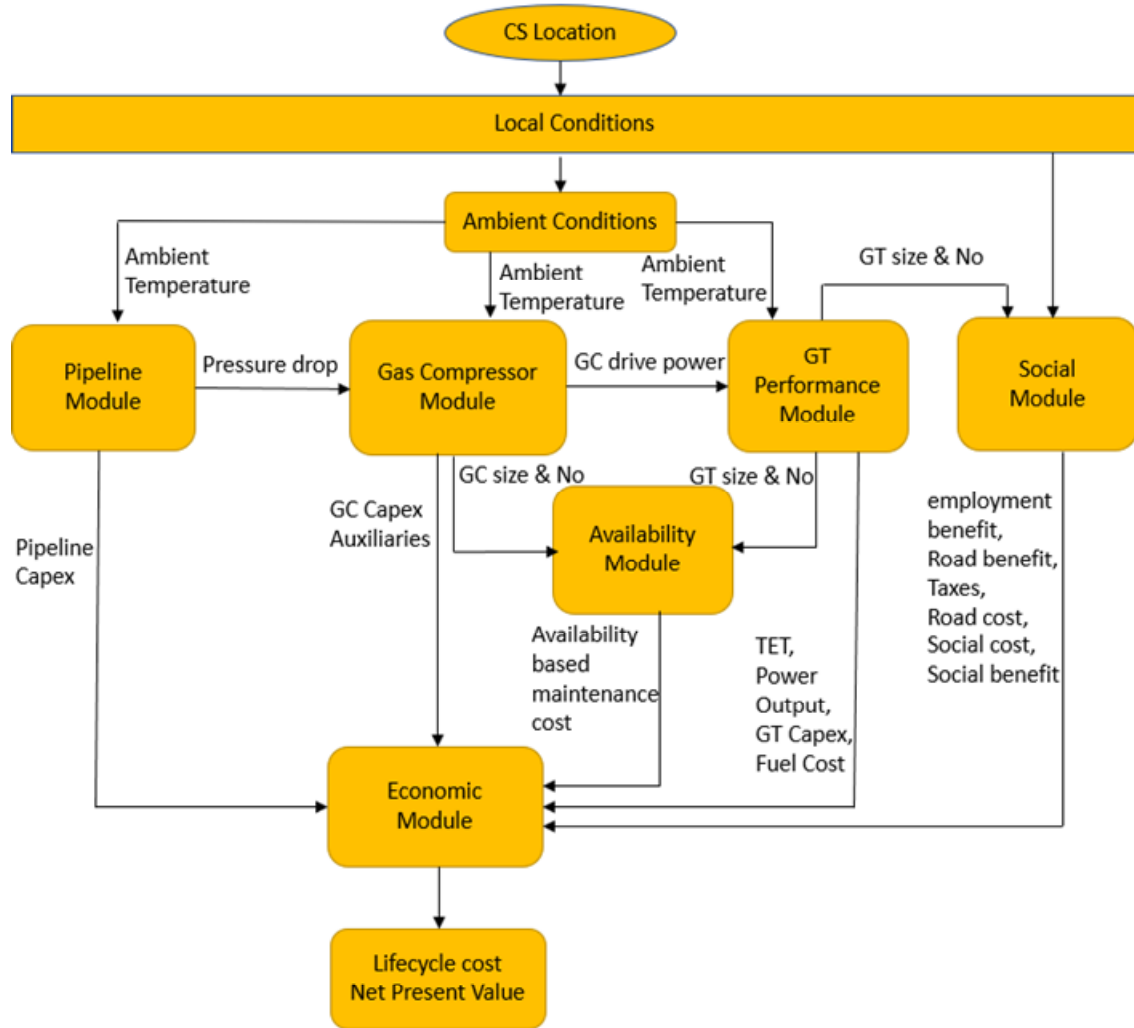


Figure 3-5 TERA Framework showing the input to the Economic Module

3.8 TERA Optimisation Approach

Evaluation of the optimal compressor station location through optimisation studies can help minimise the total life cycle cost since capital and life cycle costs estimate are the significant factors determining the economic feasibility of any project. In this research, optimisation studies are carried out on different compressor station configurations of gas compressors and gas turbines. An economic analysis is performed using the compressor station and pipeline system lifecycle cost as the objective function, compressor station location as a decision variable, to maximise profit through decision-making on the most cost-effective scenario.

The TERA optimisation is evaluated in techno-economic optimisation and techno socio-economic optimisation. The techno-economic optimisation was performed using SIMULINK block diagrams and response optimisation tool available in MATLAB SIMULINK graphical user interface. The results are compared using the genetic algorithm optimisation method in MATLAB. Subsequently, techno socio-economic optimisation was performed using a developed code in MATLAB environment and genetic algorithm optimisation techniques available in MATLAB toolbox. In both scenario-based approaches, the objective function is the project life cycle cost. Maximum allowable pipe pressure, which is a function of the power required is the constraint. At the same time, the compressor station location is the decision variable. The inclusion of the optimisation methods in the TERA framework will affect the results.

The lifecycle cost of the compressor stations and pipeline systems represents the objective function of the optimisation scheme. The lifecycle cost comprises the gas compressor, pipeline, gas turbine, auxiliaries, fuel, and maintenance costs. The job cost and road cost constitute the additional costs element of the lifecycle cost for the techno socio-economic case study. The job cost is the employment cost incurred from the construction, installation, operation and maintenance of the compressor station and pipeline system. In this research, the lifecycle cost is to be minimised.

The Optimisation problem to optimise the compressor station and pipeline system is formulated as follows:

Minimise the objective function:

$$L_c(L) = P_t(L) + GC_t(L) + GT_c(L) + P_{aux}(L) + F_{lc}(L) + M_{lc}(L) \quad (3-1)$$

Subject to the constraint:

$$P_1 \leq 10000 \quad (3-2)$$

$$P_G \leq 0.9P_T \quad (3-3)$$

$$200 \leq L_1 \leq 390 \quad (3-4)$$

$$580 \leq L_2 \leq 770 \quad (3-5)$$

$$960 \leq L_3 \leq 1150 \quad (3-6)$$

$$L_{n,min} \leq L_n \leq L_{n,max} \quad (3-7)$$

Where:

L_c = Techno-economic lifecycle cost, \$

P_1 = Maximum allowable operating pressure at the pipe inlet, kPa

P_G = Gas compressor power, kW

P_T = Gas turbine power, kW

$L_1, L_2, \dots, L_n$ = Optimised compressor station locations

P_t = Total pipeline cost, \$

GC_t = Total gas compressor cost, \$

GT_c = Gas turbine capital cost, \$

P_{aux} = Auxiliaries cost, \$

F_{lc} = Lifecycle fuel consumption cost, \$

M_{lc} = Lifecycle maintenance cost, \$

The techno-economic lifecycle cost integrates the technical aspect of the project with the economic aspect. It considers the technological characteristics of the project with the economic aspect.

The objective function to be minimised for the techno socio-economic case can be written as:

Minimise the objective function:

$$L_T(L) = P_t(L) + GC_t(L) + GT_c(L) + P_{aux}(L) + F_{lc}(L) + M_{lc}(L) + E_c(L) + R_c(L) \quad (3-8)$$

Where:

L_T = Techno socio-economic lifecycle cost, \$

E_c = Employment cost, \$

R_c = Road construction cost, \$

The techno socio-economic lifecycle cost integrates the social aspect with the technical and economic aspects of the project. Equation (3-8) was considered due to its higher cost to the owner to deliver social benefits. It quantifies the extra cost to the owner in terms of E_c and R_c to achieve the evaluated social benefits. The social benefits are linked with the position of the compressor station so that social benefits changes with location. The inputs to the optimiser are station positioned that triggers a social benefit calculation that is different for each location. This social benefits changes with location were included as economic value within the net present value.

As evident in the public domain, this is the first time this research aspect has been done on optimising the natural gas transmission pipeline system using the compressor station location as a decision variable.

3.9 Summary

This chapter has given an overview of the methodology utilised in this research and the complete TERA framework for pipeline application, including the different modules and optimisation that make up the adapted framework. These modules and optimisation schemes are evaluated in detail in the following chapters. The pipeline and gas compressor modules discuss the pipeline and gas compressor power estimation at varying flow conditions.

4 PIPELINE AND GAS COMPRESSOR POWER ESTIMATION AT VARYING FLOW CONDITIONS

4.1 Introduction

In this chapter, gas properties influencing the flow of natural gas through the proposed Trans-Saharan Gas Pipeline are presented. Pressure drops due to friction in the pipeline are discussed. Gas compressor power at design point and off-design conditions are estimated. Compressor performance curves and compressor station power requirements at varying flow conditions resulting in the selection of gas compressor and gas turbine models are calculated.

4.2 Methodological Approach

The pipeline and gas compressor models were developed analytically in MATLAB environment using thermodynamic gas properties, pipeline characteristics, Weymouth gas flow equation. The results were validated with Aspen HYSYS software. The developed models consider the variation in the ambient conditions and altitude based on the local conditions at each compressor station location along the pipeline route. Figure 4-1 shows the integrated pipeline and gas compressor models flow chart.

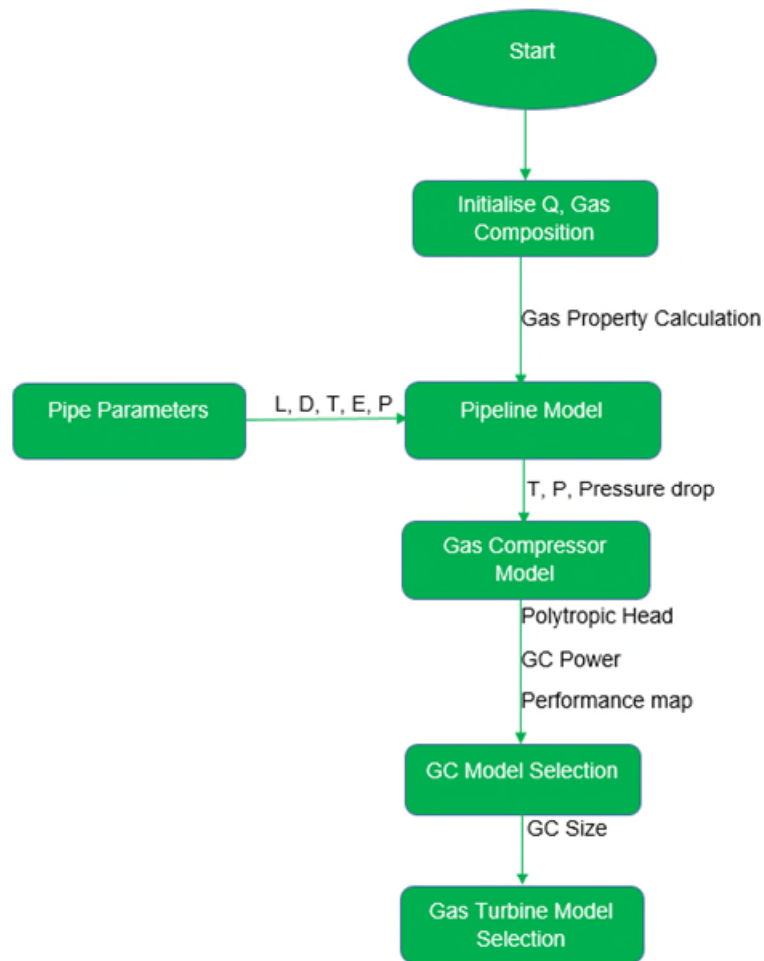


Figure 4-1 Integrated Pipeline and Gas Compressor Models Flow Chart

The methodological approach utilised in this study involves:

- ❖ Specify the pipeline parameters such as the pipe length, thickness, and diameter
- ❖ Specify the natural gas composition as retrieved from the Trans-Saharan Gas Pipeline report and perform gas properties calculation to determine gas molecular weight, gas viscosity, gas gravity and compressibility factor
- ❖ Specify the required gas volume flow and maximum allowable pipe operating pressures. Determine the downstream pipe pressure and evaluate the pipeline pressure drop using Weymouth gas flow equation considering segmented pipe length, elevation, and ambient temperature variation at varying flow conditions

- ❖ Identify the gas compressor suction conditions at the design point based on the results obtained above. Calculate the gas compressor polytropic head and power requirement using a developed code written in MATLAB environment and validate the results with Aspen HYSYS software
- ❖ Obtain the gas compressor performance curves at the off-design point based on the available Original Equipment Manufacturer curves and the results obtained above using a developed computer code written in a MATLAB environment
- ❖ Select the gas compressor models based on the analysed gas compressor power requirement
- ❖ Select the gas turbine models based on the analysed gas compressor power requirement

Figure 4-2 further shows the method of analysis utilised for the pipeline model in a flow chart format.

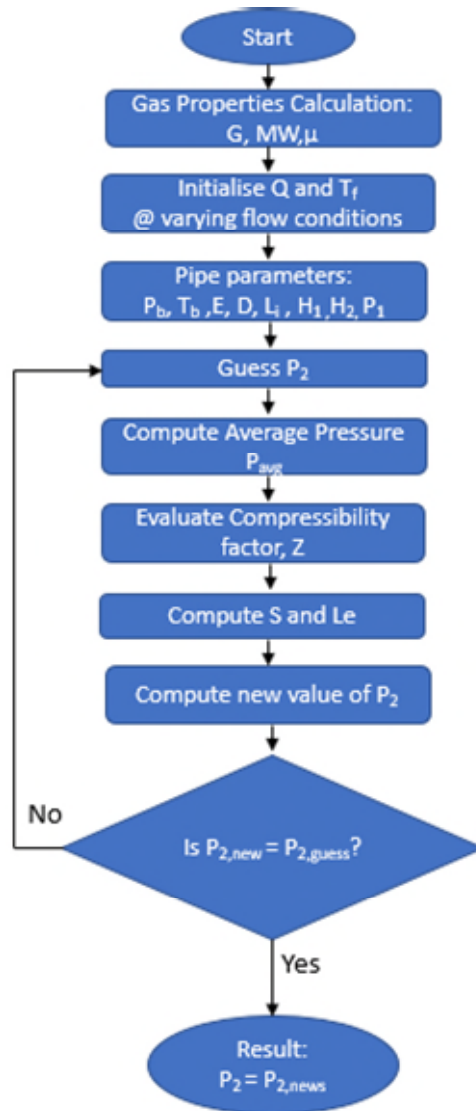


Figure 4-2 Pipeline Model Flow Chart

4.2.1 Pipeline and Gas Compressor Models Assumptions

The assumptions utilised in the analysis of the pipeline and gas compressor models are as follows:

1. Constant natural gas composition
2. Constant pipe diameter for the entire length of the pipeline
3. The gas flowing temperature is assumed to equal to the location ambient temperature at the suction or discharge point of the compressor station [38]

4. Baseline case study comprises 18 numbers of compressor stations in a predetermined location
5. The pipeline is clean
6. The operation of the gas compressors and gas turbines are based on the variation in compressor station location ambient temperatures at varying flow conditions
7. The gas compressors and gas turbines selected are expected to operate throughout the project lifecycle

4.3 Impact of Environmental Conditions

The performance of the centrifugal compressor is significantly impacted by the altitude and ambient conditions of the compressor station locations along the pipeline route. The altitude at which the compressor station and pipelines are being operated will affect the performance of major components such as the gas compressor and gas turbines since altitude affects ambient temperature. Thus, it is imperative to consider the variation in the location ambient temperature and altitude. The pipeline elevation profile is shown in Figure 3-2. Figure 4-3 shows the three-hourly variation in the average ambient temperature for one of the year's three seasons concerning the time of day of the compressor station locations along the pipeline route. It is assumed that each season has four months, with the winter season from October to January, the hot season from February to May, and the dry season from June to September. The ambient conditions form the basis for evaluating the pipeline, gas compressor, and gas turbine models in this research. These operating ambient conditions impact the techno-economics and the techno socioeconomics of the proposed Trans-Saharan Gas Pipeline project.

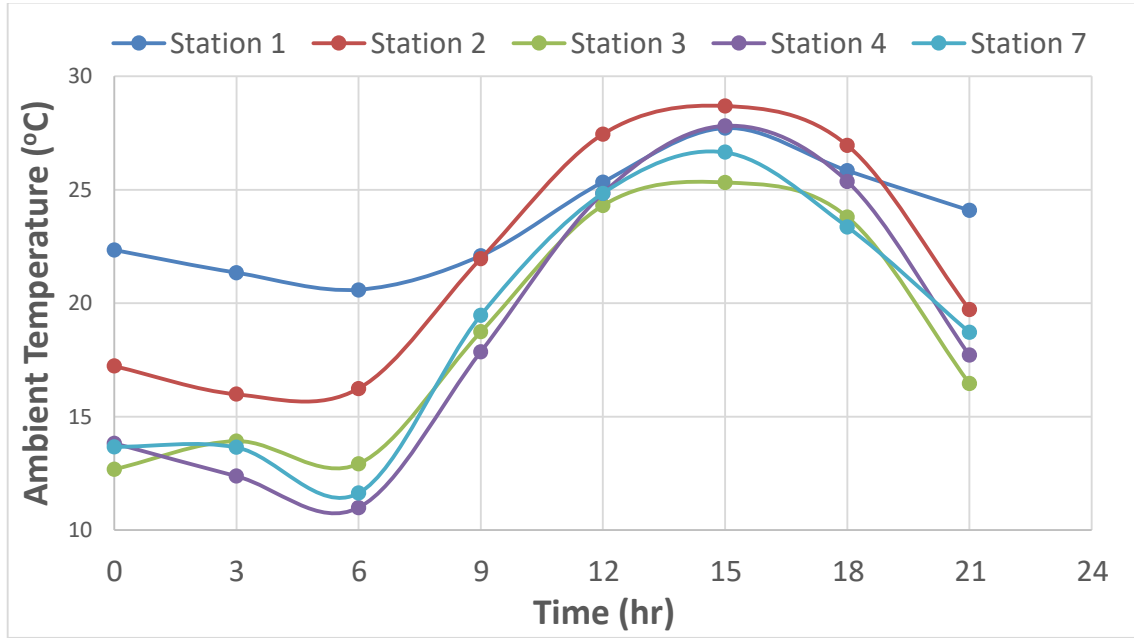


Figure 4-3 Ambient temperature at Station Locations for Winter Season

4.4 Natural Gas Composition

The natural gas composition plays a major part in the analysis of pipeline pressure drop and the performance of the gas compressor. The natural gas composition is retrieved from the Trans-Saharan Gas pipeline report and helps in the gas properties calculation. The pipeline natural gas composition is presented in Table 4-1.

Table 4-1 Natural Gas Composition

S/N	Gas Components	Molecular Weight	Volume Fraction
1	Methane (CH ₄)	16.04	0.9218
2	Ethane (C ₂ H ₆)	30.07	0.0493
3	Propane (C ₃ H ₈)	44.1	0.0056
4	Iso-Butane (C ₄ H ₁₀)	58.12	0.0031
5	N-Butane (C ₄ H ₁₀)	58.12	0.0011
6	Iso-Pentane (C ₅ H ₁₂)	72.15	0.0011
7	N-Pentane (C ₅ H ₁₂)	72.15	0.0004
8	N-Hexane (C ₆ H ₁₄)	86.18	0.0005
9	N-Heptane (C ₇ H ₁₆)	100.2	0.0003
10	N-Octane (C ₈ H ₁₈)	114.23	0.0001
11	Nitrogen (N ₂)	28.01	0.0091
12	Carbon dioxide (CO ₂)	44.01	0.0076

4.5 Pipeline Model: Gas Properties Calculation and Pressure Drop

The major factors affecting the flow of natural gas through pipelines are the pipeline parameters, gas properties, pipe inlet and outlet pressures, pipe inlet and outlet temperatures and pipe pressure drop due to friction. Gas properties calculations are important in determining pipeline pressure drop. Any change in the pipeline pressure will result in a corresponding change in the gas properties. The gas volume flow rate and other base properties were initialised through the data obtained from the preliminary report on Trans-Saharan Gas Pipeline [18].

4.5.1 Gas Properties Calculation

The degree of reliability of thermodynamic natural gas properties calculation and the natural gas equation of state will considerably influence the pipeline pressure drop and gas compressor performance. Transmission pipeline natural gas is often regarded as real gas due to the high-pressure drop that occurs while flowing through the pipeline.

The natural gas mixture properties are determined using a weighted average method from the known components' gas properties using the following equations:

$$MW = \sum_{j=1}^N y_j MW_j \quad (4-1)$$

$$T_c = \sum_{j=1}^N y_j T_{c_j} \quad (4-2)$$

$$P_c = \sum_{j=1}^N y_j P_{c_j} \quad (4-3)$$

Where MW_j , T_{c_j} , P_{c_j} are the molecular weight, critical temperature, and critical pressure of the j th component of the gas mixture with volume fraction y .

The natural gas gravity G , an estimate of the degree of the gas weight compared to air at the reference temperature, is calculated as follows:

$$G = \frac{MW}{MW_{air}} \quad (4-4)$$

The ideal gas equation of state is modified to the real gas equation of state considering the compressibility effects since natural gas pipelines often operate at higher pressures. The real gas equation of state can be written as:

$$Pv = ZRT_f \quad (4-5)$$

Where:

P = Total pressure, kPa

v = Specific molar volume, m³/kmol

Z = Compressibility factor

R = Universal gas constant

T_f = Gas flow temperature, K

The compressibility factor Z, a measure of the closeness of real gases to ideal gas, is a function of the gas gravity G, pressure, temperature, natural gas composition and critical properties. It is calculated using the California Natural Gas Association method as follows:

$$Z = \frac{1}{\left[1 + \left(\frac{344400 * P_{avg} * (10)^{1.785G}}{(T_f)^{3.825}} \right) \right]} \quad (4-6)$$

where, P_{avg} is the natural gas average pressure along the length of the pipe segment. Since the compressibility factor varies with pressure, the compressibility factor will also vary along the length of the pipeline. Thus, the compressibility factor would be estimated over the average gas pressure at any point along the pipeline. The average gas pressure along a pipe segment with suction pressure P_1 , and discharge pressure P_2 , is given by:

$$P_{avg} = \frac{2}{3} \left(P_1 + P_2 - \frac{P_1 * P_2}{P_1 + P_2} \right) \quad (4-7)$$

This average pressure is used to calculate the compressibility factor of the natural gas at the gas flowing temperature. The compressibility factor equation is reasonable when the average gas pressure exceeds 690 kPa. Otherwise, a value of unity is assumed.

The natural gas viscosity μ , measures its resistance to flow, and the degree of pressure drop in the pipeline. It depends on the gas flow temperature and pressure. A decrease in the natural gas temperature will increase the natural gas flow rate, hence a decrease in the natural gas viscosity. Conversely, an increase in the gas flow temperature will cause a corresponding decrease in the gas flow rate leading to an increase in the gas viscosity. The natural gas viscosity is calculated from its individual component's viscosity using the following equation:

$$\mu = \frac{\sum(\mu_i y_i \sqrt{MW_i})}{\sum(y_i \sqrt{MW_i})} \quad (4-8)$$

4.5.2 Pressure Drop in Pipelines

Consider a natural gas pipeline segment with volume flow rate Q , constant diameter D , and length L , as shown in Figure 4-4.

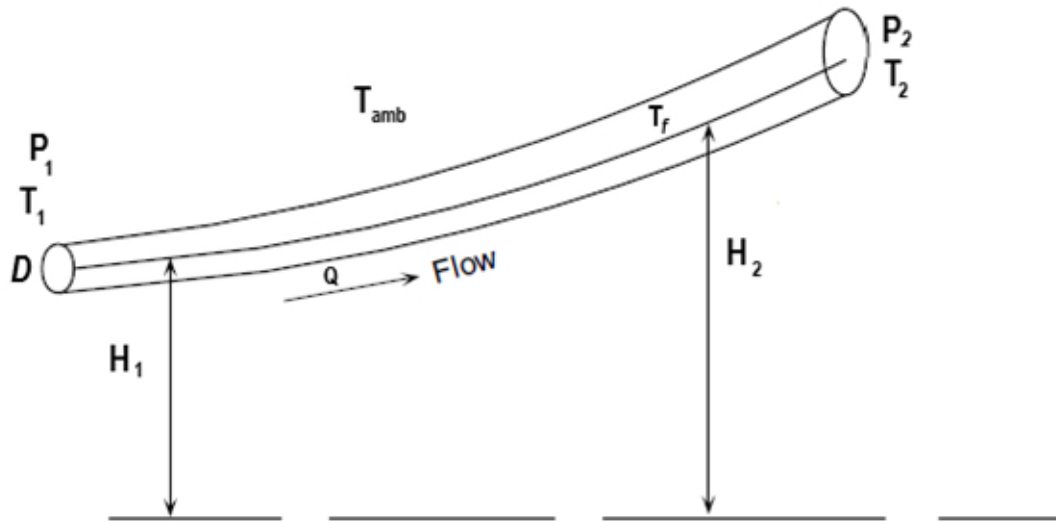


Figure 4-4 Natural Gas Pipeline Segment (Adapted from [38])

The suction and discharge conditions are P_1, T_1 and P_2, T_2 , respectively. The gas flowing temperature is T_f . The basic equation for relating the pressure drop in the pipeline with the throughput is the fundamental flow equation for the steady-state isothermal flow in a gas pipeline [38] and is given by:

$$Q = 1.1494 \times 10^{-3} \left(\frac{T_b}{P_b} \right) \left(\frac{P_1^2 - e^s P_2^2}{G T_f L_e Z f} \right)^{0.5} D^{2.5} \quad (4-9)$$

Q = Volumetric flow rate, (m³/day)

T_b = Base temperature, K

P_b = Base Pressure, kPa

P_1 = Inlet Pressure, kPa

P_2 = Outlet Pressure, kPa

T_f = Gas flow temperature, K

L_e = Pipeline equivalent length, km

G = Gas gravity, dimensionless

Z = Compressibility factor, dimensionless

D = Pipeline diameter, mm

e = 2.71828 (Euler's number)

s = Elevation adjustment parameter

f = Friction factor

This equation shows the relationship between the throughput of each pipe segment with the gas properties and pipe parameters. The net pressure drops resulting from transporting a given quantity of natural gas through the transmission pipeline depend on friction between the pipe wall and the flowing gas, pipe discharge pressure and pipe elevation. The natural gas viscosity and the pipe roughness influence the degree of friction occurring in the pipeline. The friction factor in the fundamental flow equations depends on the pipe's internal conditions and the flow pattern, which depends on the flow Reynolds number.

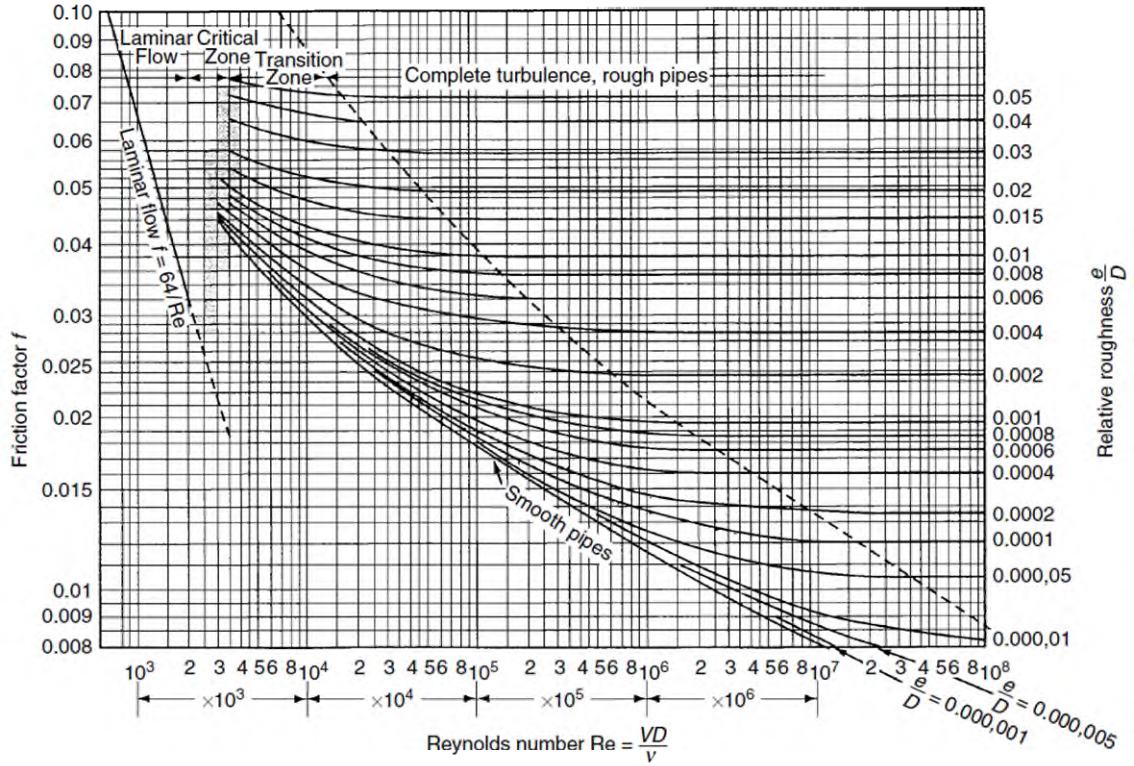


Figure 4-5 The Moody Chart [38]

Figure 4-5 shows the Moody chart depicting the graphical variation of the friction factor with the Reynolds number at different values of relative pipe roughness. The relative pipe roughness ε , is related to the pipe diameter D , and its internal roughness e , as follows:

$$\varepsilon = \frac{e}{D} \quad (4-10)$$

The friction factor f , can be calculated using Colebrook-White or American Gas Association equation. The Colebrook-White equation shows the relationship between the friction factor f , pipe inside diameter D , pipe roughness e , the flow Reynolds number Re , in gas pipelines considering turbulent flow and is given by:

$$\frac{1}{\sqrt{f}} = -2 \log_{10} \left(\frac{e}{3.7D} + \frac{2.51}{Re\sqrt{f}} \right) \quad (4-11)$$

where, Re is the flow Reynolds number which shows the relationship between the pipe internal diameter, viscosity, gas density and gas throughput. It is evaluated as follows:

$$Re = 0.5134 \left(\frac{P_b}{T_b} \right) \left(\frac{GQ}{\mu D} \right) \quad (4-12)$$

Where:

Q = Volumetric flow rate, (m³/day)

T_b = Base temperature, K

P_b = Base Pressure, kPa

G = Gas gravity, dimensionless

D = Pipeline diameter, mm

μ = Gas dynamic viscosity, Poise

The friction factor is evaluated using the above equations by iteration approach. An initial value of the friction factor is assumed and substituted into the right-hand side of Equation (4-11). This gives a second approximation for the friction factor, which is then used to calculate successive approximations until the solution converges within the desired tolerance value for f .

The equivalent length L_e , considers the variation in elevation between the ends of each pipe segment and is given by:

$$L_e = \frac{L(e^s - 1)}{s} \quad (4-13)$$

Where:

L = Pipe length, km

s = Elevation adjustment parameter

The elevation adjustment parameter s , is a function of the gas compressibility factor, gas gravity, gas flowing temperature and the pipe segment's elevation difference and is given as:

$$s = 0.0684G \left(\frac{H_2 - H_1}{T_f Z} \right) \quad (4-14)$$

Where:

H_1 = Upstream elevation, m

H_2 = Downstream elevation, m

Z = Compressibility factor, dimensionless

T_f = Gas flow temperature, K

G = Gas gravity, dimensionless

Considering the entire length of the natural gas transmission pipeline with a series of pipe segments and varying slopes. The total equivalent length L_e , of the pipeline is evaluated by summing the individual slopes that make up each pipe subsegment as follows:

$$L_e = j_1 L_1 + j_2 L_2 e^{s^1} + j_3 L_3 e^{s^2} + \dots \quad (4-15)$$

The parameter j , is given by:

$$j = \frac{e^s - 1}{s} \quad (4-16)$$

The Weymouth equation is used for high gas throughput, high pressure, and large diameter long-distance transmission pipelines. It calculates the natural gas flow rate for a given pressure without using a friction factor but considers the internal conditions of the pipe by utilising a pipeline efficiency factor. For a given pipe inlet pressure P_1 , natural gas flow rate Q , gas gravity G , gas compressibility Z , pipe length L , and pipe constant diameter D , the pipe outlet pressure P_2 , from each pipeline segment is calculated using Weymouth gas flow equation in S.I units as follows:

$$P_2 = \sqrt{\frac{1}{e^s} \left[P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 G T_f L_e Z}{(0.0037435)^2 E^2 (D^{2.667})^2} \right]} \quad (4-17)$$

The pipe outlet pressure cannot be calculated directly since the compressibility factor in Equation (4-17) is unknown. The average pressure P_{avg} in Equation (4-7) needs to be evaluated before the compressibility factor in Equation (4-6) can be determined. Since the pipe inlet pressure $P_1 = 9500 \text{ kPa}$ is known, we assume the initial value for the pipe outlet pressure and evaluate P_{avg} and then calculate the value of Z . The pipe outlet pressure is now calculated from this known value of Z . Using this estimated value of P_2 , a better approximation for Z is calculated from a new value of P_{avg} . This iterative approach is repeated until successive values of P_2 converge within the specified tolerance limit.

Hence, the pressure drop along the natural gas transmission pipeline segment is the algebraic difference between the estimated pipe outlet pressure and the known pipe inlet pressure defined by:

$$\Delta P = P_1 - P_2 \quad (4-18)$$

Table 4-2 shows the pipeline data for compressor station location 1.

Table 4-2 Pipeline Data for Compressor Station 1 [18]

S/N	Parameters	Values (Units)
1.	Natural gas flow	30 (BCM/year)
2.	Pipe nominal diameter	1422.4 (mm)
3.	Pipe outer diameter	1422.4 (mm)
4.	Pipe inner diameter	1381.2 (mm)
5.	Wall thickness	20.62 (mm)
6.	Gas gravity	0.6048 (mm)
7.	Compressibility factor	0.8273
8.	Gas temperature	288.15 (K)
9.	Base temperature	288.15 (K)
10.	Base pressure	101 (bar)
11.	MAOP	95 (barg)

12.	Elevation	100 (m)
13.	Equivalent Length	242.1 (km)
14.	Efficiency	91.8 (%)
15.	Pipe inlet pressure	95 (bar)
16.	Pipe outlet pressure	67.85 (bar)

4.6 Analysis of Gas Temperature and Ambient Temperature Assumption

Consider a long-distance gas pipeline of constant cross-section whose surface is maintained at its location ambient temperature. Figure 4-6 shows the variation of the average gas temperature along the pipeline segment.

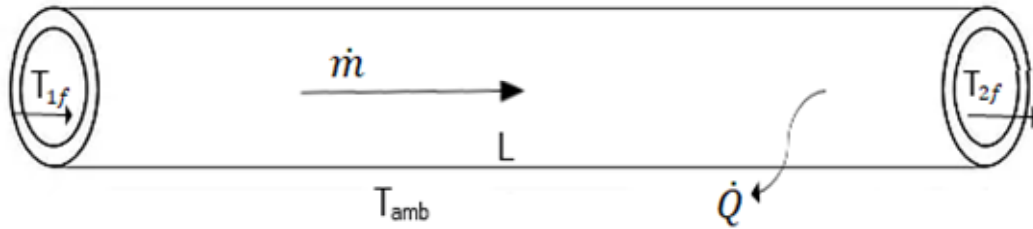


Figure 4-6 Variation of average gas temperature along a pipeline segment

The conservation of energy equation for the steady-state flow of gas from the inlet to the outlet of the pipe segment is given as:

$$\dot{Q} = -\dot{m}c_p(T_{1f} - T_{2f}) \quad (4-19)$$

Where T_{1f} and T_{2f} are the gas temperatures at the inlet and exit of the pipeline segment, respectively. $\dot{Q}$ is the heat transfer rate, $\dot{m}$ is the mass flow rate and c_p is the specific heat at constant pressure of the gas.

The rate of heat transfer from the gas flowing in the pipeline segment to the surroundings is given as:

$$\dot{Q} = -hA\Delta T = -hA(T_{amb} - T_{av}) \quad (4-20)$$

$$T_{av} = \frac{T_{1f} + T_{2f}}{2} \quad (4-21)$$

Where h is the average convection heat transfer coefficient, A is the pipeline cross-sectional area, ΔT is the average temperature difference between the gas and the surrounding ambient temperature T_{amb} , and T_{av} is the average gas temperature at the inlet and exit of the pipeline. Consider a differential control volume in the long-distance gas pipeline segment, as shown in Figure 4-7. The

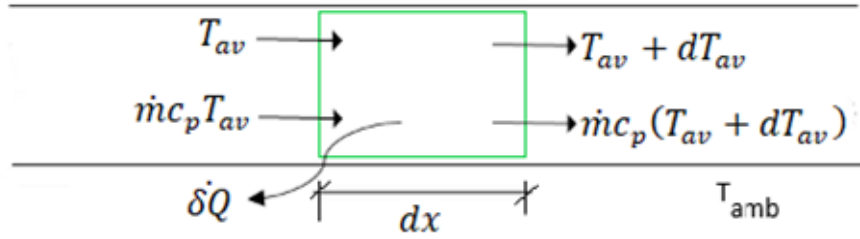


Figure 4-7 Differential Control Volume in a Long-distance Pipeline

average gas temperature will decrease in the flow direction due to heat transfer. The energy balance on the control volume is given as:

$$-\dot{m}c_p dT_{av} = -h(T_{amb} - T_{av})dA \quad (4-22)$$

$$\dot{m}c_p dT_{av} = h(T_{amb} - T_{av})dA \quad (4-23)$$

Equation (4-23) shows that the decrease in the energy of the gas is equivalent to the convection heat transfer from the gas to the surroundings. The pipeline surface area can be expressed as:

$$dA = \pi D dx \quad (4-24)$$

Similarly,

$$dT_{av} = -d(T_{amb} - T_{av}) \quad (4-25)$$

By substituting Equations (4-24) and (4-25) into Equation (4-23), we obtain:

$$-\dot{m}c_p d(T_{amb} - T_{av}) = h(T_{amb} - T_{av})\pi D dx \quad (4-26)$$

$$\frac{d(T_{amb} - T_{av})}{T_{amb} - T_{av}} = -\frac{\pi Dh}{\dot{m}c_p} dx \quad (4-27)$$

Integrating the above equation from the inlet of the pipeline where $x = 0$ to the outlet of the pipeline where $x = L$,

$$\int_{x=0}^{x=L} \frac{d(T_{amb} - T_{av})}{T_{amb} - T_{av}} = -\frac{\pi Dh}{\dot{m}c_p} \int_{x=0}^{x=L} dx \quad (4-28)$$

Noting that at:

$$x = 0; T_{av} = T_{1f};$$

$$x = L; T_{av} = T_{2f};$$

Equation (4-28) yields:

$$\ln \frac{T_{amb} - T_{2f}}{T_{amb} - T_{1f}} = -\frac{\pi DhL}{\dot{m}c_p} \quad (4-29)$$

Taking the exponent of both sides of Equation (4-29) gives:

$$\frac{T_{amb} - T_{2f}}{T_{amb} - T_{1f}} = e^{-\frac{\pi DhL}{\dot{m}c_p}} \quad (4-30)$$

Simplifying Equation (4-30) for T_{2f} yields:

$$T_{2f} = T_{amb} - (T_{amb} - T_{1f})e^{-\frac{\pi DhL}{\dot{m}c_p}} \quad (4-31)$$

As $L \rightarrow \infty$; the term $\frac{\pi DhL}{\dot{m}c_p} \rightarrow \infty$; also $e^{-\frac{\pi DhL}{\dot{m}c_p}} \rightarrow 0$. Taking these into consideration,

Equation (4-31) yields:

$$T_{2f} = T_{amb} \quad (4-32)$$

Hence, the average gas temperature at the exit of a long-distance pipeline is equivalent to the ambient temperature.

4.7 Gas Compressor Model

The outlet pressure of the natural gas pipeline is equivalent to the gas compressor suction pressure. Similarly, the inlet pressure of the pipeline is the gas compressor discharge pressure. The gas compressor discharge pressure is the maximum allowable operating pressure of the pipeline and equals 9500 kPa. The compression ratio of the gas compressor at each compressor station location is evaluated as follows:

$$\text{Compression ratio} = \frac{P_1}{P_2} \quad (4-33)$$

Where:

P_1 = Gas compressor discharge pressure, kPa

P_2 = Gas compressor suction pressure, kPa

The gas compressor discharge temperature could cause strain on the compressor components and affect the compressor reliability. Thus, it is essential to control this temperature by adequate cooling or keeping it within an acceptable limit. The gas compressor discharge temperature for a polytropic process depends on the gas compressor inlet temperature, compression ratio, polytropic exponent and the compressibility factors and is defined by:

$$T_1 = T_2 \left(\frac{Z_2}{Z_1} \right) \left(\frac{P_2}{P_1} \right)^{\frac{-(n-1)}{n}} \quad (4-34)$$

Where:

T_1 = Gas compressor discharge temperature, K

T_2 = Gas compressor suction temperature, K

Z_2 = Compressibility factor at suction condition

Z_1 = Compressibility factor at discharge condition

P_1 = Gas compressor discharge pressure, kPa

P_2 = Gas compressor suction pressure, kPa

n = Polytropic exponent

The polytropic head developed by the gas compressor is the quantity of energy imparted to the natural gas per unit mass of gas. It is dependent on the inlet temperature, molecular weight, compression ratio, polytropic exponent and compressibility factor. It is defined as follows:

$$H_p = Z_{avg} R T_f \frac{n}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{-(n-1)}{n}} - 1 \right] \quad (4-35)$$

$$R = \frac{R_o}{MW} \quad (4-36)$$

Where:

H_p = Polytropic head, KJ/kg

Z_{avg} = Average gas compressibility factor

R = Gas constant, KJ kg⁻¹ K⁻¹

R_o = Universal gas constant, KJ kg⁻¹ K⁻¹

T_f = Gas flow temperature, K

MW = Gas molecular weight

The gas compressor power requirement depends on the gas flow temperature, pressure, polytropic head and throughput. The increase in gas temperature and pressure leads to a corresponding increase in throughput, polytropic head and gas power required. The gas compressor power requirement can be written as:

$$P_{GC} = 4.0639 Q T_f \frac{n}{n-1} \left(\frac{1}{\eta_p} \right) Z_{avg} \left[\left(\frac{P_2}{P_1} \right)^{\frac{-(n-1)}{n}} - 1 \right] \quad (4-37)$$

Where:

P_{GC} = Gas compressor power, kW

η_p = Polytropic efficiency

Q = Gas volumetric flow rate, Mm³/day

Z_{avg} = Average gas compressibility factor

T_f = Gas flow temperature, K

P_1 = Gas compressor discharge pressure, kPa

P_2 = Gas compressor suction pressure, kPa

n = Polytropic exponent

Combining Equations (4-35) - (4-37) the gas compressor power requirement is expressed as follows:

$$P_{GC} = \frac{mH_p}{3600\eta_p} \quad (4-38)$$

Where:

P_{GC} = Gas compressor power, kW

H_p = Polytropic head, KJ/kg

η_p = Polytropic efficiency

m = Mass flow rate, kg/s

The polytropic efficiency η_p , is independent of the natural gas thermodynamic properties but is only a function of the isentropic exponent k , and polytropic exponent n . It is defined as follows:

$$\eta_p = \frac{\left(\frac{n}{n-1}\right)}{\left(\frac{k}{k-1}\right)} \quad (4-39)$$

The gas compressor actual volume flow rate at suction conditions Q_{act} , is given by:

$$Q_{act} = QZ_2 \left(\frac{P_b}{P_2} \right) \left(\frac{T_f}{T_b} \right) \quad (4-40)$$

Where:

Q_{act} = Actual volume flow rate, m³/hour

Q = Gas volumetric flow rate, m³/day

Z_2 = Compressibility factor at suction

P_b = Base pressure, kPa

P_2 = Gas compressor suction pressure, kPa

T_f = Gas flow temperature, K

T_b = Base temperature, K

The gas compressor actual mass flow rate m , at suction conditions is given by:

$$m = Q_{act}\rho_s \quad (4-41)$$

Where, ρ_s is the suction density given by:

$$\rho_s = \frac{P_2}{Z_2RT_f} \quad (4-42)$$

R is the gas constant. The change in gas flow temperature will affect the actual volume flow rate since the gas compressor suction condition is a function of temperature and pressure.

4.7.1 Gas Compressor Power Evaluation at Varying Flow Conditions

The gas compressor power requirements were evaluated at varying gas flow temperature conditions based on three scenarios with the assumption that the gas flowing temperature is equivalent to the location ambient temperature at the

suction or discharge point of the compressor station. These scenarios are explained below:

1. Isothermal flow conditions: This scenario assumes a constant gas flowing temperature of 22°C throughout the day at all seasons of the year and all compressor station locations.
2. Non-isothermal flow conditions: This scenario assumes that gas-flowing temperature is equivalent to the prevailing time-based ambient temperature for the three seasons of the year; winter, dry and hot. A change in the compressor station location ambient temperature will lead to a corresponding change in the gas flowing temperature at the reference time.
3. Intermediate flow conditions: This scenario assumes the constant average value of the above two cases for isothermal and non-isothermal flow conditions throughout the day at all seasons of the year, dependent on the prevailing non-isothermal ambient temperatures at each compressor station location.

These scenarios depict the different operating conditions of the gas compressor as would be expected in the oil and gas industry dealing with long-distance natural gas transmission pipelines. They represent the whole temperature ranges experienced at the compressor station locations and pipeline route.

4.8 Validation of the Gas Compressor Model with Aspen HYSYS

Aspen HYSYS [133] is frequently employed for process simulation in the oil and gas industry. It can be used for optimising compressor operations based on feeds and ambient conditions, visualise compressor behaviour, perform a compressor study across a range of scenarios while still saving time, accessible and producing accurate results. The gas compressor model was validated with Aspen HYSYS software. The Peng-Robinson equation of state was chosen as the fluid package to determine the natural gas thermodynamic properties. The following show the gas compressor modelling procedures with Aspen HYSYS:

- ❖ Start Aspen HYSYS

- ❖ Define the natural gas mixture involved in the simulation by adding individual component properties
- ❖ Select a fluid package. The Peng-Robinson equation of state is chosen
- ❖ Enter the simulation environment. Add and specify the upstream and downstream material streams. Material streams are defined as natural gas. The inlet temperature and pressure, outlet pressure and the volume flow are specified by entering and normalising the natural gas composition with individual component volume fraction
- ❖ Select the compressor from the object palette by dragging and placing it on the main flowsheet. Add and connect compressor with material streams
- ❖ Define the energy, inlet, and outlet stream of the compressor
- ❖ Specify the compressor efficiency under the design parameter tab
- ❖ Obtain the compressor outlet temperature, duty, pressure, pressure drop and pressure ratio from the design parameter tab
- ❖ Obtain the compressor polytropic head, polytropic efficiency, power, and other required results from the performance tab

4.9 Gas Compressor Performance Map

The gas compressor performance maps show the variation of the polytropic head, pressure ratio, efficiency, and discharge temperature with actual volume flow rates at varying speeds. The gas compressor performance maps were obtained from the scaling of original equipment manufacturer maps (see Appendix B). The following show the steps utilised in obtaining the corrected mass flow rate for the new maps:

- a) Obtain the actual volume flow at the design point from the original equipment manufacturer map
- b) Correct this flow
- c) Obtain the actual volume flow at the design point for the new map
- d) Correct this flow
- e) Obtain the scaling factor for the corrected mass flows (or corrected volume flows)

- f) Obtain the actual volume flow at off-design conditions from the original equipment manufacturer map
- g) Correct these flows
- h) Obtain the corrected mass flow (or corrected volume flow) at off-design conditions for the new map using the scaling factor obtained previously
- i) Obtain the actual volume flow for these corrected flows for the new map

The corrected mass flow rate incorporating humidity effects [134] for a constant diameter machine such as the gas compressor is given as:

$$\dot{m}_c = \dot{m}_{act} \frac{\rho_{ref} a_{ref}}{\rho_{act} a_{act}} \quad (4-43)$$

Where:

$\dot{m}_c$ = Corrected mass flow rate, kg/s (or corrected volume flow, m³/h)

$\dot{m}_{act}$ = Actual mass flow rate, kg/s (or actual volume flow, m³/h)

ρ_{ref} = Reference gas density, kg/m³

ρ_{act} = Actual gas density, kg/m³

a_{ref} = Sound speed at reference condition, m/s

a_{act} = Actual sound speed, m/s

Where:

$$a_{ref} = \sqrt{k_{ref} Z_{ref} R_{ref} T_{ref}} \quad (4-44)$$

$$a_{act} = \sqrt{k_{act} Z_{act} R_{act} T_{act}} \quad (4-45)$$

$$\rho_{ref} = \frac{P_{ref}}{Z_{ref} R_{ref} T_{ref}} \quad (4-46)$$

$$\rho_{act} = \frac{P_{act}}{Z_{act} R_{act} T_{act}} \quad (4-47)$$

Where:

k_{ref} = Polytropic exponent at reference condition

Z_{ref} = Compressibility factor at reference condition

R_{ref} = Gas constant at reference condition, KJ kg⁻¹ K⁻¹

T_{ref} = reference temperature, K

k_{act} = Actual polytropic exponent

Z_{act} = Actual compressibility factor

R_{act} = Actual gas constant, KJ kg⁻¹ K⁻¹

T_{act} = Actual temperature, K

P_{ref} = Reference pressure, kPa

P_{act} = Actual pressure, kPa

Substituting Equations (4-44) - (4-47) into Equation (4-43), we obtain the simplified form of the corrected mass flow rate as follows:

$$\dot{m}_c = \dot{m}_{act} \frac{P_{ref}}{P_{act}} \sqrt{\frac{Z_{act}}{Z_{ref}}} \sqrt{\frac{R_{act}}{R_{ref}}} \sqrt{\frac{k_{ref}}{k_{act}}} \sqrt{\frac{T_{act}}{T_{ref}}} \quad (4-48)$$

The actual volume flow for the new compressor map was obtained using Equation (4-48) and the scaling factor for the corrected mass flow rate defined by:

$$\dot{m}_{c_SF} = \frac{\dot{m}_{c_DP}}{\dot{m}_{c_OEM_DP}} \quad (4-49)$$

Where:

$\dot{m}_{c_SF}$ = Scaling factor for corrected mass flow (or corrected volume flow)

$\dot{m}_{c_DP}$ = Corrected mass flow at the design point, kg/s (or corrected volume flow, m³/h)

$\dot{m}_{c_OEM_DP}$ = Corrected mass flow at design point from OEM, kg/s (or corrected volume flow, m³/h)

The following show the steps utilised in obtaining the pressure ratio curves for the new maps:

- a) Obtain the pressure ratio at the design point for the new map
- b) Obtain the pressure ratio at the design point from the original equipment manufacturer map
- c) Obtain the scaling factor for pressure ratio at design point
- d) Generate pressure ratio data at off-design conditions from the original equipment manufacturer map
- e) Compute the equivalent pressure ratio at off-design conditions for the new map using the scaling factor obtained previously

New gas compressor maps for the pressure ratio were obtained by a scaling factor defined by:

$$PR_{SF} = \frac{PR_{DP} - 1}{PR_{OEM_DP} - 1} \quad (4-50)$$

Where:

PR_{SF} = Scaling factor for pressure ratio

PR_{DP} = Pressure ratio at design point

PR_{OEM_DP} = Pressure ratio at design point from OEM

Similarly, new compressor maps were obtained for the compressor polytropic efficiency, polytropic head and discharge temperature by defining their scaling factors as follows:

$$\eta_{SF} = \frac{\eta_{DP}}{\eta_{OEM_DP}} \quad (4-51)$$

$$H_{SF} = \frac{H_{DP}}{H_{OEM_DP}} \quad (4-52)$$

$$T_{SF} = \frac{T_{DP}}{T_{OEM_DP}} \quad (4-53)$$

Where:

η_{SF} = Scaling factor for polytropic efficiency

η_{DP} = Polytropic efficiency at design point

η_{OEM_DP} = Polytropic efficiency at design point from OEM

H_{SF} = Scaling factor for polytropic head

H_{DP} = Polytropic head at design point

H_{OEM_DP} = Polytropic head at design point from OEM

T_{SF} = Scaling factor for discharge temperature

T_{DP} = Discharge temperature at design point

T_{OEM_DP} = Discharge temperature at design point from OEM

4.10 Pipeline and Gas Compressor Model Results

Figure 4-8 shows the pipeline pressure gradient for compressor station 3 location. Figure 4-9 shows the pressure profile along the natural gas transmission pipeline for the 18 numbers of compressor stations with a total pipeline distance of 4180 km as proposed from the Trans-Saharan Gas Pipeline report for the baseline case. The pipeline inlet pressure is 9500 kPa, equivalent to the compressor discharge pressure. The pressure drops at compressor station 3 varies with the pipe distance and the gas flowing temperature, as shown in Figure 4-8. At isothermal and intermediate temperatures of 295.15 K and 305.05 K respectively, the pressure drops increase with the increase in pipe length until they attain their maximum pressure drops at a pipe length of 240 km. These maximum pressure drops are equivalent to the low pipe discharge pressures experienced at compressor station 3.

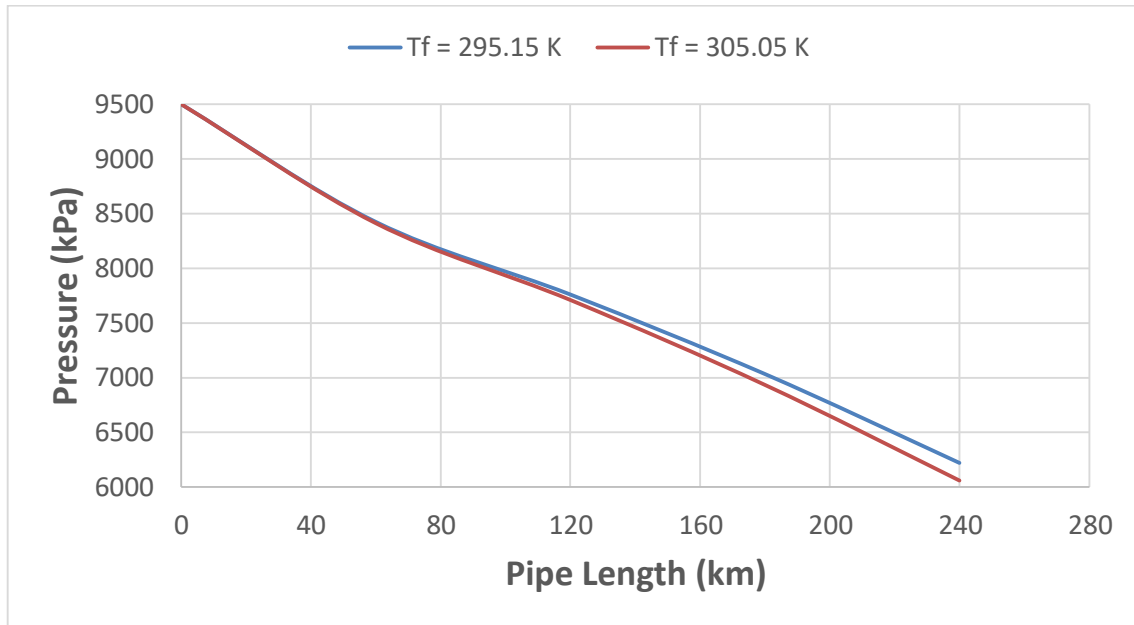


Figure 4-8 Pressure drops along the pipeline for compressor station 3

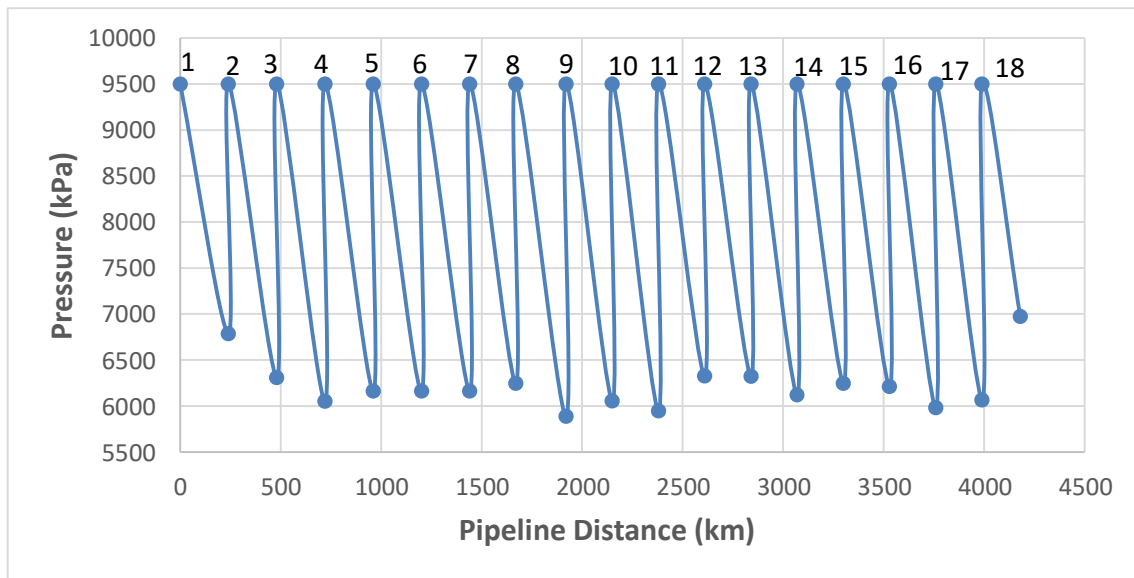


Figure 4-9 Pipeline Pressure drops at Various Compressor Station Locations

Considering the non-isothermal scenario with variation in gas flowing temperature. A rise in the gas flow temperature from 295.15 K to 305.05 K at a particular pipe length leads to a corresponding increase in the pressure drop. Similarly, a fall in the gas temperature leads to a corresponding decrease in the pressure drops through the pipeline.

The variation in pressure drops with pipeline distance at the maximum gas flowing temperatures at each compressor station location along the pipeline is depicted in Figure 4-9. The pressure drops to 6785 kPa and 6312 kPa at compressor stations 2 and 3, respectively. Thus, gas compressors are needed at these locations to boost these low pressures to the pipeline operating pressures of 9500 kPa to ensure a continuous supply of natural gas through the pipelines.

4.10.1 Effect of Gas Compressor Suction Pressure and Pressure Ratio

Figure 4-10, Figure 4-11, and Figure 4-12 show the gas compressor inlet pressure at each compressor station location along the pipeline route for isothermal, intermediate and non-isothermal flow conditions, respectively.

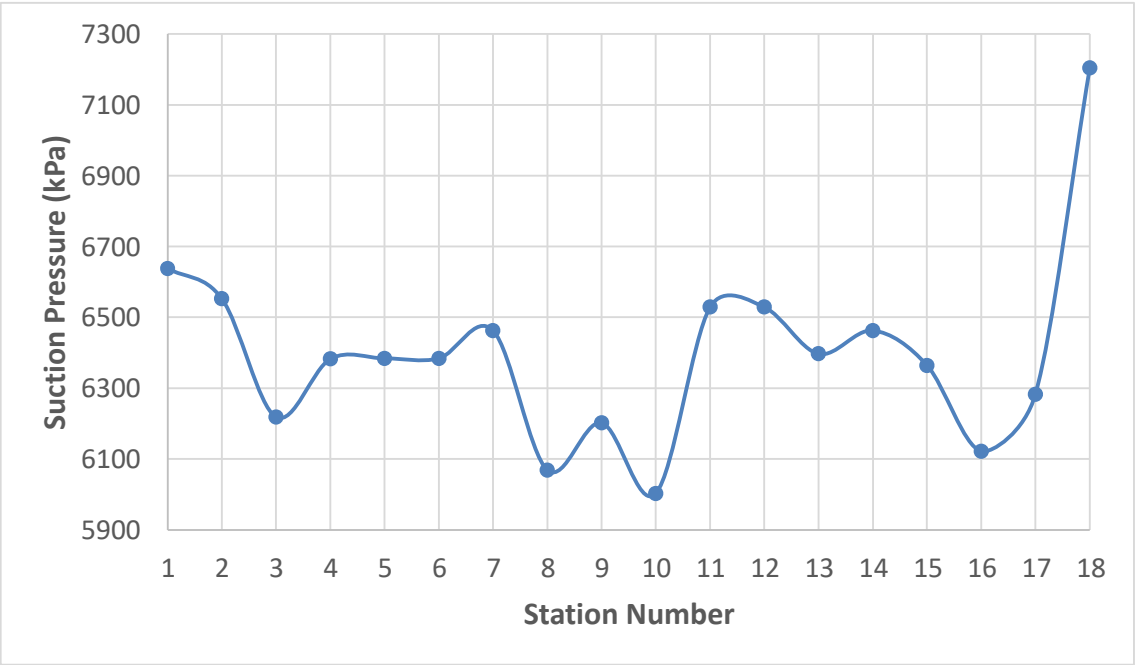


Figure 4-10 Gas Compressor Suction Pressure at Isothermal Flow Conditions

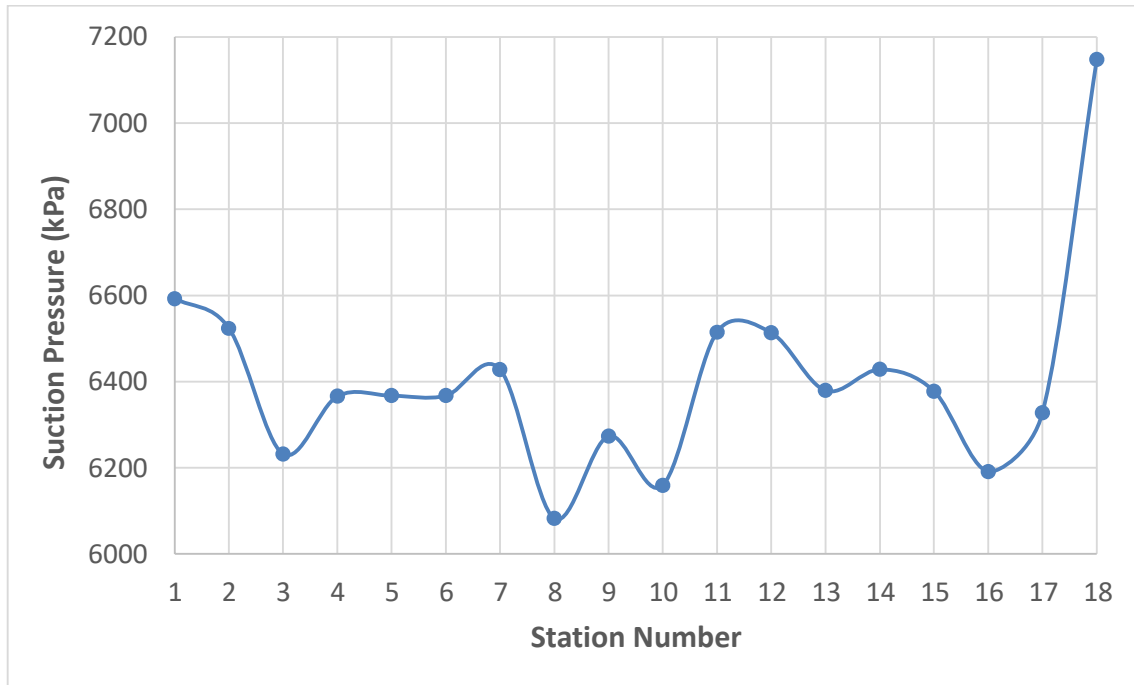


Figure 4-11 Gas Compressor Suction Pressure at Intermediate Flow Conditions

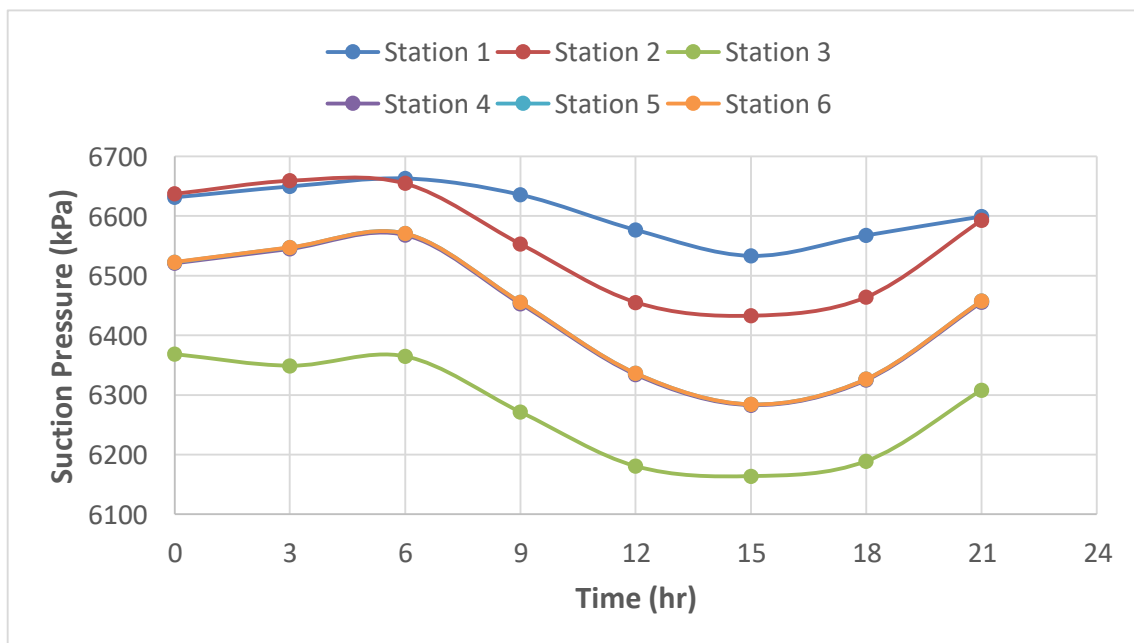


Figure 4-12 Gas Compressor Suction Pressure at Non-Isothermal Conditions (Winter Season)

The suction pressure varies from one location to another location and depends on the pipe distance, elevation, and ambient temperature. Compressor station

locations 10 and 8 have the lowest suction pressures at isothermal and intermediate flow conditions, respectively. These locations are associated with the lowest average pipeline pressures, thus high gas compressor power requirements are desired at these locations. Conversely, compressor station location 18 has the highest suction pressure at isothermal and intermediate flow conditions. This location is associated with the highest average pipeline pressure. Thus, low gas compressor power requirement is needed at this location.

For the non-isothermal condition (Figure 4-12), the gas compressor suction pressure is lowest at 15:00 hours of the day where the ambient temperature is highest, more so, the average pipeline pressure is lowest at this time of the day, thus high gas compressor power is required. Conversely, the gas compressor suction pressure is highest at 06:00 hours of the day where the ambient temperature is lowest. The average pipeline pressure is highest at this time of the day, thus low gas compressor power is required.

Figure 4-13, Figure 4-14, and Figure 4-15 show the gas compressor pressure ratio at each compressor station location along the pipeline route for isothermal, intermediate and non-isothermal flow conditions, respectively.

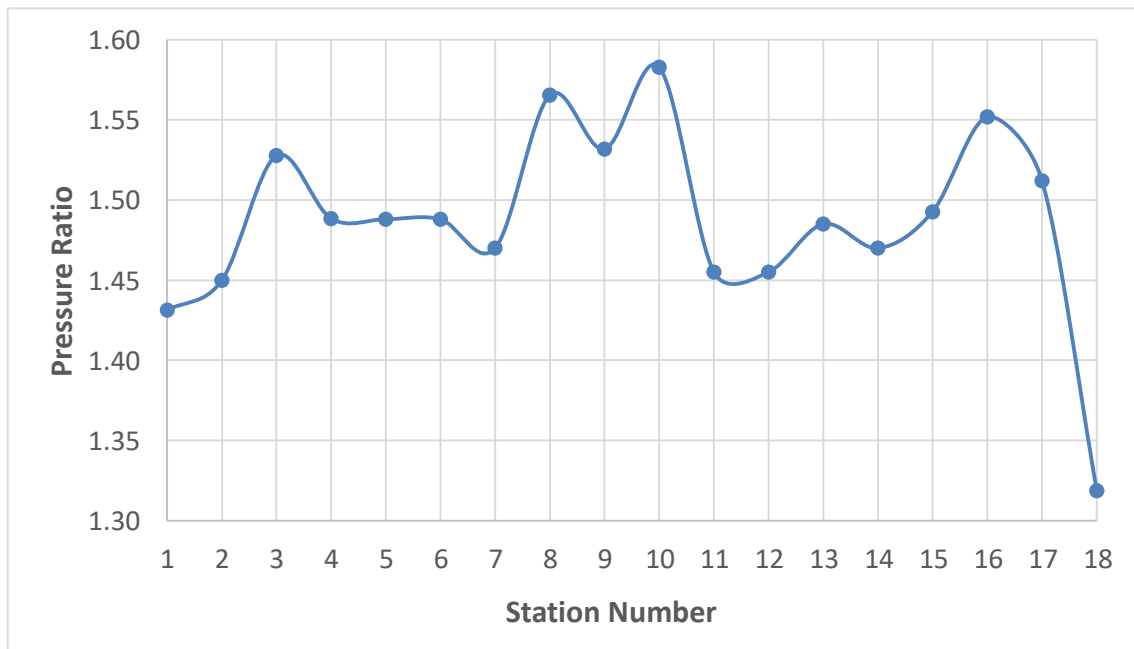


Figure 4-13 Gas Compressor Pressure Ratio at Isothermal Flow Conditions

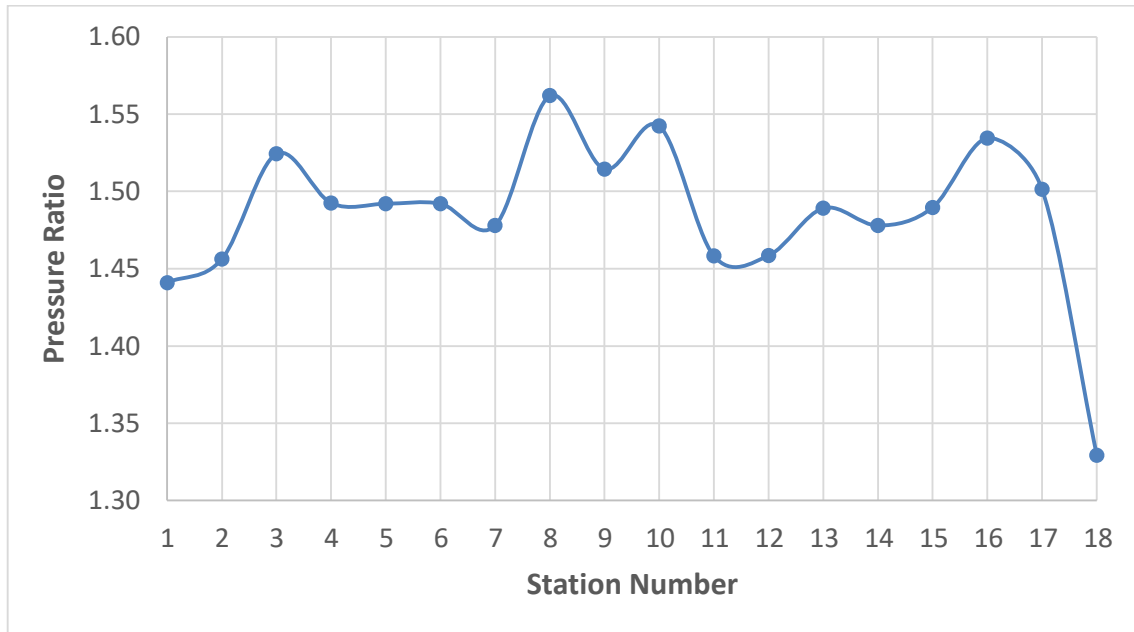


Figure 4-14 Gas Compressor Pressure Ratio at Intermediate Flow Conditions

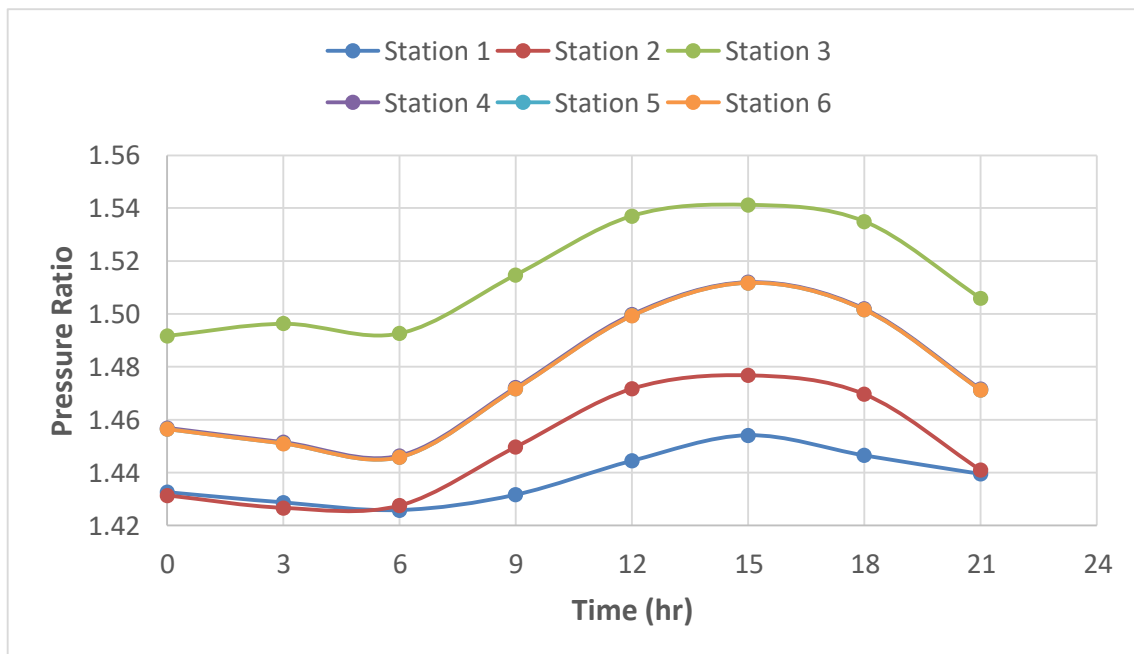


Figure 4-15 Gas Compression Ratio at Non-Isothermal Conditions (Winter Season)

The compression ratio of the gas compressor is the ratio of its discharge pressure to its suction pressure. In this study, the compressor discharge pressure is the maximum allowable operating pressure of the pipeline equal to 9500 kPa. For the isothermal and intermediate flow conditions, compressor station location 18 has the lowest pressure ratio thus will require the lowest gas compressor power.

In contrast, compressor station locations 10 and 8 with the highest pressure ratios at isothermal and intermediate flow conditions, respectively, will require the highest gas compressor power. For the non-isothermal conditions, a larger number for pressure ratio at 15:00 hours of the day will require more compressor power, while a smaller number for pressure ratio at 06:00 hours of the day will require less compressor power.

4.10.2 Effects of Gas Compressor Discharge Temperature

Figure 4-16, Figure 4-17, and Figure 4-18 show the gas compressor discharge temperature at each compressor station location along the pipeline route for isothermal, intermediate and non-isothermal flow conditions, respectively.

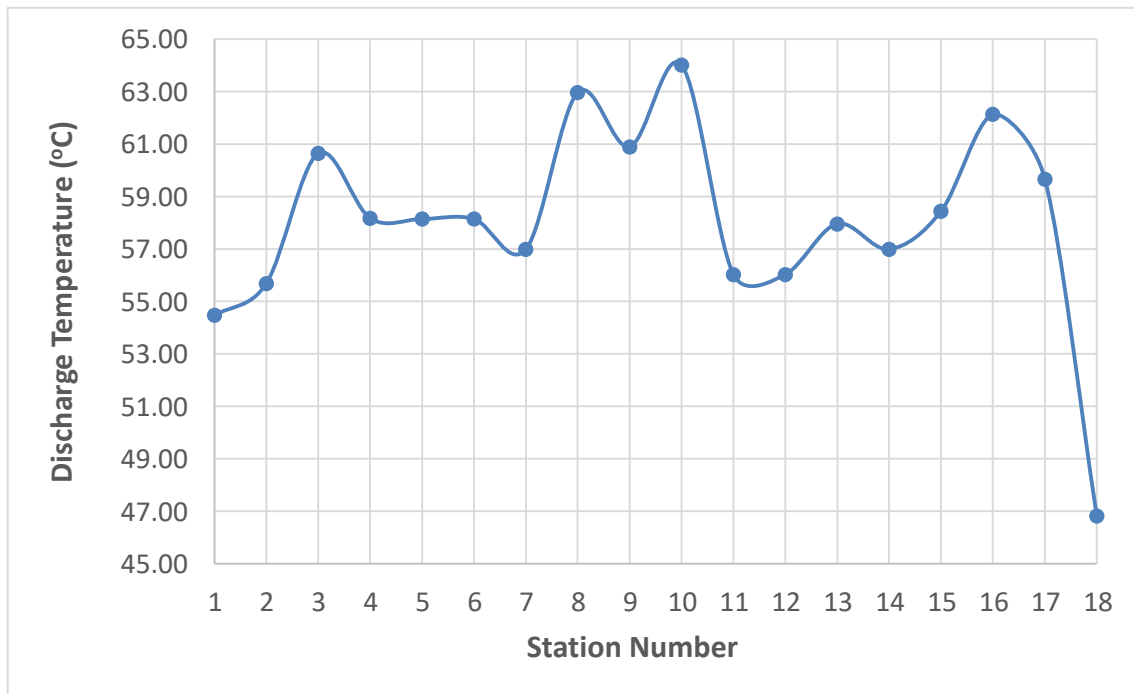


Figure 4-16 Gas Compressor Discharge Temperature at Isothermal Conditions

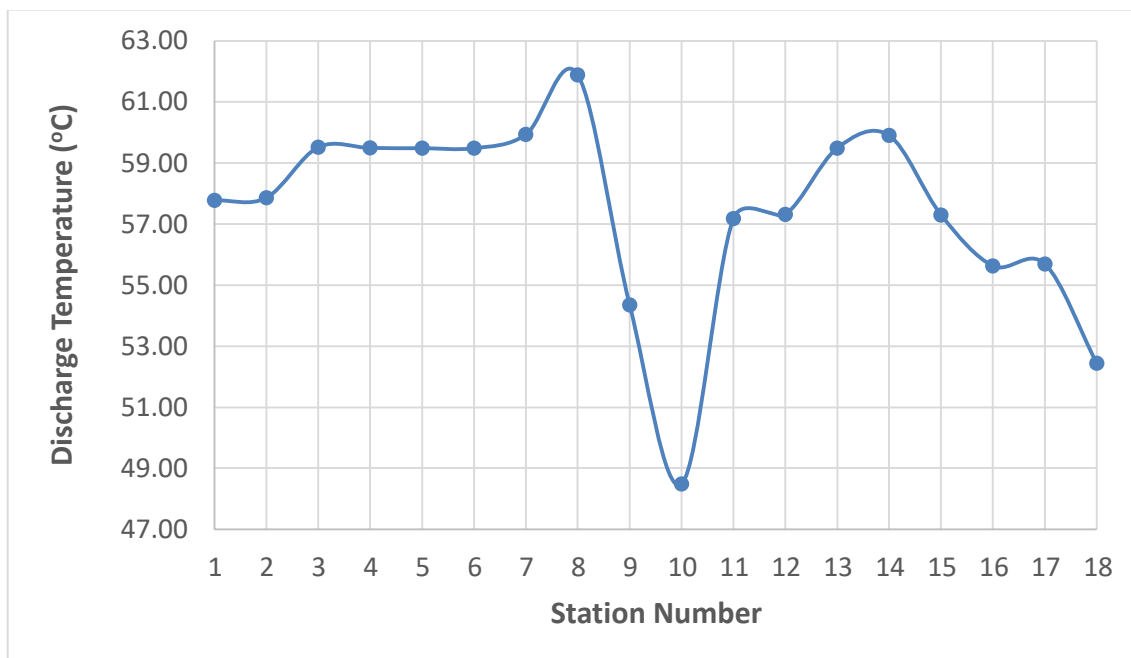


Figure 4-17 Gas Compressor Discharge Temperature at Intermediate Conditions

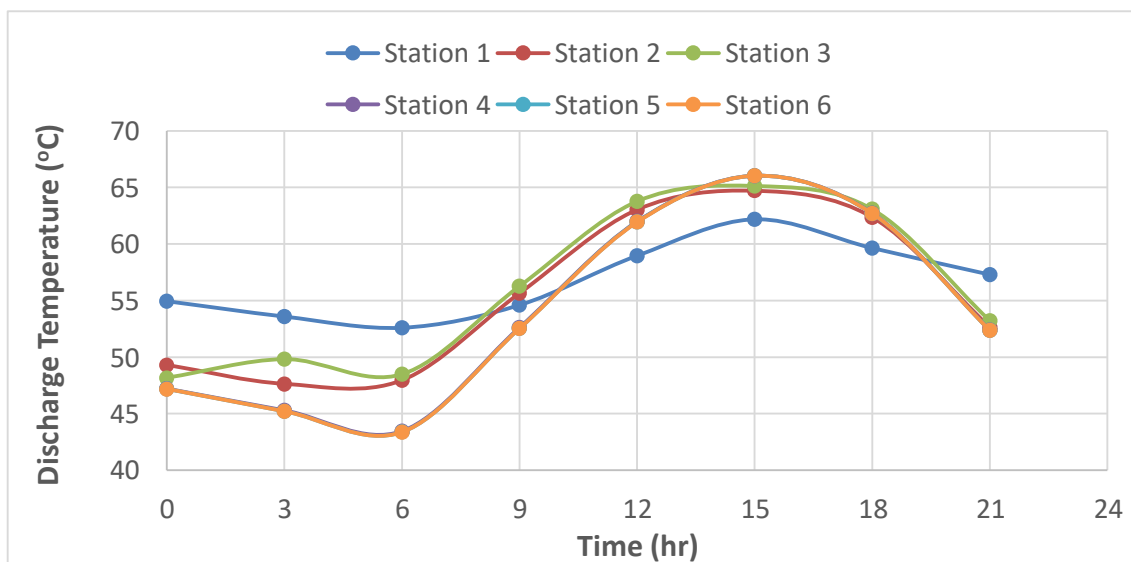


Figure 4-18 Gas Compressor Discharge Temperature at Non-Isothermal Conditions (Winter Season)

The discharge temperature is the increase in the gas temperature due to gas compression. Comparing Figure 4-13, Figure 4-14, Figure 4-15 with Figure 4-16, Figure 4-17, Figure 4-18, the discharge temperature of the gas increases with the compression ratio. The higher the gas compression ratio, the higher the

discharge temperature of compressed gas. Compressor station locations 10 and 8, with the highest gas compressor pressure ratio for isothermal flow condition have the highest discharge temperature. For the non-isothermal case, the highest discharge temperature occurs at 15:00 hours of the day with the highest gas compression ratio. However, compressor station location 10 with the second highest gas compression ratio in Figure 4-14 has the lowest discharge temperature as shown in Figure 4-17 for the intermediate flow condition. This result is due to the low suction intermediate temperature experienced at this location compared to other compressor station locations. It is desirable to control the discharge temperature within an acceptable limit for efficient gas transportation. This could be achieved by providing a cooling device at the discharge of the gas compressor.

4.10.3 Effects of Gas Compressor Power at Varying Flow Conditions

Figure 4-19, Figure 4-20, and Figure 4-21 show the gas compressor power requirement at each compressor station location along the pipeline route for isothermal, intermediate and non-isothermal flow conditions, respectively.

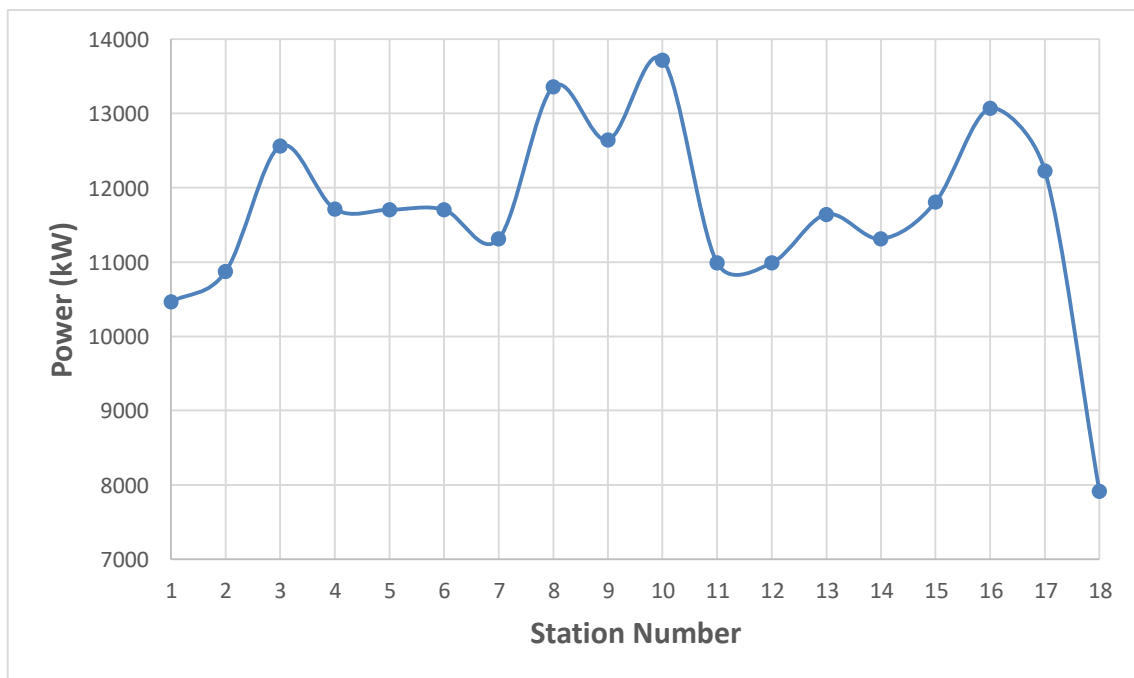


Figure 4-19 Gas Compressor Power Requirement at Isothermal Flow Conditions

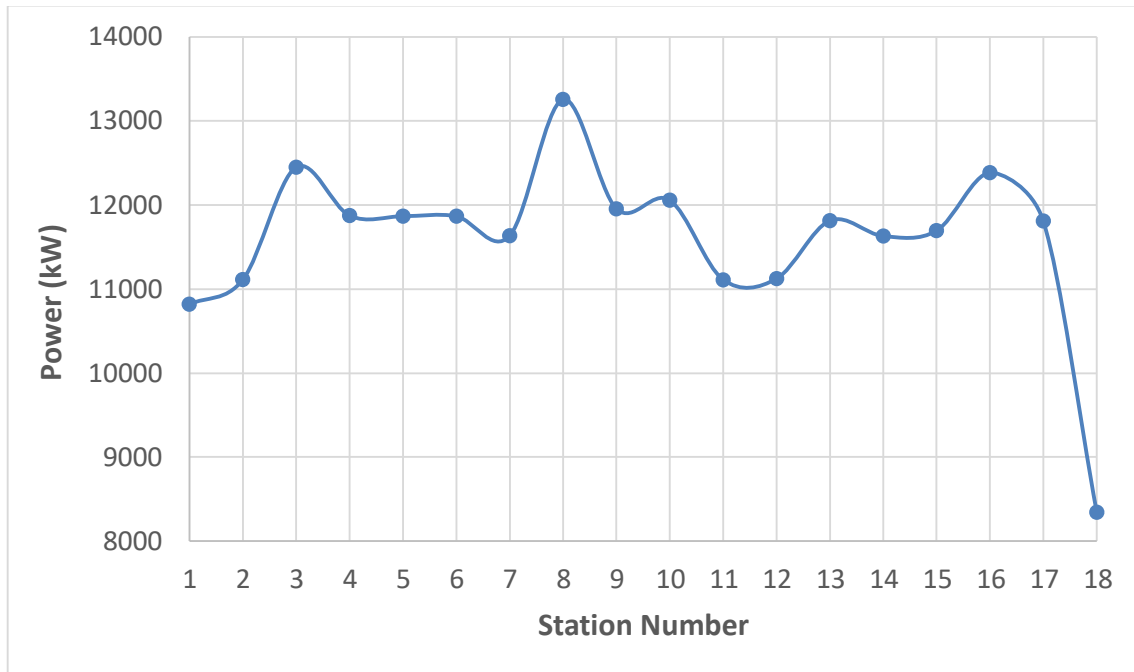


Figure 4-20 Gas Compressor Power Requirement at Intermediate Flow Conditions

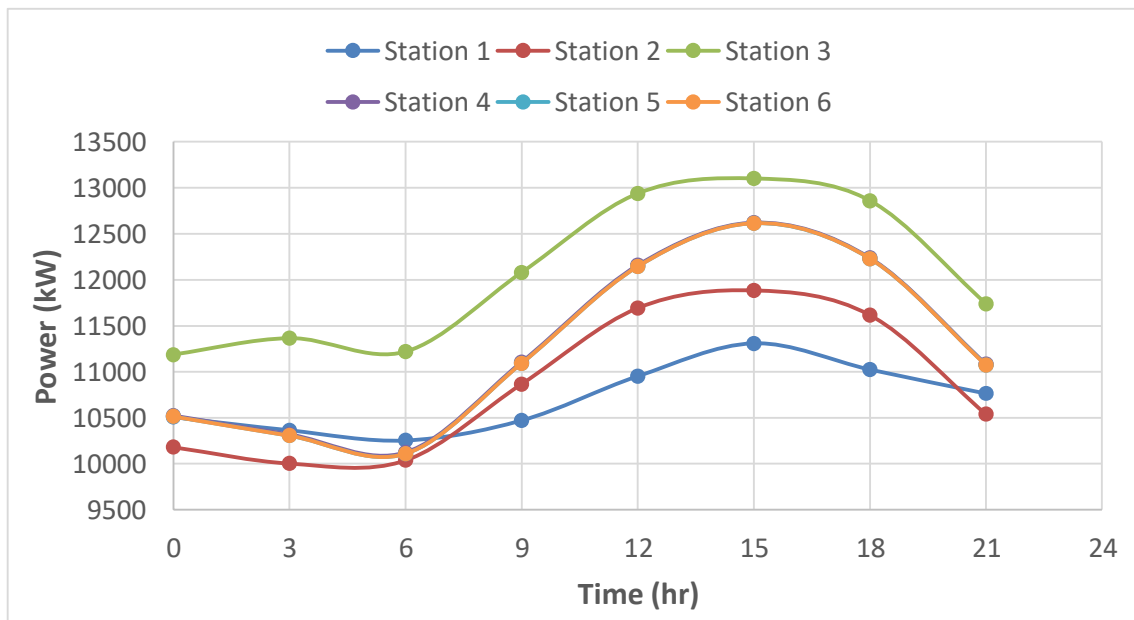


Figure 4-21 Gas Compressor Power Requirement at Non-Isothermal Conditions (Winter Season)

The highest gas compressor power occurs at stations 10 and 8 considering isothermal flow conditions shown in Figure 4-19. These locations are associated with the lowest suction pressure, lowest average pressure, and highest gas compression ratio. The increase in the distance and elevation lead to a corresponding decrease in the gas compressor suction pressure resulting in an increase in the gas compression ratio, increase in polytropic head and increase in the gas compressor power requirement. However, station 10 has a lower gas compressor power for the intermediate case shown in Figure 4-20 compared to the isothermal case in Figure 4-19. This is due to the low suction intermediate temperature experienced at this location. In both flow conditions in Figure 4-19 and Figure 4-20, the lowest gas compressor power requirement occurs at compressor station location 18 with the highest suction pressure, highest pipeline average pressure and lowest gas compression ratio. The gas compressor power decreases with an increase in suction pressure because of a decrease in gas compression ratio and polytropic head.

For non-isothermal conditions, the compressor power requirement is significantly affected by the compressor station location characteristics, which depends on the prevailing ambient temperature and time of the day at different seasons of the year since the pipe diameter, gas composition and gas flow rate are constant. The gas compressor power requirement is highest at 15:00 hours of the day where the ambient temperature is highest and lowest at 06:00 hours of the day where the ambient temperature is lowest at all compressor station locations as shown in Figure 4-21. The gas compressor power requirement varies from one compressor station location to another due to the changing location ambient temperature with changing time of the day (see Figure 4-3 and Appendix A) and location characteristics.

Results show that the gas compressor inlet temperature and station location characteristics strongly influence the gas compressor power requirements.

4.10.4 Result Validation with Aspen HYSYS

The gas compressor power requirement results at isothermal flow conditions obtained analytically from a developed code in MATLAB environment are

validated with the simulation results obtained from Aspen HYSYS. Table 4-3 shows a comparison between the MATLAB model results and Aspen HYSYS.

Table 4-3 Result Validation with Aspen HYSYS

Station Number	Gas Compressor Power (kW)	
	Analytical	Aspen HYSYS
1	10463.2	10458.2
2	10872.8	10872.2
3	12560.0	12579.2
4	11714.8	11723.8
5	11706.4	11715.3
6	11706.4	11715.3
7	11313.7	11318.1
8	13359.8	13388.8
9	12645.4	12665.6
10	13721.2	13754.8
11	10988.2	10989.0
12	10988.2	10989.0
13	11642.1	11650.2
14	11313.7	11318.1
15	11807.4	11817.5
16	13071.9	13097.3
17	12224.0	12239.0
18	7914.5	7886.9

The results show good agreement between the analytical results and simulation results obtained from Aspen HYSYS. The maximum absolute percentage difference between the gas compressor powers is about 0.048% at all compressor station locations except for compressor station location 18 with a percentage difference of 0.348%. Nevertheless, this difference is negligible thus the analytical methods utilised in this research is acceptable and could be applied in the pipeline natural gas industry.

4.10.5 Gas Compressor Performance Map Results

Figure 4-22 shows the variation of gas compressor pressure ratio with actual inlet volume flow on the gas compressor performance map for compressor station location 3.

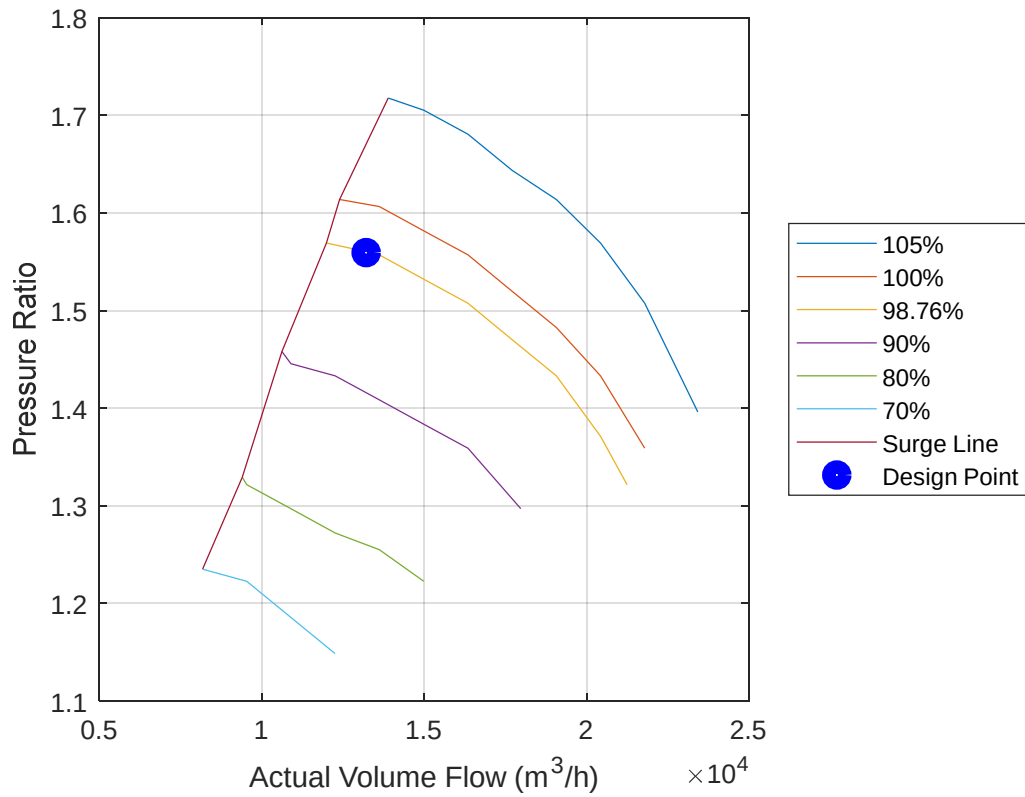


Figure 4-22 Pressure Ratio Curve for Station 3

The result shows an increase in the gas compressor pressure ratio and actual inlet volume flow rate with increasing gas compressor shaft rotational speed. At constant gas compressor shaft rotational speed, the gas volumetric flow rate decreases at decreasing suction pressure.

Figure 4-23 shows the variation of gas compressor polytropic head with actual inlet volume flow on the gas compressor performance map for compressor station location 3.

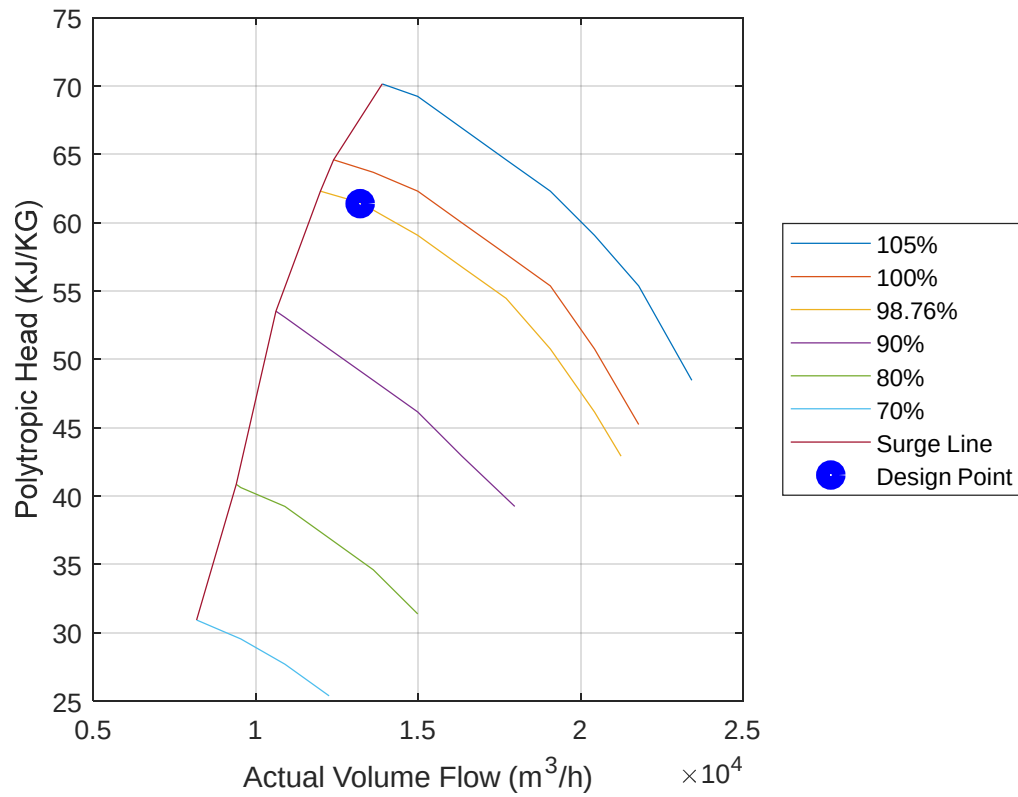


Figure 4-23 Polytropic Head Curve for Station 3

The result shows an increase in the gas compressor polytropic head and actual inlet volume flow rate with increasing gas compressor shaft rotational speed. At constant gas compressor shaft rotational speed, a decrease in the gas volumetric flow rate occurs at increasing polytropic head arising from a decrease in gas compressor suction pressure.

Figure 4-24 shows the variation of gas compressor discharge temperature with actual inlet volume flow on the gas compressor performance map for station location 3.

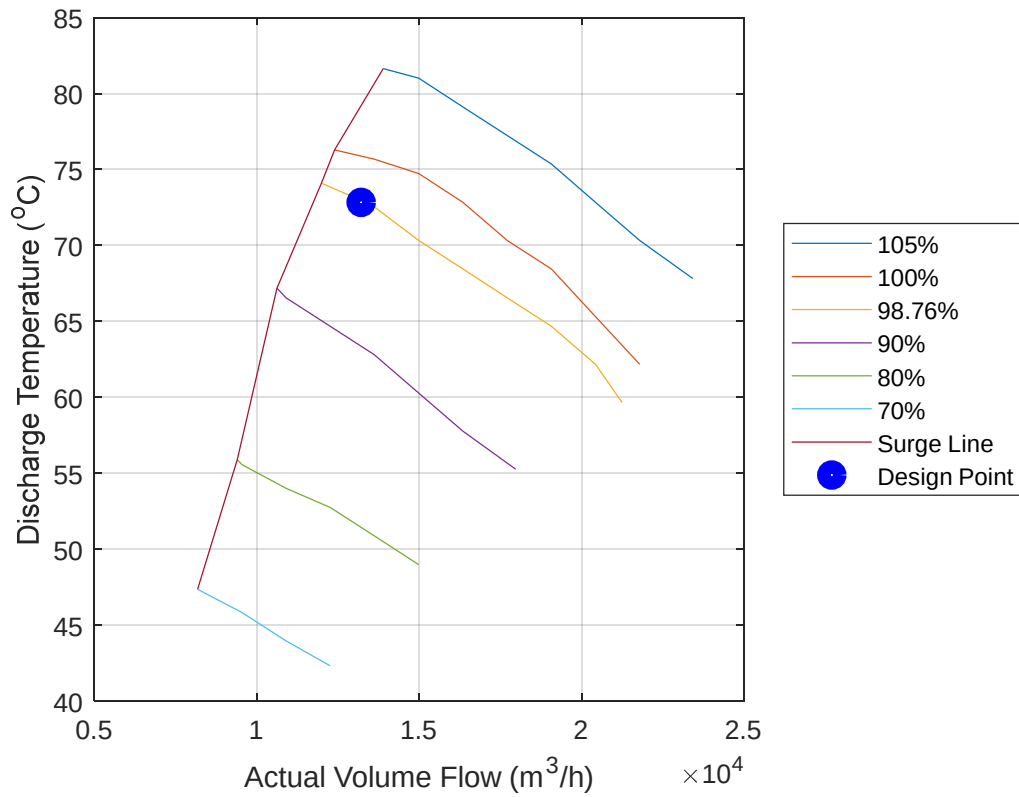


Figure 4-24 Discharge Temperature Curve for Station 3

The result shows an increase in the gas compressor discharge temperature and actual inlet volume flow rate with increasing gas compressor shaft rotational speed. At constant gas compressor shaft rotational speed, the gas volumetric flow rate increases at decreasing gas compressor discharge temperature. More so, the surge margin is reduced due to this temperature decrease.

The gas compressor surge line and design point are also shown on the performance maps.

Figure 4-25 shows the variation of gas compressor polytropic efficiency with actual inlet volume flow at different rotational speeds on the gas compressor performance map for compressor station location 3.

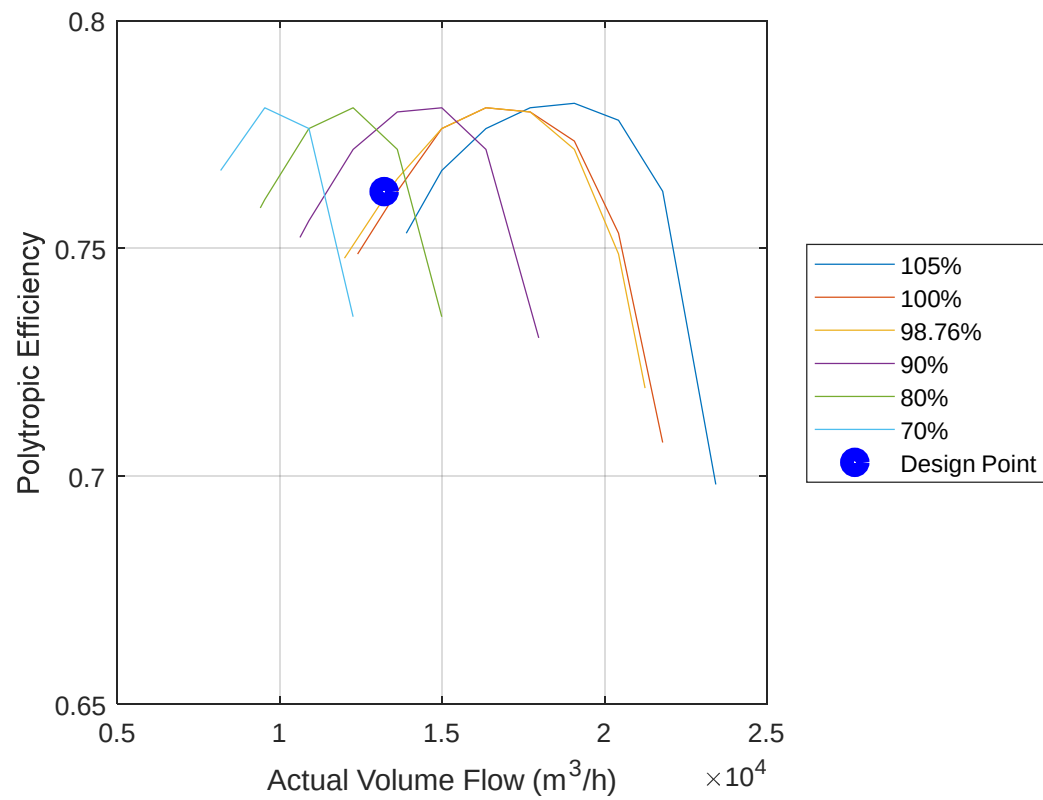


Figure 4-25 Polytypic Efficiency Curve for Station 3

The gas compressor polytypic efficiency increases with an increase in the actual inlet volumetric flow rate until it attains a maximum efficiency point, after which it starts to decrease.

Figure 4-26 shows the variation of gas compressor power requirement at design and off-design conditions with actual inlet volume flow at different rotational speeds on the gas compressor performance map for compressor station location 3.

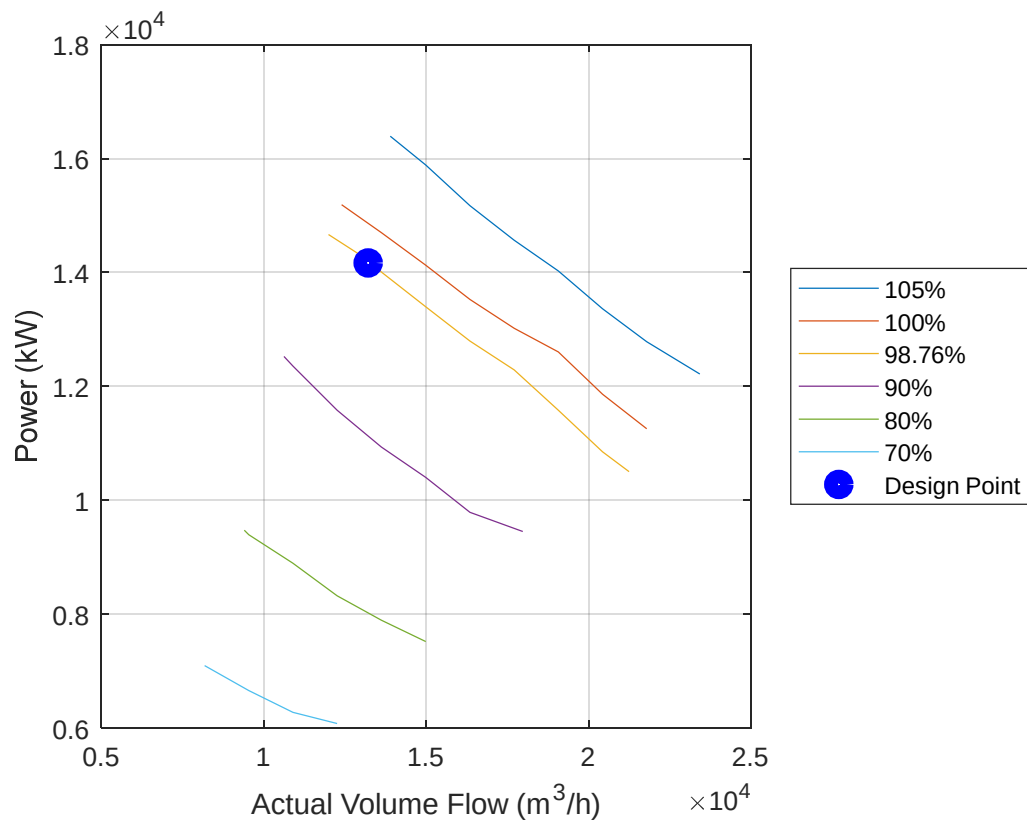


Figure 4-26 Power Curve for Station 3

The result shows an increase in the gas compressor power and actual inlet volume flow rate with increasing gas compressor shaft rotational speed. At constant gas compressor shaft rotational speed, a decrease in the gas volumetric flow rate occurs at increasing gas compressor power requirement arising from an increase in the polytropic head due to an increase in the gas flowing temperature.

4.10.6 Impacts of Operating Points at Varying Flow Conditions

Figure 4-27 and Figure 4-28 show compressor performance curves for station 2, showing operating points in different flow conditions.

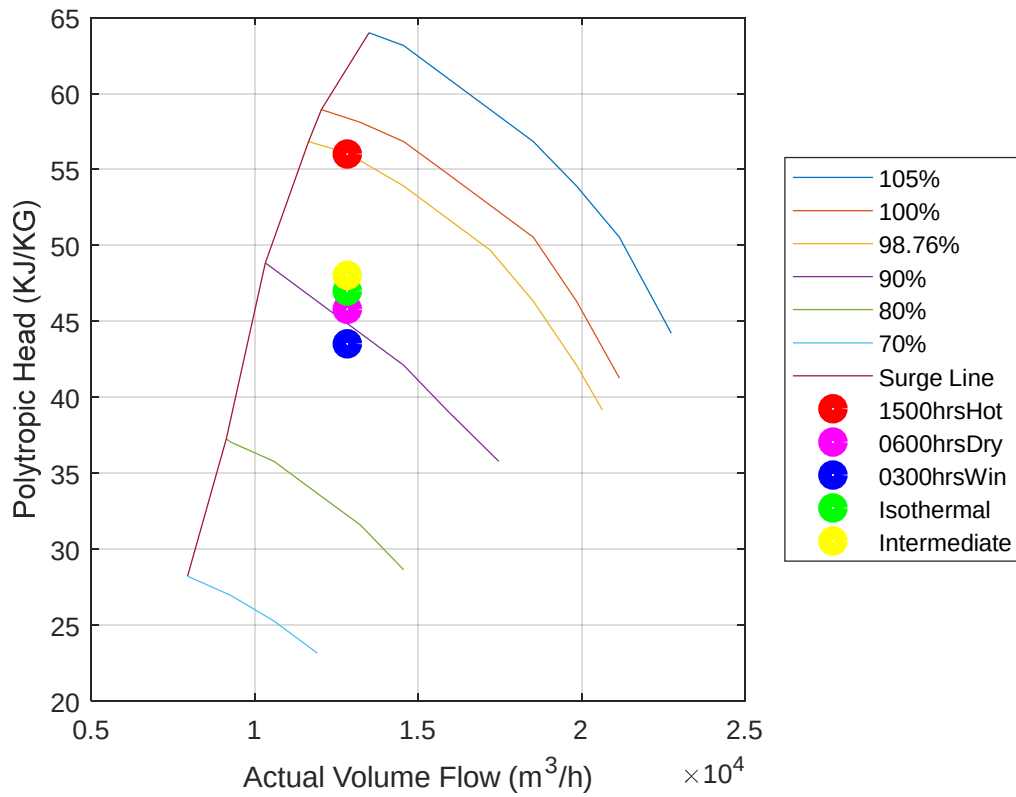


Figure 4-27 Polytypic Head Curve for Station 2 showing Operating Points in Different Conditions

The results show the impact of changing operating conditions at different points. A change in the ambient temperature at 03:00 hours in the winter season to 06:00 hours in the dry season to 15:00 hours in the hot season for the non-isothermal flow conditions leads to new operating points as shown in Figure 4-27 and Figure 4-28. However, the gas compressor operating points are always the same at isothermal and intermediate flow conditions where the temperatures are constants.

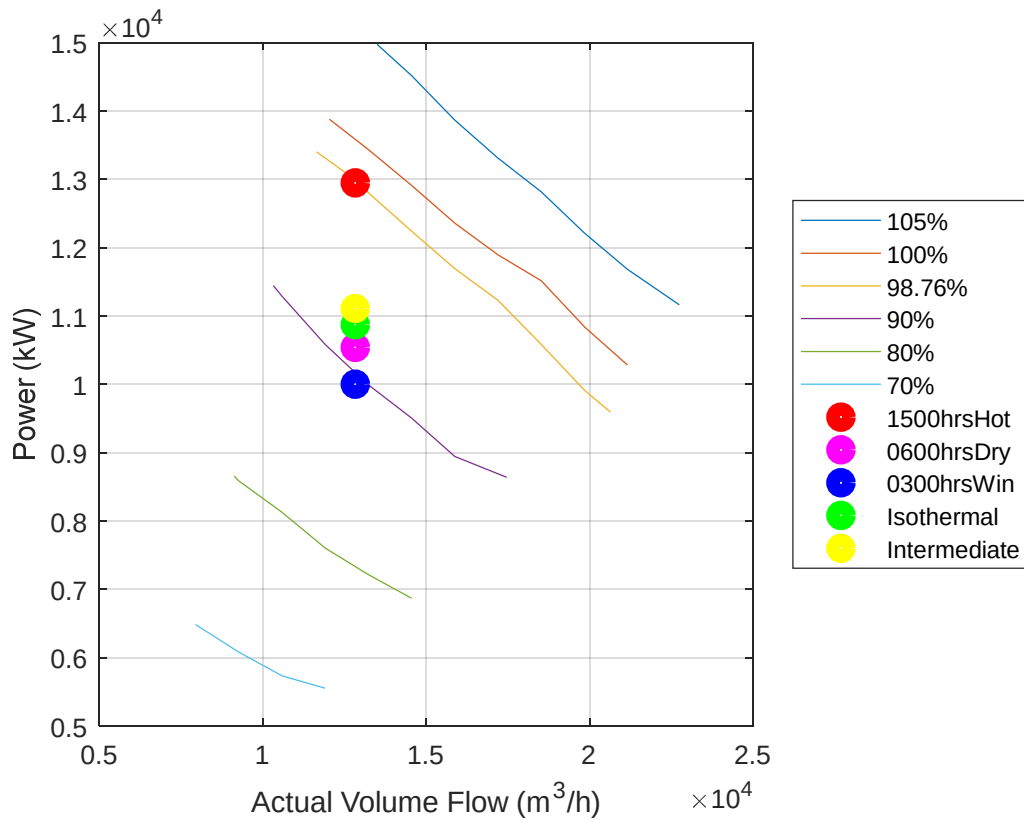


Figure 4-28 Power Curve for Station 2 showing Operating Points in Different Conditions

At 03:00 hours of the day in the winter season where the temperature is lowest, the polytropic head is 43.51 kJ/kg and gas power required is 10030 kW. At 06:00 hours in the dry season the polytropic head is 45.79 kJ/kg and the gas power required is 10539 kW. Furthermore, at 15:00 hours in the hot season where the temperature is the highest the polytropic head is 56.01 kJ/kg and the gas power required is 12950 kW. The gas power required increases with the polytropic head at a constant actual volume flow rate because of an increase in the gas flow temperature. Results show that at constant gas composition and volume flow rate, the gas temperature strongly influence the gas compressor performance.

4.11 Gas Compressors and Gas Turbines Selection

Gas Compressors are selected based on the highest ambient temperature, compression ratio and compressor power requirement at all flow conditions. For the baseline case consisting of eighteen compressor stations along the pipeline

route, four identical gas compressors arranged in parallel were selected, each gas compressor producing the same compression ratio, power and compressing the same volume of natural gas. Figure 4-29 shows the gas compressors arranged in parallel. Parallel compressors arrangement was selected due to the large volume flow rate needed to be transported through the transmission pipelines. Additionally, the gas compressors discharge temperature is low compared to the series arrangement since the natural gas does not go through multiple compression ratios. The total gas compressors discharge temperature for this parallel arrangement at each compressor station for the baseline case will be the same as that of a single compressor installed in the station with the same compression ratio.

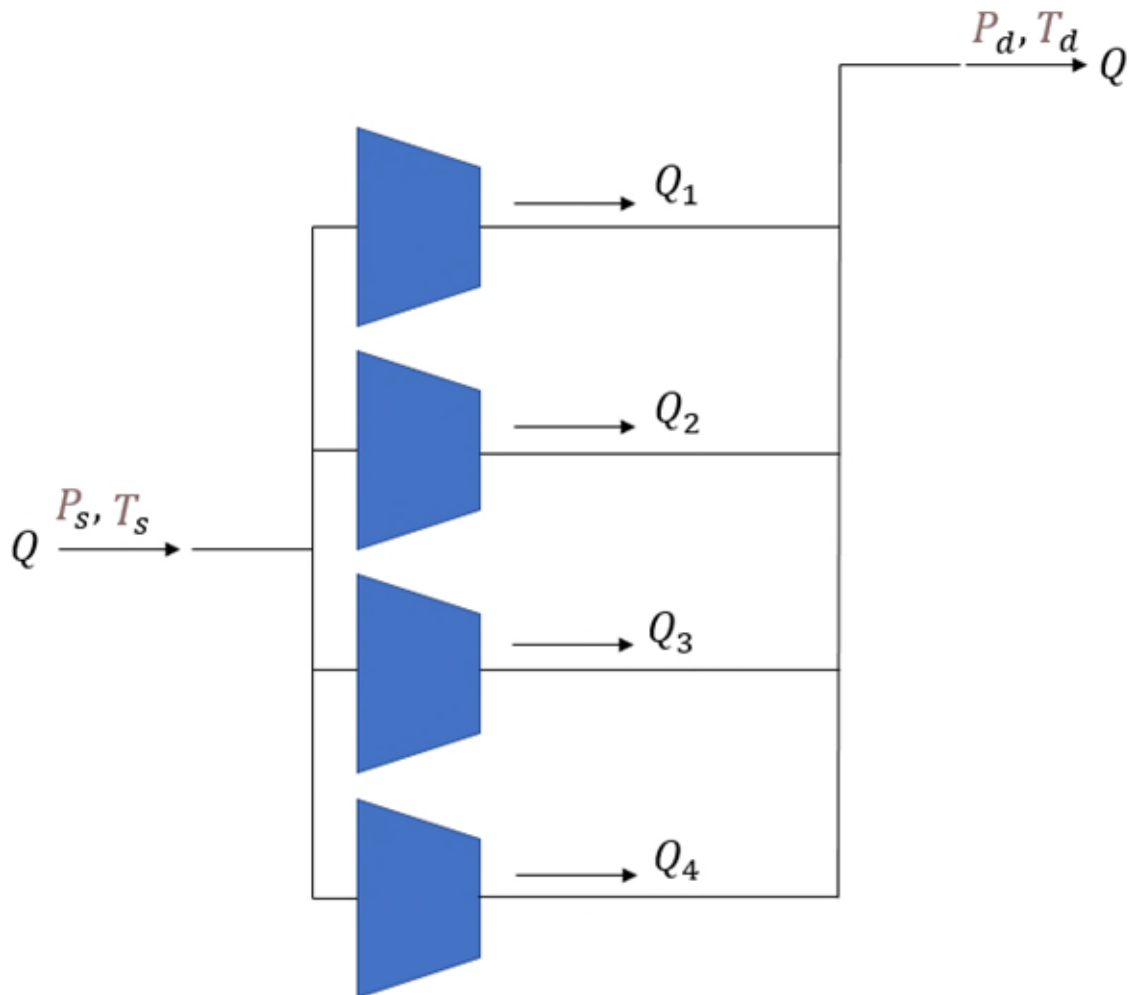


Figure 4-29 Parallel Gas Compressors Arrangement

Figure 4-30 shows the gas compressor power requirement based on the maximum ambient temperature at all flow conditions at each compressor station location, and the first station is assumed to operate at International Standard Atmospheric condition. The maximum temperatures were obtained at 15:00 hours of the day during the hot season of the year and aided the selection of appropriate gas compressor models in this research work.

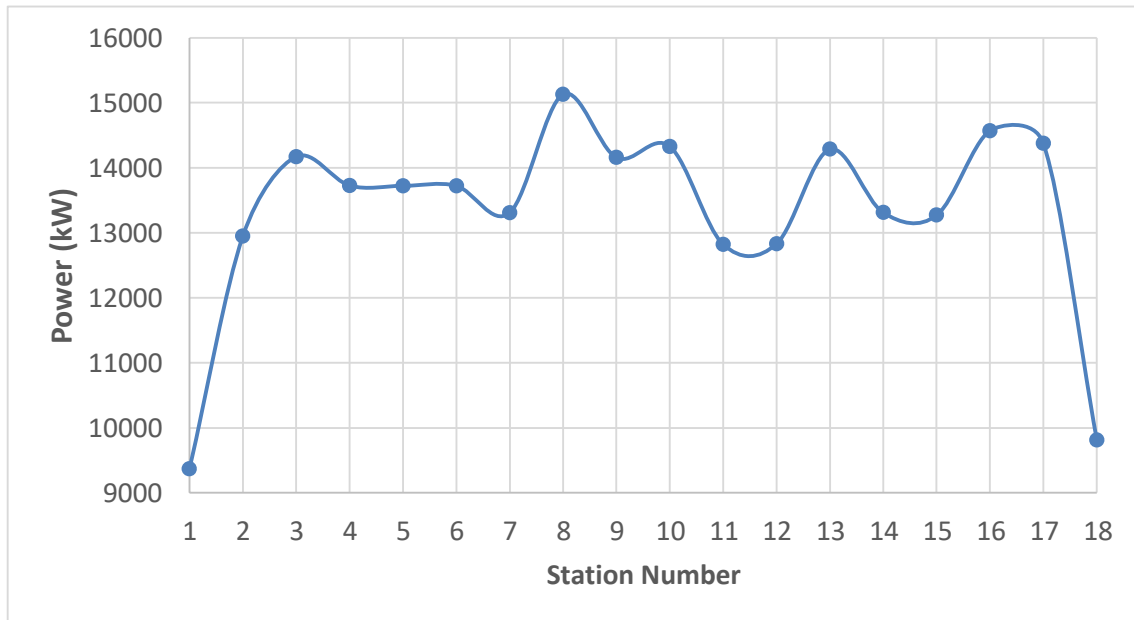


Figure 4-30 Gas Compressor Power based on Maximum Ambient Temperature at All Flow Conditions

Four gas compressor models inspired by Siemens's pipeline compressor packages STC-SV compressor, a single-shaft pipeline compressor, General Electric centrifugal compressors, and high-efficiency Dresser-Rand DATUM P and DATUM C compressor trains are selected based on the gas compressor power requirements at all flow conditions. More detailed information on the chosen gas compressor models can be found in references [135]; [136]; [137]. The gas compressor models were chosen considering their small footprints, engine availability and the total project lifecycle costs.

Four gas turbine models inspired by double-shafts industrial gas turbine of 13.4 MW capacity denoted by SGT-400, triple-shafts aero-derivative gas turbine of 15.2 MW capacity denoted by LM1600, triple-shafts aero-derivative gas turbine

of 17 MW capacity denoted by GT-35 and triple-shafts industrial gas turbine of 19.3 MW capacity denoted by SGT-500 are selected based on the gas compressor power requirements at all flow conditions.

The baseline case has eighteen compressor stations along the pipeline route with four identical gas compressors arranged in parallel, each connected in series with the selected gas turbines. Table 4-4 shows the gas compressors and gas turbine models selected at each compressor station location.

Table 4-4 Gas Compressors and Gas Turbine Models

Station Number	Gas Compressor Models	Gas Turbine Models
1	Siemens STC-SV compressor	Double-shafts industrial GT
2	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (15.2 MW)
3	Dresser-Rand DATUM P	Triple-shafts aero-derivative GT (17 MW)
4	Dresser-Rand DATUM C	Triple-shafts aero-derivative GT (17 MW)
5	Dresser-Rand DATUM C	Triple-shafts aero-derivative GT (17 MW)
6	Dresser-Rand DATUM C	Triple-shafts aero-derivative GT (17 MW)
7	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (17 MW)
8	GE Centrifugal compressor	Triple-shafts industrial GT
9	Dresser-Rand DATUM P	Triple-shafts aero-derivative GT (17 MW)
10	GE Centrifugal compressor	Triple-shafts industrial GT
11	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (15.2 MW)
12	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (15.2 MW)
13	GE Centrifugal compressor	Triple-shafts industrial GT
14	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (17 MW)
15	Siemens STC-SV compressor	Triple-shafts aero-derivative GT (17 MW)
16	GE Centrifugal compressor	Triple-shafts industrial GT
17	GE Centrifugal compressor	Triple-shafts industrial GT
18	Siemens STC-SV compressor	Double-shafts industrial GT

However, buying identical engine units is more beneficial than buying multiple different engine units. Similar gas turbine units will reduce the inventory of spare parts and minimise maintenance. More so, it is much easier and cheaper to maintain eight similar 17 MW gas turbine units than to maintain three 15.2 MW, two 17 MW, two 13.4 MW, and one 19.3 MW gas turbine unit. Although in some cases, the advantages of utilising similar gas turbine units by reducing spare parts and inventory are outweighed by the extra cost involved. In the subsequent chapter, this trade-off will be analysed by performing an economic optimisation using the compressor station location as a decision variable. Furthermore, low fuel consumption will be attained when the gas turbine units are identical compared to those that are not identical. Consequently, similar gas turbine units will improve overall compressor station and pipeline system efficiency.

All the selected gas turbines have an independent power turbine in addition to their gas generator components. The advantage of the independent power turbine is that the gas generator and the power turbine can operate at different speeds. These speeds can vary relative to each other. The power turbine is used to drive the gas compressor where there is a great variation in the gas compressor speed with its power requirement. In this situation, the gas compressor may run at low speed but require large power. Therefore, the power turbine can run at the gas compressor speed independent of the gas generator, and the gas generator can run at its maximum speed. The power turbine is responsible for converting the kinetic energy at the exit from the gas generator into shaft power required to drive the gas compressor. If the power produced by the independent power turbine is greater than the power required by the gas compressor, the power turbine and the gas compressor will accelerate until equilibrium is established. Consequently, the independent power turbine allows greater flexibility in operation for driving the variable speed load as experienced in the gas compressor for pipeline application.

4.12 Discussion

This study shows the effect of the variation in gas temperature on the pipeline pressure drops. At non-isothermal flow conditions characterised by varying gas

flow temperature with the changing time of the day and seasons of the year, the pressure drops in the transmission pipeline increase with gas temperature. At constant and average gas temperatures depicted by the isothermal and intermediate flow conditions, respectively, the pressure drops increase with pipe distance and elevation. At the maximum pressure drop corresponding to the maximum allowable operating pressures of the Trans-Saharan Gas pipeline at any compressor station location, gas compressors are needed to boost the low pressures back to the pipeline operating pressures to ensure a continuous supply of natural gas through the pipelines.

For the first time, the gas compressor power requirements at varying flow conditions at each compressor station location were examined in the TERA. Results show that for the isothermal and intermediate flow conditions, the highest gas compressor power occurs at the compressor station location with the lowest suction pressure, highest gas compression ratio and highest polytropic head due to the increase in distance and elevation and vice versa. For the non-isothermal flow conditions, the compressor power requirement is significantly affected by the compressor station location characteristics, dependent on the prevailing ambient temperature and time of the day at different seasons of the year since the pipe diameter, gas composition and gas flow rate are constant. The gas compressor power requirement varies from one compressor station location to another due to the changing location ambient temperature and the changing time of the day. Results show that the gas compressor inlet temperature and station location characteristics strongly influence the gas compressor power requirements. These findings represent one of the major contributions of this research work. The gas compressor power requirement results are validated with the simulation results obtained from Aspen HYSYS. Comparison of the results shows good agreement between both methods with the maximum absolute percentage difference between the gas compressor powers equivalent to 0.048% at all compressor station locations except for compressor station location 18 with a percentage difference of 0.348%. Nevertheless, this difference is negligible and could be applied in the pipeline natural gas industry.

The gas compressor performance map results show the performance characteristic of the gas compressor pressure ratio, polytropic head, discharge temperature and power with actual inlet volume flow rate at design point and off-design conditions. The gas compressor power curve at design and off-design conditions shown in Figure 4-26 shows an increase in the gas compressor power and actual inlet volume flow rate with increasing gas compressor shaft rotational speed due to an increase in the polytropic head arising from the increase in the gas flowing temperature.

The results show the impact of changing operating conditions at different points and varying flow conditions. For the non-isothermal flow conditions, a change in the ambient temperature due to varying time of the day and seasons leads to new operating points. However, the gas compressor operating points are always the same at isothermal and intermediate flow conditions where the temperatures are constant. These findings are a major contribution of my research work.

Gas Compressors are selected based on the highest ambient temperature, compression ratio and compressor power requirement at all flow conditions. The gas compressor models were selected considering their small footprints, engine availability and the total project lifecycle costs. Gas Turbines are selected based on the gas compressor power requirements at all flow conditions.

4.13 Summary

The objectives of this study were in two parts. Firstly, was to model the proposed Trans-Saharan Gas pipeline characteristics leading to pressure drops evaluation and consequently estimate the gas compressor power requirements at design and off-design conditions leading to gas compressors and gas turbines selection. Secondly, was to determine the compressor station power requirements at varying flow conditions.

This study has developed a method for evaluating the integrated pipeline and gas compressor models analytically. It considered in the TERA the variation in the ambient temperature at varying flow conditions and location characteristics for the first time. The pipeline characteristics and pressure drop, gas compressor

power requirements and performance curves at design and off-design conditions were evaluated considering segmented pipe length, elevation, and ambient temperature variation at varying flow conditions. The gas compressor and gas turbine models were selected based on the analysed gas compressor power requirements at varying flow conditions.

Results show that the gas compressor inlet temperature and compressor station location characteristics, including the prevailing ambient temperature, distance, and elevation strongly influence the gas compressor power requirements and affect the selection of the most appropriate turbo-compressor models. These findings represent one of the major contributions of this research work. The validation results show good agreement between the present study and Aspen HYSYS, with the maximum absolute percentage difference between the gas compressor powers equivalent to 0.048% at all compressor station locations except for compressor station location 18 with a percentage difference 0.348%. Nevertheless, this difference is negligible and could be applied in the pipeline natural gas industry. The performance simulation of the selected gas turbine models is presented in the next chapter to show its correlation with the present study.

5 GAS TURBINE PERFORMANCE

5.1 Introduction

This chapter looks at the design and off-design performance of the selected gas turbine models as prime movers for centrifugal gas compressors for natural gas transportation in pipelines. The design point and off-design performance simulations were made using Turbomatch software. The validation of the performance results at the design point is presented. The influence of ambient conditions, including the ambient temperature and altitude on the performance of the gas turbine is described. Gas turbine compressor maps are illustrated. The variation of gas compressor and gas turbine powers as the time of the day changes at all flow conditions was examined. Finally, the gas turbine entry temperature, fuel flow, and shaft power that matches the power requirement of the centrifugal gas compressors at all flow conditions were explored.

5.2 Operating Conditions of the selected Gas Turbines

The ambient conditions of the compressor station locations along the pipeline route affect the gas turbine performance since the operational life of the gas turbine engine is spent at environmental conditions in variance from the conditions from which it was initially designed. Thus, it is important to consider the changes in the compressor station location ambient temperature and altitude because of their significant impact on the performance of the gas turbine. The gas turbine power output and efficiency vary with ambient conditions which are influenced by compressor station locations. This variation will have a significant impact on the fuel consumption and the economics of the project. Figure 4-3 shows the three-hourly variation in the average ambient temperature for one of the three seasons of the year with respect to the time of day of the compressor station locations along the pipeline route. Appendix A shows the ambient temperature variation at the remaining compressor station locations for each season of the year. The ambient temperature variation encompasses the temperatures for all flow conditions examined in this research throughout the project life, namely isothermal, non-isothermal, and intermediate flow conditions.

The ambient conditions experienced at each compressor station locations form the basis for the performance evaluation of the selected gas turbine models at off-design point conditions in this research. The techno-economics and the techno socioeconomics of the proposed Trans-Saharan Gas Pipeline project is impacted by these operating ambient conditions.

5.3 Gas Turbine Performance Simulation at Design Point

Gas turbine performance simulation is important in the prediction of engine's fuel consumption an essential parameter in the estimation of the project lifecycle cost. Gas turbine engine models have been selected to meet the compressor drive power requirements at all examined flow conditions.

The design and off-design points performance of the selected gas turbine models are simulated using Turbomatch to draw out essential performance data required for the techno-economic and techno-socioeconomic analysis. Turbomatch is an in-house FORTRAN programmed software developed at Cranfield University. Its modularity enables detailed design of any gas turbine. Turbomatch can simulate the steady-state design and off-design points performance of the gas turbine engines components to produce power output, fuel flow and efficiency using pre-programmed routines called bricks and codewords. Bricks correspond to models of individual gas turbine components. The fuel selected for the Turbomatch simulation is natural gas with a lower calorific value of 46 MJ/kg. The design point simulation of the selected gas turbine engine models was done by varying the bleeds, turbine entry temperatures, compressors, and turbine efficiencies in other to obtain similar results to those in the literature. The selected gas turbine engine models Turbomatch design point input files are depicted in Appendix G.

5.3.1 SGT-400 Gas Turbine Performance Simulation at Design Point

The SGT-400 is a high-efficiency simple cycle twin-shaft industrial gas turbine ideal for mechanical drive application. It is configured with a dry low emission combustion system using natural gas as fuel. It consists of a gas generator and a two-stage power turbine. Its small footprint, flexibility of operation and high performance in rugged environmental conditions make it the direct driver of

choice for centrifugal pipeline compressors for gas boosting and natural gas transmission in this study. Figure 5-1 shows the sectional view of the SGT-400 gas turbine.

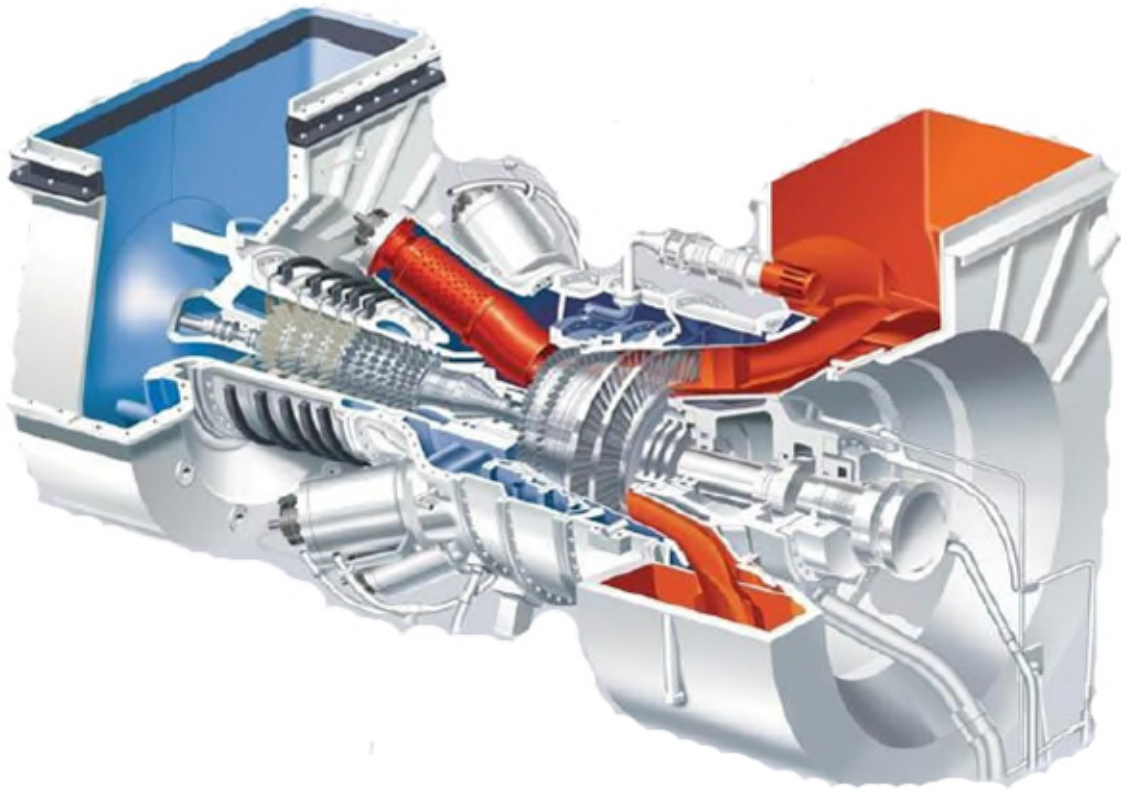


Figure 5-1 Sectional View of SGT-400 Gas Turbine [138]; [139]

Table 5-1 shows the SGT-400 gas turbine performance simulation at the design point obtained from Turbomatch and validation of the simulation results with the available original equipment manufacturer's data obtained from Siemens website.

Table 5-1 SGT-400 Gas Turbine Validation at Design Point

S/N	Parameter	Siemens Website	Turbomatch	Absolute difference (%)
1.	Power Output (MW)	13.4	13.4	0
2.	Efficiency (%)	36.2	36.5	0.83
3.	Pressure Ratio	16.8	16.8	0
4.	Fuel Flow (Kg/s)	0.8046	0.8052	0.07
5.	Inlet Mass Flow (Kg/s)	38.6	38.6	0
6.	TET (K)	—	1450	—

There is good agreement between the Turbomatch simulation results and the literature.

5.3.2 LM1600 Gas Turbine Performance Simulation at Design Point

The LM1600 is a lightweight, efficient, simple cycle three-shaft aero-derivative gas turbine derived from an aircraft engine that can be used for mechanical drive applications such as pipeline compression of natural gas. It consists of a dual rotor gas generator and an aerodynamically coupled power turbine. LM1600 has a three-stage low pressure compressor, a seven-stage high pressure compressor, an annular combustor, a single-stage high pressure turbine, a single-stage low pressure turbine and a two-stage power turbine. The power turbine operates over a cubic load curve for mechanical drive applications while the gas generator runs at an overall pressure ratio of 22:1. Figure 5-2 shows the pictorial view of the LM1600 gas turbine.

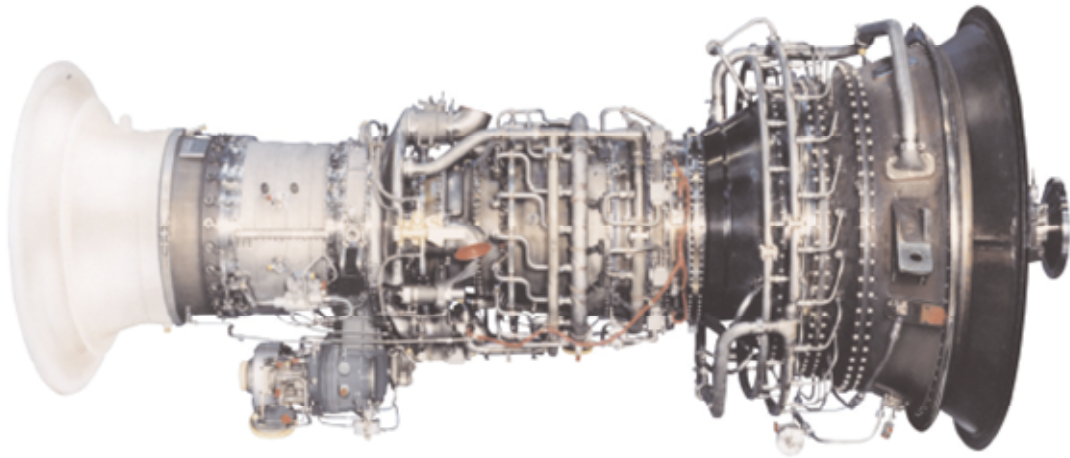


Figure 5-2 Pictorial View of LM1600 Gas Turbine [140]

Table 5-2 shows the LM1600 gas turbine performance simulation at design point obtained from Turbomatch and validation of the simulation results with the available original equipment manufacturer's data obtained from General Electric's website.

Table 5-2 LM1600 Gas Turbine Validation at Design Point

S/N	Parameter	GE website	Turbomatch	Absolute difference (%)
1.	Power Output (MW)	15.2	15.2	0
2.	Efficiency (%)	36.9	37.4	1.35
3.	Pressure Ratio	22.0	22.0	0
4.	Fuel Flow (Kg/s)	0.8949	0.8914	0.39
5.	Inlet Mass Flow (Kg/s)	45.81	46.0	0.41
6.	TET (K)	—	1560	—

Comparison of the results show good agreement between the Turbomatch simulation results and the literature.

5.3.3 SGT-500 Gas Turbine Performance Simulation at Design Point

The SGT-500 is a triple-shaft industrial gas turbine consisting of low- and high-pressure compressors. It is used for mechanical drive application and can be operated on natural gas as fuel. It is a reliable gas turbine with low emissions combustion system and low operational costs. Its low firing temperature offers ease of maintenance, high availability and makes it a driver of choice for gas compression application. Figure 5-3 shows the sectional view of the SGT-500 gas turbine.

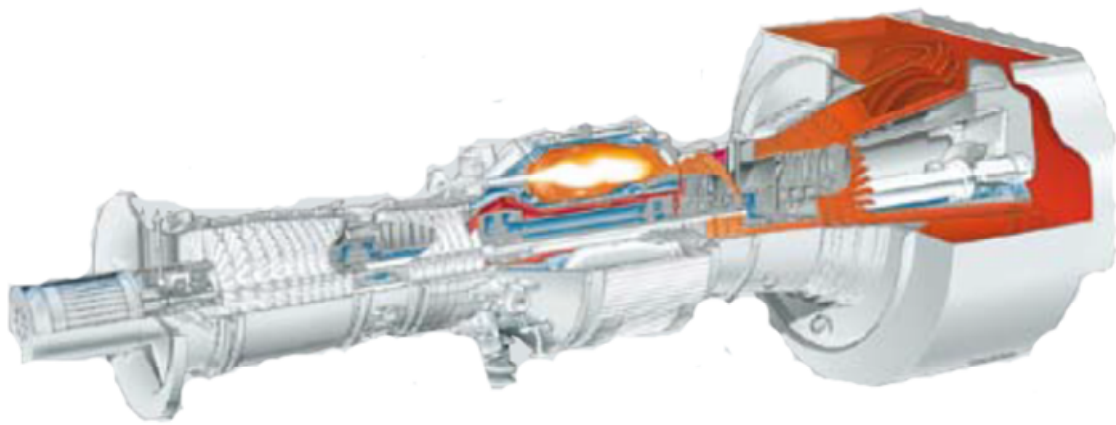


Figure 5-3 Sectional View of SGT-500 Gas Turbine [141]

Table 5-3 shows the SGT-500 gas turbine performance simulation at design point obtained from Turbomatch and validation of the simulation results with the available original equipment manufacturer's data obtained from Siemens website.

Table 5-3 SGT-500 Gas Turbine Validation at Design Point

S/N	Parameter	Siemens Website	Turbomatch	Absolute difference (%)
1.	Power Output (MW)	19.3	19.3	0
2.	Efficiency (%)	34.2	34.3	0.29
3.	Pressure Ratio	13.0	13.0	0
4.	Fuel Flow (Kg/s)	1.2272	1.2340	0.55
5.	Inlet Mass Flow (Kg/s)	96.67	96.0	0.69
6.	TET (K)	—	1220	—

Comparison of results show good agreement between the Turbomatch simulation results and the literature.

5.3.4 GT-35 Gas Turbine Performance Simulation at Design Point

The GT-35 is a lightweight triple-shaft aeroderivative industrial gas turbine with low maintenance requirement and high availability. Its double spool gas generator has a low- and high- pressure compressors, seven combustors, two-stage low pressure turbine and single-stage high pressure turbine. The exit gas from the gas generator is expanded through a two-stage free power turbine. The GT-35 has been used for mechanical drive applications and is suitable as direct driver for centrifugal gas compressors in natural gas transmission. Figure 5-4 shows the sectional view of the GT-35 gas turbine.

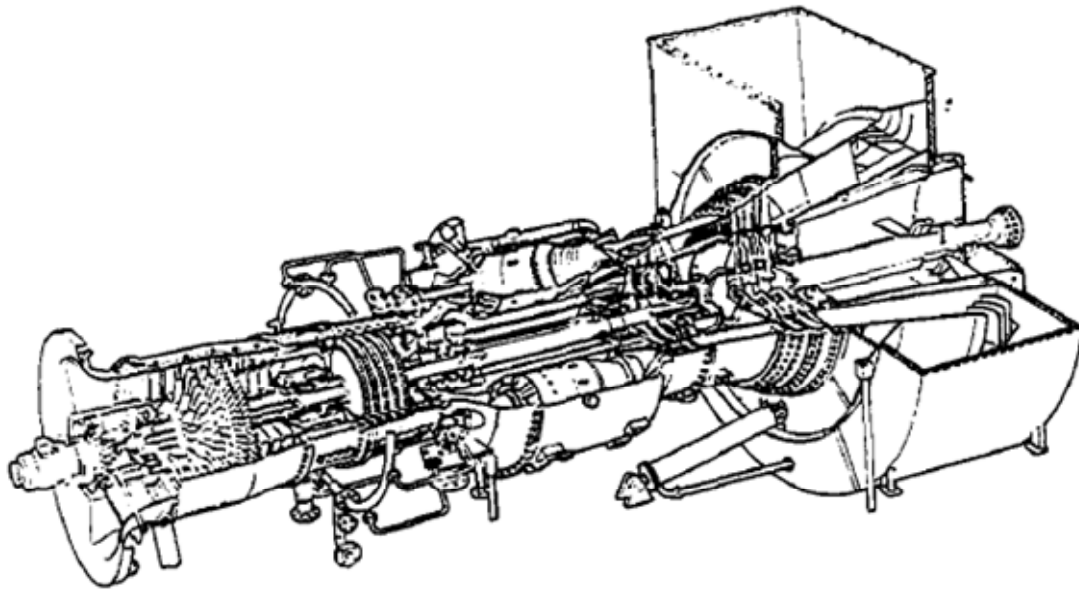


Figure 5-4 Sectional View of GT-35 Gas Turbine [142]

Table 5-4 shows the GT-35 gas turbine performance simulation at design point obtained from Turbomatch and validation of the simulation results with the available original equipment manufacturer's data obtained from ABB's website.

Table 5-4 GT-35 Gas Turbine Validation at Design Point

S/N	Parameter	ABB website	Turbomatch	Absolute difference (%)
1.	Power Output (MW)	17	17	0
2.	Efficiency (%)	32	32.0	0
3.	Pressure Ratio	12	12	0
4.	Fuel Flow (Kg/s)	1.1550	1.1655	0.9
5.	Inlet Mass Flow (Kg/s)	91.84	91.84	0
6.	TET (K)	—	1190	—

There is good agreement between the Turbomatch simulation results and the literature.

5.4 Off-Design Performance Simulation of the Selected Gas Turbines

This section assessed the off-design performance of the selected gas turbine engine models at each compressor station location along the transmission pipeline route over different operating ambient conditions. The off-design performances of the selected gas turbine models are simulated using Turbomatch at varying ambient temperatures and altitude. The objective of the off-design performance simulation is to make sure that the gas turbine prime mover can supply the necessary power required by the gas compressor under all flow conditions and for the worst case of ambient temperature experienced at each compressor station location. The ambient temperature variation under all flow conditions viz.: isothermal, intermediate and non-isothermal conditions at each compressor station location along the pipeline route and the gas turbine entry temperature are the parameters considered for the off-design performance simulation.

5.5 Results and Discussion

5.5.1 Effects of Ambient Temperature on Gas Turbine Power Output, Efficiency and Fuel Flow

Figure 5-5 shows the effect of turbine entry temperature and the compressor station location ambient temperature on the power output based on all flow conditions. The power output increases as the turbine entry temperature increases and decreases as the ambient temperature increases.

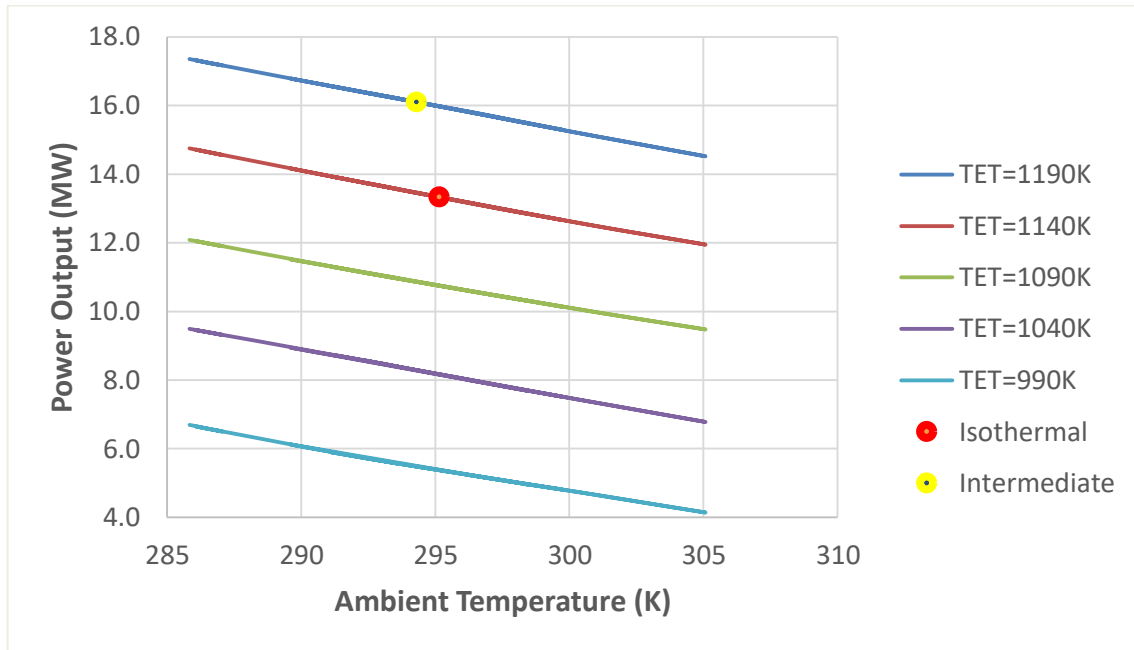


Figure 5-5 Power Output against Ambient Temperature at Different Turbine Entry Temperature for Station 3

For the isothermal and intermediate flow conditions with constant ambient temperatures, the power output is constant at fixed turbine entry temperatures, respectively.

Figure 5-6 shows the effect of turbine entry temperature and the compressor station location ambient temperature on the engine thermal efficiency based on all flow conditions. The thermal efficiency increases as the turbine entry temperature increases and decreases as the ambient temperature increases.

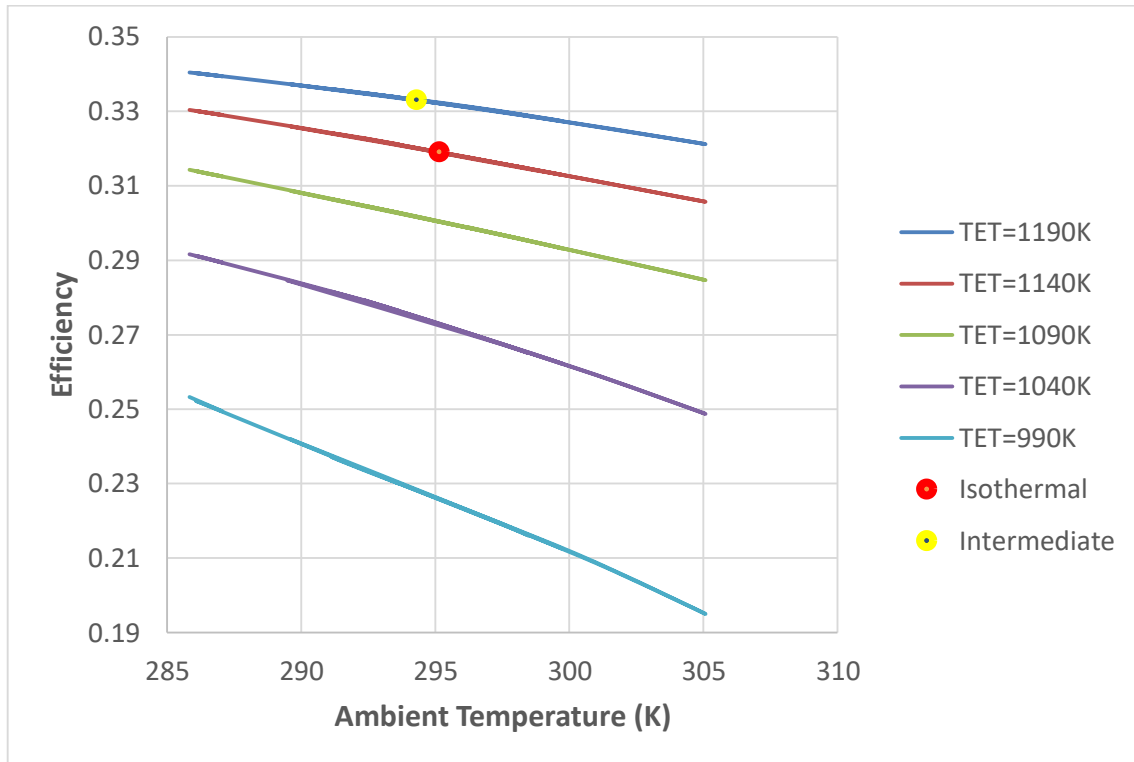


Figure 5-6 Efficiency against Ambient Temperature at Different Turbine Entry Temperature for Station 3

For the isothermal and intermediate flow conditions with constant ambient temperatures, the engine thermal efficiency is constant at fixed turbine entry temperatures, respectively.

Figure 5-7 shows the effect of turbine entry temperature and the compressor station location ambient temperature on the fuel flow into the engine based on all flow conditions. The fuel flow increases as the turbine entry temperature increases and decreases as the ambient temperature increases.

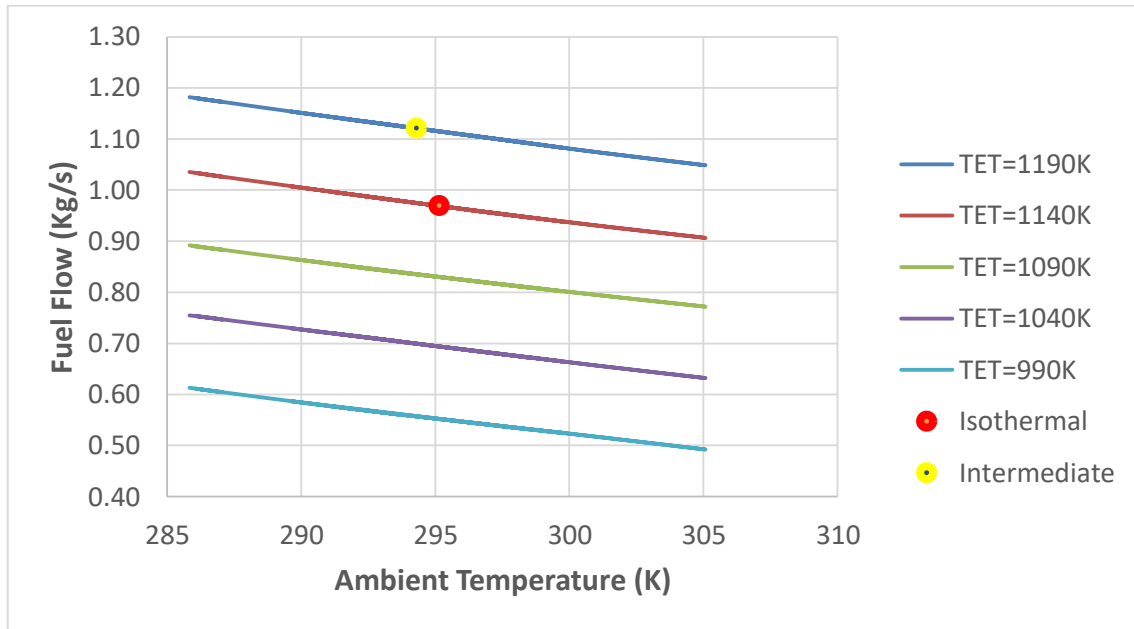


Figure 5-7 Fuel Flow against Ambient Temperature at Different Turbine Entry Temperature for Station 3

For the isothermal and intermediate flow conditions with constant ambient temperatures, the fuel flow is constant at fixed turbine entry temperatures, respectively.

At high ambient temperature, density of inlet air into the engine decreases. Thus, at constant volume flow rate, the mass flow rate into the gas turbine engine decreases. More so, the useful work from the gas turbine reduces since more work is needed for hot air compression. Thus, leading to a decrease in the engine thermal efficiency and power output with a consequent reduction in the fuel flow. The increase in the power output and thermal efficiency with increase in the turbine entry temperature is a result of the increased fuel flow into the engine. Although, there is a limit to which the turbine entry temperature can be increased in order to prevent its harmful effect on engine life.

The gas turbine off-design performance results obtained from Turbomatch simulation for other compressor station locations are shown in Appendix H.

5.5.2 Gas Turbine Compressor Maps

Figure 5-8 shows the low-pressure compressor map. Figure 5-9 shows the high-pressure compressor map for compressor station location 3.

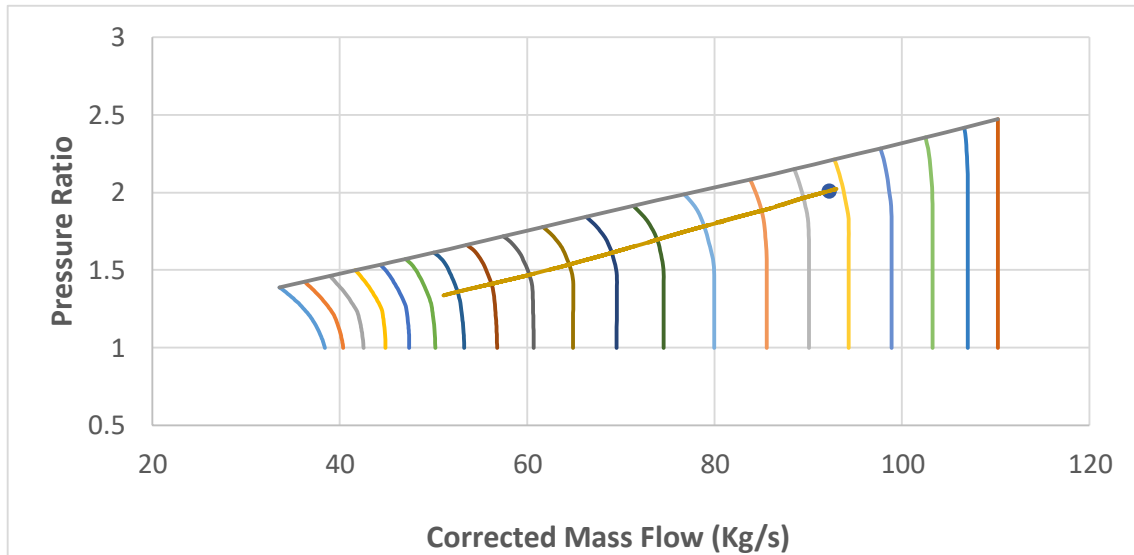


Figure 5-8 Low Pressure Compressor Map for Station 3

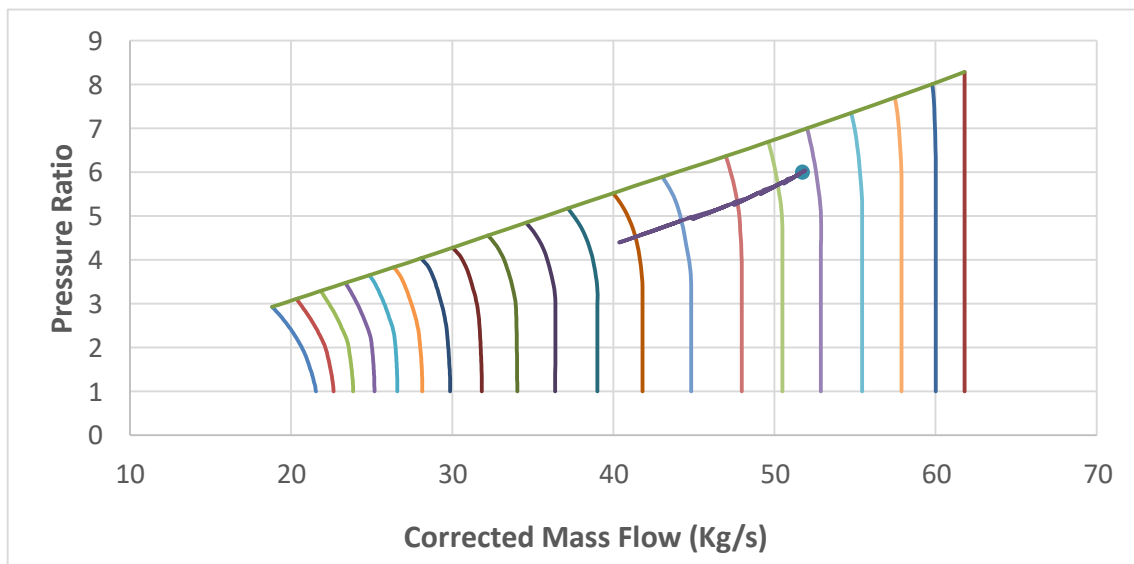


Figure 5-9 High Pressure Compressor Map for Station 3

The compressor maps were drawn using the variation in the corrected mass flow and pressure ratio at varying rotational speeds. The compressor running line and the design point were shown on the compressor maps.

5.5.3 Shaft Power, Fuel Flow and Turbine Entry Temperature Required by Gas Compressor at All Flow Conditions

Table 5-5, Table 5-6, and Table 5-7 show the gas turbine shaft power, fuel flow and the turbine entry temperature obtained from the Turbomatch simulation that is needed to drive the gas compressor power requirement at each compressor station location considering all flow conditions examined in this study.

For the non-isothermal flow conditions depicted in Table 5-5, the location ambient temperature varies with changing time of the day for the three seasons of the year: winter, dry and hot seasons. According to the assumption made in this research, the gas flowing temperature is assumed to equal to the location ambient temperature at the suction or discharge point of the compressor station [38], which was also verified by Equation (4-32). Consequently, the gas temperature varies as time of the day changes. Furthermore, if the gas temperature varies along the pipeline, the compressibility factor, a function of the gas temperature will change. Additionally, the polytropic head, which is a function of the compressibility factor will change. Thus, the gas compressor power which is a function of the polytropic head will also vary. A change in the time of the day equivalent to a change in the ambient temperature thus has a changing effect on the gas turbine shaft power output. Appendix I show the shaft power, fuel flow and turbine entry temperature required by the gas compressor for other compressor station locations at non-isothermal flow.

Table 5-5 Shaft Power, Fuel Flow and TET Required by Gas Compressor for Station 3, 600 m Altitude, 480 km from Origin at Non-Isothermal Flow

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	285.83	1080	11.186	11.556	0.86364
	03:00	287.06	1080	11.366	11.375	0.85522
	06:00	286.07	1080	11.221	11.52	0.86199
	09:00	291.88	1110	12.080	12.235	0.90591
	12:00	297.46	1140	12.938	12.987	0.95313
	15:00	298.48	1150	13.099	13.37	0.97515
	18:00	296.95	1140	12.859	13.061	0.95651
	21:00	289.61	1100	11.739	12.045	0.89337
Dry						
	00:00	290.62	1100	11.890	11.894	0.88639
	03:00	289.61	1100	11.739	12.045	0.89337
	06:00	289.61	1100	11.739	12.045	0.89337
	09:00	293.91	1120	12.388	12.457	0.92036
	12:00	297.96	1150	13.018	13.445	0.97853
	15:00	299.74	1160	13.300	13.71	0.99551
	18:00	296.44	1140	12.780	13.13	0.95992
	21:00	292.39	1110	12.157	12.161	0.9025
Hot						
	00:00	293.65	1120	12.349	12.493	0.9219
	03:00	292.32	1110	12.146	12.172	0.90301
	06:00	291.12	1110	11.966	12.346	0.91107
	09:00	293.4	1120	12.311	12.533	0.92374
	12:00	300.26	1160	13.384	13.638	0.99217
	15:00	305.09	1190	14.171	14.523	1.0485
	18:00	301.02	1160	13.506	13.531	0.98733
	21:00	296.19	1140	12.740	13.172	0.96157

Table 5-6 Shaft Power, Fuel Flow and TET Required by Gas Compressor at Isothermal Flow

Station No	Isothermal Temperature (K)	Compressor Power (MW)	TET (K)	Shaft Power (MW)	Fuel Flow (Kg/s)
1	295.15	10.458	1390	10.696	0.66783
2	295.15	10.872	1460	10.892	0.67515
3	295.15	12.579	1130	12.799	0.9401
4	295.15	11.724	1110	11.759	0.88407
5	295.15	11.715	1110	11.759	0.88407
6	295.15	11.715	1110	11.759	0.88407
7	295.15	11.318	1110	11.759	0.88407
8	295.15	13.389	1160	13.874	0.96906
9	295.15	12.666	1130	12.799	0.9401
10	295.15	13.755	1160	13.874	0.96906
11	295.15	10.989	1100	11.248	0.85659
12	295.15	10.989	1100	11.248	0.85659
13	295.15	11.650	1110	11.759	0.88407
14	295.15	11.318	1110	11.759	0.88407
15	295.15	11.817	1120	12.280	0.91202
16	295.15	13.097	1150	13.135	0.93353
17	295.15	12.239	1140	12.403	0.89827
18	295.15	7.887	1290	8.018	0.52591

For the isothermal and intermediate flow conditions depicted in Table 5-6 and Table 5-7 where the ambient temperature and consequently, gas flowing temperature is constant as time of the day changes throughout the three seasons of the year at each compressor station location. The compressibility factor, a function of the gas temperature will be unchanged. Furthermore, the polytropic head which is a function of the compressibility factor will remain constant. Hence, the gas compressor power which is a function of the polytropic head will remain unchanged. More so, a change in the time of the day equivalent to constant ambient temperature has a corresponding effect on the gas turbine shaft power output for these flow conditions.

Table 5-7 Shaft Power, Fuel Flow and TET Required by Gas Compressor at Intermediate Flow

Station No	Intermediate Ambient Temperature (K)	Compressor Power (MW)	TET (K)	Shaft Power (MW)	Fuel Flow (Kg/s)
1	297.61	10.820	1410	11.065	0.6884
2	296.77	11.112	1480	11.384	0.7012
3	294.31	12.449	1130	12.920	0.9458
4	296.14	11.873	1120	12.139	0.9056
5	296.15	11.866	1120	12.139	0.9056
6	296.15	11.866	1120	12.139	0.9056
7	297.39	11.634	1120	11.964	0.8976
8	294.36	13.257	1150	13.313	0.9410
9	290.17	11.955	1100	11.961	0.8895
10	283.30	12.057	1100	12.076	0.8698
11	296.03	11.111	1100	11.128	0.8511
12	296.13	11.125	1100	11.128	0.8511
13	296.31	11.815	1120	12.117	0.9045
14	297.36	11.631	1120	11.969	0.8978
15	294.28	11.694	1110	11.881	0.8896
16	290.20	12.384	1130	12.738	0.9088
17	292.13	11.810	1130	12.319	0.8909
18	299.73	8.342	1320	8.422	0.5493

For the non-isothermal case, at 03:00 hours, 09:00 hours, and 15:00 hours, time of the day in winter, dry, and hot seasons respectively. The gas compressor power requirements were 11.366 MW, 12.388 MW, and 14.171 MW, respectively. The gas turbine entry temperatures of 1080 K, 1120 K, and 1190 K will provide the shaft powers matching of 11.375 MW, 12.457 MW, and 14.523 MW, respectively, for the centrifugal gas compressor.

For the isothermal and intermediate cases where the temperatures are constant with changing times of the day in the three seasons of the year. The gas

compressor power requirements were 12.579 MW and 12.449 MW, respectively. The gas turbine entry temperature of 1130 K will provide the shaft powers matching of 12.799 MW and 12.920 MW, respectively, at compressor station location 3 for the centrifugal gas compressor.

The results show that the gas turbine power output is enough for the gas compressor power requirements at all examined flow conditions, even for the worst case of the locations' ambient temperature experienced at 15:00 hours of the day in the hot season of the year.

The fuel flow is one of the important parameters obtained in the gas turbine off-design performance simulation that affects the economics of the proposed Trans-Saharan Gas Pipeline project.

5.6 Summary

The objective of this study was to analyse the design and off-design performances of the selected gas turbine models as prime movers for the centrifugal gas compressors for natural gas transportation in pipelines.

The design and off-design points performance of the selected gas turbine models were simulated using Turbomatch to draw out essential performance data required for the techno-economic and techno-socioeconomic analysis. The design point performance results were validated with available original equipment manufacturers' data. The off-design performances of the selected gas turbine models are simulated at varying ambient conditions at each compressor station location with the objective that the gas turbine prime mover can supply the power required by the gas compressor under all flow conditions. The ambient temperature variation under all flow conditions and the gas turbine entry temperature were considered for this simulation.

Comparison of performance results at design point show good agreement between the Turbomatch simulation and the literature. The off-design performance results show an increase in power output and efficiency with increasing turbine entry temperature due to increasing fuel flow into the engine. As the ambient temperature increases, the power output and efficiency decrease

with a consequent reduction in the fuel flow. For the isothermal and intermediate flow conditions with constant ambient temperatures, the power output, efficiency, and fuel flow are constant at fixed turbine entry temperatures, respectively. The results show that the gas turbine power output is enough for the gas compressor power requirements at all flow conditions, even for the worst case of the locations' ambient temperature.

Results obtained for the fuel flow will be inputted into the economic module and used to analyse the baseline gas turbines operating lifecycle fuel costs.

6 THE IMPACT OF TURBO-COMPRESSOR AVAILABILITY ON THE TECHNO-ECONOMICS OF NATURAL GAS PIPELINE TRANSPORTATION

6.1 Introduction

The efficient operation and feasibility of the proposed Trans-Saharan gas pipeline and any compressor station and pipeline project require the successful evaluation of gas compressor, gas turbine, and turbo-compressor units, compressor station subsystems and system availability. The effects of either the unit's or subsystem's unavailability may be the reduction of the engine power or the expected volume flowrate through the compressor station and pipeline system and in some cases, total shutdown of the compressor stations. Therefore, analysing the gas compressor, gas turbine and turbo-compressor units and subsystems' availability will help in improving the operation of the compressor station systems by increasing the subsystems time to failure or decreasing downtime due to engine overhauls, scheduled and unscheduled maintenance. Thus, preventing unpleasant risks to the compressor station and pipeline system. This availability study is needed to quantify the significance of the compressor station components and subsystems availability and predict their techno-economic performance on the compressor station and pipeline system under different operating conditions.

Investment in any compressor station and pipeline project is always associated with corresponding costs. These costs include the capital, operation and maintenance costs sustained over the project lifecycle. The investment must be regulated by economic gains otherwise a potential loss in revenue will make the project unfeasible and unprofitable. Scenarios-based studies are essential in mitigating potential risks from the investment in the proposed Trans-Saharan gas pipeline project. The economic success of the compressor station and pipeline project is dependent on the component's capital and operating cost, the quality of maintenance routine performed over the project lifecycle and compressor station system availability.

6.2 Methodological Approach

Figure 6-1 shows the flow chart of the methodological approach for the availability-based techno-economic analysis utilised in this study.

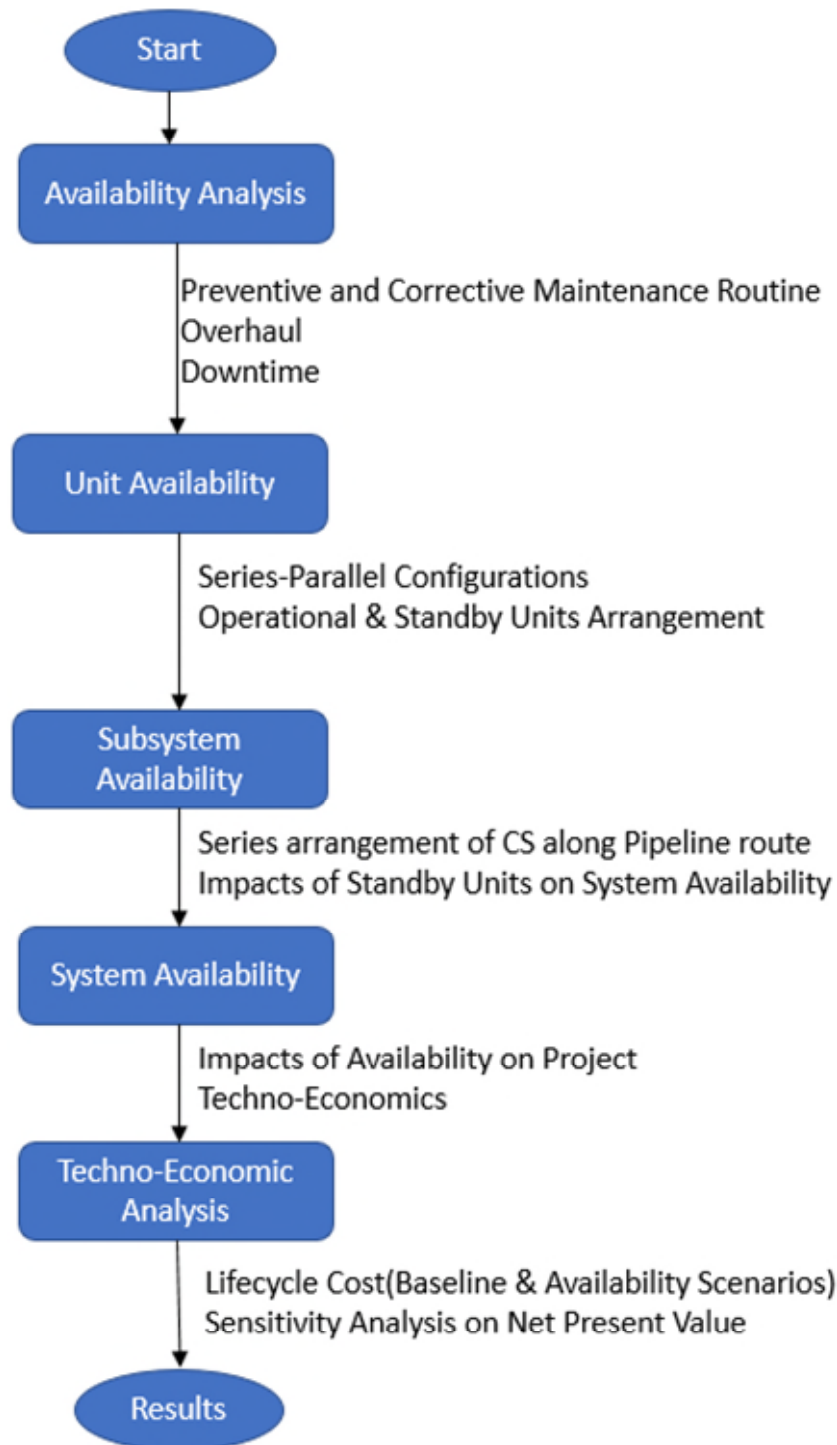


Figure 6-1 Availability-based Techno-Economic Analysis Flowchart

6.2.1 Availability Assumptions

The following availability assumptions are made to simplify the subsequent analysis:

- ❖ Each compressor station configuration consists of four identical parallel gas compressor units driven by four identical parallel gas turbine units. Each gas turbine unit is in series with each gas compressor unit
- ❖ Each unit and compressor station subsystem are assumed to behave independently
- ❖ Each identical gas turbine and gas compressor unit has equal running hours, respectively
- ❖ Downtime due to overhauls, scheduled and unscheduled maintenance is considered
- ❖ Each gas turbine and gas compressor unit are shut down for preventive maintenance 15 hours per year
- ❖ Gas turbine and gas compressor overhauls occur every 25000 and 20000 operating hours, respectively
- ❖ It takes 36 hours for each gas turbine and gas compressor replacement, assuming a standby unit is available and 192 hours for each gas turbine and gas compressor overhauls and replacement, assuming no standby unit is available
- ❖ The gas compressor failure rate is 0.08716545 failures per year [143]
- ❖ The gas turbine failure rate is 0.00547945 failures per running day [144]; [145]

6.2.2 Local Maintenance Schedule

Figure 6-2 shows the developed local maintenance schedule relevant to this research. The maintenance schedule is like typical original equipment manufacturer maintenance schedule usually supplied with the purchased equipment. It includes preventive maintenance routine and overhauls with and without stand-by units. The preventive maintenance and overhauls are performed periodically at pre-determined dates.

[illegible]

Appendix J shows the local maintenance schedule for the remaining compressor station locations, including the gas compressor maintenance schedule. The maintenance schedule shows the maintenance strategy to be adopted throughout the operational life of the compressor station system. It is one of the most important factors affecting the compressor station system availability. The gas compressor, gas turbine, and turbo-compressor unit availability were evaluated based on this developed maintenance schedule. The unit availability is the basis for the analysis of the compressor station subsystem and system availability needed for the techno-economic assessment of the proposed Trans-Saharan gas pipeline project.

Unplanned downtimes are excluded from the developed local maintenance schedule. However, the failure rates retrieved from literature studies are incorporated with the developed local maintenance schedule to show the combined effects of unscheduled and scheduled maintenance on engine availability. Moreover, the unplanned downtime deserves further attention in the additional work section.

6.3 Gas Turbine, Gas Compressor and Turbo-Compressor Unit Availability

The developed gas turbine and gas compressor maintenance schedule, and the failure rates retrieved from literature studies, were utilised to show the effects of maintenance schedule on gas compressor and gas turbine unit availability as a function of the local condition. The gas compressor and gas turbine unit availability analysis and their impacts on the compressor station subsystem and overall system availability and economics are of fundamental importance during the design phase of any compressor station and pipeline project. The unit availability considers the downtime due to engine overhauls, preventive and corrective maintenance. The corrective maintenance considers each unit's failure rate. The unavailability of compressor station components could have a great impact on the techno-economics of natural gas transportation through the proposed Trans-Saharan gas pipeline leading to strong economic consequences.

Considering the individual gas compressor and gas turbine unit availability, if each unit overhauls occur every u_o operating hours, this event will happen about f_o times throughout the project lifecycle of t years. The frequency f_o , of each unit overhauls over the project lifecycle is given by:

$$f_o = \frac{8760t}{u_o} \quad (6-1)$$

The total time T_n , for each individual gas compressor and gas turbine overhauls and replacement at each compressor station location assuming no standby unit is available is calculated as:

$$T_n = R_n f_o \quad (6-2)$$

where, R_n is the time taken for individual unit overhaul and replacement assuming no standby unit is available. Similarly, the total time T_s , for each individual gas compressor and gas turbine replacement at each compressor station location assuming standby unit is available is calculated as:

$$T_s = R_s f_o \quad (6-3)$$

where, R_s is the time taken for individual unit replacement, assuming a standby unit is available.

The lifecycle downtime t_s , at which an individual unit is shut down for preventive maintenance purposes is evaluated as:

$$t_s = P_m t \quad (6-4)$$

where, P_m , is the annual preventive maintenance downtime.

The downtime per individual unit failure is the sum of the overhaul, replacement and preventive maintenance downtimes and is given by:

$$D_n = T_n + t_s \quad (6-5)$$

$$D_s = T_s + t_s \quad (6-6)$$

Where, D_n and D_s are the downtimes per individual unit failure, assuming no standby and standby units, respectively.

Each gas compressor and gas turbine unit running hours u_n and u_s assuming no standby and standby units, respectively, over the project lifecycle is given by:

$$u_n = 8760t - D_n \quad (6-7)$$

$$u_s = 8760t - D_s \quad (6-8)$$

The individual gas compressor and gas turbine unit total downtime D_{t_n} and D_{t_s} assuming no standby unit and standby unit respectively, is evaluated as follows:

$$D_{t_n} = D_n F \quad (6-9)$$

$$D_{t_s} = D_s F \quad (6-10)$$

Where, F is the individual unit failure rate. The failure rate considers the unscheduled maintenance downtime.

The individual gas compressor and gas turbine unit availability is the operational lifecycle availability A_u , which considered preventive maintenance based on the developed local maintenance schedule and corrective maintenance based on the unit's failure rate and is written as:

$$A_{u_n} = \frac{u_n}{u_n + D_{t_n}} \quad (6-11)$$

$$A_{u_s} = \frac{u_s}{u_s + D_{t_s}} \quad (6-12)$$

where, A_{u_n} and A_{u_s} are the individual unit availability assuming no standby unit and standby unit, respectively.

According to the assumption that each gas compressor unit is in series with each gas turbine unit. The availability of a turbo-compressor unit A_{t_n} and A_{t_s} assuming no standby unit and standby unit, respectively, is evaluated according to the series arrangement rule as follows:

$$A_{t_n} = A_{ugc_n} A_{ugt_n} \quad (6-13)$$

$$A_{t_s} = A_{ugc_s} A_{ugt_s} \quad (6-14)$$

where, A_{ugc_n} , A_{ugt_n} , and A_{ugc_s} , A_{ugt_s} are the individual gas compressor and gas turbine unit availability assuming no standby unit and standby unit, respectively.

6.4 Compressor Station Availability

It is imperative that compressor station availability analysis is incorporated into the techno-economics of the proposed Trans-Saharan gas pipeline and any pipeline project at the design and development phase. This is to ensure their profitability and positive returns on investment throughout the project lifecycle. Compressor station availability analysis can identify compressor station component's configurations that can affect the whole system availability and the project's feasibility. Since downtime of the major components due to overhauls,

scheduled or unscheduled maintenance can have significant impact on revenue generation. Thus, there is the need for a method able to consider the impact of compressor station configuration on the whole compressor station system availability. In this study, the compressor station is modelled as a series-parallel configuration. The baseline case consists of four parallel gas compressor units each in series with their gas turbine drivers. The compressor station subsystems availability is dependent on their unit's availability and configurations. Figure 6-3 shows the compressor station configuration depicting a parallel arrangement of compressor units in operational and standby modes.

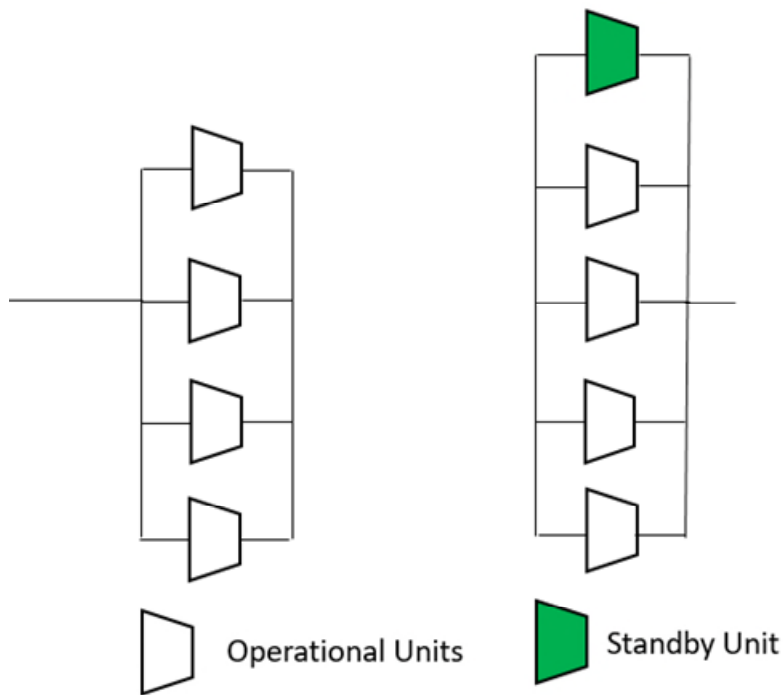


Figure 6-3 Compressor Station Configuration with Parallel Compressor Units

The availability of the compressor station subsystems without standby unit is evaluated analytically using binomial distribution method developed in MATLAB environment using the following equation:

$$P(K) = \frac{N!}{K!(N-K)!} (1 - A_u)^K A_u^{N-K} \quad (6-15)$$

Where:

$P(K)$ = Fraction of time the station is available to generate power

N = Total number of installed units

A_u = Unit Availability

K = Number of units shut down

Similarly, the availability of the compressor station subsystems with installed standby unit is evaluated analytically using binomial distribution method developed in the MATLAB environment using the following equation:

$$P(K) = \sum_{K=0}^1 \frac{N!}{K! (N-K)!} (1 - A_u)^K A_u^{N-K} \quad (6-16)$$

Where:

$P(K)$ = Fraction of time the station is available to generate power

N = Total number of installed units

A_u = Unit Availability

K = Number of units shut down

6.5 Compressor Station System Availability

Compressor station system availability analysis plays a vital role in the techno-economic evaluation of any compressor station and pipeline project. Since techno-economic analysis is significant in assisting policymakers in decision-making during the design and development stage of any project. This section assessed the compressor station availability at the system level comprising the whole compressor station subsystems in series arrangement along the proposed Trans-Saharan gas pipeline route. Compressor station system availability not only depends on individual gas compressor and gas turbine unit configuration but also on the subsystem's arrangement along the pipeline route. The system availability is indirectly impacted by the quality of maintenance policy employed, the prevailing environmental conditions and the unit's operating conditions. Scenarios-based approach was performed to show the sensitivities of the compressor station system to availabilities in terms of the number of installed

standby units. Figure 6-4 and Figure 6-5 show the compressor station system configuration depicting parallel arrangement of compressor units in each station in operational and standby modes, respectively.

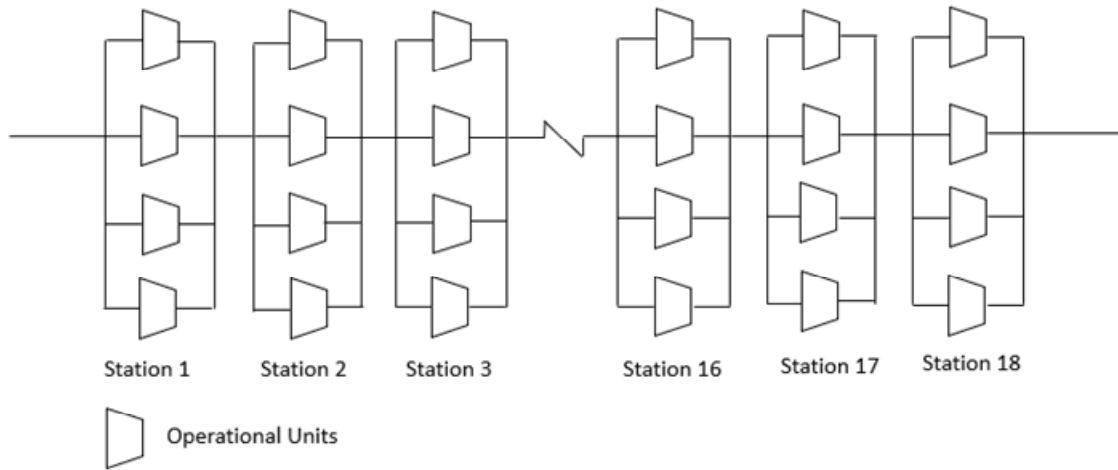


Figure 6-4 Compressor Station System Configuration with Parallel Compressor Units in Operational mode per Station

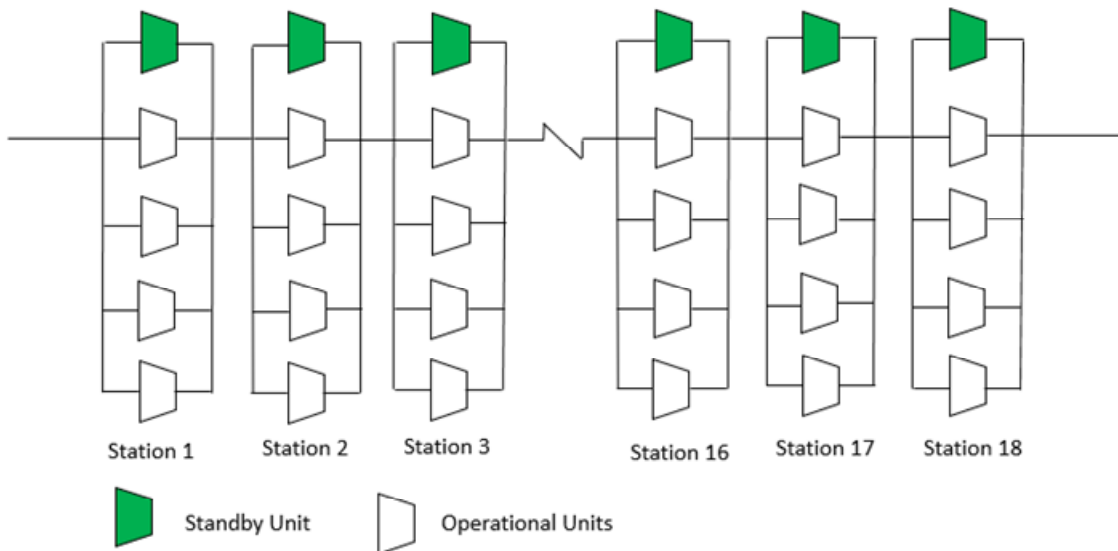


Figure 6-5 Compressor Station System Configuration with Parallel Compressor Units in Standby mode per Station

The whole compressor station system availability analysis was performed based on the following scenarios:

1. Baseline case: Availability is 100% or 1

2. Scenario 1: No standby unit installed at all compressor station locations (No standby unit)
3. Scenario 2: One standby unit installed at first eight compressor station locations giving a total of eight installed standby units (8 standby units)
4. Scenario 3: One standby unit installed at all compressor station locations giving a total of eighteen installed standby units (18 standby units)

The availability of the compressor station system with each compressor station arranged in series is evaluated by multiplying the availability of individual compressor station subsystems that make up the overall compressor station system and is evaluated as follows:

$$A_s = A_{cs1} * A_{cs2} * A_{cs3} * ... * A_{cs18} \quad (6-17)$$

The availability of the compressor station system given by Equation (6-17) can be re-written according to the series arrangement rule as:

$$A_s = \prod_{K=1}^{18} A_K \quad (6-18)$$

Where:

A_s = Compressor station system availability

A_K = Availability of compressor station K

$K = 1, 2, 3 \dots 18$

6.6 Availability Results

Figure 6-6 shows the availability of the gas compressor, gas turbine, and turbo-compressor units with no standby and standby units, respectively.

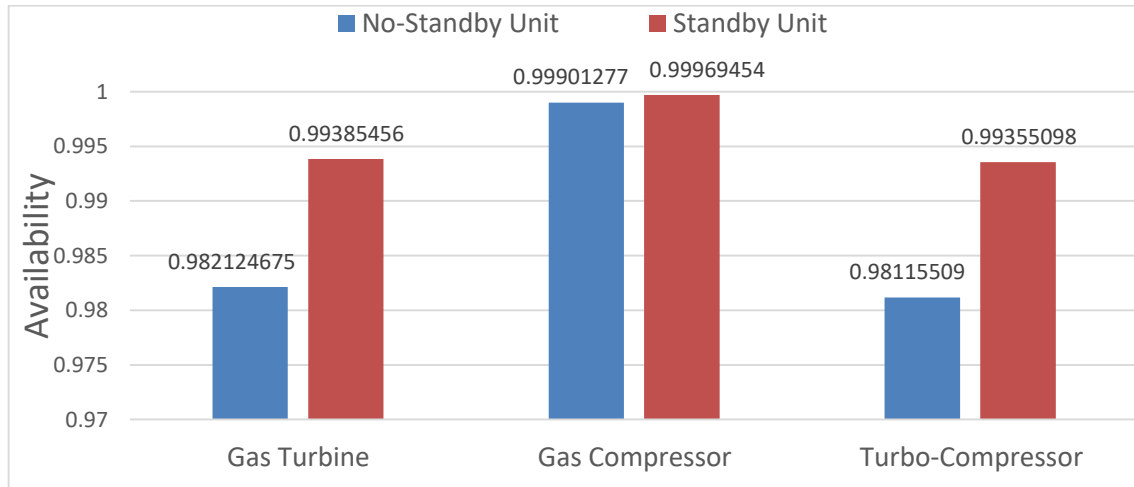


Figure 6-6 Unit Availability

The results show that the gas compressor with the highest availability is a more reliable component. The unit availability assuming no standby gas turbine unit is available is 0.982. The evaluated units availability agree with literature reports [42]; [146] and are within the recommended original equipment manufacturer operational requirement. Figure 6-7 shows the compressor station availability, while Figure 6-8 shows the compressor station system availability for the scenarios considered in this study. Considering the turbo-compressor configurations, the compressor station availability with no standby installed unit is 0.9267. The compressor station availability with installed standby unit is 0.9996.

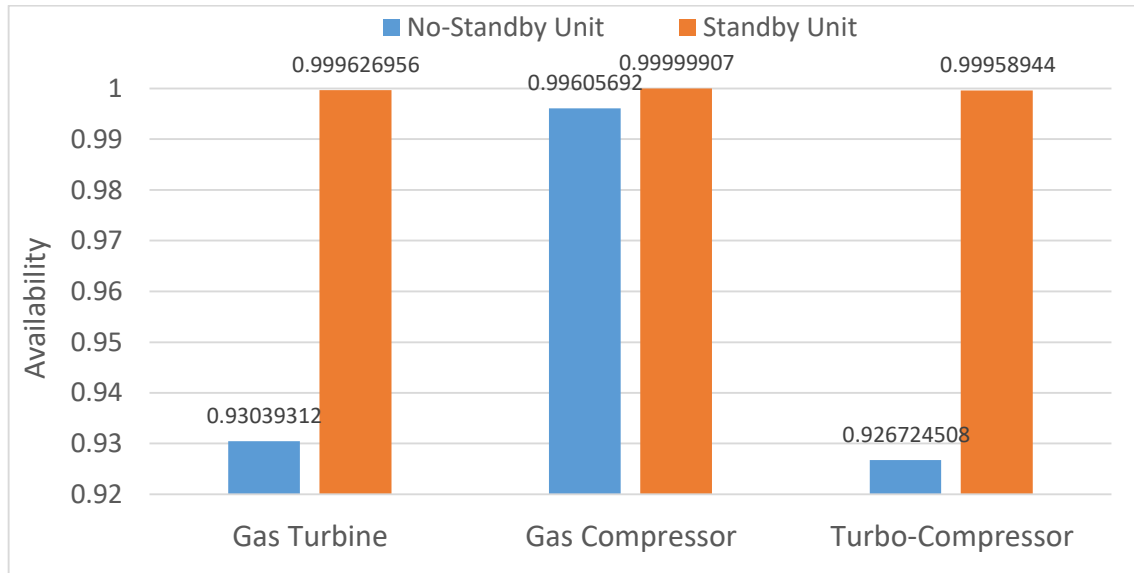


Figure 6-7 Compressor Station Availability

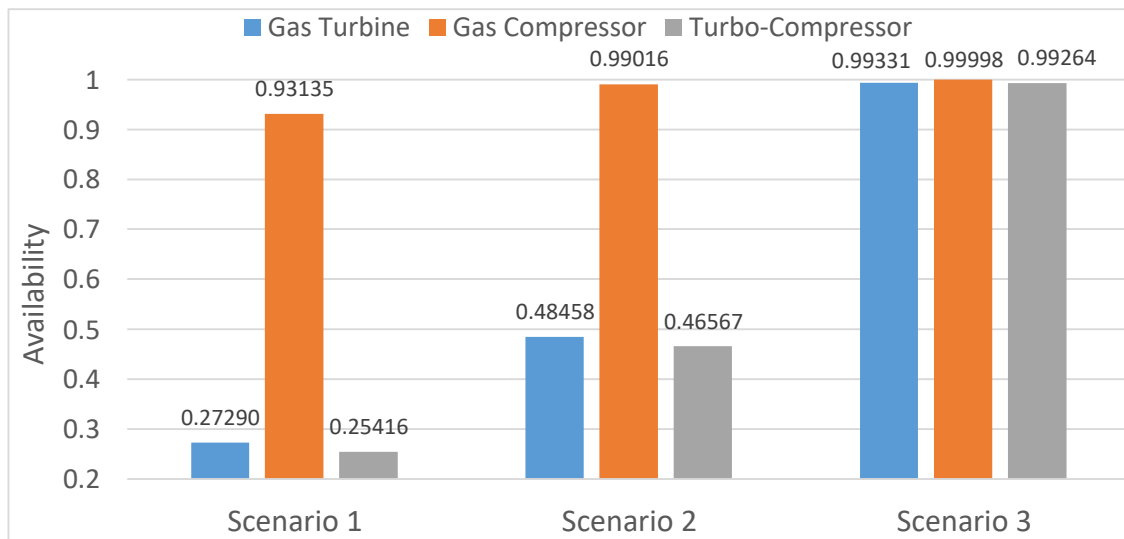


Figure 6-8 Compressor Station System Availability

The results for the scenario-based approach show a compressor station system availability of 0.25416 for scenario 1 with no standby turbo-compressor unit at all compressor station locations. Results show an increase in the system availability to 0.46567 for scenario 2, with one standby turbo-compressor unit per station at the first eight compressor station locations. The highest compressor station system availability of 0.99264 occurs in scenario 3, with one standby turbo-compressor unit per station at all compressor station locations. Thus, minimising engine downtime and ensuring a continuous supply of natural gas through the

transmission pipelines to end-users. Results show the sensitivity of compressor station subsystems and system availability to the variation in standby units at compressor station locations. Increasing the number of standby units at compressor station locations greatly impacts the whole compressor station system availability. The effect is a corresponding increase in the overall system availability. This could be beneficial in the techno-economic evaluation of the compressor station system by mitigating risks and uncertainties during the design and development phase of the proposed Trans-Saharan gas pipeline and any pipeline project.

Results are inputted into the economic module to determine the impact of turbo-compressor availability on the lifecycle cost and net present value.

6.7 Techno-Economic Analysis

This study utilises a discounting method based on the lifecycle cost and the net present value for the economic assessment of the proposed Trans-Saharan gas pipeline project. The economic module is developed based on the data received from the pipeline module, gas compressor module, gas turbine performance module, maintenance, and availability module to determine the economics of the compressor station and pipeline systems. Consequently, the feasibility of the proposed Trans-Saharan gas pipeline project. The economic module considers the lifecycle cost for the project's duration based on the capital cost, operating cost, and availability-based maintenance costs. The success of the proposed Trans-Saharan gas pipeline project will depend on these costs, considering the techno-economic assumptions made during the subsequent analysis.

The techno-economic model is developed using SIMULINK block diagrams and a developed code in MATLAB environment. This is used to estimate the capital cost, operation, and availability-based maintenance costs of the proposed Trans-Saharan gas pipeline project. The model is based on the variation in compressor station location ambient temperatures at varying flow conditions for isothermal, intermediate and non-isothermal conditions, respectively. The gas compressor power was considered at isothermal, intermediate and non-isothermal flow conditions. Their corresponding gas turbine shaft power, fuel flow, and turbine

entry temperatures required to drive the gas compressor, which is expected to have a major impact on the projects fuel consumption and engine availability-based maintenance costs, were considered in the techno-economic analysis.

6.7.1 Economic Assumption

Table 6-1 shows the assumptions made for the economic analysis in this research.

Table 6-1 Economic Assumptions

S/N	Parameter (Unit)	Value	References
1.	Plant Life (years)	30	
2.	Pipe Material Cost (\$/metric ton)	1312	[147]
3.	Pipe Thickness (mm)	20.574	[18]
4.	Pipe Outer Diameter (mm)	1422.4	[18]
5.	Coating and wrapping (\$/feet)	5	[38]
6.	Pipe Grade	API 5L X70	[18]
7.	Fuel Cost (\$/kg)	0.168	[18]
8.	Discount Rate (%)	15	[18]
9.	Natural Gas Price (\$/MMBtu)	6.80	[148]
10.	Natural Gas Higher Heating Value (Btu/m ³)	38480	[149]
11.	Fixed O & M Cost (\$/kW-year)	12	[150]
13.	Variable O & M Cost (\$/MWh)	4.7	[151]
14.	Maintenance Factor 1	20% of Variable O & M Cost	[152]

6.8 SIMULINK Model of the TERA Framework

SIMULINK [153] is a block diagram environment integrated with MATLAB to support system-level design and simulation. It provides a graphical user interface and solvers for model-based design and simulation of dynamic systems. The techno-economic model was implemented using a SIMULINK block diagram integrating the TERA framework consisting of engine availability values, pipeline and gas compressor modules, performance, and economic modules. The developed model is used to determine the lifecycle cost of the proposed Trans-Saharan gas pipeline project. The model is divided into six subsystems:

1. Pipeline subsystem
2. Gas compressor subsystem
3. Pipeline cost subsystem
4. Gas compressor cost subsystem
5. Gas turbine cost subsystem
6. Auxiliaries cost subsystem.

The whole system was developed by connecting sequentially individual subsystem along with the fuel and maintenance blocks according to the TERA framework. The output from the pipeline subsystem representing a source serve as input to the gas compressor subsystem. Similarly, the output from the gas compressor subsystem serve as input to the gas compressor cost subsystem. The output from the gas compressor cost, pipeline cost, and gas turbine cost subsystems respectively summed up together formed the pipeline initial project cost. This also serve as input to the auxiliaries cost subsystem. The sum of the outputs from the auxiliaries cost subsystem, pipeline initial project cost, fuel, and maintenance blocks make up the lifecycle cost estimate for the compressor station and pipeline system which is dependent on the location ambient temperature at varying flow conditions. Figure 6-9 shows the integrated techno-economic model of the TERA framework using SIMULINK block diagrams.

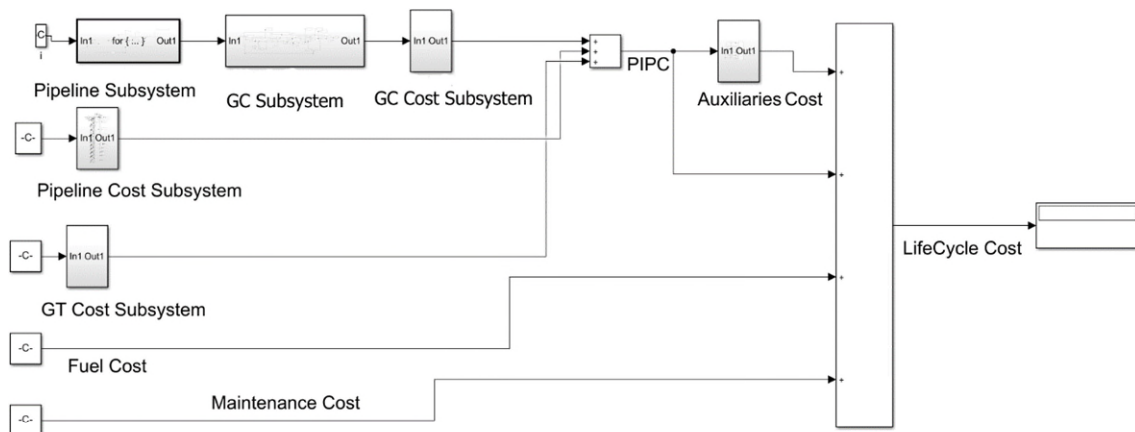


Figure 6-9 The Integrated Techno-Economic Model

6.9 Project Capital Cost Estimates

According to Menon [38], the major components that contribute to the initial capital cost in a natural gas pipeline transportation system are the pipelines, compressor stations, and auxiliaries such as the mainline valve stations, telecommunications, and supervisory control and data acquisition system, right of way, environmental and permitting, engineering and construction management, and contingencies.

The input to the economic module consists of the pipeline cost, gas compressor cost, gas turbine cost, and auxiliaries' costs. These costs are the major components of the capital costs of the compressor station and pipeline project. The pipeline cost consists of pipeline material cost, pipe installation cost, pipe coatings and wrapping cost. The gas compressor cost consists of the gas compressor purchased and installation costs. The gas turbine capital cost includes the gas turbine equipment cost, installation, and shipping costs. Auxiliaries' costs comprise the mainline valve stations, telecommunications, and supervisory control and data acquisition system, right of way, environmental and permitting, engineering and construction management, and contingencies. The total project capital expenditure for the techno-economic analysis is the sum of the pipeline cost, gas compressor cost, gas turbine cost, and auxiliaries' costs. The output from the economic module is the compressor station and pipeline project lifecycle cost. The lifecycle cost for the techno-economic analysis is made up of the pipeline cost, gas compressor cost, gas turbine cost, auxiliaries' costs, fuel cost, and maintenance cost. The economic model was evaluated based on the lifecycle cost and net present value analysis.

6.9.1 Pipeline Cost Estimate

Table 6-2 shows the proposed Trans-Saharan gas pipeline data utilised for the pipeline cost estimate. Pipeline cost consists of pipeline material cost, pipe coatings and wrapping cost, and pipeline installation cost [38]. The pipeline material cost is a function of the pipe diameter, pipe wall thickness, pipe material, and pipe length.

Table 6-2 Pipeline data [18]

S/N	Parameters	Values (Units)
1.	Natural gas flow	30 (BCM/year)
2.	Pipe nominal diameter	1422.4 (mm)
3.	Pipe outer diameter	1422.4 (mm)
4.	Pipe inner diameter	1381.2 (mm)
5.	Wall thickness	20.62 (mm)
6.	Design Pressure	100 (barg)
7.	MAOP	95 (barg)
8.	Pipe Grade	API 5L X70
9.	Design Code	0.72
10.	Design Factor	ASME B31.8
12.	Pipe Roughness	7.62 (μm)

The pipeline material cost P_{mat} , is estimated using the following equation:

$$P_{mat} = 0.0246(D - T)TLC \quad (6-19)$$

Where:

L = Pipe length, km

D = Pipe outside diameter, mm

T = Pipe wall thickness, mm

C = Pipe material cost (\$/metric ton)

The average value of the pipe material cost estimates from 2010 to 2016 for line pipe greater than 24 inches based on the report prepared by Inner City Fund and submitted to American Petroleum Institute and others in the United States [147] was assumed in this research.

Pipeline installation cost was estimated based on the Institute of Transportation studies [154] generalised estimate as a function of the pipeline outer diameter and length. A quadratic best-fit curve was obtained for the installation cost, this is expressed in the following equation:

$$y = 343.21x^2 + 2073.9x + 170013 \quad (6-20)$$

Where:

y = Installation cost (\$/mile)

x = Outer diameter (inches)

It is assumed that the pipe is externally coated and wrapped at an extra cost P_{c_w} , of \$5 per feet. The total pipeline cost P_t in \$ is estimated using the following equation:

$$P_t = P_{mat} + (0.6214y + 3280.84P_{c_w})L \quad (6-21)$$

Figure 6-10 shows the developed SIMULINK model of the pipeline subsystem while Figure 6-11 shows the corresponding pipeline cost subsystem.

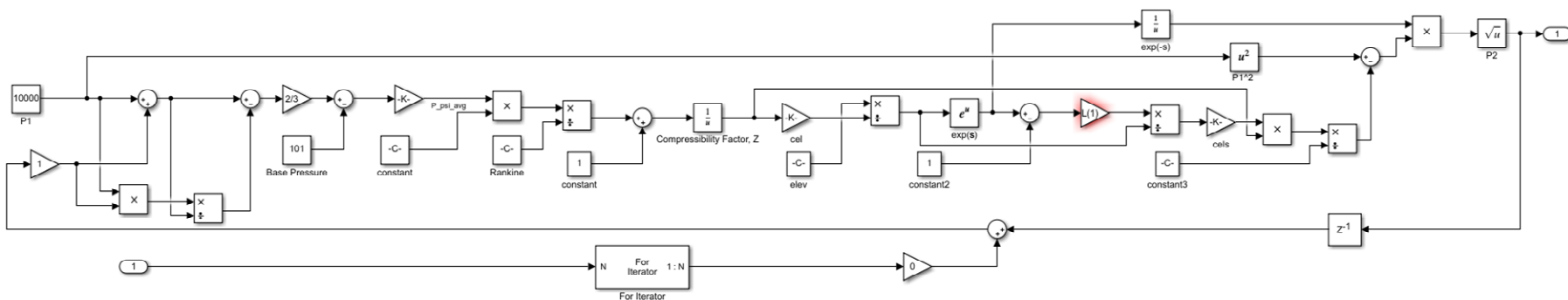


Figure 6-10 Pipeline Subsystem

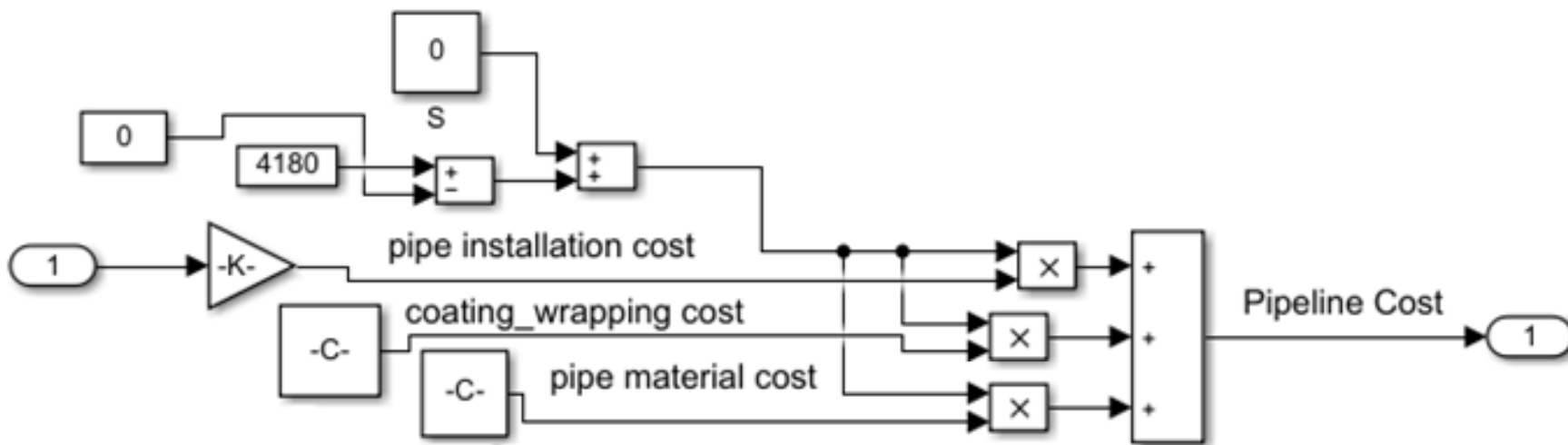


Figure 6-11 Pipeline Cost Subsystem

6.9.2 Gas Compressor Cost

The gas compressor purchased, and installation costs are estimated using the following equations:

$$P_p = \left(\frac{M\&S}{280} \right) (517.5) (bhp^{0.82}) F_c \quad (6-22)$$

$$P_i = \left(\frac{M\&S}{280} \right) (517.5) (bhp^{0.82}) (2.11 + F_c) \quad (6-23)$$

Where:

P_p = Gas compressor purchased cost (\$)

P_i = Gas compressor installation cost (\$)

$M\&S$ = Marshall and Swift cost index, equivalent to 1638.2 for 2018 [155]

F_c = Correction factor, equivalent to 1.15 for gas turbine driven centrifugal compressors

bhp = Gas compressor power, horsepower

The total gas compressor cost GC_t , is the sum of the purchased and installation costs given by:

$$GC_t = P_p + P_i \quad (6-24)$$

Figure 6-12 shows the developed SIMULINK model of the gas compressor subsystem while Figure 6-13 shows the corresponding gas compressor cost subsystem.

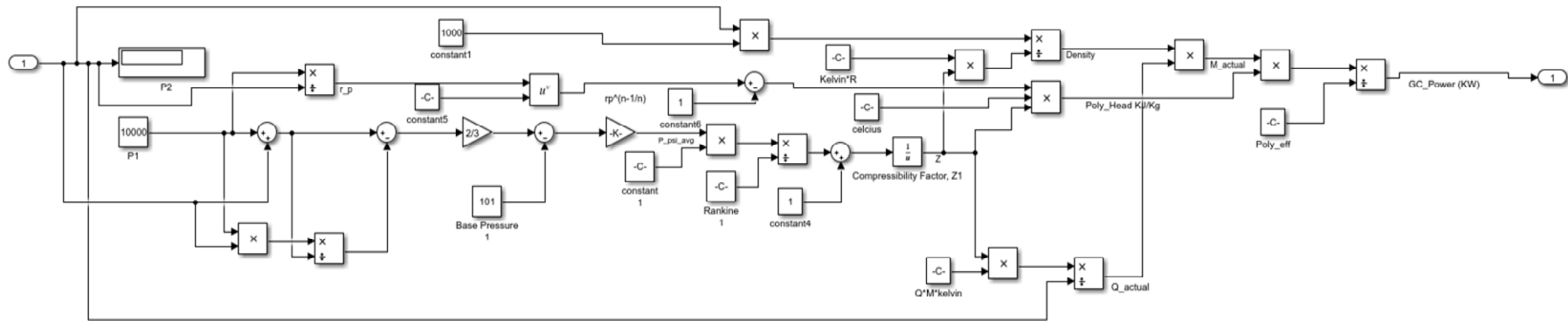


Figure 6-12 Gas Compressor Subsystem

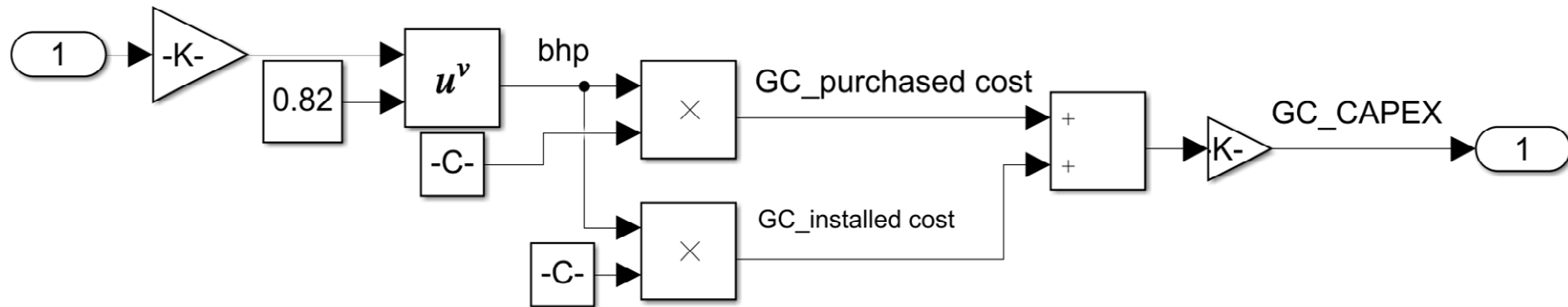


Figure 6-13 Gas Compressor Cost Subsystem

6.9.3 Gas Turbine Cost

The gas turbine equipment cost GT_{eq} , was estimated based on the best fit curve equation developed for gas turbines cost estimation provided by the 2018 Gas Turbine World Handbook [156] and is given by:

$$GT_{eq} = 8118(shp^{-0.294}) \quad (6-25)$$

Where shp is the gas turbine shaft horsepower. Assuming factors of 2 and 1.38 to cater for installation and shipping cost respectively [18], gas turbine capital cost GT_c , is estimated using the following equation:

$$GT_c = 2.76NGT_{eq} \quad (6-26)$$

Where, N is the number of gas turbine installed per compressor station location.

Figure 6-14 shows the developed SIMULINK model of the gas turbine cost subsystem.

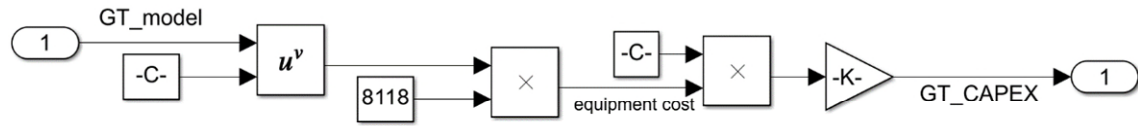


Figure 6-14 Gas Turbine Cost Subsystem

The pipeline project initial cost P_i is the sum of the pipeline cost P_t , gas compressor cost GC_t , and gas turbine cost GT_c , and is given by:

$$P_i = P_t + GC_t + GT_c \quad (6-27)$$

6.9.4 Auxiliaries Cost

Pipeline accessories are estimated as percentages of the pipeline project initial cost P_i , as recommended by [38].

Table 6-3 shows the assumed percentages based on [38] recommendations for pipeline accessories.

Table 6-3 Pipeline Accessories Assumptions [38]

S/N	Accessories	Percentage of P_i
1.	Main Valve Station	0.5%
2.	SCADA	2%
3.	Environmental & permitting	10%
4.	Right of Way (ROW)	6%
5.	Engineering & Construction Mgt.	15%
6.	Contingency	10%

The auxiliaries' cost P_{aux} , is the algebraic sum of each accessory cost as shown in Table 6-3. Figure 6-15 shows the developed SIMULINK model of the auxiliaries cost subsystem.

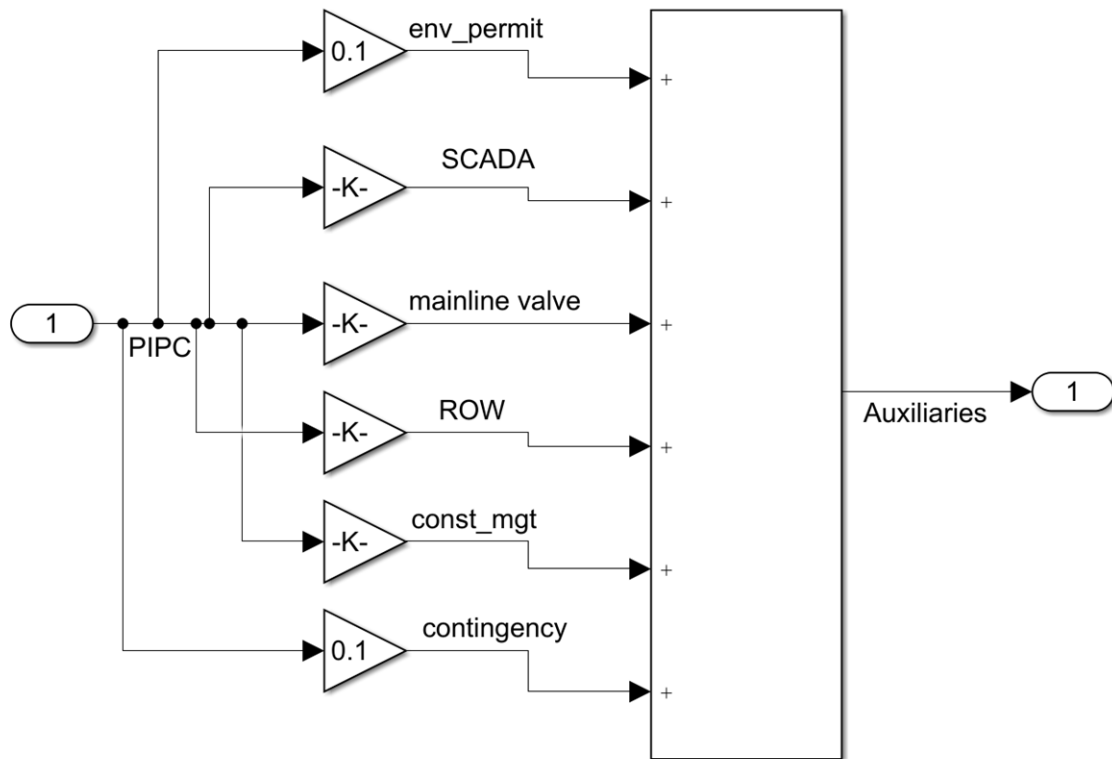


Figure 6-15 Auxiliaries Cost Subsystem

The total project capital expenditure P_{to} , is the sum of the pipeline project initial cost P_i , and auxiliaries cost P_{aux} , and is given by:

$$P_{to} = P_i + P_{aux} \quad (6-28)$$

6.10 Operation and Maintenance Cost

The operation and maintenance costs are the costs related to the operation and maintenance of the compressor station and pipeline system under varying operating conditions and comprise of fixed and variable costs. As with other pipeline projects, after the construction and installation of the compressor station and pipeline system there will be operation and maintenance costs over the proposed Trans-Saharan gas pipeline project's lifecycle. In this study, the operational life of the compressor station and pipeline system is assumed to be 30 years. The operating cost depends on the operating conditions of the compressor station equipment and the fuel consumption cost. The fuel consumption cost is an essential component of the variable cost. It contributes to one of the highest operating costs of the compressor station and pipeline system. It is usually evaluated separately from the maintenance cost. The gas turbines shaft powers, fuel flows and turbine entry temperatures required to drive the gas compressors at isothermal, intermediate and non-isothermal flow conditions corresponding to varying ambient conditions of the compressor station locations along the pipeline route have been obtained from the gas turbine performance simulation presented in chapter five. They are applied to evaluate the operation and maintenance costs in this study.

6.10.1 Fuel Cost

The fuel cost is the most important cost factor in the operational cost incurred during the operation of the compressor station and pipeline system. It could influence the overall project profitability to a great extent. This study assumed a fixed value for the fuel cost per unit weight of fuel over the project lifecycle. The fuel consumption cost is estimated based on the variation in compressor station locations ambient temperature considering isothermal, intermediate and non-isothermal flow conditions. The fuel flow results at varying flow conditions obtained from the gas turbine performance analysis enable the evaluation of the

annual and lifecycle fuel consumption cost for each gas turbine at each compressor station location.

The annual and lifecycle fuel consumption costs at each compressor station location for isothermal, intermediate, and non-isothermal flow conditions, respectively, are evaluated using the following equations:

$$F_{ac} = 3600F_uF_fO_fN \quad (6-29)$$

$$F_{lc} = F_{ac}t \quad (6-30)$$

Where:

F_{ac} = Annual fuel consumption cost, \$

F_u = Fuel cost per kg of fuel, (\$/kg)

F_f = Fuel Flow at isothermal, intermediate or non-isothermal conditions (kg/s)

O_f = Operational period at isothermal, intermediate or non-isothermal case (hrs)

F_{lc} = Lifecycle fuel consumption cost, \$

t = Project lifecycle

N = Number of installed units

6.10.2 Maintenance Cost

The fuel consumption cost has been estimated separately from the maintenance cost due to the significant cost involved. The maintenance cost consists of fixed, variable, and major maintenance costs. These costs also result from engine downtime due to overhauls and replacement. They depend on the maintenance pattern adopted, whether scheduled or unscheduled maintenance, operating ambient conditions, compressor station availability, type of technology employed, and station location. They also depend on the overall decision taken during the design and development stage of the proposed Trans-Saharan gas pipeline project. Thus, the economic feasibility of the project will be influenced by the

maintenance costs and these factors. The maintenance cost evaluation in this study considers the compressor station availability. The compressor station availability analysed previously was utilised to calculate the maintenance cost over the project lifecycle.

6.10.2.1 Fixed Maintenance Cost

The fixed maintenance cost estimates are based on the 2019 Annual Technology Baseline data retrieved from [150]. The annual and lifecycle fixed maintenance costs at each compressor station locations for isothermal, intermediate, and non-isothermal flow conditions respectively are evaluated using the following equations:

$$M_{afc} = 1000P_{GT}m_fN \quad (6-31)$$

$$M_{lfc} = M_{afc}t \quad (6-32)$$

Where:

M_{afc} = Annual fixed maintenance cost, \$

P_{GT} = Gas turbine power at isothermal, intermediate or non-isothermal conditions, (MW)

m_f = Fixed maintenance cost factor, (\$/kW-year)

M_{lfc} = Lifecycle fixed maintenance cost, \$

t = Project lifecycle

N = Number of installed units

6.10.2.2 Availability-Based Variable Maintenance Cost

The availability-based variable maintenance cost estimates are based on the evaluated compressor station availability and 2020 cost data estimated by [151] for the United States Energy Information Administration. The annual and lifecycle availability-based variable maintenance costs at each compressor station

locations for isothermal, intermediate, and non-isothermal flow conditions respectively are evaluated using the following equations:

$$M_{avc} = P_{GT}m_vO_fP(K)N \quad (6-33)$$

$$M_{lvc} = M_{avc}t \quad (6-34)$$

Where:

M_{avc} = Annual availability-based variable maintenance cost, \$

m_v = Variable maintenance cost factor, (\$/MWh)

M_{lvc} = Lifecycle availability-based variable maintenance cost, \$

$P(K)$ = Compressor station availability

t = Project lifecycle

N = Number of installed units

P_{GT} = Gas turbine power at isothermal, intermediate or non-isothermal conditions, (MW)

O_f = Operational period at isothermal, intermediate or non-isothermal case (hrs)

Nasir [16] and Tukur [18] assumed an annual value of \$30 per kW for the maintenance cost in their pipeline TERA. Aziaka et al. [157] in their economic evaluation, attempted to incorporate availability but they were not able to do so and only assumed availability of unity. This research utilises the actual compressor station availability values based on the developed maintenance schedule and failure rates to evaluate the actual availability-based maintenance cost in the pipeline TERA.

6.10.2.3 Availability-Based Major Maintenance Cost

The creep life values of the engine at isothermal, intermediate and non-isothermal flow conditions corresponding to the location ambient temperatures were estimated using a simple relationship between the engine turbine entry temperatures and the engine creep life [152]. According to this relationship, the

creep life reduces by half for every 20 K increase in turbine entry temperature. More so, for every 20 K reduction in turbine entry temperature, the creep life increases by half [158]. The design point turbine entry temperature was assumed to be the baseline with a creep life of 25000 hours. The estimated creep life values were used to calculate the availability-based major maintenance cost. The annual and lifecycle availability-based major maintenance costs at each compressor station locations for isothermal, intermediate, and non-isothermal flow conditions respectively are evaluated using the following equations:

$$M_{amc} = P_{GT} m_{v2} O_f P(K) N \quad (6-35)$$

$$M_{lmc} = M_{amc} t \quad (6-36)$$

$$M_{v2} = m_{v1} \left(\frac{C_{dp}}{C} \right) \quad (6-37)$$

Where:

M_{amc} = Annual availability-based major maintenance cost, \$

m_{v2} = maintenance cost factor 2, (\$/MWh)

m_{v1} = maintenance cost factor 1, (\$/MWh)

M_{lmc} = Lifecycle availability-based major maintenance cost, \$

$P(K)$ = Compressor station availability

C_{dp} = Expected engine life, hours

C = Engine creep life, hours

t = Project lifecycle

N = Number of installed units

P_{GT} = Gas turbine power at isothermal, intermediate or non-isothermal conditions, (MW)

O_f = Operational period at isothermal, intermediate or non-isothermal case (hrs)

The expected engine life is the assumed engine creep life at design point. The total annual and lifecycle maintenance cost M_{ac} , and M_{lc} respectively, is the sum of the fixed and availability-based variable and major maintenance costs and is given by:

$$M_{ac} = M_{afc} + M_{avc} + M_{amc} \quad (6-38)$$

$$M_{lc} = M_{lfc} + M_{lvc} + M_{lmc} \quad (6-39)$$

Where:

M_{ac} = Total annual maintenance cost, \$

M_{afc} = Annual fixed maintenance cost, \$

M_{avc} = Annual availability-based variable maintenance cost, \$

M_{amc} = Annual availability-based major maintenance cost, \$

M_{lc} = Total lifecycle maintenance cost, \$

M_{lfc} = Lifecycle fixed maintenance cost, \$

M_{lvc} = Lifecycle availability-based variable maintenance cost, \$

M_{lmc} = Lifecycle availability-based major maintenance cost, \$

The steps in which the maintenance cost analysis could be improved are explained in the further work section in the subsequent chapter.

6.11 Project Life Cycle Cost

The lifecycle cost for the proposed Trans-Saharan gas pipeline is the total cost incurred during the construction, installation, operation and maintenance of the compressor station and pipeline system. The lifecycle cost consists of the gas compressor, gas turbine, pipeline, auxiliaries, fuel, and total maintenance costs. The total maintenance cost consists of the fixed and availability-based variable and major maintenance costs. The lifecycle cost L_c , for the techno-economic study in this research can be written as:

$$L_c = P_t + GC_t + GT_c + P_{aux} + F_{lc} + M_{lc} \quad (6-40)$$

Where:

L_c = Techno-economic lifecycle cost, \$

P_t = Total pipeline cost, \$

GC_t = Gas compressor cost, \$

GT_c = Gas turbine cost, \$

P_{aux} = Auxiliaries cost, \$

F_{lc} = Lifecycle fuel consumption cost, \$

M_{lc} = Total lifecycle maintenance cost, \$

6.12 Net Present Value Analysis

The net present value is usually used to determine the economic viability of projects. The net present value can be estimated using the following equation:

$$NPV = \sum_{j=1}^n \frac{CF_j}{(1+r)^j} - C_o \quad (6-41)$$

Where:

CF_j = Net cash flow for year j

j = Year of project cash flow

r = Assumed discount rate

C_o = Initial Capital Investment

n = Total project duration

The annual net cash flow is the net sum of the project's annual cash inflow and outflow. The yearly cash outflows are the operation and maintenance costs, including fuel costs. The annual cash inflow is the annual revenue generated from

selling natural gas to the end-users. A positive net present value indicates that the project is economically viable and acceptable. A negative net present value suggest that the project may not break even and thus, economically not viable. When two competing alternative projects have a positive net present value, the one with the highest net present value is usually chosen in preference to the other. The discount rate is the rate at which future cash flows are discounted to convert them to present values. The discount rate is usually set in such a way as to generate a net positive value in the project's worth based on the expected project profitability. The gross annual revenue R_g , generated from the project is estimated using the following equation:

$$R_g = G_p H_v p_g \quad (6-42)$$

Where:

G_p = Gas price, (\$/MMBtu)

H_v = Gas higher heating value, (Btu/m³)

p_g = Annual gas production, (MMm³)

The lost annual revenue R_l , from the project due to engine downtime is estimated using the following equation:

$$R_l = D_a r_l \quad (6-43)$$

Where:

D_a = Total annual downtime, hours

r_l = Estimated lost revenue per hour

The net annual revenue R_{net} , from the project is the algebraic difference between the gross annual revenue and lost annual revenue and is evaluated as:

$$R_{net} = R_g - R_l \quad (6-44)$$

The annual cash outflow CF_a , is the sum of the annual fuel cost F_{ac} , and annual maintenance cost M_{ac} , and is given by:

$$CF_a = F_{ac} + M_{ac} \quad (6-45)$$

The annual net cash flow CF , is given by:

$$CF = R_{net} - CF_a \quad (6-46)$$

6.13 Results

6.13.1 Fuel Costs at Varying Flow Conditions

The lifecycle fuel costs are \$9.82 billion, \$9.79 billion, and \$9.85 billion for isothermal, intermediate, and non-isothermal flow conditions, respectively. The three flow conditions define the whole operating range of the proposed Trans-Saharan Gas Pipeline system. The fuel costs are an important cost element of the compressor stations and pipeline systems. The fuel cost estimation is nearly the same for all flow conditions. The results depict the fuel costs that could be experienced over the operating range throughout the project lifecycle of 30 years.

6.13.2 The Impact of Turbo-Compressor Availability on Capital Cost

Figure 6-16 shows the impact of availability on capital cost for the three availability scenarios. The project capital cost is \$18.23 billion for scenario 1, consisting of no standby turbo-compressor units at all compressor station location. The capital cost is \$19.05 billion for scenario 2, consisting of one standby turbo-compressor unit at the first eight compressor station location. The capital cost is \$20.10 billion for scenario 3, consisting of one standby turbo-compressor units at all compressor station locations. Availability directly impacts the project's capital cost in terms of the additional first cost incurred from the installed standby units.

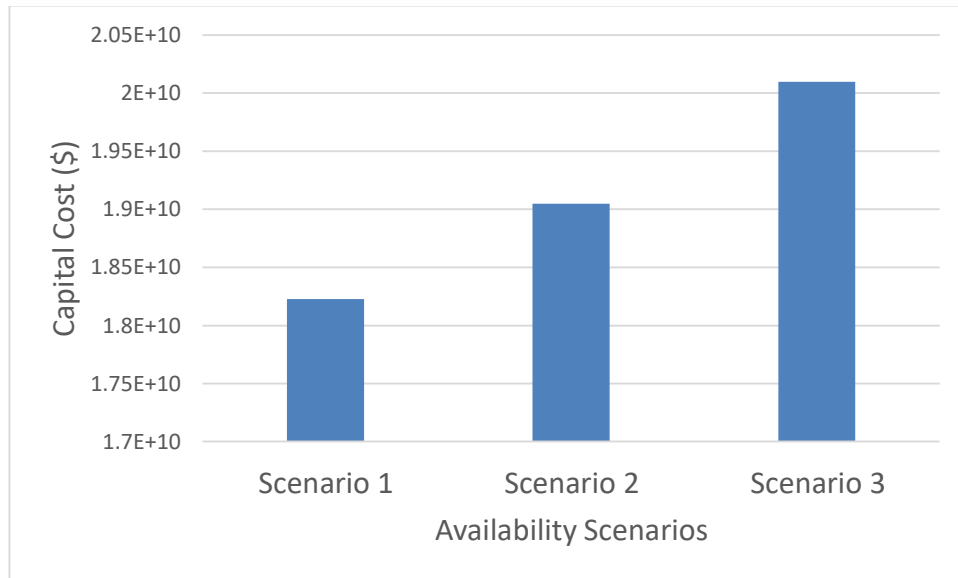


Figure 6-16 Impact of availability on capital cost

6.13.3 The Impact of Turbo-Compressor Availability on Fuel Cost

Figure 6-17 shows the impact of availability on fuel cost for the three availability scenarios. The fuel cost is about \$9.85 billion for each availability scenario. There is no additional cost related to the standby unit's fuel consumption. The results show that availability has no direct impact on the fuel cost since the fuel cost is identical for all scenarios and the spare units are in standby mode.

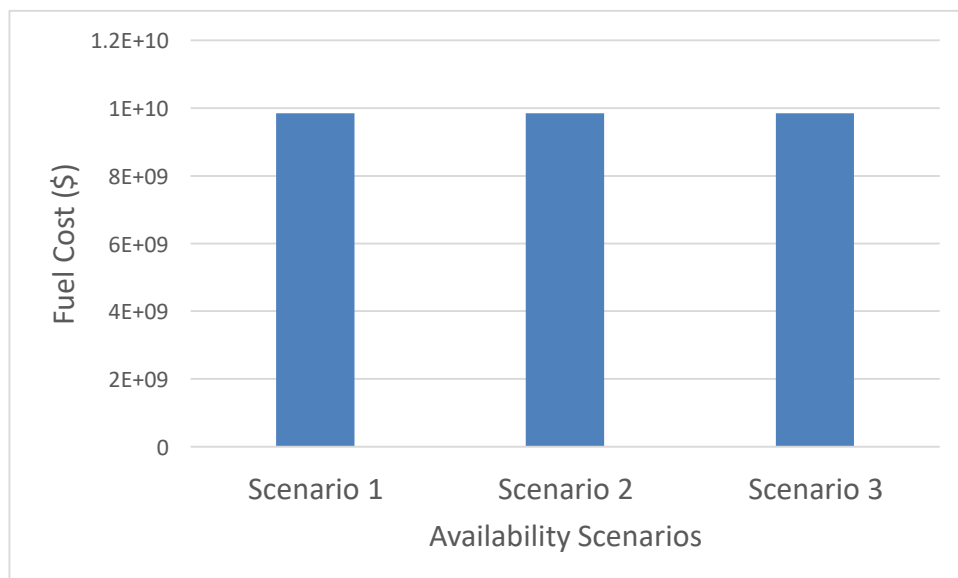


Figure 6-17 Impact of availability on fuel cost

6.13.4 The Impact of Turbo-Compressor Availability on Maintenance Cost

Figure 6-18 shows the impact of availability on maintenance cost for the three availability scenarios. The maintenance cost is \$8.40 billion for scenario 1, \$8.44 billion for scenario 2, and \$8.48 billion for scenario 3. The operational cost of the project is impacted by the increase in maintenance cost with an increase in compressor station system availability due to the installation of standby units.

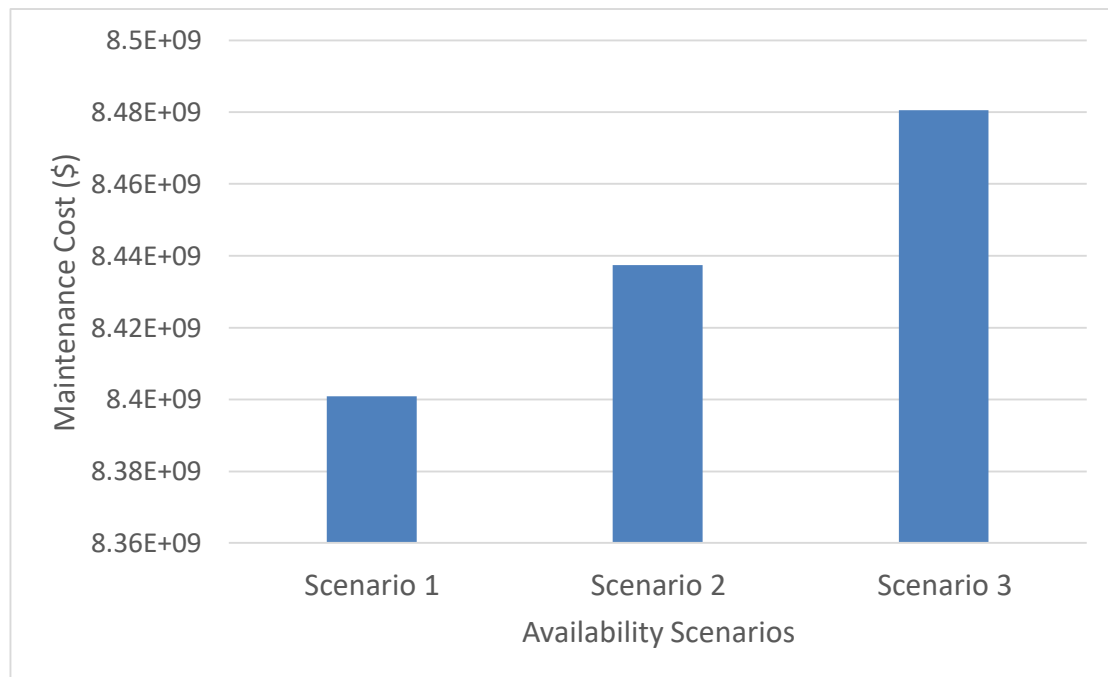


Figure 6-18 Impact of availability on maintenance cost

6.13.5 The Impact of Turbo-Compressor Availability on Life Cycle Cost

Figure 6-19 and Figure 6-20 show the breakdown of project cost for the baseline case and one of the availability scenarios. These included:

1. Baseline case: Availability is 100% or 1
2. Scenario 1: No standby unit installed at all compressor station locations (No standby unit)
3. Scenario 2: One standby unit installed at first eight compressor station locations giving a total of eight installed standby units (8 standby units)

4. Scenario 3: One standby unit installed at all compressor station locations giving a total of eighteen installed standby units (18 standby units)

The lifecycle cost of the proposed Trans-Saharan gas pipeline project consists of gas compressor cost, gas turbine cost, auxiliaries cost, fuel cost, and maintenance cost. In both the baseline and scenario 3 cases, the fuel cost has the highest impact on the project, accounting for 26.94% and 25.63%, respectively, of the lifecycle cost. The maintenance cost, pipeline cost, auxiliaries cost, gas compressor cost, and gas turbine cost accounted for 23.20%, 19.51%, 15.85%, 10.67%, and 6.26%, respectively, of the lifecycle cost for scenario 3. Appendix K shows the breakdown of the project cost for other availability scenarios.

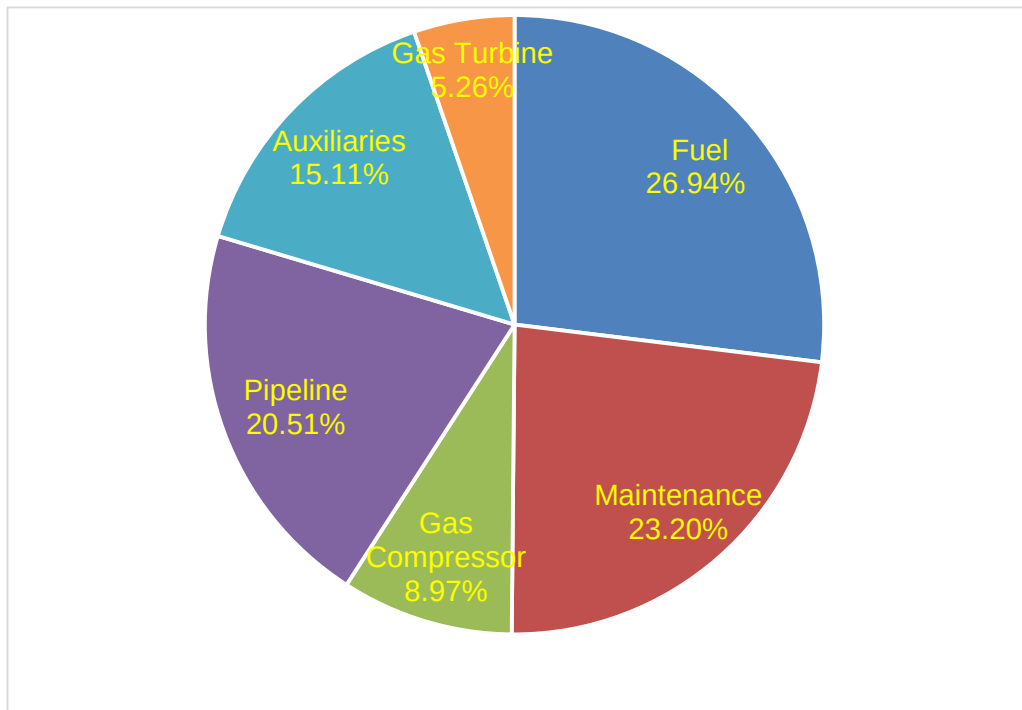


Figure 6-19 Breakdown of Project Cost for Baseline Case

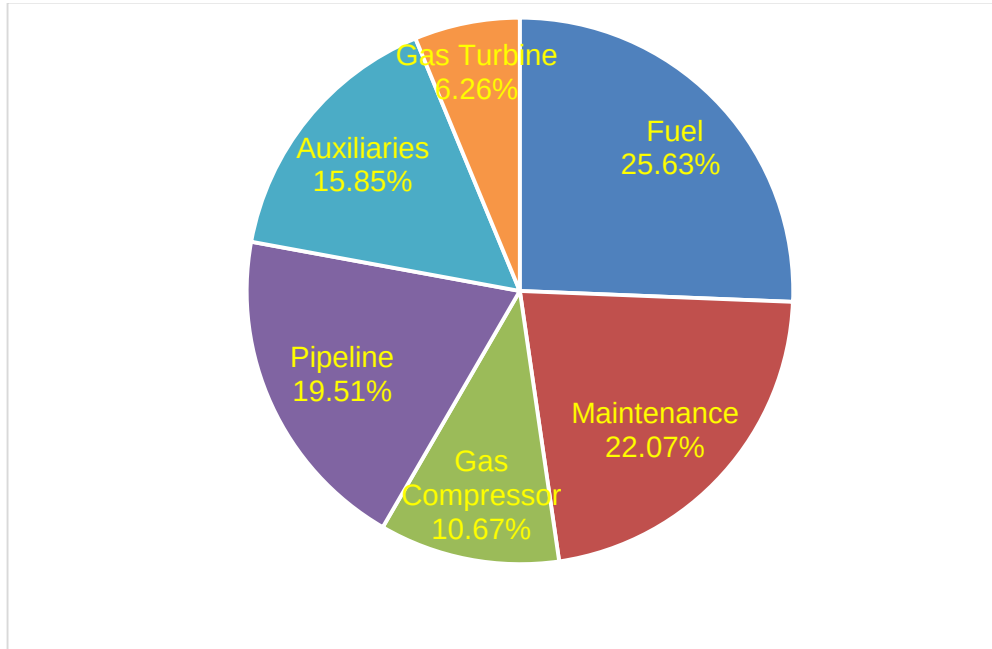


Figure 6-20 Breakdown of Project Cost for Availability Scenario 3

Figure 6-21 shows the impact of availability on lifecycle cost for the availability scenarios. The project capital cost is \$18.23 billion, and the lifecycle cost is \$36.56 billion for the baseline case. The project lifecycle costs are \$36.48 billion for scenario 1, \$37.34 billion for scenario 2, and \$38.43 billion for scenario 3, assuming a discount rate (DR) of zero. At a 15% discount rate, the project lifecycle costs are \$22.24 billion for the baseline case and \$22.22 billion for scenario 1. At the same discount rate, the project lifecycle costs are \$23.05 billion for scenario 2 and \$24.11 billion for scenario 3. Availability has a significant impact on the lifecycle cost. This is confirmed from the baseline case and scenario 1 with the same number of operational turbo-compressor units but different availability. Both have the same capital cost of \$18.23 billion but different maintenance costs due to their different availability values, as reflected in their lifecycle cost estimate.

Consequently, an increase in availability leads to a corresponding increase in the lifecycle cost estimate. Arising from the increase in capital cost due to additional installed standby units and increased maintenance cost due to increased availability. The increase in compressor station availability is more reflected in the

high capital cost, a major component of the lifecycle cost due to the additional standby units.

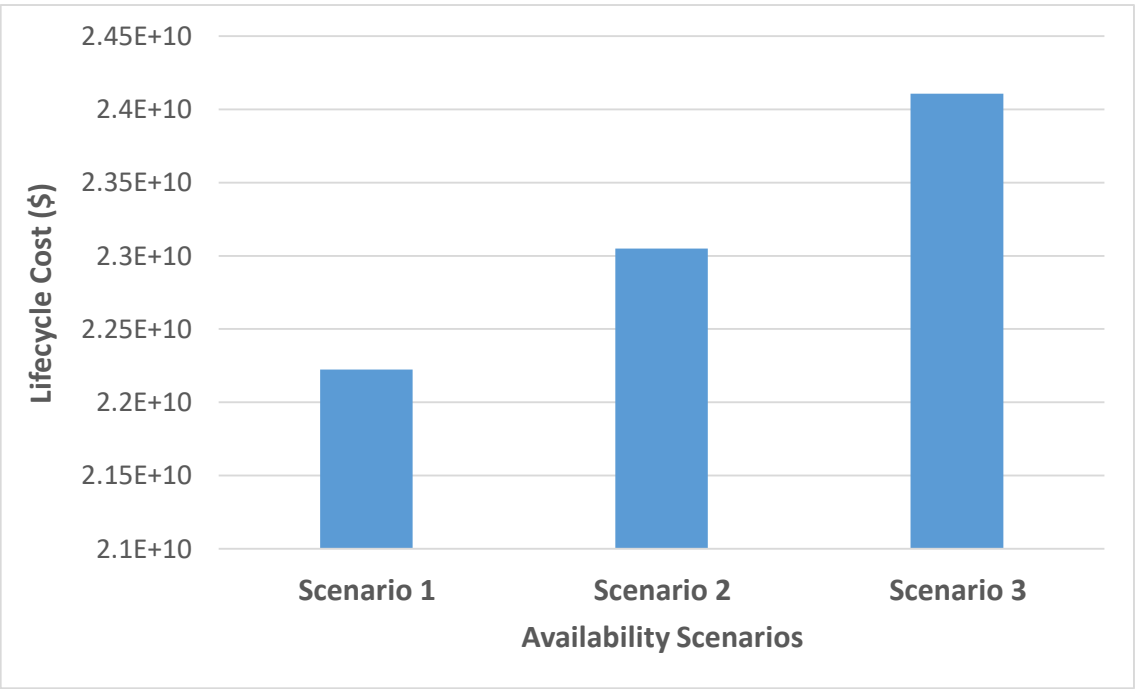


Figure 6-21 Impact of availability on lifecycle cost

6.13.6 The Impact of Turbo-Compressor Availability on Net Revenue

The unavailability of compressor station components can lead to a significant loss in revenue. Figure 6-22 shows the impact of availability on net revenue generated from the project for the three availability scenarios. The net revenue generated from the project is \$35.51 billion for scenario 1, \$36.63 billion for scenario 2, and \$37.76 billion for scenario 3. Scenario 3, with the highest availability value, has the highest amount of revenue generated from the project. The increase in compressor station availability leads to a corresponding increase in the income or revenue generated from the project. When the units are available, the compressor station operates continuously to meet its required throughput and supply of natural gas to end-users.

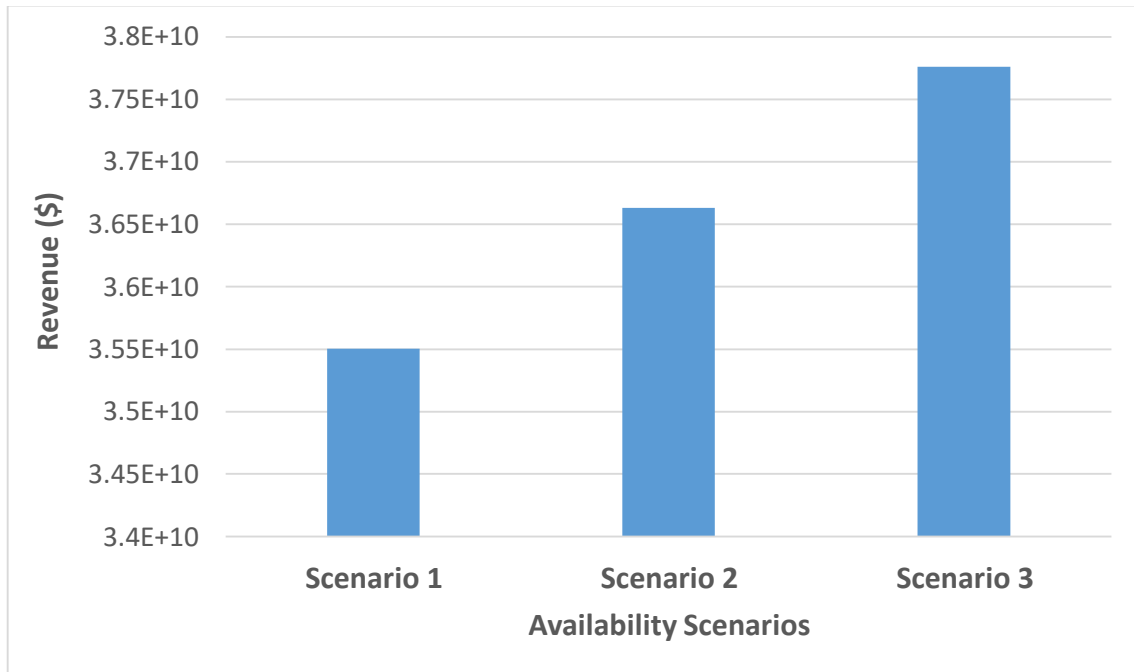


Figure 6-22 Impact of availability on net revenue

In contrast, the impact of the compressor station components and subsystem unavailability may be the reduction of the engine power or the expected volume flow rate through the pipeline systems. In some cases, total shutdown of the compressor stations. This unavailability usually arises from scheduled or unscheduled maintenance downtime, thus leading to the loss of revenue.

6.13.7 Sensitivity Analysis on Net Present Value

The discounted cash flow method using the net present value approach enhances better comprehension of the relationship between the revenues accrued from the project and the cash outflows. Including selecting the best alternatives among the considered scenarios. The results obtained for the net present value analysis show that at a 15% discount rate, the baseline case with an assumed 100% availability value has net present value of \$29.30 billion. At the same discount rate, the net present values are \$13.28 billion for scenario 1, \$13.58 billion for scenario 2, and \$13.65 billion for scenario 3. All project alternatives have positive net present value. At a 15% discount rate, scenario 3, consisting of one standby turbo-compressor unit at all compressor station

locations, should be selected. Since it is the project with the highest net present value among the considered scenarios.

Sensitivity analyses are carried out to determine the effect of the discount rate on the net present value. Figure 6-23 shows the variation of the net present value with discount rates for availability scenarios.

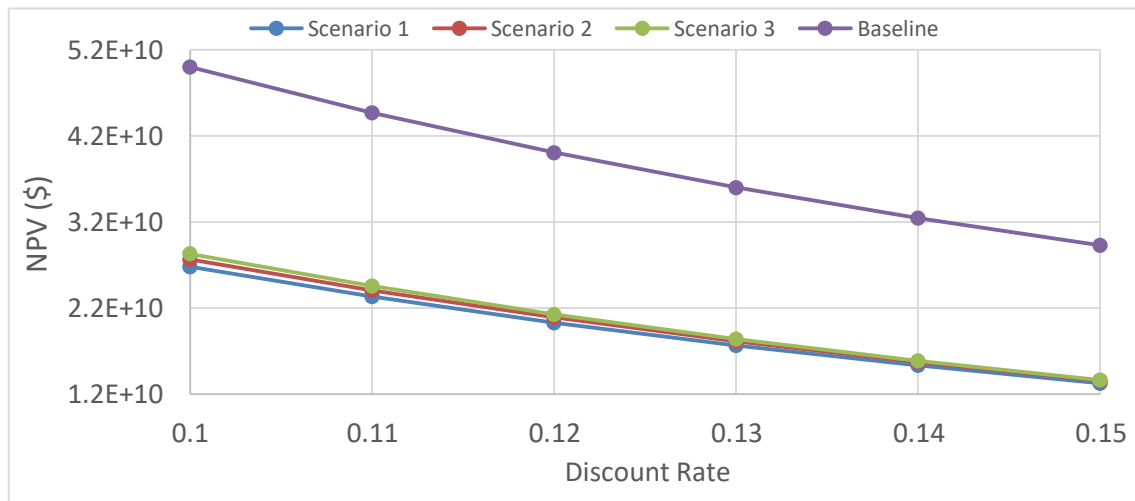


Figure 6-23 Variation of NPV with discount rates for availability scenarios

Sensitivity analysis shows an increase in net present value with a decreasing discount rate for all scenarios. Scenario 3 has the highest net present value at all discount rates. Results show that the most economically viable alternative is scenario 3, consisting of a standby turbo-compressor unit at all compressor station locations along the pipeline route. Consequently, scenario 3 is expected to produce the lowest risk associated with an investment in the proposed Trans-Saharan gas pipeline project. The results further show that assuming 100% availability value as seen in the baseline case is not realistic. As it is nearly impossible to achieve perfect operating conditions throughout the project life. The results obtained have shown the importance of incorporating an availability analysis into the pipeline TERA.

6.14 Discussion

This study looks at the impact of turbo-compressor availability on the techno-economics of natural gas pipeline transportation. Results show the importance of

increased unit, subsystem, and system availability in minimising engine downtime. This will ensure a continuous supply of natural gas through the transmission pipelines to end-users. Improvement in the unit's availability could be achieved by increasing the time to failure and decreasing downtime due to scheduled or unscheduled maintenance. The author could not find any public studies that have adapted TERA by applying a typical original equipment manufacturer maintenance schedule to determine the impact of turbo-compressor availability on the whole compressor station and pipeline system investments. Results show the sensitivity of compressor station subsystems and system availability to the variation in standby units at compressor station locations. Increasing the number of standby units at compressor station locations greatly impacts the availability of the whole compressor station system. The effect is a corresponding increase in the overall system availability. Results for the scenario-based study are dependent on the unit's and subsystem availability, the number of standby units, compressor station arrangement, and configurations.

Results show that availability has an important impact on the techno-economics of the proposed Trans-Saharan Gas Pipeline project. Availability has a direct impact on the project's capital cost. This is in terms of the additional first cost incurred from the installed standby units. In contrast, there is no additional cost related to the standby unit's fuel consumption. Thus, availability has no direct impact on the fuel cost. However, the operational cost of the project is impacted by the increase in maintenance cost with increase in compressor station system availability due to the installation of standby units. Availability has a significant impact on the lifecycle cost. An increase in availability leads to a corresponding increase in the lifecycle cost estimate. This arises from the increase in capital cost due to additional installed standby units and an increase in the maintenance cost due to the increased availability. These findings are a major contribution to knowledge in this study. These findings are important because the unavailability of compressor station components can lead to significant loss in revenue. More so, the findings showed that the increase in the compressor station system lifecycle cost due to an increase in availability is acceptable than its unavailability. A small percentage reduction in the unit, subsystem or system availability might

lead to a partial or total shutdown of the compressor stations and pipeline systems. Thus, affecting natural gas transportation and consequently, loss of income or revenue from the project. The net present value analysis has shown the economic viability of an increased availability to the project. The higher the availability, the higher the net present value. Scenario 3 was the most economically viable alternative among the considered scenarios due to its highest availability and net present value. These findings represent an additional contribution to knowledge in this study.

The results further show the unrealistic nature of the baseline case with 100% availability assumption because perpetual operating conditions, even throughout the project life is impossible. The results have demonstrated the significance of incorporating an availability analysis integrated with projects techno-economics into the pipeline TERA.

6.15 Summary

The objective of this study was to analyse the concept and implication of availability on gas turbine operation and economics.

This study has evaluated the gas compressor, gas turbine, and turbo-compressor unit availability based on a developed maintenance schedule by the present author and failure rate retrieved from literature studies. The author could not find any public studies that have adapted TERA by applying a typical original equipment manufacturer maintenance schedule to determine the impact of turbo-compressor availability on the whole compressor station and pipeline system investments. The analysis considered the impact of compressor station subsystem configuration on the whole compressor station system availability. A scenarios-based approach was performed to show the sensitivities of the compressor station systems to availabilities in terms of the number of installed standby units. The economic assessment of the project was done using a discounted cash flow method based on the lifecycle cost and net present value. The techno-economic model was developed using SIMULINK block diagrams and a developed code in MATLAB environment. This is based on the variation in compressor station location ambient temperatures at varying flow conditions. The

gas compressor powers were considered at isothermal, intermediate and non-isothermal flow conditions. Their corresponding gas turbine shaft power, fuel flow, and turbine entry temperatures required to drive the gas compressor, which is expected to have a major impact on the projects fuel consumption and engine availability-based maintenance costs, were also considered in the analysis. Sensitivity analyses were carried out to determine the effect of the discount rate on the net present value.

The evaluated unit availability is in good agreement with literature reports and is within the recommended original equipment manufacturer operational requirement. Results show that increasing the compressor station availability demonstrated through scenarios-based study has a great impact on the compressor station system availability and the techno-economics of the proposed Trans-Saharan gas pipeline project. These findings represent one of the major contributions to knowledge in this study. Therefore, the availability analysis of compressor station components, subsystems, and systems could be beneficial in the techno-economic assessment of the compressor stations and pipeline systems. This is because the profitability of the project is greatly dependent on turbo-compressor availability. Considering the installation of standby turbo-compressor units at some or all compressor station locations could enhance the system availability. This could mitigate potential risk or uncertainties associated with the proposed Trans-Saharan gas pipeline and any gas pipeline projects. The methods utilised in this study could identify the subsystems availability, which has a greater impact on the overall compressor station system availability.

The accuracy of the results obtained is dependent on the relevant assumptions made based on literature studies. The adopted methodology will provide the decision-maker with better insight into the expected risks and uncertainties associated with investment into the proposed Trans-Saharan gas pipeline and any gas pipeline projects. It will guide the selection of appropriate strategies needed to mitigate them. The results obtained could help in forecasting the lifecycle cost and expected performance of the compressor station systems. It could also help in predicting the economic and social impacts that could assist

policymakers in decision-making and on the feasibility of the proposed Trans-Saharan gas pipeline project. The proposed approach utilised in this study will help decision-makers better understand the importance of the individual gas turbine and gas compressor components and subsystems on the overall availability of the compressor station systems. Thus, leading to effective resource and financial management.

7 SOCIAL BENEFITS ANALYSIS AND THE INTEGRATED TECHNO SOCIO-ECONOMIC SCENARIOS

7.1 Introduction

In addition to tackling the techno-economic aspect, the construction, installation, and operation of gas turbine compressor stations at identified locations along the natural gas pipeline route is expected to improve the socio-economic benefits on the local communities. These socio-economic benefits are in terms of employment and road benefits. Previous studies have failed to quantify and incorporate the local community's social and socio-economic values into compressor stations and pipeline projects at the design and development phase. Social value is the measurement of the comparative significance that the community places on the changes they experience because of siting the compressor station and pipeline project near their location. It is equivalent to the social impact obtained from the construction, installation, and operation of the compressor station and pipeline project. Social value is about creating more positive social impact and less negative social impact. Thus, investment in the compressor stations and pipeline project must be socially and socio-economically valuable in the sense that it can improve the standard of living of the local communities where they are sited.

Although, the conventional way of measuring social impacts of energy technologies on the local communities have been through field research. However, they present many challenges, delay, and costly to the researchers. Thus, it is imperative to develop a theoretical framework that can effectively quantify the direct social impacts and benefits of compressor stations and pipeline projects on the local communities where they are sited. To the best of the present author's knowledge, no study exists by adapting TERA the social impacts and benefits on the local communities within the social influence areas of gas turbine compressor stations along the natural gas pipeline route as a function of location and power required. The objective of this study is to predictively quantify the direct social impacts and social benefits in terms of the predicted jobs creation and road infrastructure impacts on the local communities. This arises from the construction,

installation, and operation of gas turbine compressor stations at identified locations along the pipeline route. New jobs creation will increase the local communities' earnings, social well-being, job benefits, and improve their engagement in the project. New road creation will make the local communities safer, accessible, and grow faster. Additional objective is to evaluate the socioeconomic costs and benefits. This arises from the social impacts and social benefits of gas turbine compressor stations on the local communities based on developed techno socio-economic scenarios. This represents a significant novelty of this research work since this is the first time the social impact and social benefits using the TERA approach are examined for gas turbine compressor stations for pipeline applications.

7.2 Methodological Approach

This study utilises an analytical method based on a bottom-up approach using a developed code in a MATLAB environment incorporated with social benefit algorithms. In a bottom-up approach, each subsystem of a system is connected to produce a complete system which is bigger and more complex than the subsystem. The social impacts and benefits at each gas turbine compressor station location are quantified based on relevant assumptions, employment index, compressor station location characteristics, population area characteristics, and the total installed capacities of the gas turbines dependent on the gas compressor power requirements at each compressor station location. The social impacts and benefits considered in this study are positive aspects expected to improve the quality of life of the local communities. The direct social impacts and benefits of gas turbine compressor station's locations are quantified under the following criteria:

- ❖ Predicted jobs creation
- ❖ Road infrastructure

Other social benefits could be considered such as water infrastructure and provision of electricity. But because this is a start, only two are included in this study to describe the social impacts and benefits created by the proposed Trans-

Saharan gas pipeline project. They can also be applied to any pipeline project. Figure 7-1 shows the social module flowchart employed in this research work.

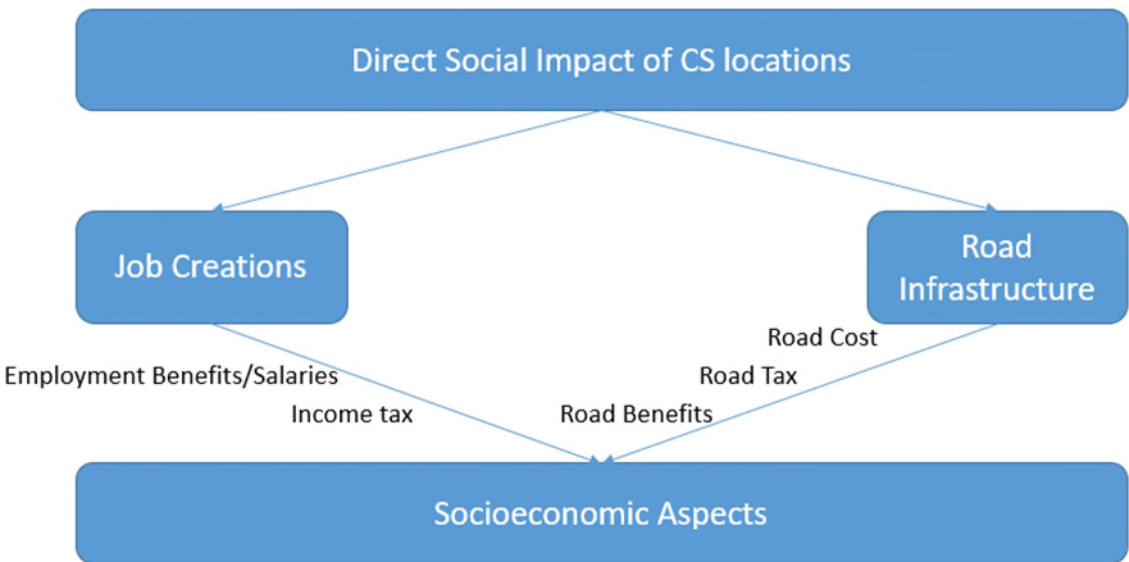


Figure 7-1 Social Module Flowchart

The socio-economic aspect quantifies in a first uncertain step the direct positive social impacts on the quality of life of the local communities in monetary units. The predicted jobs creation is quantified by the number of local jobs created and the equivalent employment cost and benefits in monetary units of employees' salaries and income taxes generated. Road infrastructures are quantified in terms of road benefits, road construction costs, and road tax. Figure 7-2 shows the complete socio-economic model utilised in this study.

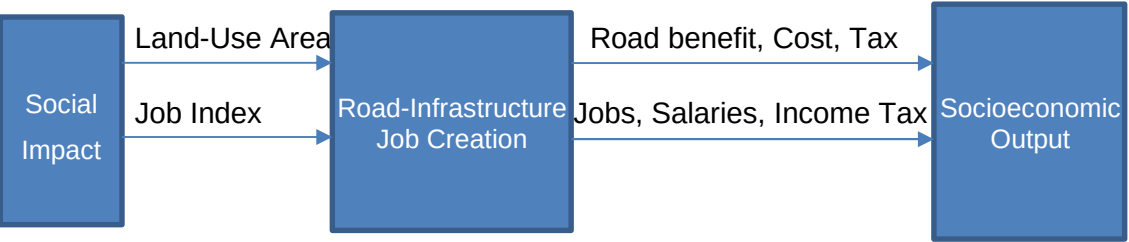


Figure 7-2 The Socio-economic Model

The input to the socio-economic model represents each of the social impact criteria evaluated in this research. The gas turbine compressor stations and pipeline systems land-use areas incorporating the social influence areas are inputs to road infrastructure impacts. The job index obtained from literature

studies are inputs to predicted jobs creation. The outputs from the socio-economic model are the socio-economic costs and benefits derived from each social impact and benefits analysis. The socio-economic output from the predicted jobs creation is the employment benefits in terms of employees' salaries and income taxes. The socio-economic outputs from the road infrastructure impacts are road benefits, road construction costs, and road tax.

7.3 Social Impacts and Benefits Analysis

The base map of the compressor station locations social influence areas along the pipeline route is constructed to evaluate the social impacts and benefits. The crux of this part of the research from a social benefit perspective is as follows. How will the local communities with different social profiles, population characteristics, and location characteristics within the social influence areas along the pipeline route benefit from the construction, installation, and operation of the gas turbine compressor stations? How are these compressor station activities perceived considering the resulting social benefits in terms of new jobs and new roads? The following were identified within this map areas:

- ❖ Population areas and location characteristics and classified as rural, suburban, or urban
- ❖ Level of wealth and classified as low-, middle-, or high-income group
- ❖ The location and layout of potential routes for road infrastructure land-use impact areas. Land use impact areas are land areas directly impacted for new road infrastructure creation due to the construction, installation, and operation of gas turbine compressor stations
- ❖ Areas not to be touched for environmental or cultural reasons

The constructed maps serve as templates for showing the link between the compressor station locations and identified social benefits. They are used in subsequent analyses of the predicted jobs creation and road infrastructure impacts at each gas turbine compressor station location along the pipeline route.

7.3.1 General Social Benefits and Socio-economic Assumptions

1. Social benefit width is assumed to be 100 km to each side of each gas turbine compressor station along the pipeline route. In this study, social benefit width is the extent of the social influence areas from each side of the compressor station and pipeline system. It shows how wide the social influence area is from each side of the compressor station and pipeline system.
2. Population densities are classified into three types: rural, suburban, or urban
3. The level of wealth is classified as low-, middle-, or high-income group
4. Different salaries apply to each income group
5. Direct positive social impacts on the local communities are considered in this study. The indirect social impact such as indirect employment and negative social impacts such as accident fatalities, the potential death of employees, and displacement of local communities from the compressor stations are not considered
6. Project life of 30 years
7. Construction and installation duration is 3 years
8. Operation and maintenance occur over the project lifecycle
9. I considered discrete pipeline segments, each 10 km long. Each pipeline segment has a social influence area about 100 km wide
10. Techno-economic aspect of gas turbine compressor station locations for natural gas transportation in pipelines has no direct impact on the quality of life of the local communities but depends on the decision-makers and pipeline investors choices

The population map depicted in Figure 3-3 shows the population densities observed at specific locations along the proposed Trans-Saharan gas pipeline route. Table 3-1 shows the corresponding wealth map information according to the income group utilised in this study.

7.3.2 Predicted Jobs Creation

It is a well-known fact that power plants provide job opportunities to people throughout their lifecycle, and the locality where these power plants are installed have based their prosperity and development on them [98]. The construction, installation, and operation of gas compressors and gas turbine power plants at each compressor station location along the natural gas pipeline route is expected to improve the social benefits on the local communities. This is in form of new jobs creation that will lead to enhanced quality of life of the community. The direct social impact of gas turbine compressor stations in terms of employment is quantified by the number of local and foreign jobs created. Employment created in the construction and installation phase of the project is temporary jobs measured in jobs-years. In this situation, the employment index is spread over the construction and installation duration of the project to obtain an average annual job number that can be directly added to the operation and maintenance jobs. Employment created in operation and maintenance phase is permanent jobs measured in jobs. The permanent jobs are average over the project lifecycle to obtain annual operation and maintenance jobs. The total employment associated with each gas turbine compressor station location is estimated using a common metric of annual jobs created per 10000 population in the construction and installation stage and the operation and maintenance stage. This is summed together over the project lifecycle. The following shows the sources and assumptions for the job index utilised in this study:

- ❖ The employment index is 0.25 jobs/MW for the construction and installation stage, and 0.70 jobs/MW for the operation and maintenance stage
- ❖ The employment index for the construction and installation stage was taken from a combination of three sources: Kammen et al. [159], Fankhaeser et al. [123], and Mu et al. [160]
- ❖ Employment index for the operation and maintenance stage were taken from combination of four sources: Kammen et al. [159], Mu et al. [160], Cai et al. [126], and Wang et al. [161]

- ❖ Direct jobs creation from gas turbine compressor station locations are considered, indirect and induced employment impacts are not considered. Direct jobs are jobs directly created from the construction, installation, and operation of the compressor station. Indirect employment is employment not directly related to the operation of the compressor station. They are jobs generated by other businesses located around the compressor station. Those in the indirect jobs support the operation of the compressor station and pipeline project by selling goods and services to those in the direct jobs. Induced employment is employment that depends on the purchases made by the employees in direct and indirect employments. An example of induced employment is employees in either direct or indirect employment spending part of their salaries at any business centre in their communities. This business centre is not related to the operation of the compressor station and pipeline project. However, the salaries are re-distributed into the economy and aid in sustaining other jobs produced from the business centres.
- ❖ Local jobs are assumed to reside to each side within the social benefit influence areas of the gas turbine compressor station locations along the pipeline route.
- ❖ I considered scenarios in which the predicted local jobs created consisted of assumed percentages of potential total jobs evaluated at each gas turbine compressor station location along the pipeline route. The potential total jobs are made up of local jobs and foreign jobs.

The following five local jobs scenarios were evaluated at each compressor station location:

1. Local jobs equivalent to 20% of the potential total jobs at the first year of project
2. Local jobs equivalent to 40% of the potential total jobs at the second year of project
3. Local jobs equivalent to 60% of the potential total jobs at the third year of project

4. Local jobs equivalent to 80% of the potential total jobs at the fourth year of project
5. Local jobs equivalent to 100% of the potential total jobs from the fifth year of project up to the project lifecycle

The predicted jobs creation is quantified based on the employment index of natural gas-fired power plants, compressor station location characteristics, population area characteristics of compressor station locations along the pipeline route and the installed capacity of each gas turbine compressor station location dependent on the gas compressor power requirement. The predicted local jobs creation J_{local} , is a function of the compressor station location characteristics L_s . Mathematically, this is expressed as follows:

$$J_{local} = f(L_s) \quad (7-1)$$

The population area characteristics determine the magnitude and type according to income level the predicted local jobs created at each gas turbine compressor station location. The gas compressor and gas turbine performance characteristics are evaluated following the methodology and procedures outlined in chapters 4 and 5 of this research work.

For a given gas compressor discharge pressure P_1 , flow rate Q , gas gravity G , gas compressibility Z , pipeline constant diameter D , and pipeline distance, L . The gas compressor suction pressure, P_2 , a function of the pipeline distance L , equivalent to the distance between compressor stations. Thus, a function of compressor station locations is evaluated using Weymouth gas flow equation given by:

$$P_2 = \sqrt{\frac{1}{e^s} \left[P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 G T_f L_e Z}{(0.0037435)^2 E^2 (D^{2.667})^2} \right]} \quad (7-2)$$

Where:

E = Pipeline efficiency, %

s = Elevation adjustment parameter

T_f = Gas flow temperature, K

P_b = Base pressure, kPa

T_b = Base temperature, kPa

L_e = Pipeline equivalent length, km

P₂ = Gas compressor suction pressure

P₁ = Gas compressor discharge pressure

The polytropic head developed by the gas compressor is given by:

$$H_p = Z_a R T_f \frac{n}{n-1} \left[\left(\frac{P_2}{P_1} \right)^{\frac{n-1}{n}} - 1 \right] \quad (7-3)$$

Where:

H_p = Polytropic head, KJ/kg

Z_a = Average compressibility factor

R = Gas constant, KJ kg⁻¹ K⁻¹

T_f = Gas flow temperature, K

n = polytropic exponent

P₂ = Gas compressor suction pressure

P₁ = Gas compressor discharge pressure

The gas compressor power requirements at each compressor station location are evaluated using the following equation:

$$P_G = \frac{m H_p}{3600 \eta_p} \quad (7-4)$$

Where:

P_G = Gas compressor power requirement, kW

m = mass flow rate, kg/s

H_p = Polytropic head, KJ/kg

η_p = Polytropic efficiency

Substituting for P_2 in Equation (7-3) and H_p in Equation (7-4), the gas compressor power requirement can be written as:

$$P_G = \frac{mZ_aRT_f \frac{n}{n-1}}{3600\eta_p} \left[\left(\frac{\sqrt{\frac{1}{e^s} \left[P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 T_f^2 Z^2 (e^s - 1) L}{(9.5854e - 7) E^2 D^{5.334} (H_2 - H_1)} \right]}}{P_1}} \right)^{\frac{-(n-1)}{n}} - 1 \right] \quad (7-5)$$

Where:

P_G = Gas compressor power requirement, kW

m = mass flow rate, kg/s

η_p = Polytropic efficiency

Z_a = Average compressibility factor

R = Gas constant, KJ kg⁻¹ K⁻¹

T_f = Gas flow temperature, K

n = polytropic exponent

P_1 = Gas compressor discharge pressure

Q = Volumetric flow rate, (m³/day)

T_b = Base temperature, K

P_b = Base Pressure, kPa

L = Pipe length, km

Z = Compressibility factor, dimensionless

D = Pipeline diameter, mm

$e = 2.71828$ (Euler's number)

s = Elevation adjustment parameter

H_1 = Upstream elevation, m

H_2 = Downstream elevation, m

The gas turbine installed capacities were evaluated by considering a minimum power margin M , between the gas turbine power and the gas compressor power requirement at each compressor station location. American Petroleum Institute standard 616 [162] recommended a minimum power margin of 10%. The gas turbine installed capacity P_T , measured in megawatt based on gas compressor power requirement is evaluated as follows:

$$P_T = \frac{(M + P_G)}{1000} \quad (7-6)$$

Where:

P_G = Gas compressor power requirement, kW

P_T = Gas turbine installed capacity, MW

M = Power margin between gas compressor and gas turbine powers

The gas compressor power requirement is a function of the compressor station location. Thus, the gas turbine installed capacities are functions of the gas compressors' power requirement and the compressor station locations.

The common method used in the literature to estimate direct jobs created by energy technologies is to determine the ratios of direct jobs created per installed capacity. In this approach, the direct jobs created is a function of the employment

index and the installed capacity. References [99]; [100]; [126]; [161] utilise this method. The present study derives the direct jobs created based on this approach and in terms of the compressor station location. Consequently, the predicted local jobs creations are a function of the compressor station location. Notably, the predicted jobs were evaluated based on the maximum compressor station location ambient temperature at all seasons of the year.

The social influence area at each compressor station location is a function of the compressor station location. It is evaluated as follows:

$$A_s = w_s * L \quad (7-7)$$

Where:

A_s = Social influence area at each compressor station location, km²

w_s = social benefit width, km

L = Pipe distance, km

The total population estimated at each social influence area of each compressor station location is given by:

$$P_s = A_s * D_s \quad (7-8)$$

Where:

A_s = Social influence area at each compressor station location, km²

D_s = Population density, (Person/km²) (from map)

P_s = Social influence area population, Persons

By substituting equation (7-7) into equation (7-8) the social influence area population can be written as:

$$P_s = w_s * L * D_s \quad (7-9)$$

The annual local and foreign jobs created per 10000 head populations in the construction and installation stage J_c , at each compressor station location is

evaluated based on references [99]; [100]; [126]; [161] and in terms of compressor station location. By utilising equations (7-7) and (7-8), the annual jobs created per 10000 head populations in the construction and installation stage J_c , at each compressor station location is evaluated as follows:

$$J_c = \frac{10000 * E_C * P_T}{T_C * w_s * L * D_s} \quad (7-10)$$

Where:

E_C = Employment index for construction and installation stage, (jobs-years/MW)

T_C = Construction and installation duration, (years)

w_s = Social benefit width, (km)

D_s = Population density, (Person/km²) (from map)

L = Pipe length, km

P_T = Gas turbine installed capacity, MW

Substituting for P_G from Equation (7-5) and P_T from Equation (7-6) into Equation (7-10) the annual jobs created per 10000 head populations in the construction and installation stage are expressed as follows:

$$J_c = \frac{E_C \left[M + \frac{mZ_a R T_1 \frac{n}{n-1} \left[\left(\frac{\frac{1}{e^s} P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 T_f^2 Z^2 (e^s - 1) L}{(9.5854e - 7) E^2 D^{5.334} (H_2 - H_1)}}{P_1} \right)^{\frac{-(n-1)}{n}} - 1 \right]}{3600 \eta_p} \right]}{0.1 T_C w_s L D_s} \quad (7-11)$$

Similarly, the annual local and foreign jobs created per 10000 head populations in the operation and maintenance stage J_M , at each compressor station location is evaluated based on references [99]; [100]; [126]; [161] and in terms of compressor station location. By utilising equations (7-7) and (7-8), the annual jobs created per 10000 head populations in the operation and maintenance stage J_M , at each compressor station location is evaluated as follows:

$$J_M = \frac{10000 * E_M * P_T}{w_s * L * D_s} \quad (7-12)$$

Where:

E_M = Employment index for operation and maintenance stage, (jobs/MW)

w_s = Social benefit width, (km)

D_s = Population density, (Person/km²) (from map)

L = Pipe length, km

P_T = Gas turbine installed capacity, MW

Substituting for P_G from Equation (7-5) and P_T from Equation (7-6) into Equation (7-12) the annual jobs created per 10000 head populations in the operation and maintenance stage J_M , at each compressor station location is expressed as follows:

$$J_M = \frac{E_M}{M + \frac{mZ_aRT_1}{n-1} \left[\left(\frac{\frac{1}{e^s} P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 T_f^2 Z^2 (e^s - 1) L}{(9.5854e - 7) E^2 D^{5.334} (H_2 - H_1)}}{P_1} \right)^{\frac{-(n-1)}{n}} - 1 \right]} \cdot \frac{3600\eta_p}{0.1w_sLD_s} \quad (7-13)$$

Where:

E_M = Employment index for operation and maintenance stage, (jobs/MW)

w_s = Social benefit width, (km)

M = Power margin between gas compressor and gas turbine powers

D_s = Population density, (Person/km²) (from map)

Other terms in the above equations have their usual meaning. The total annual jobs created J_t , is the sum of the annual jobs created in the construction and installation stage J_C , and the operation and maintenance stage J_M , respectively, and is given by:

$$J_t = J_C + J_M \quad (7-14)$$

The total jobs created at a particular compressor station location over the project lifecycle J_l , can be written as:

$$J_l = \sum_{i=1}^{n=30} J_t \quad (7-15)$$

The total jobs created by the whole compressor station and pipeline system over the project lifecycle J_s , is the algebraic sum of the lifecycle jobs created at each compressor station location and is given by:

$$J_s = \sum_{k=1}^N J_l \quad (7-16)$$

Where:

$$k = 1, 2, 3 \dots N$$

$$N = 18 \text{ (baseline case)}$$

7.3.3 Employment Benefits

7.3.3.1 Assumptions

1. Annual salaries per local job created are classified according to the level of wealth and are different for each income group.
2. Salaries are assumed to be the same for all stages over the project lifecycle. These stages comprise the construction and installation stage, and the operation and maintenance stage.
3. Annual average salary data are taken from the 2019 National Occupational Employment and Wage Estimates, United States Bureau of Labour Statistics [163] for installation, maintenance and repair occupations and assumed as the annual salaries per foreign job created according to income groups.
4. The annual gross salary according to income groups is evaluated for Nigeria in naira and converted to dollars based on the exchange rate for the reference year. The 2020 calendar year value for the low-income rural Nigeria is reported as NGN 1,664,136 equivalent to \$ 4,380 [164]. The middle-income average annual salary is reported as NGN 4,068,000, equivalent to \$9,804. The high-income average annual salary is reported as NGN 18,120,000 equivalent to \$43,704 [165]. These are assumed to be the annual salaries per local job created according to income groups.

5. The social discount rate is 5% [166]. The social discount rate has been used to calculate the present value of a project's future social costs and benefits. Following suggestions in the literature, this study uses a social discount rate to discount future social costs and benefits. Warusawitharana [166] suggested an average social discount rate of 5% for developing countries after adjusting for inflation. Based on this suggestion, this study utilises an assumed social discount rate of 5% in discounting future benefits to the reference time at year zero.

Table 7-1 shows the annual salary data per foreign job created according to income groups.

Table 7-1 Annual salary data per foreign job according to income groups [163]

S/N	Income Group	Annual Salary
1.	Low	\$28,190
2.	Middle	\$48,750
3.	High	\$64,490

The employment benefit S_N , is a function of the predicted jobs created and the income level S , of the identified social benefit population areas. Mathematically, this is expressed as follows:

$$S_N = f(J_C, J_M, S) \quad (7-17)$$

The future annual salaries are discounted to the reference year zero at the beginning of the project. The employment benefits at a particular compressor station location estimated over the project lifecycle are given by:

$$S_N = \sum_{i=1}^{n=30} \frac{J_t P_s S}{(1 + r_s)^i} \quad (7-18)$$

Where:

S_N = Employment benefit (\$)

J_t = Annual jobs created per 10000 head population, (job/person)

P_s = Total population at the social influence area of each compressor station location, (persons)

S = Annual salary per local job created according to income level ($\$/_{job}$)

r_s = Social discount rate

$i = 1, 2, 3 \dots 30$

The employment benefits received from the whole compressor station and pipeline system is given by:

$$S_t = \sum_{j=1}^n S_N \quad (7-19)$$

Where:

S_t = Total employment benefits received from the project

$j = 1, 2, 3 \dots n$

$n = 18$ (Baseline case)

7.3.4 Jobs Creation: Non-Dimensional Social Uplift

In this section, a new variable of social uplift in monetary terms called the employment benefit ratio is proposed. According to the assumptions made in this study; discrete pipeline segments each 10 km long and has a social influence area about 100 km wide is considered. The population value and level of wealth for each 10 km pipeline segment are identified based on the population density and income groups for the gas turbine compressor station locations for the baseline case. They are shown in Figure 3-3 and Table 3-1, respectively.

An existing level of wealth S_E , is defined as the product of the population and the average salary according to income groups for each pipeline segment with

respect to the wealth map obtained along the pipeline route as depicted in Table 3-1 and is given by:

$$S_E = P_S S \quad (7-20)$$

The cumulative value of new salaries, otherwise known as employment benefit S_N , is defined as the algebraic sum of the salaries associated with the predicted jobs created at the gas turbine compressor station if the station is in that pipeline segment. A new variable of social uplift from jobs created within the social influence areas at each compressor station location along the pipeline route is proposed. This is called the employment benefit ratio or non-dimensional social uplift from jobs creation EBR , and is given by:

$$EBR = \frac{S_N}{S_E} \quad (7-21)$$

Where:

EBR = Employment Benefit Ratio, (dimensionless)

S_N = Cumulative value of new salaries (employment benefit), (\$)

S_E = Cumulative value of existing salaries (existing level of wealth), (\$)

Appendix R shows employment benefit test case.

7.3.5 Land Use - Road Infrastructure Creation

The objective of this section is to quantify the direct land-use impact areas requirement on the local community associated with road infrastructure creation. Also, is to determine the benefits of new roads within the social influence areas at each gas turbine compressor station location along the pipeline route. To the best of the present author's knowledge, this is the first-time direct lifecycle land-use impact areas are examined for gas turbine compressor stations for pipeline

applications. The following assumptions are considered in the estimation of the land-use impacts:

- ❖ Pipeline distance equivalent to transmission pipeline land length
- ❖ Transmission pipeline right-of-way land width is 23m [39]
- ❖ Project lifecycle of 30 years
- ❖ Land-use quality is not considered in this study
- ❖ Direct land-use impact in the installation and operation stage over the project lifecycle is considered in this study

Table 7-2 shows the percentage distribution of the compressor stations impact areas based on data from the Trans-Saharan gas pipeline report, other projects, and informed engineering judgement.

Table 7-2 Distribution of Compressor Station Impact Areas

S/N	Impact Areas	Percentage Share of Areas
1.	Gas Turbine Power Plant Area	2%
2.	Gas Compressor Area	2%
3.	Roads Infrastructure	29%
4.	Transmission Pipeline Area	60%
5.	Other	7%

The land-use impact estimates the direct land impact area requirements from the installation and operation of gas turbine compressor stations for natural gas transportation in pipelines. The compressor station land areas, transmission pipeline land areas, road infrastructure, and other land areas made up the gas turbine compressor stations and pipeline system total equivalent land-use areas. In this study, 'Other' land areas are defined to include pipeline auxiliaries, staging areas, and construction-related areas. The transmission pipeline land-use area is estimated using the following equation:

$$A_p = W_p L \quad (7-22)$$

Where:

A_p = Transmission pipeline land-use area, (km²)

W_p = Transmission pipeline land-use width, (km)

L = Transmission pipeline land-use length, (km)

Equation (7-22) is normalised based on the transmission pipeline percentage share of area SA_p , and the total land-use equivalent area SA_t . The transmission pipeline percentage share of area SA_p , obtained from Table 7-2 is equal to 60%. The percentage share of the total land-use equivalent area SA_t is the sum of the percentage shares of compressor station land areas, transmission pipeline land areas, road infrastructure, and other land areas obtained from Table 7-2. It is equal to 100%. Thus, the normalised total land-use area is given by:

$$A_t = \left(\frac{SA_t}{SA_p} \right) A_p \quad (7-23)$$

Where:

A_t = Total compressor station and pipeline system land-use equivalent area (km²)

SA_t = Percentage share of the total land-use equivalent area, (%)

SA_p = The transmission pipeline percentage share of area, (%)

A_p = Transmission pipeline land-use area, (km²)

The gas turbine power plant and gas compressor land-use areas, A_T and A_G , are estimated based on their percentage share of areas SA_T and SA_G respectively, and are given by the following equations:

$$A_T = SA_T A_t \quad (7-24)$$

$$A_G = SA_G A_t \quad (7-25)$$

The compressor station land-use area A_C , is the algebraic sum of the gas turbine and gas compressor land-use areas and is given by:

$$A_C = A_T + A_G \quad (7-26)$$

The road infrastructure land-use area A_R , and other land-use area A_o , are estimated using the following equations:

$$A_R = SA_R A_t \quad (7-27)$$

$$A_o = SA_o A_t \quad (7-28)$$

Substituting for A_t , the road infrastructure land-use impact area can be written as:

$$A_R = \left(\frac{5}{3}\right) SA_R W_p L \quad (7-29)$$

Where, SA_R and SA_o are their percentage share of areas, respectively.

The road infrastructure creation is quantified based on the land-use and compressor station location characteristics, population area characteristics of compressor station locations along the pipeline route and the installed capacity of each gas turbine compressor station location dependent on the gas compressor power requirement. The road infrastructure creation is a function of the land-use characteristics A_R , compressor station location characteristics L_s , and gas turbine performance characteristics, P_T . Mathematically, this is expressed as follows:

$$LU_R = f(A_R, L_s, P_T) \quad (7-30)$$

Where, LU_R is the road infrastructure impact area, (km²/MW) per 10000 head population at the evaluated compressor station location.

The population area characteristics determine the magnitude and type according to income level the road infrastructure created at each gas turbine compressor station location. The gas compressor and gas turbine performance

characteristics are evaluated following the methodology and procedures outlined in chapters 4 and 5 of this research work.

For a given gas compressor discharge pressure P_1 , flow rate Q , gas gravity G , gas compressibility Z , pipeline constant diameter D , and pipeline distance, L . The gas compressor suction pressure, P_2 , a function of the pipeline distance L , equivalent to the distance between compressor stations and thus a function of compressor station locations is evaluated using Weymouth gas flow equation depicted by Equation (7-2). The polytropic head developed by the gas compressor is given by Equation (7-3).

The gas compressor power requirements at each compressor station location are evaluated using Equations (7-4) and (7-5). The gas turbine installed capacities were evaluated by considering a minimum power margin M , between the gas turbine power and the gas compressor power requirement at each compressor station location. American Petroleum Institute standard 616 [162] recommended a minimum power margin of 10%. The gas turbine installed capacity P_T , measured in megawatt based on gas compressor power requirement is evaluated using Equation (7-6).

The gas compressor power requirement is a function of compressor station location. Thus, the gas turbine installed capacities are functions of the gas compressors power requirement and the compressor station locations. Consequently, the road infrastructure creations are function of the installed capacities and compressor station location. More so, it is pertinent to note that the road infrastructure creations were evaluated based on the maximum compressor station location ambient temperature at all seasons of the year. Concentrating on the areas of the compressor stations impacted, the land-use impact areas are evaluated using the following equation:

$$LU_{C_j} = \frac{10000A_{C_j}}{P_T w_s L D_s} \quad (7-31)$$

Where:

LU_C = Land-use impact area of compressor station and pipeline system component C, (km²/MW) per 10000 population

A_C = Land area of compressor station and pipeline system component C, (km²)

C = Pipeline, Road, Compressor Station, Other

j = 1, 2, 3, ... 18 (Baseline case)

w_s = Social benefit width, (km)

D_s = Population density (Person/km²) (from map)

P_T = Gas turbine installed capacity, MW

The road infrastructure impact created per 10000 head of populations at each compressor station location is evaluated from equation (7-31) using the following equation:

$$LU_R = \frac{10000A_R}{P_T w_s L D_s} \quad (7-32)$$

The road infrastructure impact created per 10000 head populations at each compressor station location is evaluated as a function of the compressor station location.

By substituting for A_R in equation (7-29) and P_T in equation (7-6) into equation (7-32) the road infrastructure impact created per 10000 populations at each compressor station location can be written as:

$$LU_R = \frac{A_R * 10^7}{mZ_a RT_1 \frac{n}{n-1} \left[\left(\frac{1}{e^s} \left[P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 T_f^2 Z^2 (e^s - 1) * L}{(9.5854e - 7) E^2 D^{5.334} (H_2 - H_1)} \right] \right)^{\frac{-(n-1)}{n}} - 1 \right]} + \frac{3600 \eta_p}{w_s L D_s} \quad (7-33)$$

Where, LU_R is the road infrastructure impact area, (km²/MW) per 10000 head population to one side of the social influence area at the evaluated compressor station location. Other terms in the above equations have their usual meaning.

7.3.6 Road Benefits

The social benefits of the presence of new roads due to the road infrastructure impacts within the social influence areas are numerous:

- ❖ Reduction in local communities' isolation from other communities, markets, and other social infrastructures
- ❖ Improvement in the quality of transportation and increased access to other social services
- ❖ Travel time reduction, cheaper cost of transportation, and travel time cost savings.

These benefits might lead to increase trade and jobs creation through the improved movement of goods, services, and people from the local communities to market, trade, and job centres. The following shows the social benefits assumptions for road infrastructure creation.

7.3.6.1 Social Benefit Assumption for Road Infrastructure

1. Road users are assumed to have two routes: existing route and new road infrastructure route, respectively.
2. The mode of transportation for the existing and new road infrastructure route is bus mode.
3. Both routes are assumed to have the same origin and destination, as depicted in Figure 7-3.
4. Average bus speeds for the new route are classified according to demographic areas and are shown in Table 7-3 [167].
5. The average bus speed for the existing route is 3 miles per hour.
6. The monetary value of travel time from new roads creation due to additional trade, new employment, and increased socio-economic activities are according to income groups and are assumed to reflect employee's wages and trader's income (see Table 7-4).
7. The road width is 11 m.
8. Travel area is equivalent to the road infrastructure area.
9. Non-wage labour cost including labour-related overheads is negligible.
10. Five road trips per job are made per week.
11. The social discount rate is 5%. The social discount rate has been used to calculate the present value of a project's future social costs and benefits. Following suggestions in the literature, this study uses a social discount rate to discount future social costs and benefits. Warusawitharana [166] suggested an average social discount rate of 5% for developing countries after adjusting for inflation. Based on this suggestion, this study utilises an assumed social discount rate of 5% in discounting future benefits to the reference time at year zero.

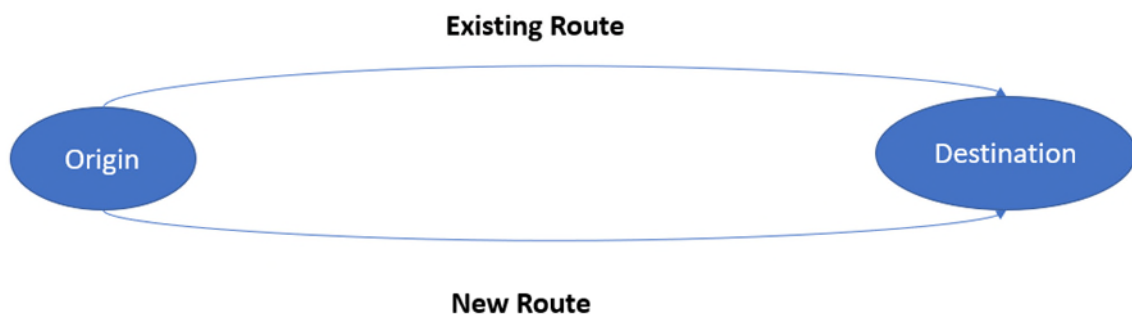


Figure 7-3 Assumed Existing and New Road Infrastructure Layout

Table 7-3 Average Bus Speed (source: [167])

S/N	Demographic Classification	Average speed (mph)
1.	Urban	10
2.	Suburban	14.3
3.	Rural	20

In this study, the evaluation of the social benefits of the presence of new roads in terms of the value of travel time savings (VTTS) was inspired by the work of Fayyaz et al. [111]. Their study aims to compare the route choice behaviour of general population respondents. Participants were urged to imagine travelling from home to work by car with two route alternatives: the motorway and urban road. The former alternative has a speed limit of 90 km/h, no traffic lights, and a travel time of 6 minutes. The latter alternative has a speed limit of 50 km/h, four traffic lights, and a longer travel time of 12 minutes. The reader can find a more detailed description in reference [111].

However, due to a lack of data, the value of travel time savings in dollars per hour (\$/hr) for each income group is calculated using the cost-savings approach. The cost-savings approach assumes that the value of the time savings is equal to the wage rate, including labour-related overheads [113]; [115]. Given that the new road infrastructure to be assessed in this study benefits the entire population. This research assumes that the non-wage labour cost component of the wage rate is negligible. This is a reasonable assumption because it prevents an overestimation of the value of travel time savings using the cost-savings approach. It involves the computation of the average annual gross wage for each income group. These average gross wages are divided by annual work hours to obtain the average cost per hour for each income group. The results are utilised in the journey time changes to get the social benefit of the new road infrastructures.

The annual hours of work per year, excluding holidays based on 52 weeks per year, five days per week, and eight contract hours of work per day, are evaluated for the 2020 calendar year to be 2068 hours. The annual gross salary according to income groups is evaluated for Nigeria in naira and converted to dollars based on the exchange rate for the reference year. The 2020 calendar year value for the low-income rural Nigeria is reported as NGN 1,664,136 equivalent to \$ 4,380 [164]. The middle-income average annual salary is reported as NGN 4,068,000, equivalent to \$9,804. The high-income average annual salary is reported as NGN 18,120,000 equivalent to \$43,704 [165]. The value of travel time savings in dollar per hour (\$/hr) for each income group is evaluated as follows:

$$(VTTS)(\frac{\$}{hr}) = \frac{Annual\ gross\ salary\ (\$)}{Annual\ hours\ of\ work\ (hr)} \quad (7-34)$$

Table 7-4 shows the estimated value of travel time savings (*VTTS*) according to income groups for this study.

Table 7-4 Value of travel time savings according to income groups

S/N	Income Group	VTTS (\$/hr)
1.	Low	2.12
2.	Middle	4.74
3.	High	21.13

Moreover, it is recommended that other approaches, such as the willingness-to-pay approach based on the revealed preference method and stated preference method, be explored in future studies for the value of travel time savings estimation.

This study evaluates the monetary value of the highlighted social benefits of the presence of a new road within the social influence area arising from the road infrastructure impacts at each compressor station location. This road benefit is in terms of travel time cost savings between the existing and new road infrastructures layout (see Figure 7-3) using a developed code written in MATLAB

environment. The road benefit R_B , is a function of the road infrastructure impact LU_R , the value of travel time cost savings $(T_e - T_n)$, annual jobs created J_t , and the income level S , of the identified social benefit population areas. Mathematically, this is expressed as follows:

$$R_B = f(LU_R, T_e, T_n, J_t, S) \quad (7-35)$$

The travel area at each compressor station location is expressed in terms of the road infrastructure impact area LU_R , obtained from equation (7-32) as follows:

$$A_R = \frac{LU_R P_s P_T}{10000} \quad (7-36)$$

Where:

A_R = Travel area, km² (equivalent to road infrastructure area)

P_s = Social influence area population, (Persons)

LU_R = Road infrastructure impact area, (km² MW⁻¹ Persons⁻¹)

P_T = Gas turbine installed capacity, MW

The travel distance at each compressor station location is evaluated using the following equation:

$$D = \frac{A_R}{W} \quad (7-37)$$

Where:

D = Travel distance, km

A_R = Travel area, km² (equivalent to road infrastructure area)

W = Road width, km

The travel time at each compressor station location for the existing route is evaluated using the following equation:

$$t_e = \frac{D}{U_e} \quad (7-38)$$

Where:

D = Travel distance, km

t_e = Travel time for existing road, hour

U_e = Travel speed for existing road, km/hour

The travel time cost at each compressor station location for the existing route is evaluated using the following equation:

$$T_e = t_e(VTTS) \quad (7-39)$$

Combining equations (7-36) to (7-39) the travel time cost at each compressor station location for the existing route is evaluated as follows:

$$T_e = \frac{LU_R P_s P_T (VTTS)}{10000 W U_e} \quad (7-40)$$

Where:

T_e = Travel time cost for existing road, (\$/road trip)

$VTTS$ = Value of travel time savings (\$/hr)

U_e = Travel speed for existing road, (km/hr)

W = road width, (km)

P_s = Social influence area population, (Persons)

LU_R = Road infrastructure impact area, (km² MW⁻¹ Persons⁻¹)

P_T = Gas turbine installed capacity, MW

Similarly, the travel time at each compressor station location for the new route is evaluated using the following equation:

$$t_n = \frac{D}{U_n} \quad (7-41)$$

Where:

D = Travel distance, km

t_n = Travel time for new road, hour

U_n = Travel speed for new road, km/hour

The travel time cost at each compressor station location for the new route is evaluated using the following equation:

$$T_n = t_n(VTTS) \quad (7-42)$$

Combining equations (7-33), (7-37), (7-41) and (7-42), the travel time cost at each compressor station location for the new road infrastructure route is evaluated using the following equation:

$$T_n = \frac{LU_R P_s P_T (VTTS)}{10000 W U_n} \quad (7-43)$$

Where:

T_n = Travel time cost for new road, (\$/road trip)

$VTTS$ = Value of travel time savings, (\$/hr)

U_n = Travel speed for new road, (km/hr)

W = road width, (km)

P_s = Social influence area population, (Persons)

LU_R = Road infrastructure impact area, (km² MW⁻¹ Persons⁻¹)

P_T = Gas turbine installed capacity, MW

The social benefits of the presence of a new road R_B , in \$, within the social influence area at each compressor station location in terms of the travel time cost savings is then calculated as follows:

$$R_B = (T_e - T_n)N_t J_t \quad (7-44)$$

Where, N_t is the number of road trips per job and J_t is the annual jobs created (see Appendix Q). The future road benefits are discounted to the reference year zero at the beginning of the project using the assumed social discount rate of 5%.

7.3.7 Road Infrastructure Creation: Non-Dimensional Social Uplift

In this section, a new variable of social uplift in monetary terms called the road benefit ratio is proposed. According to the assumptions made in this study; discrete pipeline segments each 10 km long and has a social influence area about 100 km wide is considered. The population value and level of wealth for each 10 km pipeline segment is identified based on the population density and income groups for the gas turbine compressor station locations for the baseline case and are shown in Figure 3-3 and Table 3-1 respectively.

An existing level of wealth S_E , is defined as the product of the population and the average salary according to income groups for each pipeline segment with respect to the wealth map obtained along the pipeline route as depicted in Table 3-1 and is given by Equation (7-20). A new variable of social uplift from new road infrastructure creation within the social influence areas at each compressor station location along the pipeline route is proposed. This is called the road benefit ratio or non-dimensional social uplift from new road infrastructure creation RBR , and is given by:

$$RBR = \frac{R_B}{S_E} \quad (7-45)$$

Where:

RBR = Road Benefit Ratio, (dimensionless)

R_B = Road benefit, (\$)

S_E = Existing level of wealth at the social influence area for each pipe segment (\$)

7.4 Social Benefits Results and Discussion

7.4.1 Predicted Jobs Creation

Figure 7-4 shows a comparison of total potential foreign and local jobs created to one side of the social influence area at each compressor station location for the baseline case comprising 18 compressor station locations along the pipeline route. One potential local job is created per 10000 population at compressor station locations 1 and 2. Surprisingly, there are no foreign jobs imported at both locations.

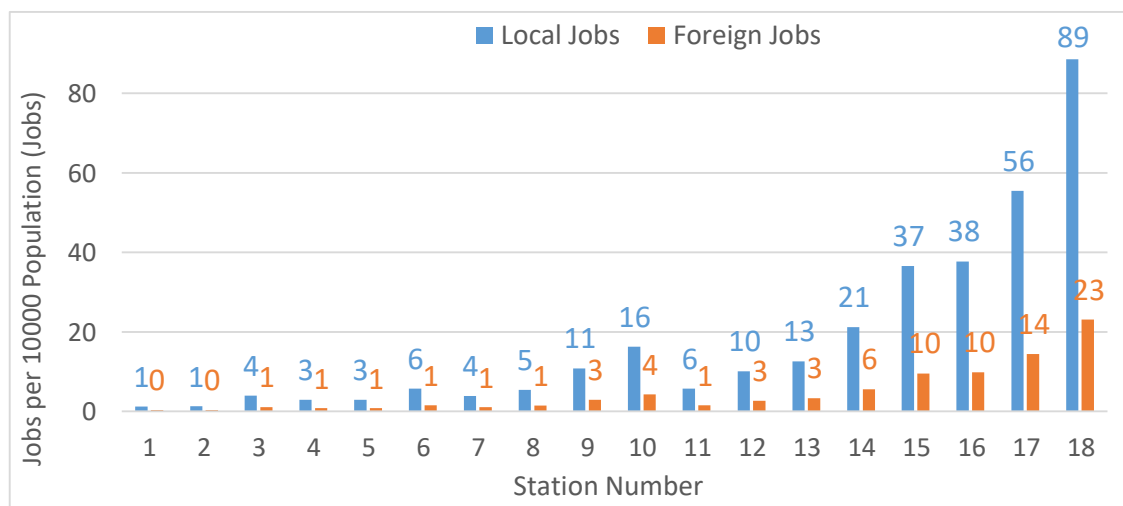


Figure 7-4 Comparison of Potential Foreign and Local Jobs Created to One Side of each Compressor Station Location

In contrast, eighty-nine local jobs are created per 10000 population at compressor station location 18. More so, twenty-three foreign jobs are imported at the same location. The high number of foreign jobs imported at compressor station location 18 correlates with the high number of local jobs created at the same location. This location is expected to be associated with rural communities in the low-income group. The high number of unskilled local jobs created will necessitate the need for additional foreign skilled jobs. Additionally, employees have low-salaried jobs at this location compared to urban dwellers. Thus, they do not have the means to commute long distances outside their location as they have limits on their geographic movement to work. Consequently, these factors might make the rural communities the preference for local jobs.

However, compressor station locations 1 and 2, each with one local job and no foreign job, are expected to be associated with city dwellers in the high-income group and with the most skilled workgroup. Additionally, employees at these locations have high-salaried jobs compared to rural dwellers and have the means to commute long distances to their workplaces irrespective of how far they are from their locations. Consequently, the additional value of jobs created at these locations will have little effect.

Figure 7-5 shows the social uplifts from jobs creation in terms of the employment benefit ratio at each compressor station location for the baseline case comprising 18 station locations.

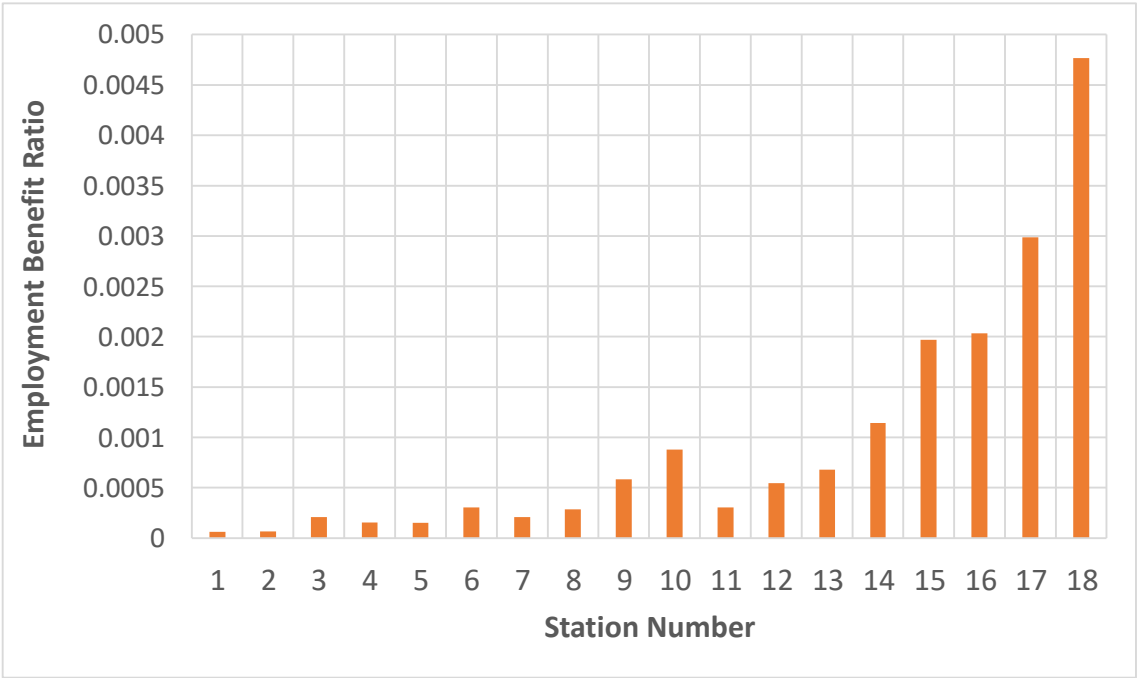


Figure 7-5 Social Uplifts from Jobs Creation at each Compressor Station Location (Baseline)

The employment benefit ratio is about 6.41×10^{-5} and 6.58×10^{-5} at compressor station locations 1 and 2, respectively. At compressor station location 18, the employment benefit ratio is about 0.00477. The employment benefit ratio at compressor station location 18 is almost two orders of magnitude greater than those of locations 1 and 2. The results show high social uplifts from new jobs creation at compressor station location 18 associated with rural dwellers and a

high number of potential local jobs creation compared to the low social uplifts from jobs creation experienced at compressor station locations 1 and 2 that is associated with city dwellers and with little or no jobs creation. The results obtained for the employment benefit ratio from Figure 7-5 is seen to verify the assertions made from the potential jobs created from Figure 7-4. A similar explanation can be given for other evaluated compressor station locations.

7.4.2 Road Infrastructure Impact

Figure 7-6 shows that the average gas turbine impact area aligns with estimates reported by Chatzimouratidis and Pilavachi [98] and Afgan and Carvalho [102], respectively. The differences observed present no serious implications since this is the first-time direct land-use impact is applied to compressor stations and pipeline systems.

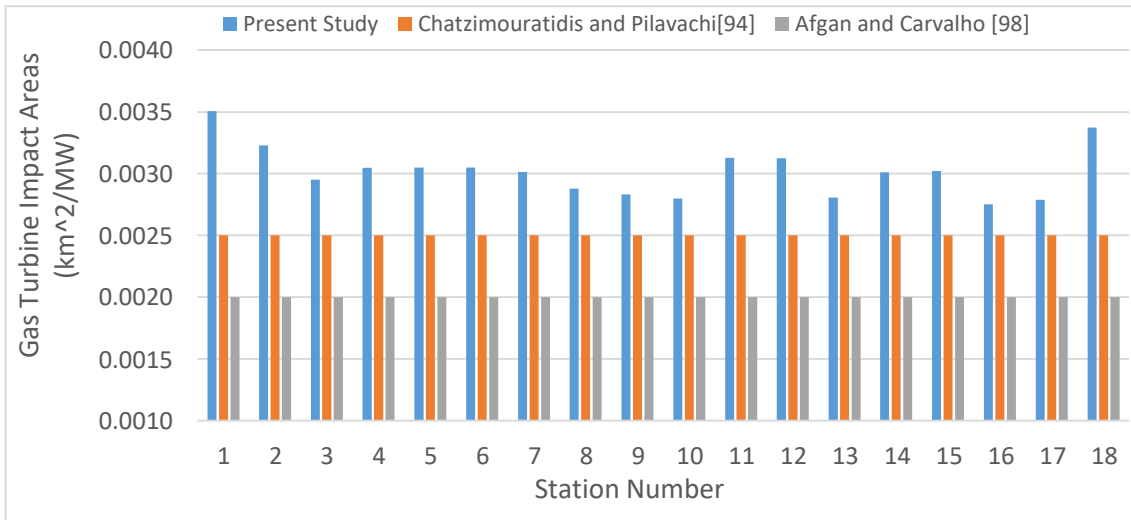


Figure 7-6 Comparison of Gas Turbine Direct Land-use Impact Areas with Literature Estimates

Figure 7-7 shows the distribution of direct land-use impact areas for the gas turbine compressor stations and pipeline systems. The compressor station impact area comprises gas turbine power plant and gas compressor impact areas. Most of the direct social impacts are associated with road infrastructure.

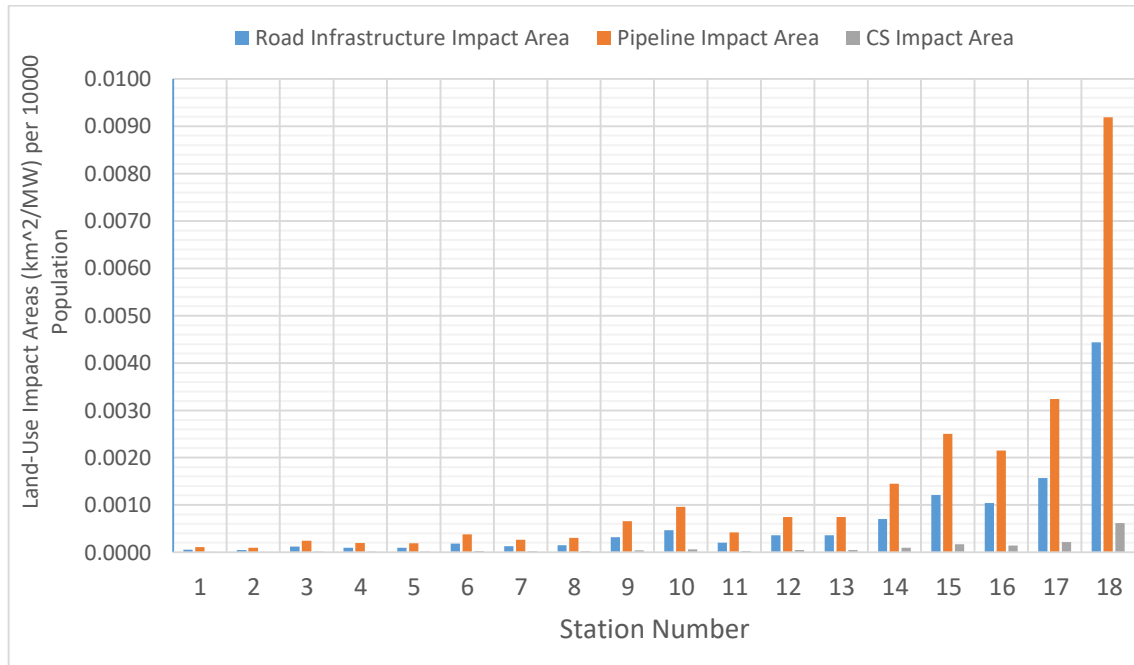


Figure 7-7 Distribution of Direct Land-use Impact Areas

The road infrastructure impact areas are about 0.0001 km²/MW per 10000 population at compressor station locations 1 and 2, respectively. The road infrastructure impact area is about 0.0002 km²/MW per 10000 population at compressor station location 11. The impact areas vary across the gas turbine compressor station locations and depend on the land-use characteristics, station location characteristics, population characteristics, performance characteristics, and income level. Results show that about 0.0044 km²/MW per 10000 population will be directly impacted by the anticipated land use for road infrastructure creation at compressor station location 18 to improve the local community's socio-economic growth and development and to meet the daily natural gas production over the lifecycle of the proposed Trans-Saharan gas pipeline project.

Additionally, the road infrastructure impact at compressor station location 18 is over four times one order of magnitude larger than the impacts obtained at compressor station locations 1 and 2. Thus, compressor station location 18 is expected to be associated with rural dwellers in the low-income group since there are little or no existing transportation networks at this location. Hence, new road infrastructures will have greater socioeconomic benefits in these communities. However, compressor station locations 1 and 2 with the lowest impact areas

respectively, are expected to be associated with urban dwellers in the high-income group.

Figure 7-8 shows the social uplift from road infrastructure in terms of the road benefit ratio at each compressor station location for the baseline case comprising 18 compressor station locations.

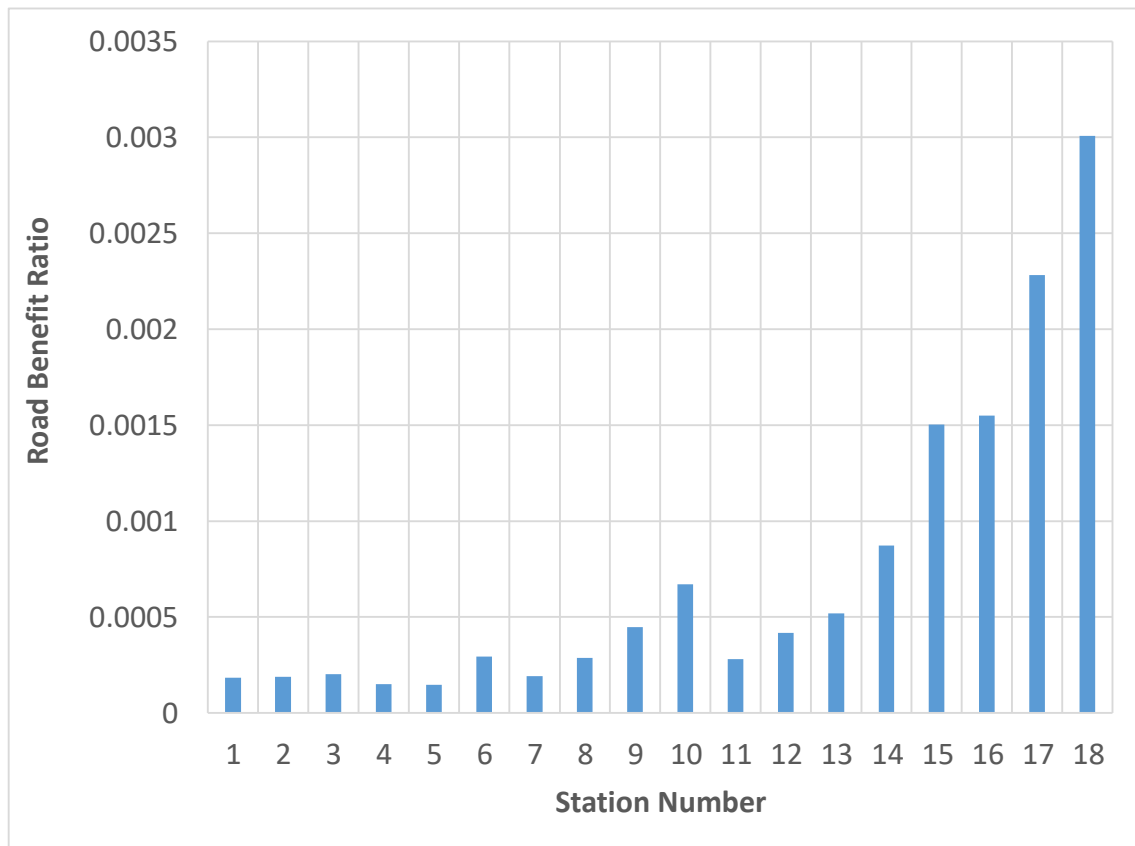


Figure 7-8 Social Uplift from Road Infrastructure at each Compressor Station Location (Baseline)

The road benefit ratio is about 1.8×10^{-4} at compressor station locations 1 and 2, respectively. At compressor station location 18, the road benefit ratio is about 0.003. The road benefit ratio at compressor station location 18 is over one order of magnitude greater than those of compressor station locations 1 and 2. The results show high social uplifts obtained from the creation of new roads along the social influence areas at compressor station location 18. This location is associated with rural dwellers and high road infrastructure impact compared to

the low social uplifts from new roads creation experienced at compressor station locations 1 and 2. These locations are associated with city dwellers and with little or no road infrastructure impact. The smaller social benefits observed at these locations are probably because there might be existing road transportation networks in the city. Thus, the additional value of the road infrastructure will have little effect since there are other similar infrastructures at these locations. The results obtained for the road benefit ratio from Figure 7-8 is seen to verify the assertions made from the road infrastructure impacts from Figure 7-7. Similar explanation can be given for other evaluated compressor station locations.

The road infrastructure connects the compressor stations to other transportation networks, enhancing the quality of life of the community. The transmission pipeline impact area will suffer little or no damage at the construction phase and could be used for agricultural activities, animal grazing and other benefits.

The results further show that the employment benefit ratio and the road benefit ratio would increase by a factor of 10 and reciprocal of new location. This ratio is for every 10 km decrease in the distance at each compressor station location. These findings represent one of the major contributions and novelty of this research.

Results show promising improved stakeholders' engagement. This will minimise potential future delays and conflicts of interests by creating cooperation, stable long-term policies and trust relationships between the organisation and stakeholders (local community, employees). This is due to the resulting positive social benefits obtained from the installation and operation of the gas turbine compressor stations and pipeline project.

7.5 Socio-Economic Analysis: Road Infrastructure Costs

This study investigates five essential components of the road construction costs, namely:

1. Surveying and staking
2. Site preparation: Clearing, Piling, and Grubbing
3. Earthwork

4. Drainage
5. Pavement/Surfacing

This research utilises the unit costs estimation methods to calculate the total road construction cost. The total unit cost of the road construction per unit length of road will be the sum of the individual component's costs. The following analyses estimate the individual road construction component's unit costs.

7.5.1 Surveying and Staking Cost

The surveying costs are dependent on the compressor station's location, terrain, and ambient conditions of the road infrastructure impact areas. Table 7-5 shows the assumptions for the surveying and staking cost computation. The data are obtained by scaling the values in [168] based on the ratio of per capita gross domestic product (GDP) between Nigeria and the United States derived from purchasing power parity (PPP) calculations. On this basis, the World Bank estimates that the GDP per capita in US\$ PPP is \$ 63,544, \$48 073, \$ 44,916 and \$5,187 for the United States, Canada, United Kingdom, and Nigeria, respectively [169]. This gross domestic product estimate implies that the standard of living in Nigeria is about one-twelfth that of the United States. This scaling procedure is utilised in subsequent calculations involving data obtained from the United States and other industrialised countries.

Table 7-5 Assumptions for Surveying and Staking [168]

S/N	Parameter	Value
A.	Surveying Phase	
i.	Road location (\$/mile)	93.87
ii.	Traverse, Profile, x-section (P-line) (\$/mile)	420.39
iii.	Adjustment factor	1.3
B.	Staking Phase	
i.	Establishing Alignments (\$/mile)	93.87
ii.	Establishing cross-section limits (\$/mile)	334.68
iii.	Adjustment factor	1.1

The unit cost at the surveying phase is estimated as follows:

$$S_u = 0.621A_f(x + y) \quad (7-46)$$

Where:

S_u = Surveying unit cost, (\$/km)

x = Road location cost, (\$/mile)

y = Traverse, Profile, x-section costs, (\$/mile)

A_f = Adjustment factor

The unit cost at the staking phase is estimated with the following equation:

$$S_t = 0.621A_f(m + n) \quad (7-47)$$

Where:

S_t = Staking unit cost, (\$/km)

m = Establishing Alignments, (\$/mile)

n = Establishing cross section limits, (\$/mile)

A_f = Adjustment factor

The total unit cost is the algebraic sum of the individual unit cost at the surveying and staking phase, respectively, and is given by:

$$S_c = S_u + S_t \quad (7-48)$$

Where:

S_u = Surveying unit cost, (\$/km)

S_t = Staking unit cost, (\$/km)

S_c = Surveying and staking unit cost, (\$/km)

7.5.2 Site Preparation Cost: Clearing, Piling and Grubbing

Site preparation costs comprising land clearing, piling, and grubbing costs involving stump removal are evaluated by estimating the areas to be cleared, piled, and grubbed per unit length of the road infrastructure. The following are the assumptions for site preparation cost estimation.

7.5.2.1 Assumptions for Site Preparation Cost

1. Vegetation is classified as mediumly dense material ranging between 990 < trees/hectare < 1480 with no vine
2. Work is being done by a tractor of 305 hp
3. Road width is 11 m
4. Tractor owning and operating cost is \$ 21.58 per hour [170]
5. 25% of the total land area per km of road length being cleared and piled for road construction will require grubbing and stump removal.

I utilised the formulas developed by Rome Industries [171] for estimating cutting and piling time to estimate the total time required per unit road area for clearing, piling, and grubbing. The tractor clearing time T_c , is given by:

$$T_c = X(AB + M_1N_1 + M_2N_2 + M_3N_3 + M_4N_4 + DF) \quad (7-49)$$

Where:

T_c = Clearing time, (minutes/hectare)

X = Hard wood or density factor

A = Vine presence factor affecting base time

B = Base time (minute/hectare)

M = Minutes per tree in each diameter range

N = Number of trees per hectare in each diameter range

D = sum of the diameters of all trees per hectare greater than 180 cm (ft)

F = Minutes per 30 cm diameter for trees above 180 cm diameter

$X = 1.3$ for 75 – 100% hardwood

$X = 1.0$ for 25 – 75 % hardwood

$X = 0.7$ for 0 – 25% hardwood

$A = 1.0$ for mediumly dense tree vegetation materials

Table 7-6 and Table 7-7 show the factors and constants and the assumed average tree count per hectare utilised in the above equation.

Table 7-6 Production factors for felling with Rome K/G Blades [171]

Tractor	B	Diameter Range (cm)				Diameter >180 cm per 30 cm
	45	30-60	61-90	91-120	121-180	
		M_1	M_2	M_3	M_4	F
305 hp		0.2	1.3	2.2	6	1.8

Table 7-7 Assumed Average tree count per hectare

Diameter Range (cm)	< 30	31-60	61-90	91-120	121-180	Sum of trees dia > 180cm
		N_1	N_2	N_3	N_4	D
Number of trees	900	70	12	6	4	366 cm (12 ft)

The piling time T_p , in minutes per hectare for a tractor utilising a K/G blade or rake can be written as:

$$T_p = B + M_1N_1 + M_2N_2 + M_3N_3 + M_4N_4 + DF \quad (7-50)$$

Where the variables in the equation are as defined above. The factors for equation (7-50) are obtained from Table 7-8.

Table 7-8 Production factors for piling in windrows [171]

Tractor	B	Diameter Range (cm)				Diameter >180 cm per 30 cm
	111	30-60	61-90	91-120	121-180	
		M_1	M_2	M_3	M_4	F
305 hp		0.1	0.5	1.8	3.6	0.9

A factor of 1.25 was incorporated to account for increase in the total clearing and piling time due to stump removal. The total time required by the tractor per km of road length T , is given by:

$$T = \frac{5}{3} \left(0.75L_A(T_c + T_p) + 0.25 * 1.25L_A(T_c + T_p) \right) \quad (7-51)$$

Equation (7-51) is simplified to:

$$T = \frac{85}{48} L_A(T_c + T_p) \quad (7-52)$$

Where:

T = Total tractor time (hour/km)

L_A = Road infrastructure Land-use area per km of road length (km²/km)

T_p = Piling time, minutes/hectare

T_c = Clearing time, (minutes/hectare)

The site preparation unit cost is the product of the tractor time required for clearing, piling, and grubbing and the tractor owning and operating cost and is given by:

$$S_p = TV \quad (7-53)$$

Where:

S_p = Site preparation unit cost, (\$/km)

V = Tractor owning and operating cost, (\$/hour)

7.5.3 Earthwork Cost

The topographic terrain of the location and layout of potential routes for road infrastructure land-use impact areas within the social profile at each compressor station location along the pipeline route are classified as flat, rolling, or mountainous. Table 7-9 shows the topographic terrain classification for each compressor station location. The following shows the assumptions for earthwork cost estimation.

7.5.3.1 Assumptions for Earthwork

1. Flat terrain topography is classified as gently sloping ground no more than 100 m elevation with a maximum slope of 5%
2. Rolling terrain topography is classified as sloping surface at most 35% slope with elevation no more than 500 m
3. Mountainous terrain topography is classified as steeply sloping surface greater than or equal to 35% slope and elevation above 500 m
4. Allowable road gradients for rolling and mountainous terrains are 12% and 35%, respectively
5. Climatic index for flat terrain is 0.5
6. Road width is 11 m
7. Work is being done by a tractor of 305 hp with a ripper of 150 m³/hr production rate
8. Tractor owning and operating cost is \$21.58 per hour [170]

Table 7-9 Compressor station locations topographic terrain classification

Station No.	Elevation (m)	Topographic Terrain Classification
1.	100	Flat
2.	200	Rolling
3.	600	Mountainous
4.	402	Rolling
5.	400	Rolling
6.	400	Rolling

Station No.	Elevation (m)	Topographic Terrain Classification
7.	480	Rolling
8.	600	Mountainous
9.	800	Mountainous
10.	1050	Mountainous
11.	400	Rolling
12.	400	Rolling
13.	560	Mountainous
14.	480	Rolling
15.	600	Mountainous
16.	900	Mountainous
17.	700	Mountainous
18.	240	Rolling

The earthwork volume in cubic metre per km of road length for the predicted road infrastructure impacts was estimated using a model developed by Markow and Aw [122] for earthwork volume in flat, rolling, and mountainous terrain. These models were chosen because they consider the effects of topography, design standards, flooding, and road costs in developing countries. Thus, encompassing the locations of the proposed Trans-Saharan gas pipeline projects. The model prediction was based on engineering principles of road design and construction. It is simple to use being a function of road width and road length, while considering the case of little or no available data that the present author believes is the most appropriate for this present study.

The earthwork volume for a flat terrain topography is given by:

$$E_f = 684W(1 + 2.2C_i) \quad (7-54)$$

Where:

E_f = volume of earthwork for flat terrain (m³/km)

W = road width (m)

C_i = climatic index

The earthwork volume for a rolling terrain topography is given by:

$$E_r = 700W^{1.1}\{1 + \exp[-0.49(R_g - 0.5)]\} \quad (7-55)$$

Where:

E_r = volume of earthwork for rolling terrain (m³/km)

W = road width (m)

R_g = allowable road gradient

The earthwork volume for a mountainous terrain topography is given by:

$$E_m = 1900W^{1.3}\{1 + \exp[-0.25(R_g - 1.5)]\} \quad (7-56)$$

Where:

E_m = volume of earthwork for mountainous terrain (m³/km)

W = road width (m)

R_g = allowable road gradient

The earthwork volumes E_f , E_r , E_m are related to the tractor excavation and production rate as follows:

$$EX_f = \frac{P_r}{E_f} \quad (7-57)$$

$$EX_r = \frac{P_r}{E_r} \quad (7-58)$$

$$EX_m = \frac{P_r}{E_m} \quad (7-59)$$

Where:

EX_f , EX_r , EX_m = excavation rate for flat, rolling, or mountainous terrain, (km/hr)

P_r = production rate, (m³/hr)

The earthwork unit cost per km length of road for flat, rolling, or mountainous terrain is calculated using the following equations:

$$E_{cf} = \frac{V}{EX_f} \quad (7-60)$$

$$E_{cr} = \frac{V}{EX_r} \quad (7-61)$$

$$E_{cm} = \frac{V}{EX_m} \quad (7-62)$$

Where:

E_{cf} , E_{cr} , E_{cm} = earthwork unit cost for flat, rolling, or mountainous terrain, (\$/km)

V = tractor owning and operating cost, (\$/hr)

7.5.4 Drainage Cost

In this study, drainage cost is assumed to consist of the cost of installing culverts. It is assumed that the cost per linear metre of culvert is \$36.33 per m [172] (scaled on the basis of gross domestic product per capita in both countries). The number of culverts installed per unit length of road is estimated using a drainage model developed by [122] and is expressed as follows:

$$N_c = 1.43T_i^{0.16} \quad (7-63)$$

Where:

N_c = number of culverts per unit length of road, (culverts/km)

T_i = Terrain index

The terrain index for flat, rolling, or mountainous terrain is given in Table 7-10.

Table 7-10 Terrain Index [122]

Terrain type	T_i
Flat	0.3
Rolling	6.2
Mountainous	9.2

The length of pipe culvert per unit length of road is given by:

$$L_c = N_c m_i W^{n_i} \quad (7-64)$$

Where:

L_c = length of pipe culvert per km of road length, (m/km)

m_i, n_i = constants and coefficient for flat, rolling, or mountainous terrain (see Table 7-11)

Table 7-11 Constant and coefficient for terrain type [122]

Terrain type	m_i	n_i
Flat	1.41	1.1
Rolling	3.24	0.84
Mountainous	1.97	0.90

The cost per km length of culvert is estimated as follows:

$$D_c = L_c q \quad (7-65)$$

Where:

D_c = Drainage unit cost, (\$/km)

q = cost per linear metre of culvert, (\$/m)

7.5.5 Pavement Cost

7.5.5.1 Assumptions for Pavement Cost

- ❖ The cost of surfacing per unit road area is £8.08 per square metre [173] (scaled on the basis of gross domestic product per capita in both countries). This is converted to the equivalent amount in dollar (\$) based on the average exchange rate for 2020 obtained from [174]
- ❖ Road width is 11 m

The pavement cost per km of road is related to the land-use road surface area and road width. The pavement cost is estimated as follows:

$$P_c = 1000WSU_c \quad (7-66)$$

Where:

P_c = pavement unit cost, (\$/km)

W = road width, (m)

SU_c = surfacing cost, (\$/m²)

7.5.6 Road Construction Cost

The total road construction unit cost per km length of road at each compressor station location is the sum of the individual component's unit cost and is given by:

$$R_{uc} = S_c + S_p + E_{ci} + D_c + P_c \quad (7-67)$$

Where:

R_{uc} = Road construction unit cost, (\$/km)

S_c = Surveying and Staking unit cost, (\$/km)

S_p = Site preparation unit cost, (\$/km)

E_{ci} = earthwork unit cost, (\$/km)

i = flat, rolling, or mountainous terrain

D_c = Drainage unit cost, (\$/km)

P_c = pavement unit cost, (\$/km)

The road construction cost is a function of the component's road construction unit cost, compressor station location characteristics, road infrastructure land-use impact area, and the road width. The road construction cost is given by the following developed model equation:

$$R_c = R_{uc} \frac{LU_{Rj}}{W} M + \frac{mZ_a R T_1 \frac{n}{n-1} \left[\left(\frac{1}{e^s} \left[P_1^2 - \frac{Q^2 \left(\frac{P_b}{T_b} \right)^2 T_f^2 Z^2 (e^s - 1) L}{(9.5854e - 7) E^2 D^{5.334} (H_2 - H_1)} \right] \right)^{\frac{-(n-1)}{n}} - 1 \right]}{3600 \eta_p} \quad (7-68)$$

Where:

R_c = Road construction cost, (\$)

R_{uc} = Road construction unit cost, (\$/km)

W = road width, (m)

LU_{Rj} = Road infrastructure land-use impact area of compressor station location j (j = 1, 2, 3, ...18) (baseline case)

Other terms in the above equation have their usual meaning.

The road construction costs are classified as social capital costs. They were included in the capital costs estimation in the techno socio-economic aspects of the project for the lifecycle costs and net present value computation.

7.5.7 Road Tax

It is expected that revenues will be collected from road transportation when operational through imposed road tax. The following are the assumptions for the road tax estimation.

7.5.7.1 Assumptions for Road tax

- ❖ The data on road tax rates utilised to evaluate road tax revenues in this study are obtained from [175]; [176]. For the 2020 financial year, the first year and annual road tax rate for motor vehicles utilising conventional fuels and assuming a carbon dioxide emission ranging from 90-100 g/km of CO₂ are £16.17 and £17.90, respectively (scaled on the basis of gross domestic product per capita in both countries). These are converted to the equivalent amount in dollars for 2020 conversion rates [174].
- ❖ Data on the number of motor vehicles assumed registered to use the newly constructed road at each compressor station location are retrieved from a reference developing local government in Nigeria [177] and shown in Table 7-12.

Table 7-12 Number of Registered Vehicles [177]

TYPE OF VEHICLES	TYPE OF OWNERSHIP					TOTAL
	Private	Commercial	Government	Mission/ School	Corporation	
Saloon/Station wagon	2078	185	2	18	185	2468
Van, Pick-up and Kitcar	23	30			26	79
Lorry/Truck	2	69		1	83	155
Minibus	83	128	6	6	29	252
Omnibus						
Tanker		3				3
Tractor					1	1
Trailer						
Tipper	1	6			13	20
Total	2187	421	8	25	337	2978

The road tax is estimated over the project lifecycle using the following equation:

$$R_t = v[w + (l - 1)z] \quad (7-69)$$

Where:

R_t = lifecycle Road tax revenue, (\$)

l = project lifetime, years

v = number of registered vehicles

w = first-year tax rate, (\$)

z = annual tax rate, (\$)

7.6 Income Tax

7.6.1 Assumptions for Income Tax

1. Income tax rates are classified according to the level of wealth and are different for each income group
2. Personal income tax is a percentage of each employee's annual salary as stipulated in the Personal Income Tax (Amendment) Act of Nigeria [178]

Table 7-13 shows the annual salary and income tax data according to income groups.

Table 7-13 Annual salary and income tax according to income groups [163]; [178]

S/N	Income Group	Annual Salary	Income Tax
1.	Low	\$28,190	7% of annual salary
2.	Middle	\$48,750	15% of annual salary
3.	High	\$64,490	24% of annual salary

The annual income tax revenue I_t , generated from the compressor station and pipeline project is evaluated as follows:

$$I_t = I_s S_t \quad (7-70)$$

Where:

I_s = Income tax rate (%)

S_t = Total employment benefits received from the project

7.7 Socio-Economic Life Cycle Costs and Benefits

The total socio-economic lifecycle costs S_c , arising from the evaluated social impacts and social benefits from the construction, installation, and operation of gas turbine compressor stations and pipeline systems is the sum of all the social costs incurred from the proposed Trans-Saharan gas pipeline project and is given by:

$$S_c = E_c + R_c \quad (7-71)$$

Where:

E_c = Employment cost, (\$)

R_c = Road construction cost, (\$)

The total socio-economic lifecycle benefits S_b , arising from the evaluated social impacts and social benefits from the construction, installation, and operation of gas turbine compressor stations and pipeline system is the sum of all the social benefits incurred from the proposed Trans-Saharan gas pipeline project and is given by:

$$S_b = S_N + R_B + I_t + R_t \quad (7-72)$$

Where:

S_N = Employment benefits, (\$)

R_t = Road tax, (\$)

I_t = Income tax, (\$)

R_B = Road benefits, (\$)

7.8 The Integrated Techno Socio-Economic Scenarios

The techno socio-economic scenarios integrate the technical and the social aspects of the proposed Trans-Saharan gas pipeline project to give an overview

of the potential economic performance of the compressor stations and pipeline systems under all operating conditions. The social aspects are expected to improve the quality of life of the local communities. The socio-economic benefits derived from the integrated studies will lead to socio-economic growth and development of the local communities at the social influence areas within each gas turbine compressor station location along the pipeline route. Although the techno-economic aspect of the project has no direct impact on the local community's quality of life, they are greatly significant in the direction of shareholders' goal evaluation. Since the main objective of shareholders in any investment is the overall project profitability. Four techno socio-economic scenarios are considered in this study:

- ❖ Scenario 1: Turbo-compressor availability is assumed to be 100% (Baseline) while incorporating social costs and benefits comprising of the evaluated predicted jobs creation and road infrastructure
- ❖ Scenario 2: There is no standby turbo-compressor unit installed at all compressor station locations while incorporating social costs and benefits comprising of the evaluated predicted jobs creation and road infrastructure
- ❖ Scenario 3: One standby turbo-compressor unit is installed at the first eight compressor station's location while incorporating social costs and benefits comprising of the evaluated predicted jobs creation and road infrastructure
- ❖ One standby turbo-compressor unit is installed at all compressor station locations while incorporating social costs and benefits comprising of the evaluated predicted jobs creation and road infrastructure

Table 7-14 summarises the description of the techno socio-economic scenarios considered in this research.

Table 7-14 Techno socio-economic scenarios

S/N	Scenarios	Techno Socio-economic Case Description
1.	Scenario 1	Techno-economic: Baseline case, Availability is 100%
		Socio-economic: Predicted jobs creation, Road infrastructure
2.	Scenario 2	Techno-economic: Availability Scenario 1 (No standby unit)
		Socio-economic: Predicted jobs creation, Road infrastructure
3.	Scenario 3	Techno-economic: Availability Scenario 2 (one standby unit at first eight compressor station locations)
		Socio-economic: Predicted jobs creation, Road infrastructure
4.	Scenario 4	Techno-economic: Availability Scenario 3 (one standby unit at all compressor station locations)
		Socio-economic: Predicted jobs creation, Road infrastructure

The research project techno-economic lifecycle cost evaluated above consists of the gas compressor cost, gas turbine cost, pipeline cost, auxiliaries cost, fuel cost, and total maintenance cost and is given by Equation (6-40). The research project socio-economic lifecycle cost evaluated above consists of the employment and the road costs given by Equation (7-62). The integrated techno socio-economic lifecycle cost L_T , for all scenarios considered in this research can be written as:

$$L_T = L_c + S_c \quad (7-73)$$

Where:

S_c = Socio-economic lifecycle cost, (\$)

L_c = Techno-economic lifecycle cost, (\$)

7.8.1 Net Present Value Approach

The net present value analysis based on the techno socio-economic scenarios study is estimated using Equation (6-41) and section 6.12.

The total annual revenue R_t , from the project considering the techno socio-economic case, is the algebraic sum of the net annual revenue R_{net} , from the techno-economic aspects, and the net revenue obtained from the socio-economic aspects R_s , and is given by:

$$R_t = R_{net} + R_s \quad (7-74)$$

The net revenue obtained from the socio-economic aspects is the sum of the revenue obtained from the resulting social benefits in terms of the income tax, road tax and road benefits received from the projects over the project lifecycle.

The annual cash outflow CF_a , is the sum of the annual fuel cost F_{ac} , annual maintenance cost M_{ac} , and employment cost E_j , and is given by:

$$CF_a = F_{ac} + M_{ac} + E_j \quad (7-75)$$

The annual net cash flow CF , is given by:

$$CF = R_t - CF_a \quad (7-76)$$

7.9 Results and Discussion

Figure 7-9 shows the breakdown of project costs for one of the techno socio-economic scenarios. The techno socio-economic lifecycle cost of the proposed Trans-Saharan gas pipeline project consists of gas compressor cost, gas turbine cost, auxiliaries cost, fuel cost, maintenance cost, job cost, and road cost. The fuel cost has the highest impact on the project accounting for 25.19% of the lifecycle cost. The maintenance cost, pipeline cost, auxiliaries cost, gas compressor cost, gas turbine cost, and road cost accounted for 21.69%, 19.18%, 15.58%, 10.49%, and 6.15%, and 1.66%, respectively, of the lifecycle cost for scenario 4. The job cost has the lowest impact on the project accounting for

0.06% of the lifecycle cost. However, the employment benefit has the highest positive socio-economic impact on the project since it has an average higher social uplift at most compressor station locations than the road benefit (see Figure 7-10). The low percentage share for job cost makes potential job creation from the proposed Trans-Saharan gas pipeline project a positive direction for policymakers and investors in stakeholder’s goal evaluation. Since the job cost impact on the shareholder’s interest, which is aimed towards the overall project profitability is minimal.

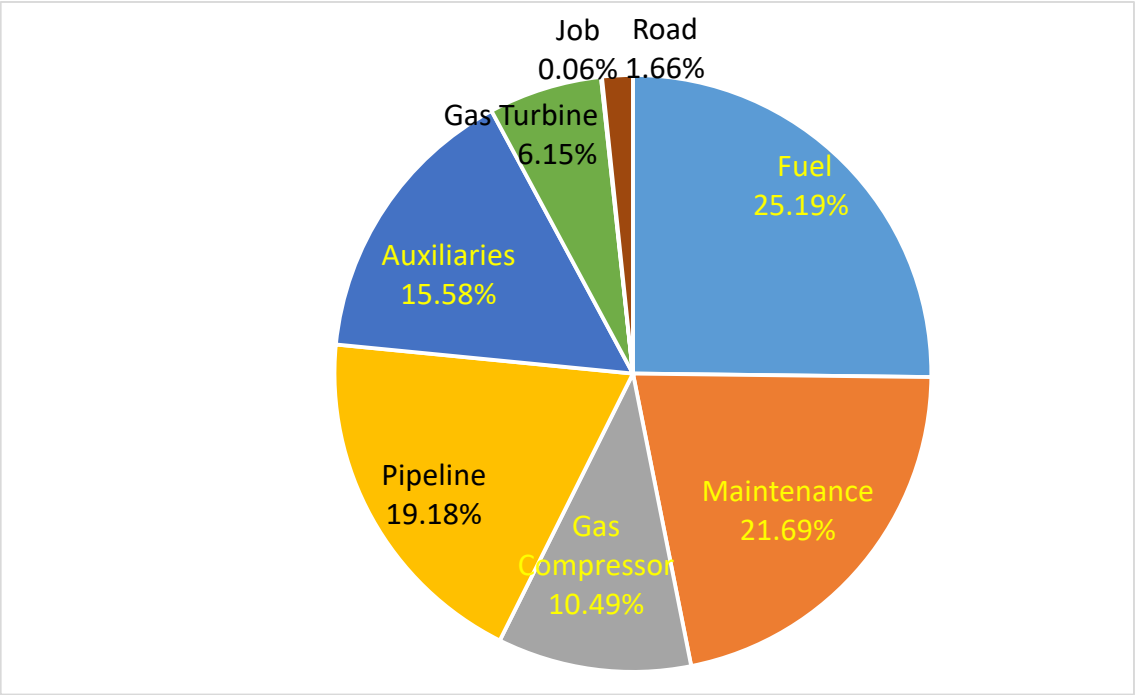


Figure 7-9 Breakdown of Project Costs for Techno Socio-economic Scenario 4

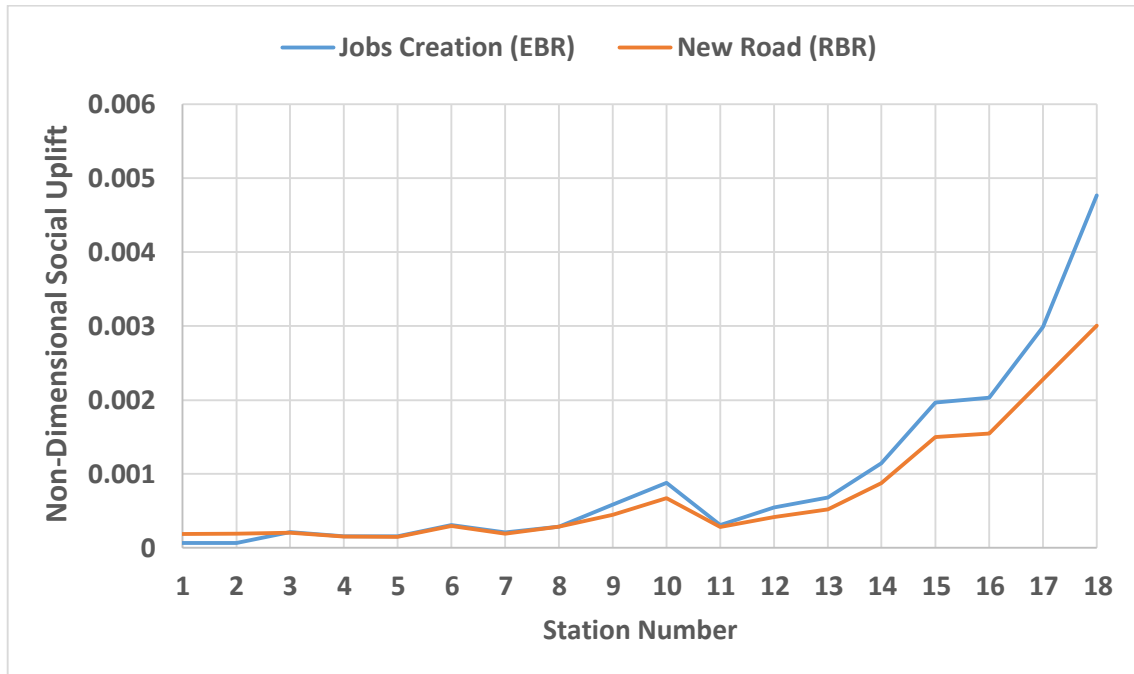


Figure 7-10 Comparison of Social Uplifts for the Compressor Station and Pipeline System (Baseline)

The project lifecycle costs are \$37.23 billion, \$37.15 billion, \$38.01 billion, and \$39.10 billion assuming a social discount rate of 5% and an economic discount rate of zero for scenarios 1, 2, 3, and 4, respectively. At 15% and 5% economic and social discount rates, the project lifecycle costs are \$22.92 billion for scenario 1 and \$22.90 billion for scenario 2. At the same discount rates, the project lifecycle costs are \$23.72 billion for scenario 3 and \$24.78 billion for scenario 4. The increase in the lifecycle costs estimates is reflected in the additional socio-economic impacts to the local communities. This also arises from the increased availability due to the installed stand-by units at some or all compressor station's locations. Thereby ensuring local community's needs are met thus contributing towards a good quality of life.

Appendix L shows the breakdown of the project cost for other techno socio-economic scenarios.

The results obtained for the net present value analysis show that at a 15% discount rate, scenario 1 has net present value of \$28.67 billion. At the same discount rate, the net present values are \$12.64 billion for scenario 2, \$12.94

billion for scenario 3, and \$13.01 billion for scenario 4. All project alternatives have positive net present values. At a 15% discount rate, scenario 4 consisting of social cost and benefits and a standby turbo-compressor unit at all compressor station locations should be selected. Since it is the project with the highest net present value among the considered scenarios.

Sensitivity analyses are carried out to determine the effect of the discount rate on the net present value. Figure 7-11 shows the variation of the net present value with discount rates for techno socio-economic scenarios.

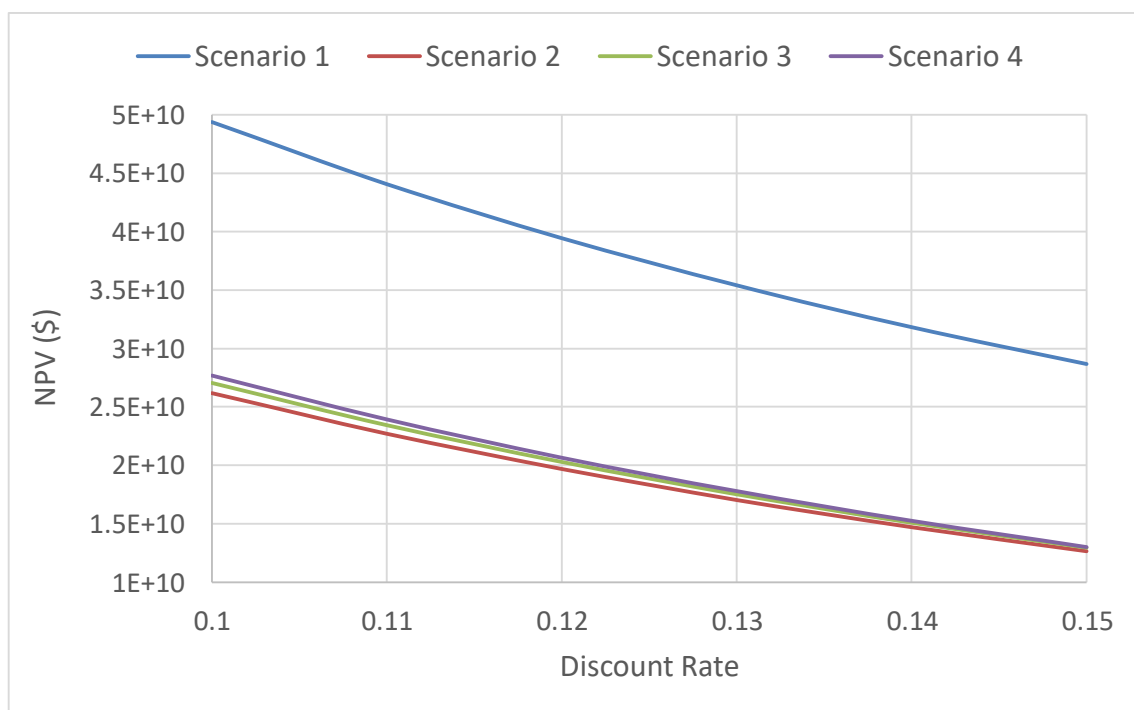


Figure 7-11 Variation of NPV with Discount Rates for Techno Socio-economic Scenarios

Sensitivity analyses show an increase in net present value with decreasing discount rate for all scenarios, with scenario 4 having the highest net present value at all discount rates. Results show that the most economically viable alternative is scenario 4 consisting of social cost and benefits and a standby turbo-compressor unit at all compressor station locations along the pipeline route. Consequently, scenario 4 is expected to produce the lowest risk associated with an investment in the proposed Trans-Saharan gas pipeline project. The results further show that assuming 100% availability value as seen in scenario 1 is not

realistic as it is nearly impossible to achieve perfect operating conditions throughout the project life. The results have shown the importance of incorporating a social benefit analysis into the pipeline TERA.

7.10 Summary

The objectives of this study were to determine the potential social impacts and social benefits of compressor station locations along the pipeline route.

This study has analysed the potential social impacts and social benefits of gas turbine compressor station locations while also evaluating an integrated techno socio-economic scenario of the proposed project in a first step. The author did not find any study to examine the social impacts on the local communities of compressor station locations by adapting TERA. This social impact includes employment opportunities and new road infrastructures as a function of compressor station location and the power required. The predicted jobs creation is quantified by the number of local jobs created and the equivalent employment cost and benefits in monetary units of employees' salaries and income taxes generated. Road infrastructures are quantified in terms of road benefits, road construction cost, and road tax. A scenario-based techno socio-economic analysis was performed to show the sensitivities of compressor station and pipeline system to social and technical aspects of the project in terms of social benefits and availabilities. The techno socio-economic assessment of the project was done using a discounted cash flow method based on the lifecycle cost and net present value. The techno socio-economic model was developed using a code written in MATLAB environment based on social benefit algorithms and the variation in compressor station location ambient temperatures at varying flow conditions. Sensitivity analyses were carried out to determine the effect of the discount rate on the net present value.

The evaluated gas turbine impact area aligns with literature reports. The differences observed present no serious implications since this is the first-time direct land-use impact is applied to compressor station and pipeline system. The potential social benefits created is expected to bring about the socio-economic development of the local communities via human skills and resources

development brought about by technological training of the local employees and the incomes generated. Results show promising improved stakeholders' engagement. This will minimise potential future delays and conflict of interests by creating cooperation, stable long-term policies and trust relationship between the organisation and stakeholders due to the resulting positive social benefits obtained from the installation and operation of the gas turbine compressor stations and pipeline project.

The accuracy of the results obtained is dependent on the relevant assumptions made based on literature studies. The adopted scenarios could give policymakers insights in maximising the positive direct social impacts and socio-economic benefits brought about by the gas turbine compressor stations. The results obtained could help in forecasting the lifecycle cost, expected performance of the compressor station systems, the economic, social impacts, and social benefits. These results could assist policy makers in decision making and on the feasibility of the proposed Trans-Saharan gas pipeline project. The results obtained in this study has shown a novel contribution investment in the proposed Trans-Saharan gas pipeline project will have through potential local jobs and new roads creations. This could serve as an indicator of the quality of life of the local communities. The developed method can guide in the quantification of social impacts and socio-economic benefits during the design and development stage of any compressor station for pipelines application and other related projects. It is hoped that the considered social impacts in terms of the potential jobs and new roads creations will serve as useful methodological basis for further studies in the techno socio-economic benefits. It will also serve as an important driver for the implementation of the proposed Trans Saharan gas pipeline and any pipeline projects.

8 ECONOMIC OPTIMISATION WITH COMPRESSOR STATION LOCATION AS THE DECISION VARIABLE

8.1 Introduction

This study looks at the economic optimisation of the compressor stations and pipeline systems, which makes up the proposed Trans-Saharan Gas Pipeline project. The compressor stations cost is a major factor determining the total cost of the natural gas transportation system. It has been estimated that the compressor stations operating cost could constitute between 25% and 50% of the whole company's operating budget [22]; [23]. Thus, determining the optimal compressor station locations along the pipeline route through optimisation studies can help in minimising the total lifecycle cost. Since capital and lifecycle cost estimates are the major factors influencing the economic success of any project. The complexity and non-linear behaviour of compressor stations and pipeline systems require an appropriate optimisation scheme to improve its efficiency in operation and flexibility. The optimisation scheme aims to reduce the lifecycle cost in the compressor stations and pipeline systems considering station location optimisation. Lifecycle cost optimisation of the compressor stations and pipeline systems is very significant from an economic perspective. It is important that considerable attention be focused on lifecycle cost optimisation with particular emphasis on compressor station location optimisation. Thus, there is a need to perform studies on lifecycle cost optimisation of compressor station and pipeline system considering station location as a decision variable where station location optimisation can result in large economic savings. As at the time of this study, there is little work done with respect to compressor station location optimisation.

The objectives of this study are to perform economic optimisations of the compressor station and pipeline system lifecycle cost as a function of the compressor station location, pipeline characteristics, availability, and social context. The optimisation problems are formulated considering compressor station location and lifecycle cost of the compressor station and pipeline

system. Scenarios-based techno-economic and techno socio-economic optimisation studies are performed to illustrate the most usual compressor station and pipeline system network configurations that could be found in real life situations. They form the basis for exploring sophisticated network configurations and for future research in these interesting aspects of the compressor stations and pipeline systems optimisation studies.

8.2 Method of Analysis

A techno-economic model of the proposed Trans-Saharan gas pipeline project has been developed in SIMULINK. The techno socio-economic model is developed using computer code implemented in a MATLAB environment. The techno-economic optimisation scheme is carried out using the SIMULINK Graphical User Interface response optimisation tool. A gradient descent optimisation method with a sequential quadratic programming algorithm is utilised by the SIMULINK optimisation tool to evaluate the optimal lifecycle cost at the optimised compressor station locations. The results are compared with a Genetic Algorithm optimisation technique available in the MATLAB toolbox. Subsequently, the techno socio-economic optimisation scheme is implemented using a Genetic Algorithm optimisation method.

8.2.1 Optimisation Assumptions

1. Project life of 30 years
2. Pipeline distance of 4180 km same for all considered scenarios
3. Pipeline maximum allowable operating pressure of 10000 kPa
4. Pipe configurations are the same with the baseline case
5. Same economic assumptions with the baseline case
6. Pipeline is divided into discrete segments, each 10 km long

For the optimiser to use station location as a decision variable, a location identification system was developed. This was linked to the distance from the source of the gas being transmitted. So, the source is at point 0 (0 km), and the gas delivery point is at 4180 km from the source. The pipeline was divided into segments. The source is in segment 1, representing 0-9 km length of the pipeline.

Each pipeline segment is 10 km long while segment 'n' is ' $10(n) - 10$ ' to ' $10(n) - 1$ ' km in length. The optimising algorithm will come out with a sequence of numbers at the optimised station locations along the pipeline route. Such an arrangement gives an automatic station position and sufficient resolution for the analysis.

8.2.2 SIMULINK Optimisation Procedures

The first step in optimisation using SIMULINK is to create the optimisation model using SIMULINK block diagrams. The SIMULINK Graphical User Interface is brought up by selecting 'Response Optimisation' from the Analysis tab. Response optimisation in SIMULINK provides an environment for incorporating the objective function, constraints, decision variable(s) and choosing the optimisation method. The SIMULINK software uses a two-level optimisation algorithm to evaluate the optimisation model. The selected optimisation method in SIMULINK is a gradient descent method with a sequential quadratic programming algorithm. The gradient descent optimisation algorithm uses a first-order iteration technique to find a local minimum of the objective function [92]. It is a robust optimisation method that appreciably minimises the simulation time. The sequential quadratic programming algorithm converts the nonlinear optimisation problem into a sequence of quadratic programming sub-problems [94]. Although, manual adjustment is tedious, the optimisation process is relatively easy to implement as fewer number of iterations are involved and takes less time for convergence to be achieved. Figure 8-1 shows the SIMULINK optimisation flowchart utilised for the techno-economic scenarios.

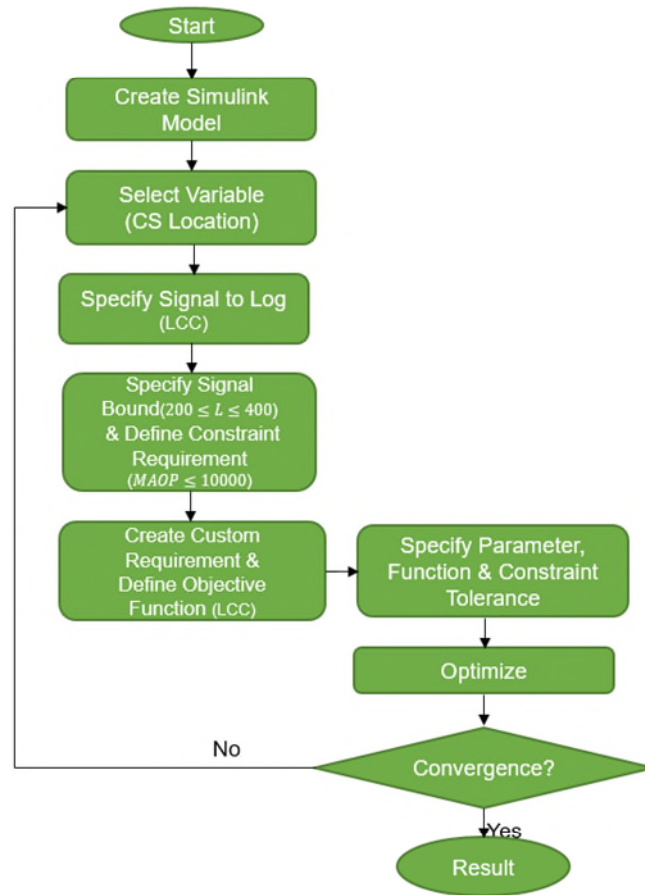


Figure 8-1 SIMULINK Optimisation Flowchart

The optimisation problem is set as follows:

- ❖ The author starts the optimisation process in SIMULINK by specifying the initial values of the decision variable to optimise in the MATLAB command window
- ❖ A new set of decision variables to be optimised is created in SIMULINK by specifying the decision variable's initial, minimum, and maximum values and the scaling factor if needed. The decision variable can be seen in the SIMULINK model workspace. The decision variable will be changing during optimisation, and the values can be seen in the design optimisation workspace
- ❖ The constraint requirements are specified by adding them from the graphical user interface. The model signal to be logged for evaluating against the constraint requirements are specified. The model signal in the present study is the lifecycle cost

- ❖ The constraint on the gas compressor power requirement dependent on the maximum allowable operating pressure of the pipeline of 10000 kPa is specified by selecting the signal bound. The requirement type is less than or equal to the power constraint
- ❖ The custom requirement is created by calling the MATLAB function that specifies this custom requirement. The minimum requirement type is selected because the lifecycle cost for the imposed gas compressor power requirement is being minimised. The MATLAB function processes the structured data, which contains the decision variable being optimised as well as the model signal in the form of an objective function
- ❖ The optimisation method was selected. A gradient descent optimisation method with a sequential quadratic programming method is chosen. The parameter tolerance, function tolerance, and constraint tolerance were set to 1e-9, respectively
- ❖ The author runs the optimisation scheme by selecting the optimise button. The optimisation tool starts working, and one can see how the decision variable being optimised changes in the design optimisation workspace and the model during the iteration process
- ❖ Convergence was achieved after a few iterations, and the optimisation stopped
- ❖ The techno-economic model was running to see that the signal is variable after the optimisation process, and the results were post-processed

8.2.3 Genetic Algorithm Optimisation Procedures

This section describes the optimisation of the techno socio-economic model of the complete TERA framework using a developed code written in MATLAB environment and a genetic algorithm optimisation method available in the MATLAB toolbox. Figure 8-2 shows the genetic algorithm optimisation flowchart.

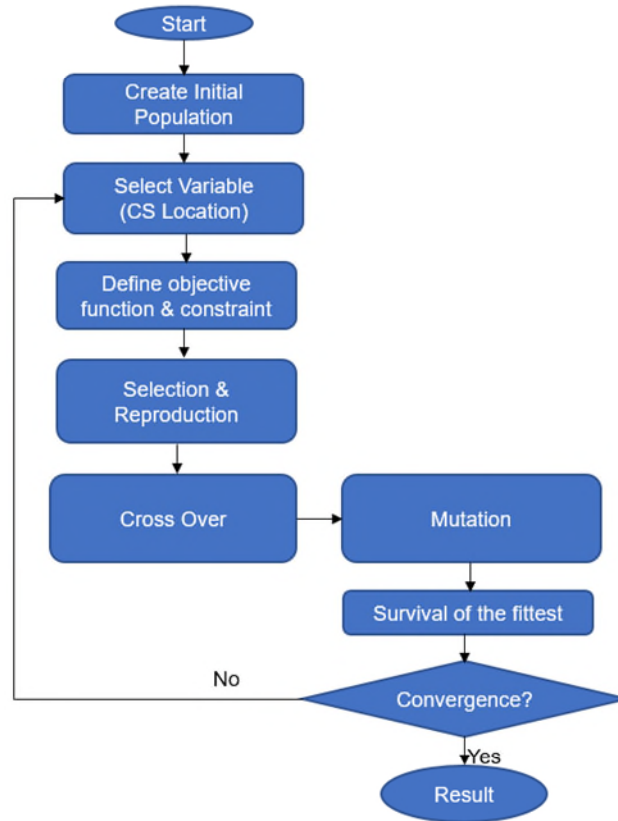


Figure 8-2 Genetic Algorithm Optimization Flowchart

The genetic algorithm optimisation process is started by creating initial population of solutions. The compressor station locations are selected as the decision variable. The objective function and constraint are defined. Subsequently, more suitable individuals from the population are selected based on their objective function and constraint values. This process of selecting more suitable individuals is known as selection and reproduction. The cross over operator starts after the selection of suitable individuals. In this process, each pair of newly formed chromosomes pass through the cross over stage with an applied probability value, say, 0.8. In most cases, the newly formed chromosomes take the best features from each parent's genes and are often better than either parent. A cross over value of 0.8 denotes that the process successfully takes place 80% of the time mating takes place while 20% of the time the selected individuals move to the subsequent generation unchanged.

A constraint dependent mutation was applied to the optimisation process. A mutation is attained by modifying a small fraction of an individual in a population.

The mutation operator makes it feasible to attain the entire search domain by introducing new characteristics not found in the original population. In the survival of the fittest, otherwise known as elitism operator, the most suitable individual is considered as the result of the genetic algorithm optimisation process. The genetic algorithm optimisation result is outputted if convergence criterion is achieved, otherwise the process is repeated until convergence is obtained.

8.2.4 Formulation of the Optimisation Problem

The optimisation problem is formulated with the objective of optimising the lifecycle cost of the compressor stations and pipeline systems considering station location as a decision variable. The baseline case comprises eighteen compressor stations at predetermined locations along the pipeline route. The study considers four scenarios for both the techno-economic and the techno socio-economic cases:

1. Scenario 1: Four units of installed simple cycle triple shafts aero-derivative gas turbine of 15.2 MW capacity driving four gas compressors arranged in parallel per compressor station
2. Scenario 2: Three units of installed simple cycle two shafts gas turbine of 30.1 MW capacity driving three gas compressors arranged in parallel per compressor station
3. Scenario 3: Two units of installed simple cycle two shafts gas turbine of 50 MW capacity driving two gas compressors arranged in parallel per compressor station
4. Scenario 4: One unit of installed intercooled aero-derivative gas turbine of 117 MW capacity driving one gas compressor per compressor station

The optimisation scheme incorporated the performance, availability, social, and economic modules. The gas compressor and gas turbine performance modules estimate the gas compressor power requirement and the gas turbine power that matches the gas compressor drive power based on the fuel consumption and the turbine entry temperatures. The availability module evaluates the turbo-compressor availability required to estimate the availability-based maintenance cost. The social module evaluates the social impacts and benefits of compressor

station location along the pipeline route. The economic module estimates the techno-economic and the techno socio-economic lifecycle costs arising from the integrated TERA framework.

Figure 8-3 shows the flowchart of the optimisation process utilised in this study.

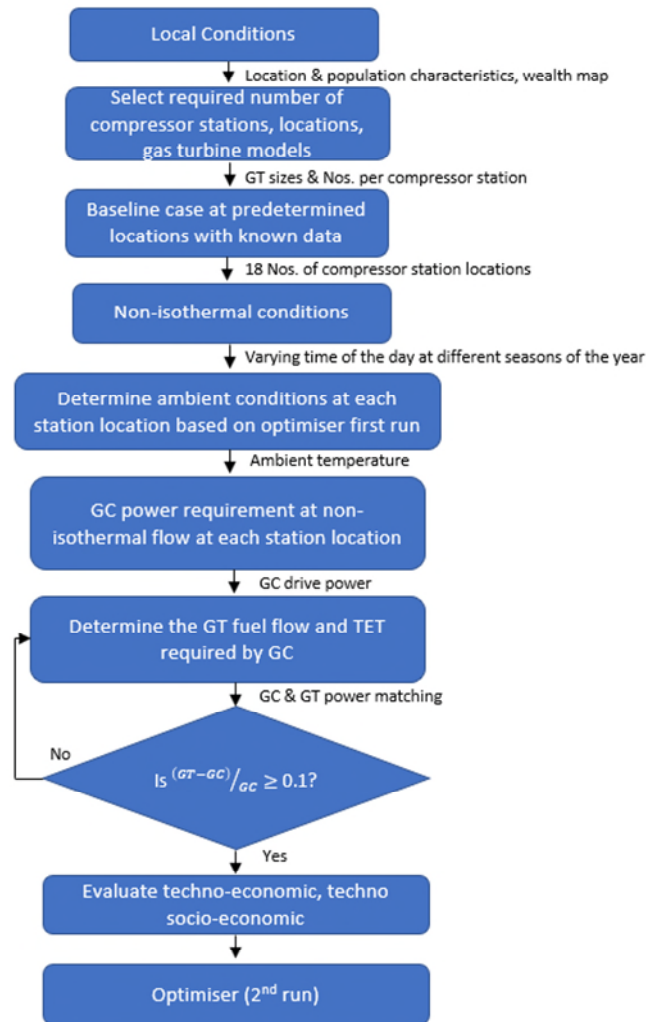


Figure 8-3 TERA Optimisation Flowchart

The required sizes and numbers of gas turbine models are selected based on the local conditions at each station. The baseline case comprising eighteen numbers of compressor station at predetermined locations with known data are defined. Subsequently, the ambient conditions at each compressor station at non-isothermal conditions and at varying times of the day at different seasons of the year for the optimised cases are determined based on the first run of the optimiser. The ambient conditions take into account changes in elevation along

the pipeline route obtained from the pipeline elevation-distance profile in Figure 3-2. The outcome is the ambient temperatures at the optimised location. The optimisation scheme estimates the gas compressor power requirement at these temperatures for winter, dry, and hot seasons of the year at non-isothermal conditions. The gas turbine fuel consumption and turbine entry temperature required by the gas compressor is evaluated. The result of this matching is noted if convergence is attained. If the fractional difference between the gas compressor power requirement and gas turbine power is less than 0.1, the iteration process is repeated until convergence is achieved. The optimisation scheme subsequently evaluates the techno-economics and the techno socioeconomics of the project accordingly. The optimisation process is repeated by varying the compressor station location until an optimal station location is attained that gives the optimal lifecycle cost for the compressor station and pipeline system with the considered scenarios.

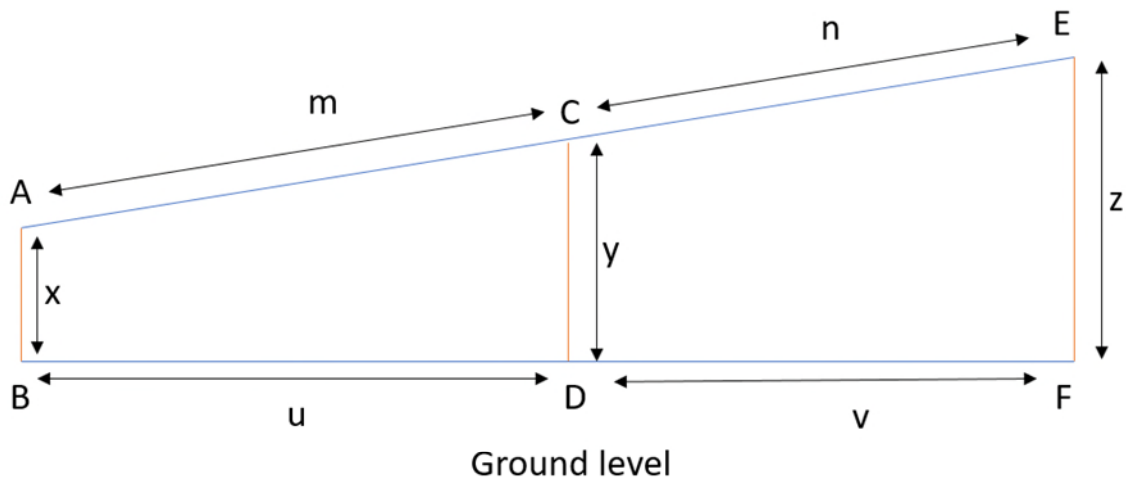


Figure 8-4 Compressor Station Locations Schematic

Consider compressor station locations A, B, C, D, E, and F as shown in Figure 8-4. Location B is at the origin while locations B, D, and F are at ground level. The local conditions at locations A and E are known while ambient condition for location C is unknown. The ambient conditions for a station at location C are to be determined. The steps involved in the solution is to interpolate for distance, altitude, and to adjust for altitude on an approximate international standard

atmosphere basis. The interpolated altitude adjustment y , for the hypothetical new station location C can be written as:

$$y = x + \frac{u(z - x)}{(u + v)} \quad (8-1)$$

Where:

x = Altitude at compressor station location A, (m)

z = Altitude at compressor station location E, (m)

u = Ground level distance between compressor station location B and D, (km)

v = Ground level distance between compressor station location D and F, (km)

The ambient temperatures based on the lapse rate at international standard atmospheric conditions for that altitude at locations A, E, and the new location C required for adjustment purposes are given by:

$$T_A = 288.15 - 0.0065x \quad (8-2)$$

$$T_E = 288.15 - 0.0065z \quad (8-3)$$

$$T_{C,h} = 288.15 - 0.0065y \quad (8-4)$$

$$T_{C,a} = 288.15 - 0.0065y_t \quad (8-5)$$

Where:

T_A = Ambient temperature at compressor station location A, K

T_E = Ambient temperature at compressor station location E, K

$T_{C,h}$ = Ambient temperature at hypothetical compressor station location C, K

$T_{C,a}$ = Ambient temperature at actual compressor station location C, K

y_t is the real station altitude from topography information obtained from the pipeline elevation-distance profile in Figure 3-2. The ambient temperature

difference, ΔT , required for the new location C altitude temperature correction is given by:

$$\Delta T = T_{C,a} - T_{C,h} \quad (8-6)$$

The hypothetical new station ground level ambient temperature T_D at interpolated altitude is given by:

$$T_D = T_B + \frac{u(T_F - T_B)}{(u + v)} \quad (8-7)$$

Where:

T_B = Ambient temperature at compressor station location B, K

T_F = Ambient temperature at compressor station location F, K

The real station ambient temperature T_r , at the real station altitude from topography information obtained from the pipeline elevation-distance profile in Figure 3-2 is given by:

$$T_r = T_D + \Delta T \quad (8-8)$$

Equation (8-8) is the determined location ambient temperature. The above procedures are utilised in the optimisation scheme to determine the temperatures at non-isothermal conditions for the three seasons of the year. A change in the compressor station location leads to a corresponding change in the ambient conditions. These ambient conditions vary at non-isothermal conditions across the winter, dry, and hot seasons of the year. The optimisation scheme utilised this change in value to estimate the gas compressor power requirement and corresponding gas turbine power needed to match the gas compressor drive power considering the imposed constraint. As the optimiser changes compressor station location, the algorithm interpolates to find the ambient conditions at the new location. The inputs for the optimiser are station positioned and location dependent. This will also trigger a social benefit calculation that is different for each location. The social benefits changes with a change in compressor station location.

For the optimiser to use station location as a decision variable, a location identification system was developed. This was linked to the distance from the source of the gas being transmitted. So, the source is at point 0 (0 km) and the gas delivery point is at 4180 km from the source. I considered discrete pipeline segments each 10 km long for the station location optimisation. The source compressor station is in segment 1, representing 0-9 km length of the pipeline. Other compressor stations can be located either in the middle or within the kilometre range of each pipe segment. Segment 'n' is ' $10(n) - 10$ ' to ' $10(n) - 1$ ' km in length. Thus, the optimising algorithm will come out with a sequence of numbers at the optimised station locations along the pipeline route. Such an arrangement gives an automatic station position and sufficient resolution for the computation.

8.2.5 The Optimisation Database

The database and search domain for the optimiser is the compressor station location characteristics comprising the pipeline elevation-distance profile (see Figure 3-2) and the ambient temperatures at each location. The pipeline maximum allowable operating pressure, gas compressor suction pressures, pressure ratios, polytropic head, and power requirements are other database components. The database has columns: sets of compressor station locations ambient temperatures and their corresponding Z , P_1 , P_2 , r_p , Q , m , H_p , and P_G . The highlighted symbols have their usual meaning. The lower and upper bounds vary for each scenario at the different compressor station locations. The step size between datapoints is fixed at 10 km. The optimiser searches the database for the gas compressor power dependent on the selected gas turbine models for each scenario which will give the optimal compressor station locations along the pipeline route. The optimiser interpolates between steps for values that lie between the data. See Appendices M, N, O, and P for part of the MATLAB and genetic algorithm optimisation codes and the optimisation database developed.

8.2.6 Decision Variable, Objective Function and Constraint

The desired compressor station location L , was selected as the decision variable whose value is required to be optimised. The decision variable L , was initialised

with a value of 200 km at the start of the techno-economic optimisation process using the SIMULINK approach. The decision variable L , was allowed to vary from a minimum of 200 km to a maximum of 400 km for the first compressor station location. The optimisation boundaries for the techno socio-economic study using genetic algorithm were set between a minimum of [200 580 960 1330 1690 2060 2420 2800 3160 3520 3880] and a maximum of [390 770 1150 1520 1880 2250 2610 2990 3350 3710 4090] for scenario 4, respectively. Similarly, minimum, and maximum boundaries were specified for the other scenarios using the genetic algorithm approach. The selected gas turbine installed power output is kept constant for each scenario considered in this study. The reason is that a fixed pipeline thickness was utilised in this research. Thus, compressor station size was not included as another decision variable not to exceed pipeline strength requirements. However, it is anticipated that the inclusion of compressor station size as another decision variable under varying pipeline thickness will be considered in future work. The final optimised compressor station location depends on the pipeline elevation-distance profile and the prevailing ambient temperatures experienced at each location along the pipeline route. However, the selected gas turbine models are different for each scenario considered in this study. The different models ensure that the power variation is also considered in optimisation.

The lifecycle cost of the compressor stations and pipeline systems represents the objective function of the optimisation scheme. The lifecycle cost comprises the gas compressor, pipeline, gas turbine, auxiliaries, fuel, and maintenance costs. The job cost and road cost constitute the additional costs element of the lifecycle cost for the techno socio-economic case study. They are another novel aspect of the optimisation scheme. In this research, the lifecycle cost for each considered scenario is to be minimised. The scenario that gives the lowest lifecycle cost estimation and possibly highest net present value is considered the best scenario.

The constraint is the maximum allowable operating pressure of the pipeline, dependent on the gas compressor power requirement based on the selected gas turbine models. This constraint was imposed to ensure the gas compressor

provided the required pressure at the pipe inlet for natural gas transportation. The gas compressor power must be less than or equal to 90% of the selected gas turbine installed power output to ensure adequate matching of the gas turbine power with the gas compressor power for each considered scenario.

The Optimisation problem to optimise the compressor station and pipeline system is formulated as follows:

Minimise the objective function:

$$L_c(L) = P_t(L) + GC_t(L) + GT_c(L) + P_{aux}(L) + F_{lc}(L) + M_{lc}(L) \quad (8-9)$$

Subject to the constraint:

$$P_1 \leq 10000 \quad (8-10)$$

$$P_G \leq 0.9P_T \quad (8-11)$$

$$200 \leq L_1 \leq 390 \quad (8-12)$$

$$580 \leq L_2 \leq 770 \quad (8-13)$$

$$960 \leq L_3 \leq 1150 \quad (8-14)$$

$$L_{n,min} \leq L_n \leq L_{n,max} \quad (8-15)$$

Where:

L_c = Techno-economic lifecycle cost, \$

P_1 = Maximum allowable operating pressure at the pipe inlet, kPa

P_G = Gas compressor power, kW

P_T = Gas turbine power, kW

$L_1, L_2, \dots, L_n$ = Optimised compressor station locations

P_t = Total pipeline cost, \$

GC_t = Total gas compressor cost, \$

GT_c = Gas turbine capital cost, \$

P_{aux} = Auxiliaries cost, \$

F_{lc} = Lifecycle fuel consumption cost, \$

M_{lc} = Lifecycle maintenance cost, \$

The objective function to be minimised for the techno socio-economic case can be written as:

Minimise the objective function:

$$L_T(L) = P_t(L) + GC_t(L) + GT_c(L) + P_{aux}(L) + F_{lc}(L) + M_{lc}(L) + E_c(L) + R_c(L) \quad (8-16)$$

Where:

L_T = Techno socio-economic lifecycle cost, \$

E_c = Employment cost, \$

R_c = Road construction cost, \$

8.2.7 The Techno socio-economic Optimisation Settings

8.2.7.1 Population Size

Population size shows how many individuals are in a generation. This study used different values for the population size. The author used population sizes of 50, 100, 200, 300, 400, 500 and above. The optimal solutions obtained for the different population sizes from 500 to 800 for scenario 1, 300 to 400 for scenario 2, 300 to 450 for scenario 3, and 200 to 500 for scenario 4 were observed to be the same for the objective function and decision variable. This observation confirms the convergence of the genetic algorithm optimisation process. The computational time for the optimal solution to be attained increases with an increase in the population size.

8.2.7.2 Lower and Upper Bounds

The lower and upper bounds vary for the different power settings and compressor station locations. For all scenarios, the lower and upper bound for the first

compressor station location were set at 200 km and 390 km, respectively. The bounds were specified to ensure optimal compressor station distances and locations for the selected gas turbine models of each scenario considered in this study.

8.2.7.3 Maximum Generation and Convergence Criteria

The maximum generation shows the maximum number of iterations for the optimisation algorithm. The maximum number of generations of 25 was specified in the algorithm for all scenarios. Although, convergence was achieved at a relatively lower number of generations.

The function tolerance and constraint tolerance were set to $1e-9$ for all considered scenarios. These tolerances are stopping criteria that determine conditions for the termination of the algorithm.

8.2.7.4 The effect of the Mutation Function

The mutation function provides genetic diversity by modifying a small fraction of an individual in the population. They make it feasible to attain the entire search domain. Adaptive feasible, a constraint-dependent mutation was selected for all scenarios in the optimisation algorithm. This mutation function ensures that feasible parents produce feasible children where feasibility depends on bounds and constraints.

8.2.7.5 Scaling Function, Selection Function and Reproduction

The scaling function turns raw fitness scores returned by the objective function to a range of values appropriate for the selection function. **Rank** fitness scaling was selected for all scenarios. Rank scaled the raw fitness scores based on each individual rank.

The selection function selects parents for the next generation based on their scaled values from the rank fitness scaling. **Roulette** was selected for all scenarios.

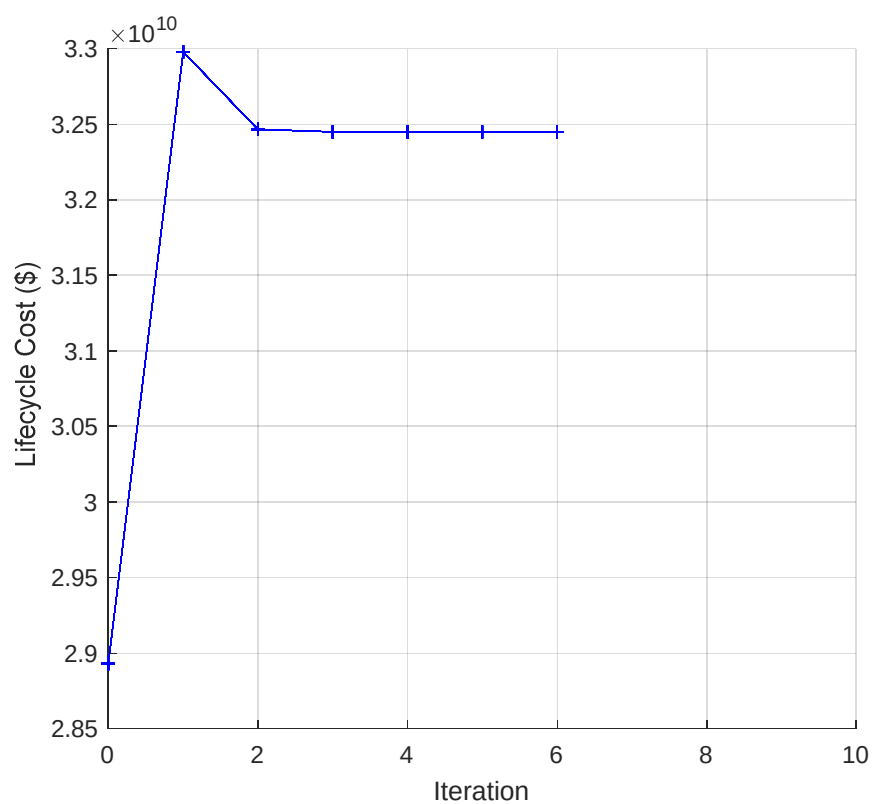
Reproduction regulates how the algorithm produces children for each new generation. An elite count of 2 was specified for scenarios 3 and 4. An elite count

of 3 was specified for scenarios 1 and 2. The elite count shows the number of individuals assured to survive to the next generation. A crossover fraction of 0.7 was specified for scenario 4, while a value of 0.8 was specified for scenarios 1, 2, and 3 in the optimisation algorithm. Crossover shows the fraction of the next generation produced by crossover.

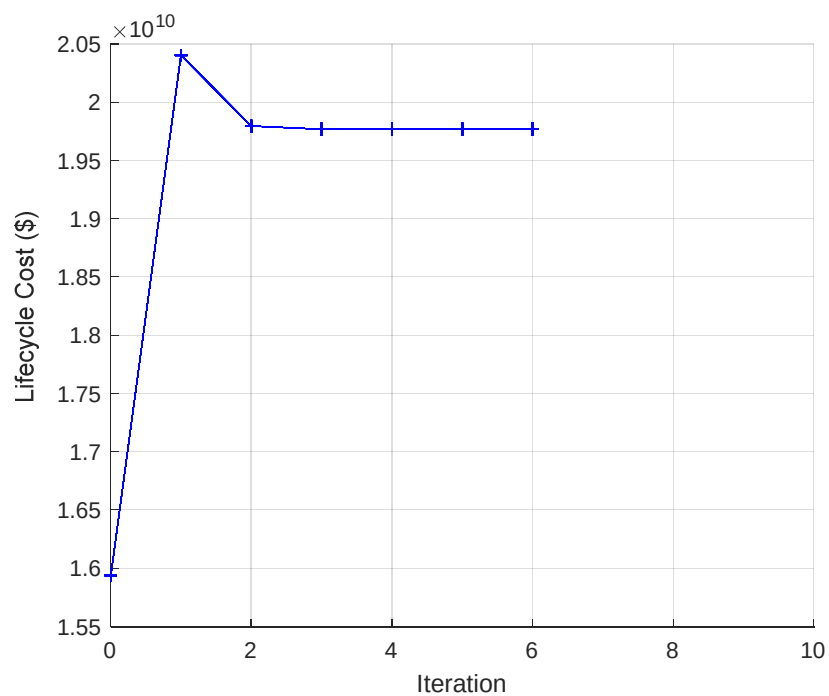
8.3 Results and Discussion

8.3.1 Case A: Techno-Economic Optimisation using SIMULINK

Figure 8-5 shows the optimised lifecycle cost using SIMULINK for scenario 1, assuming a discount rate (DR) of zero and 15%, respectively. This consists of four units of installed simple cycle triple shafts aero-derivative gas turbine of 15.2 MW capacity driving four gas compressors arranged in parallel per compressor station. Convergence was achieved after the 2nd iteration, and optimisation runs continued until the 6th iteration, demonstrating the time savings involved in the optimisation process. Optimisation shows 16 numbers of compressor station locations along the pipeline route with a reduction in the lifecycle costs from \$36.56 billion in the baseline to \$32.45 billion in scenario 1 assuming a DR of zero.



(a) (DR = 0)

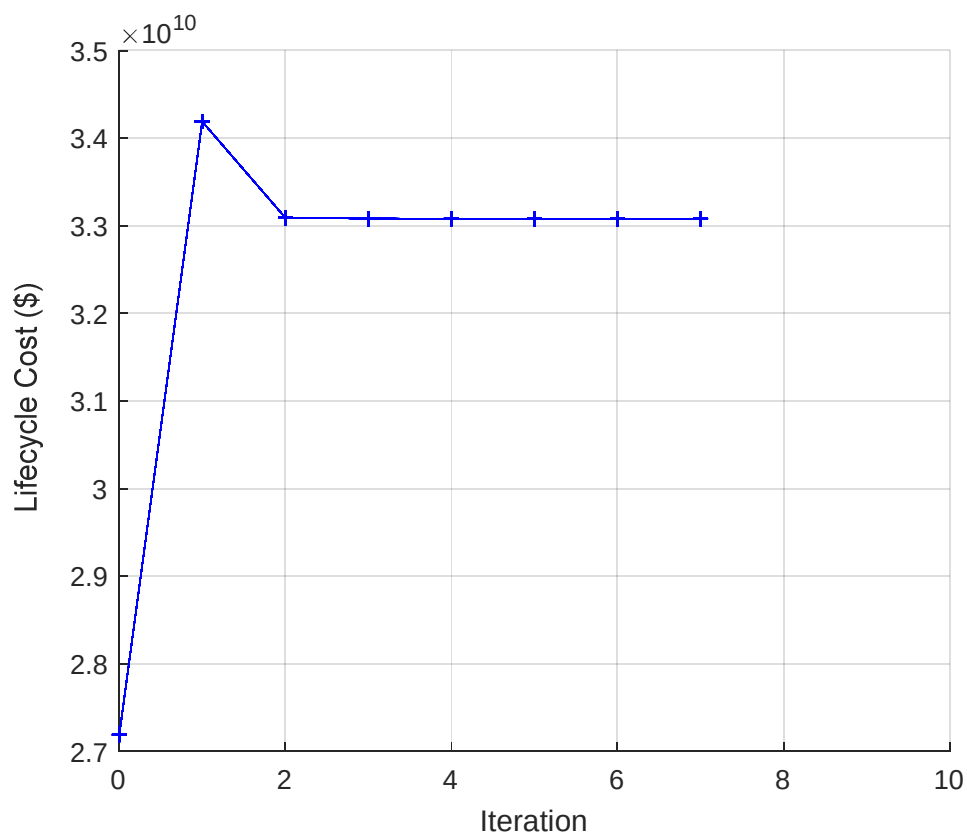


(b) (DR = 15%)

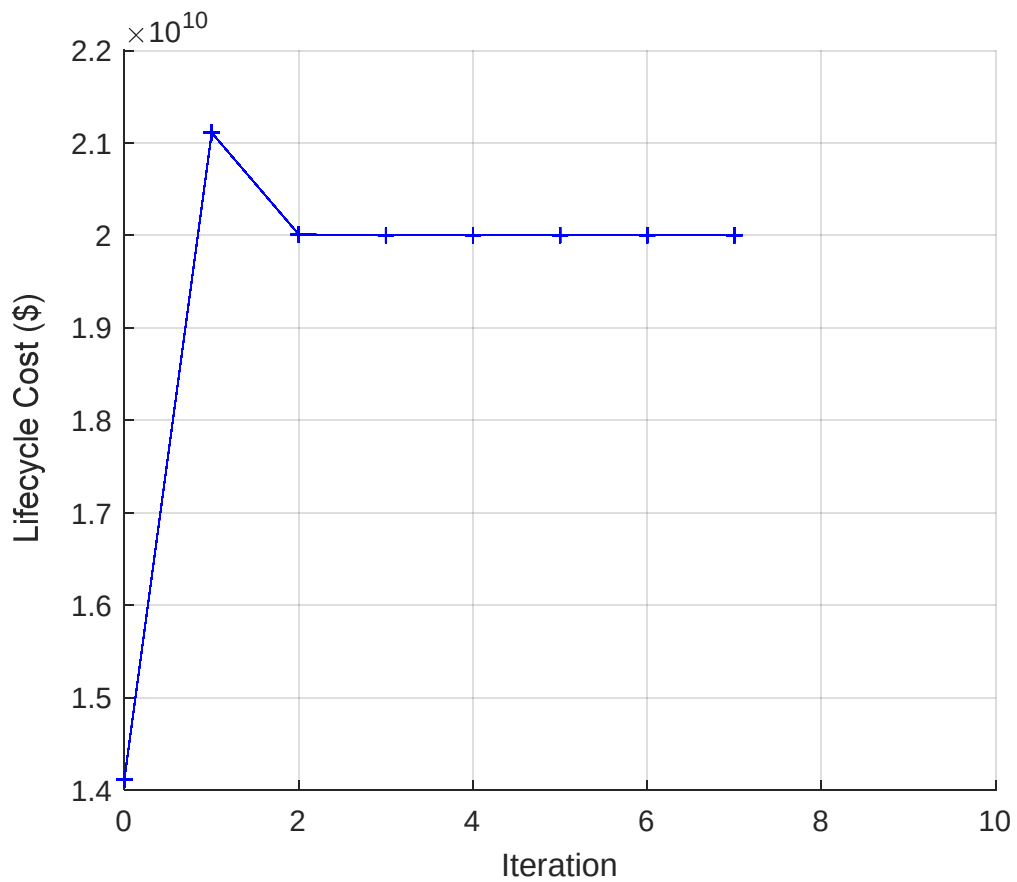
Figure 8-5 Optimised Lifecycle Cost for Techno-economic Scenario 1

The lifecycle cost reduces from \$22.24 billion in the baseline to \$19.77 billion in scenario 1, assuming a DR of 15%. The optimised compressor station locations are at 1, 28, 55, 82, 109, 135, 162, 188, 213, 240, 266, 292, 318, 344, 369, and 395 segments of the pipeline.

Figure 8-6 shows the optimised lifecycle cost using SIMULINK for scenario 2, assuming a discount rate (DR) of zero and 15%, respectively. This consists of three units of installed simple cycle two shafts gas turbine of 30.1 MW capacity driving three gas compressors arranged in parallel per compressor station. Convergence was achieved after the 2nd iteration and optimisation runs continue until the 7th iteration, demonstrating the time savings involved in the optimisation process. Optimisation shows 13 numbers of compressor station locations along the pipeline route with reduction in the lifecycle costs from \$36.56 billion in the baseline to \$33.08 billion in scenario 2 assuming a DR of zero.



(a) (DR = 0)

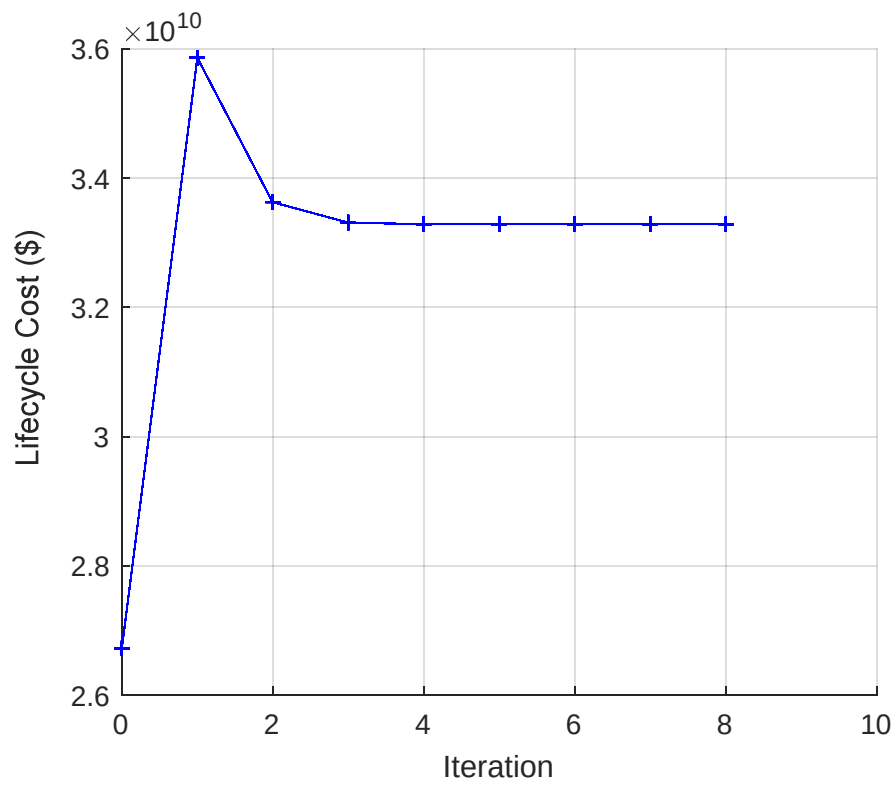


(b) (DR = 15%)

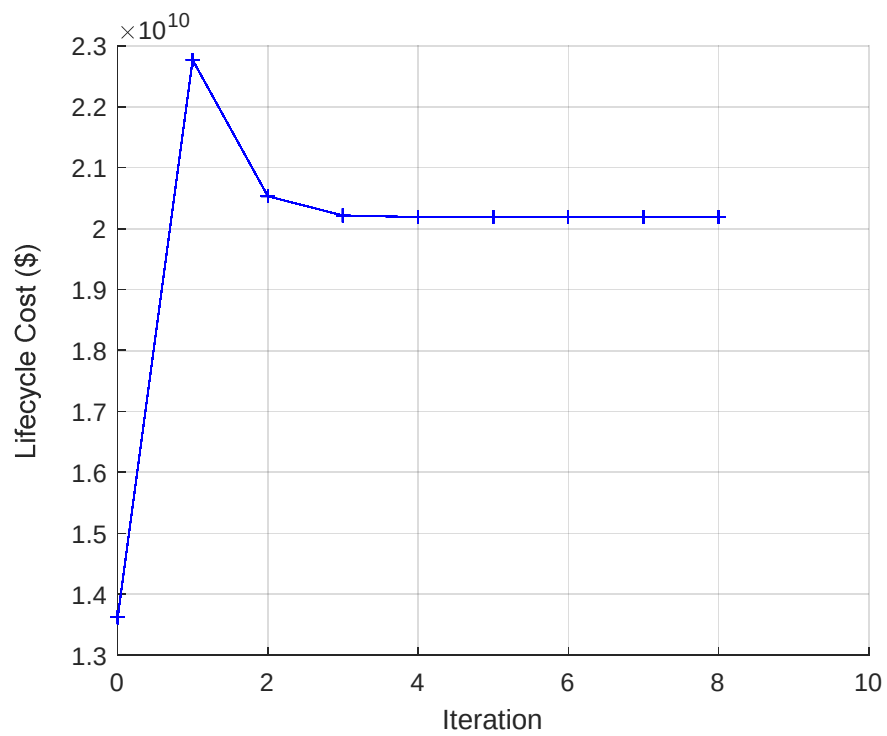
Figure 8-6 Optimised Lifecycle Cost for Techno-economic Scenario 2

The lifecycle cost reduces from \$22.24 billion in the baseline to \$20.00 billion in scenario 2, assuming a DR of 15%. The optimised compressor station locations are at 1, 35, 68, 101, 134, 167, 200, 233, 266, 298, 331, 363, and 395 segments of the pipeline.

Figure 8-7 shows the optimised lifecycle cost using SIMULINK for scenario 3, assuming a discount rate (DR) of zero and 15%, respectively. This consists of two units of installed simple cycle two shafts gas turbine of 50 MW capacity driving two gas compressors arranged in parallel per compressor station.



(a) (DR = 0)



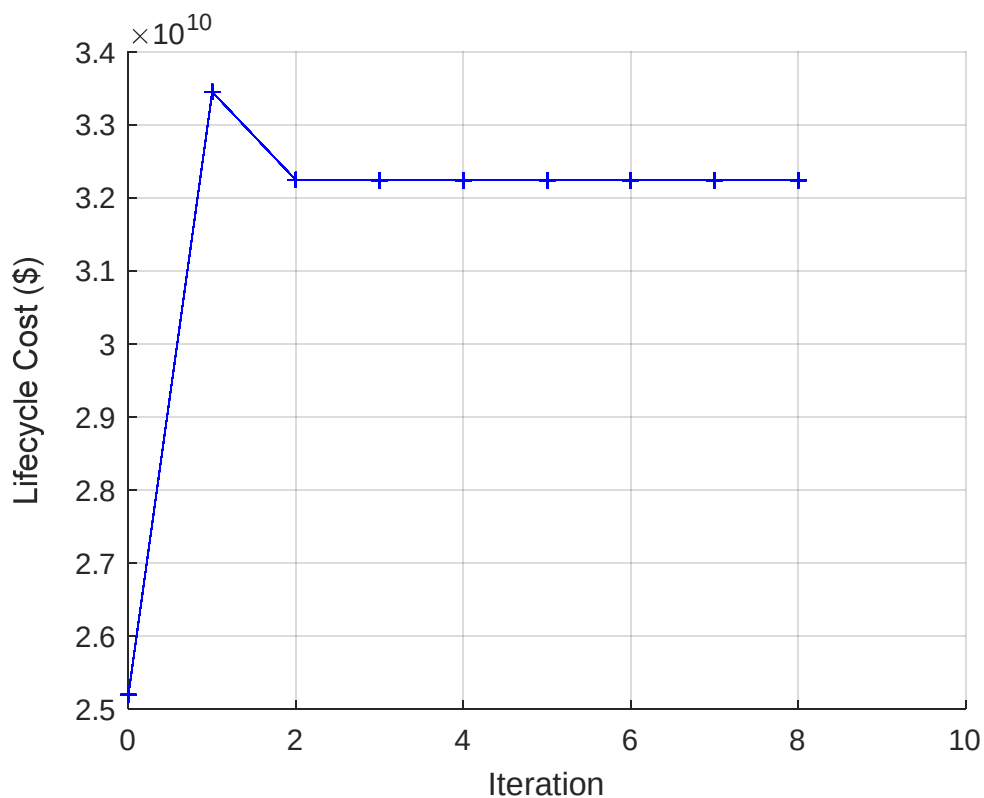
(b) (DR = 15%)

Figure 8-7 Optimised Lifecycle Cost for Techno-economic Scenario 3

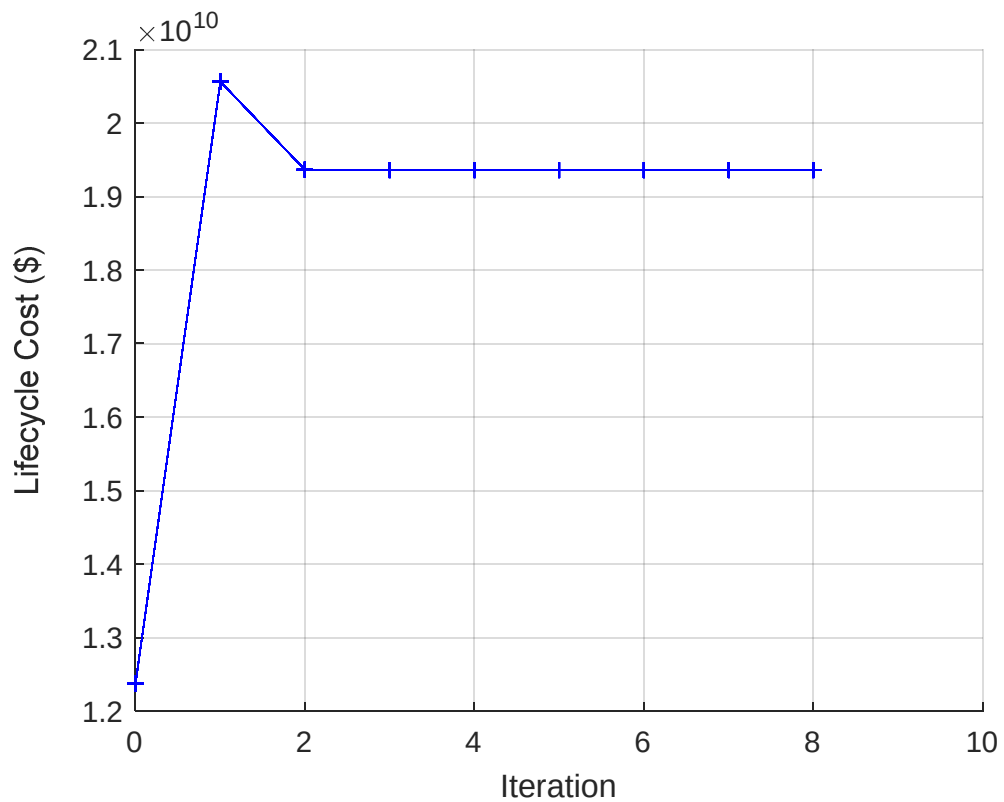
Convergence was achieved after the 3rd iteration and optimisation runs continue until the 8th iteration, demonstrating the time savings involved in the optimisation process. Optimisation shows 12 numbers of compressor station locations along the pipeline route with reduction in the lifecycle costs from \$36.56 billion in the baseline to \$33.29 billion in scenario 3 assuming a DR of zero.

The lifecycle cost reduces from \$22.24 billion in the baseline to \$20.19 billion in scenario 3, assuming a DR of 15%. The optimised compressor station locations are at 1, 36, 71, 106, 141, 175, 209, 244, 277, 312, 346, and 379 segments of the pipeline.

Figure 8-8 shows the optimised lifecycle cost using SIMULINK for scenario 4, assuming a discount rate (DR) of zero and 15%, respectively. This consists of one unit of installed intercooled aero-derivative gas turbine of 117 MW capacity driving one gas compressor per compressor station.



(a) (DR = 0)



(b) (DR = 15%)

Figure 8-8 Optimised Lifecycle Cost for Techno-economic Scenario 4

Convergence was achieved after the 2nd iteration and optimisation runs continue until the 8th iteration, demonstrating the time savings involved in the optimisation process. Optimisation shows 12 numbers of compressor stations along the pipeline route with reduction in the lifecycle costs from \$36.56 billion in the baseline to \$32.24 billion in scenario 4 assuming a DR of zero.

The lifecycle cost reduces from \$22.24 billion in the baseline to \$19.36 billion in scenario 4, assuming a DR of 15%. The optimised compressor station locations are at 1, 38, 76, 113, 150, 186, 222, 260, 296, 332, 368, and 408 segments of the pipeline.

The results are compared with genetic algorithm optimisation techniques and computer code written in MATLAB. Figure 8-9 shows the comparison results for one of the scenarios using the genetic algorithm approach.

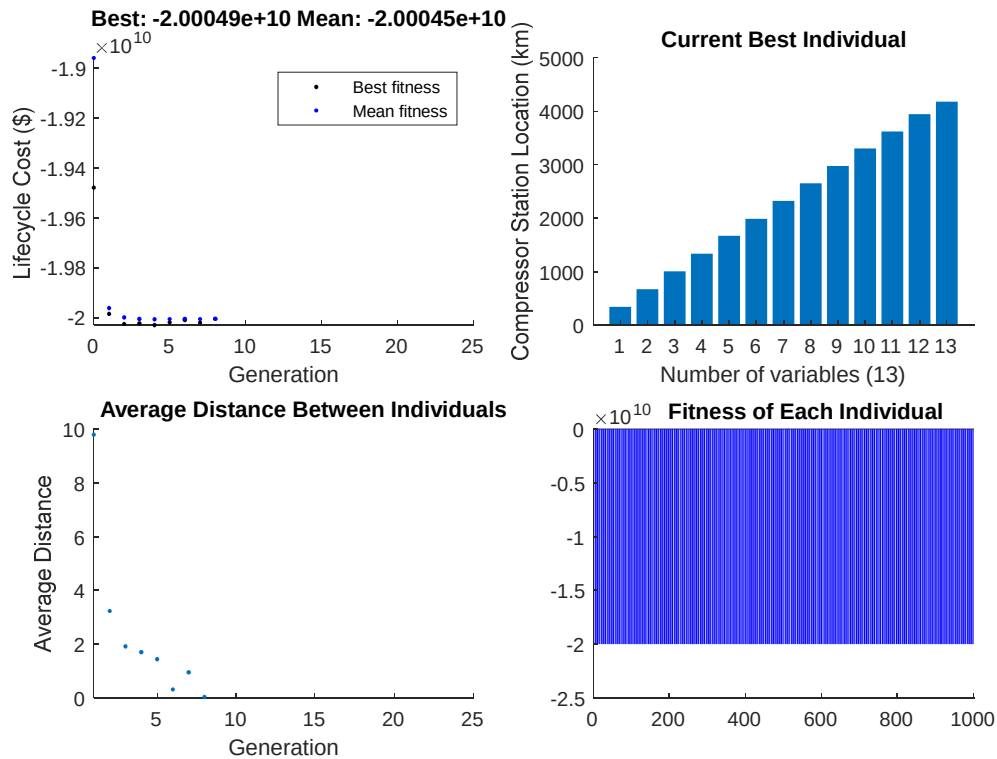


Figure 8-9 Comparison of Lifecycle Cost for Techno-economic Scenario 2 (DR = 15%)

Table 8-1 and Table 8-2 show the overview of the results obtained for the comparison process of the techno-economic case at a 15% discount rate.

Table 8-1 Comparison of Lifecycle Cost for Techno-economic Scenario 2

Station No	Location (km)	
	Simulink	GA
1	0	0
2	341.3	341.4
3	674.0	673.7
4	1007.9	1007.9
5	1339.0	1339.1
6	1669.4	1669.3
7	1990.4	1990.0
8	2322.4	2322.0
9	2653.1	2652.7
10	2976.0	2975.8
11	3306.4	3306.5

	Location (km)	
Station No	Simulink	GA
12	3622.9	3622.5
13	3948.6	3948.7
Lifecycle cost (\$ billion)	20.003	20.005

Table 8-2 Comparison of the Techno-economic Optimisation Process

	Lifecycle Cost (\$ billion)	
Scenarios	SIMULINK Approach	Genetic Algorithm Method
1.	19.768	19.765
2.	20.003	20.005
3.	20.190	20.189
4.	19.362	19.367

The SIMULINK optimisation process utilising a gradient descent method with a sequential quadratic programming algorithm yields good results. The optimal compressor station locations converge to the desired local minimum of the lifecycle cost based on the specified tolerance limits of $1e-9$. The optimal compressor station locations are close to the global optimal solution. The results show that the lifecycle cost is a differentiable convex function of the compressor station locations. Since for a convex function, the local minimum solution is also the global minimum [93]. However, the genetic algorithm optimisation method generally finds the global optimal solution of the lifecycle cost. The results show good agreement with the same number of compressor station locations and lifecycle cost estimation for each scenario. They show that the optimum locations are near the global optimum. They demonstrate the benefits of the SIMULINK optimisation method. Since this is the first time this optimisation technique is applied to compressor station location optimisation. This further illustrates the novelty of the developed integrated TERA and optimisation model in this present research.

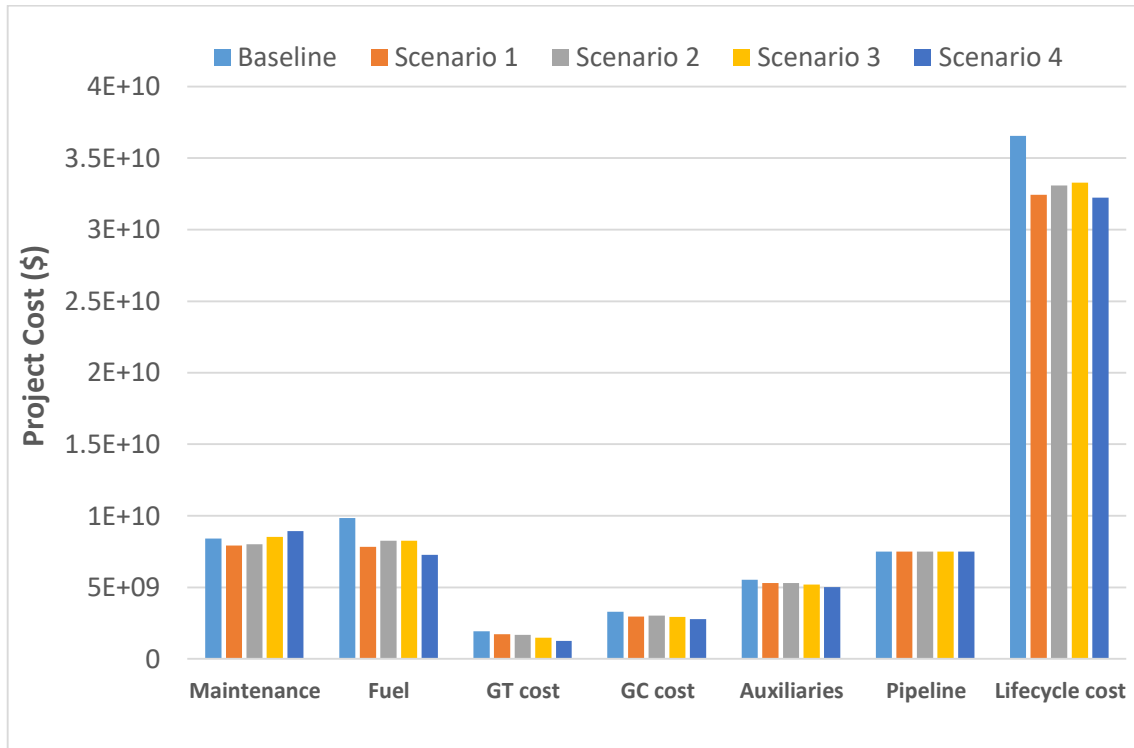


Figure 8-10 Comparison of the Techno-economic Lifecycle Project Cost

Figure 8-10 compares the techno-economic lifecycle project cost for the considered scenarios. The results show significant savings in the optimised lifecycle cost estimation for the considered scenarios compared to the baseline case. Scenarios 1, 2, 3, and 4 shows improvement of 12.67%, 10.52%, 9.82%, and 13.40%, respectively, from the baseline case. Scenario 4 has the lowest lifecycle cost among the scenarios.

8.3.2 Case B: Techno Socio-Economic Optimisation using Genetic Algorithm

Figure 8-11 shows the optimised lifecycle cost using genetic algorithm for the techno socio-economic case of scenario 1. This consists of four units of installed simple cycle triple-shafts aero-derivative gas turbine of 15.2 MW capacity driving four gas compressors arranged in parallel per compressor station.

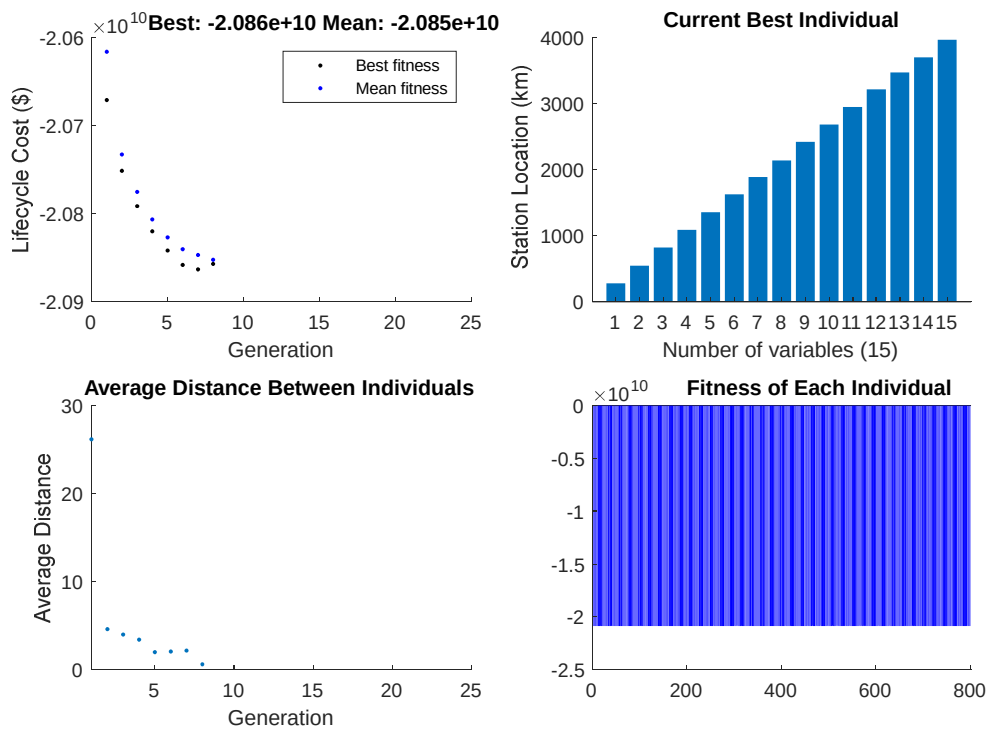


Figure 8-11 Optimised Lifecycle Cost for Techno socio-economic Scenario 1

The lifecycle cost is represented as best fitness and mean fitness values. The fitness values change during the optimisation process until convergence is attained. The negative sign shown in the figure indicates that the lifecycle cost is being minimised. The best fitness value representing the optimised lifecycle cost is \$20.86 billion. The lower left graph shows the average distance between individuals during the optimisation process. The upper right graph shows optimised station locations. The results show good convergence with 16 numbers of compressor station locations along the pipeline route. The source is at the origin. The optimised compressor station locations are at 1, 28, 55, 82, 109, 136, 163, 189, 215, 242, 269, 295, 322, 348, 371, and 397 segments of the pipeline.

Figure 8-12 shows the optimised lifecycle cost using genetic algorithm for the techno socio-economic case of scenario 2. This consists of three units of installed simple cycle two-shafts gas turbine of 30.1 MW capacity driving three gas compressors arranged in parallel per compressor station.

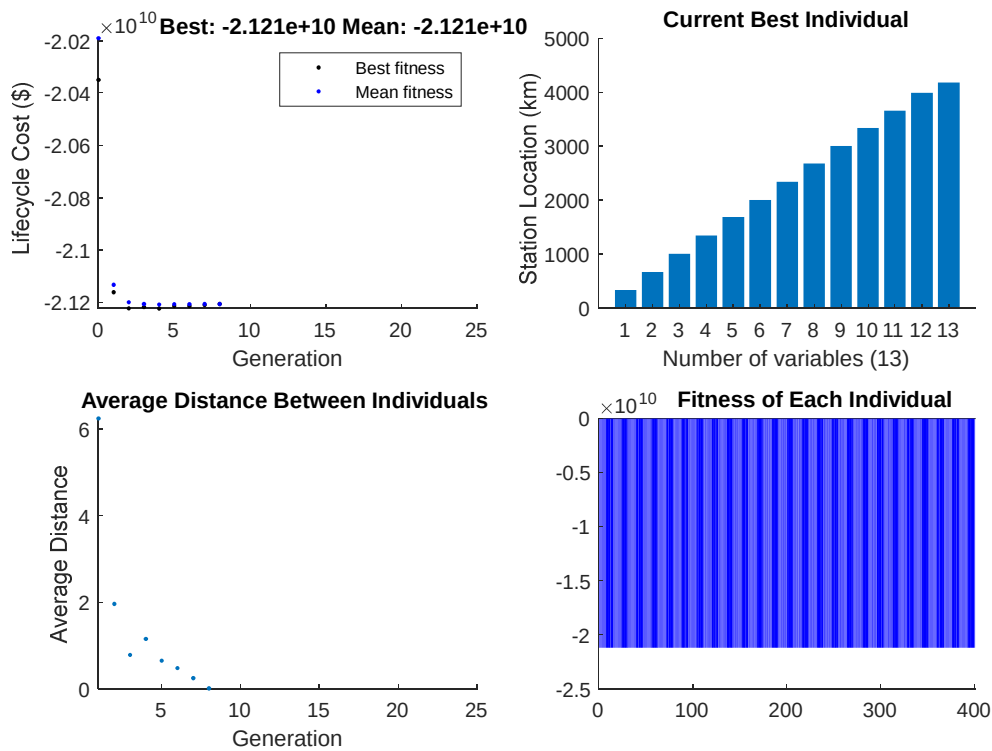


Figure 8-12 Optimised Lifecycle Cost for Techno socio-economic Scenario 2

The lifecycle cost is represented as best fitness and mean fitness values. The fitness values change during the optimisation process until convergence is attained. The best fitness value representing the optimised lifecycle cost is \$21.21 billion. The lower left graph shows the average distance between individuals during the optimisation process. The upper right graph shows optimised compressor station locations. The results show good convergence with 13 numbers of compressor station locations along the pipeline route. The source is at the origin. The optimised compressor station locations are at 1, 35, 68, 102, 136, 169, 201, 235, 268, 301, 334, 366, and 399 segments of the pipeline.

Figure 8-13 shows the optimised lifecycle cost using genetic algorithm for the techno socio-economic case of scenario 3. This consists of two units of installed simple cycle two-shafts gas turbine of 50 MW capacity driving two gas compressors arranged in parallel per compressor station.

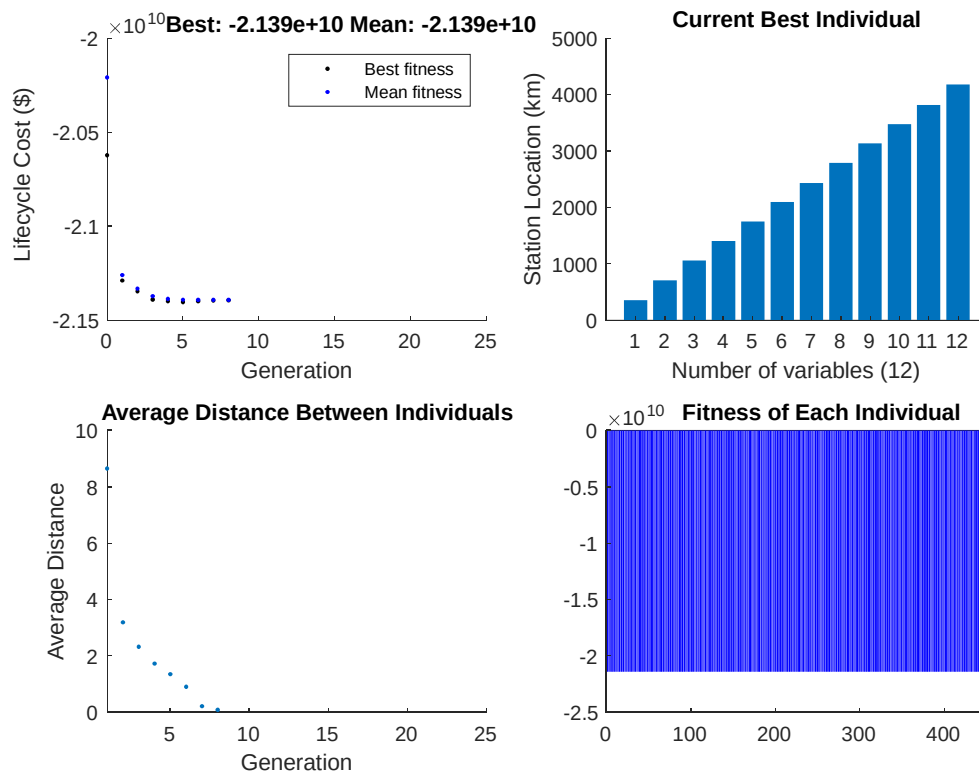


Figure 8-13 Optimised Lifecycle Cost for Techno socio-economic Scenario 3

The best fitness value representing the optimised lifecycle cost is \$21.39 billion. The results show good convergence with 12 numbers of compressor station locations along the pipeline route. The source is at the origin. The optimised compressor station locations are at 1, 36, 71, 106, 141, 176, 210, 243, 279, 314, 348, and 382 segments of the pipeline.

Figure 8-14 shows the optimised lifecycle cost using genetic algorithm for the techno socio-economic case of scenario 4. This consists of one unit of installed intercooled aero-derivative gas turbine of 117 MW capacity driving one gas compressor per compressor station.

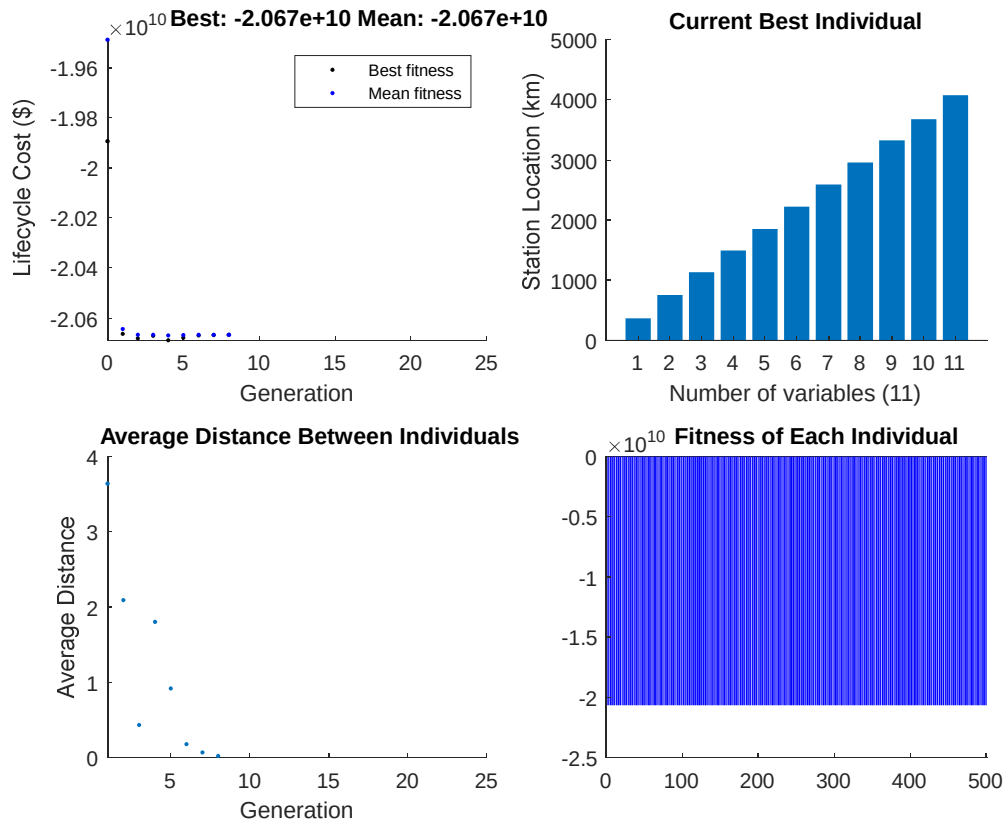


Figure 8-14 Optimised Lifecycle Cost for Techno socio-economic Scenario 4

The best fitness value representing the optimised lifecycle cost is \$20.67 billion. The results show good convergence with 12 numbers of compressor station locations along the pipeline route. The source is at the origin. The optimised compressor station locations are at 1, 37, 76, 114, 150, 186, 223, 259, 297, 333, 368, and 408 segments of the pipeline.

8.3.3 Sensitivity Analyses on the Effects of different Population Size and Genetic Algorithm Parameters on the Results

Sensitivity analyses were carried out on the effects of different population sizes and optimisation algorithm parameters on the results. Different values of the population size and optimisation algorithm parameters were used. The optimisation algorithm was run multiple times with these different values. The optimal solutions were attained for population sizes in the range of 500 to 800 for scenario 1, 300 to 400 for scenario 2, 200 to 450 for scenario 3, and 200 to 500 for scenario 4 and have been the same. The sensitivity analysis shows that

variation in the population size affects the accuracy of the results. Although, the computational time increases with an increase in the population size. These values of population sizes used when the optimal solutions are attained are acceptable. They demonstrate the convergence of the optimisation algorithm. The following shows the optimisation algorithm parameters used when the optimal solutions are achieved:

- ❖ Population sizes in the range of 500 to 800 for scenario 1, 300 to 400 for scenario 2, 200 to 450 for scenario 3, and 200 to 500 for scenario 4
- ❖ Maximum number of generations of 25 was specified for all scenarios
- ❖ Rank fitness scaling was selected for all scenarios
- ❖ Roulette was selected for all scenarios
- ❖ Constraint dependent crossover was applied to all scenarios
- ❖ Adaptive feasible mutation was chosen for all scenarios
- ❖ Elite count of 2 was specified for scenarios 3 and 4. Elite count of 3 was specified for scenarios 1 and 2
- ❖ Crossover fraction of 0.7 was specified for scenario 4 while a value of 0.8 was specified for scenarios 1, 2, and 3
- ❖ Function tolerance of $1e-9$ was specified for all scenarios
- ❖ Constraint tolerance of $1e-9$ was specified for all scenarios

8.3.4 Dynamic Convergence Characteristics

The dynamic convergence characteristics of the optimisation algorithm are shown in Figure 8-15 to Figure 8-18. The standard deviation of the objective function value (lifecycle cost) of all individuals in the population in each generation is plotted against the number of generations. The standard deviation is important in checking the dynamic convergence speed of the optimisation algorithm.

The standard deviation of the objective function value for scenario 1 is shown in Figure 8-15. The standard deviation has a significant decrease between generations 1 and 2. It continues at a relatively low level in subsequent generations except for generations 5 and 6, which experienced a slight increase. The increase in standard deviation at generations 5 and 6 may be due to the mutation operator, which makes small random changes in the individuals in the

population to produce high objective function value. The standard deviation finally reduces in the last two generations.

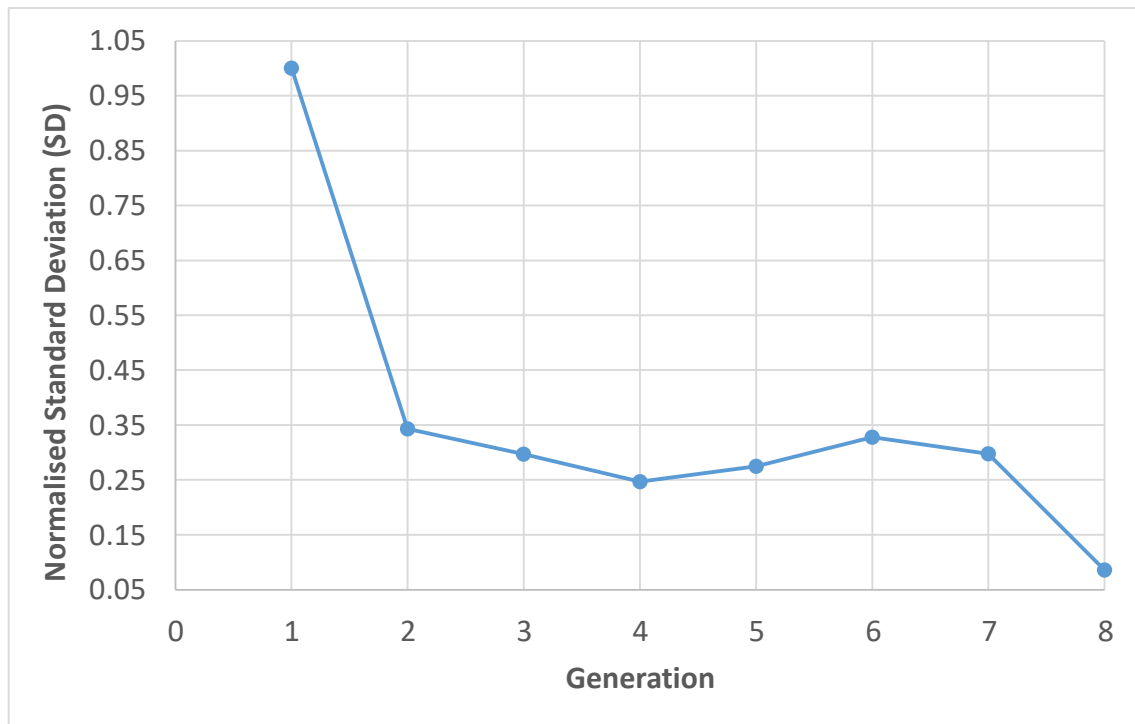


Figure 8-15 Standard deviation of the fitness value at each generation for Scenario 1

The standard deviation of the objective function value for scenario 2 is shown in Figure 8-16. The standard deviation has a great decrease in generations 1. It continues at a relatively low level in the second, third and fifth generations and experiences a moderate increase in generations 4 and 6. The increase in standard deviation may be due to the mutation operator, which makes small random changes in the individuals in the population to produce a high objective function value. The standard deviation was finally reduced in the last two generations.

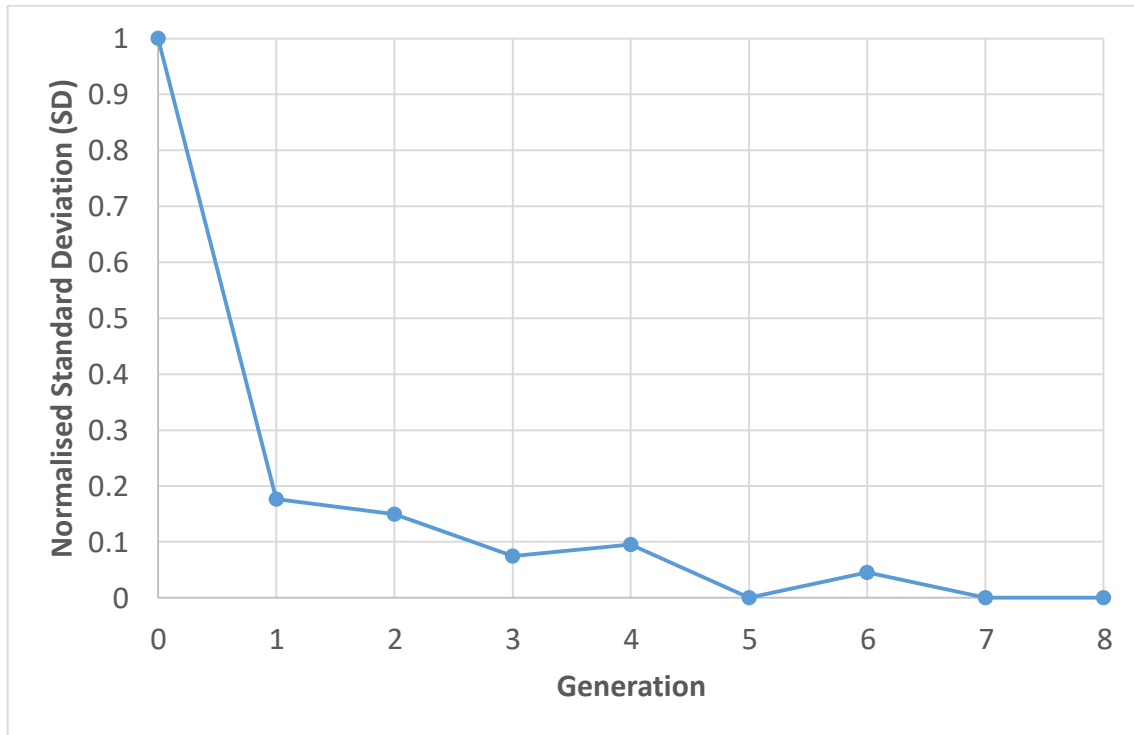


Figure 8-16 Standard deviation of the fitness value at each generation for Scenario 2

The standard deviation of the objective function value for scenario 3 is shown in Figure 8-17. The standard deviation significantly decreases in the first generation and experiences a moderate decrease in the second generation. It slightly increases in generation 3. The increase in standard deviation may be due to the mutation operator, which makes small random changes in the individuals in the population to produce a high objective function value. The standard deviation was finally reduced in the last 5 generations.

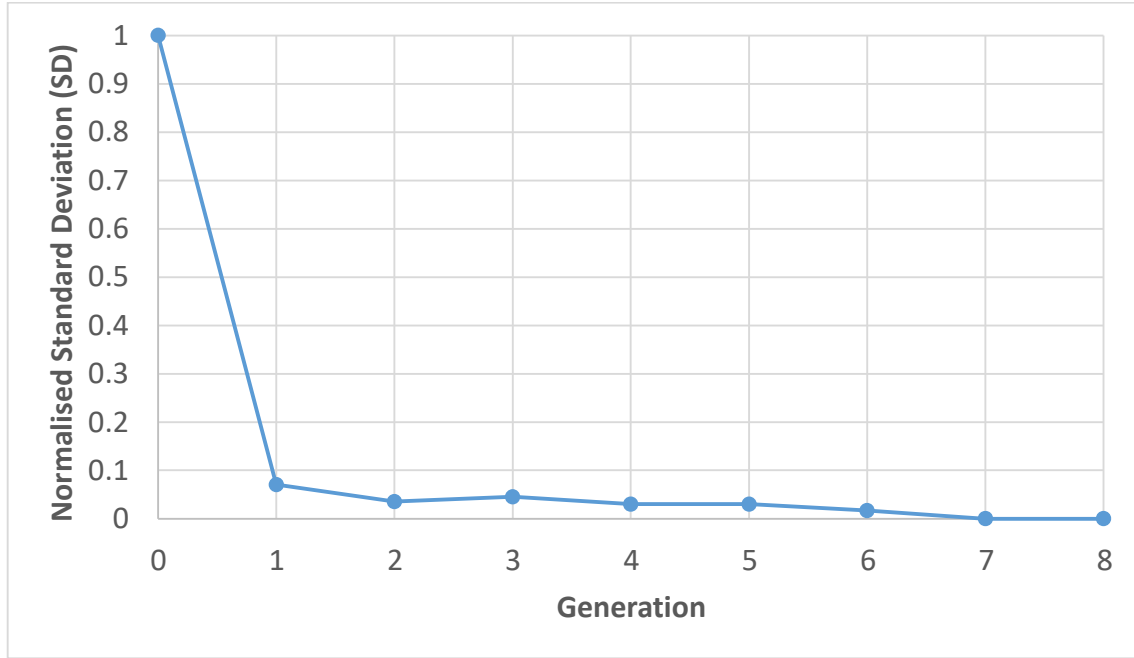


Figure 8-17 Standard deviation of the fitness value at each generation for Scenario 3

The standard deviation of the objective function value for scenario 4 is shown in Figure 8-18. The standard deviation has a significant decrease in the first generation. It experiences a further reduction in the 2nd and 3rd generations. It slightly increases in the 4th generation. The increase in standard deviation may be due to the mutation operator, which makes small random changes in the individuals in the population to produce a high objective function value. The standard deviation was finally reduced in the last 4 generations.

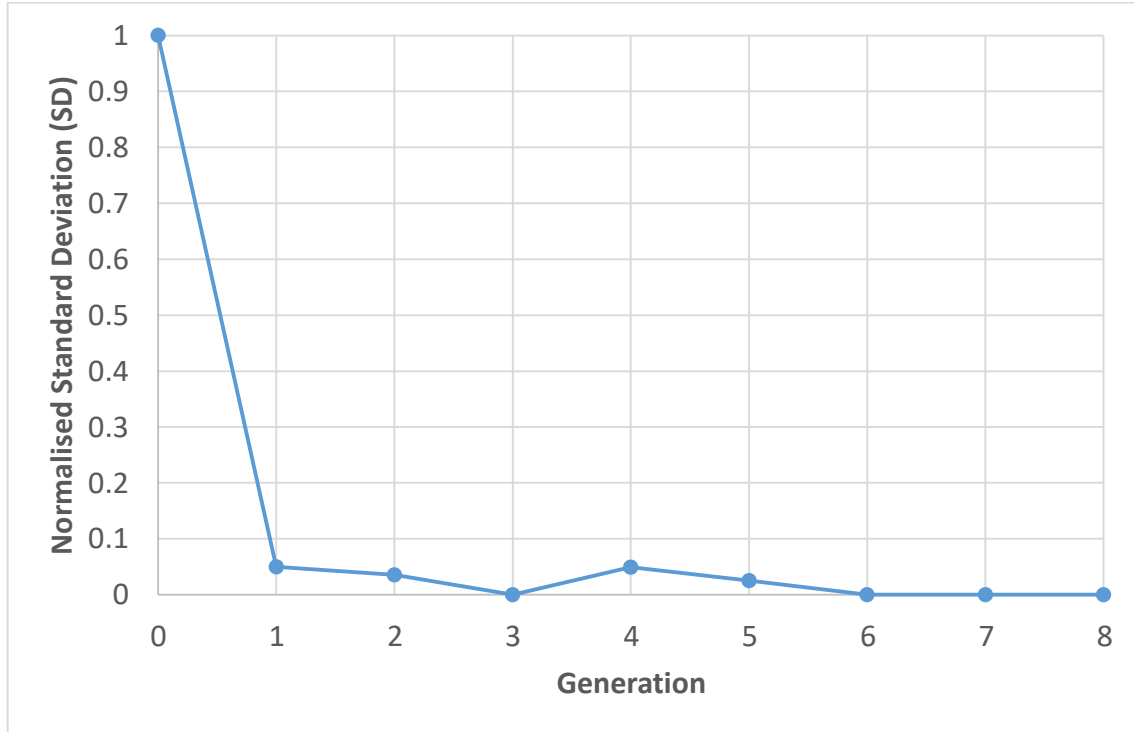


Figure 8-18 Standard deviation of the fitness value at each generation for Scenario 4

The results show a nearly continuous variation in the population's standard deviation with the number of generations. These demonstrate the reliability and validity of the genetic algorithm. Thus, the results show that the optimisation algorithm can obtain a faster dynamic convergence rate.

Tukur [18] attempted to try the genetic algorithm optimisation for the whole distance at once in his techno-economic studies but could not do so as it did not work for him and the others. Their simulations continue to fail despite attempting to use different scenarios. Consequently, their optimisation was done based on station by station. In this research, station location optimisation was done considering the whole compressor stations and pipeline systems for the techno-economic and the techno socio-economic cases. The proposed approach can also be employed for compressor station location optimisation at the unit and station level. This further demonstrates the ingenuity of this study in the techno-economic and techno socio-economic optimisation using the compressor station location as the decision variable.

Figure 8-19 shows the optimised lifecycle cost of the considered scenarios for the techno-economic and techno socio-economic cases, respectively.

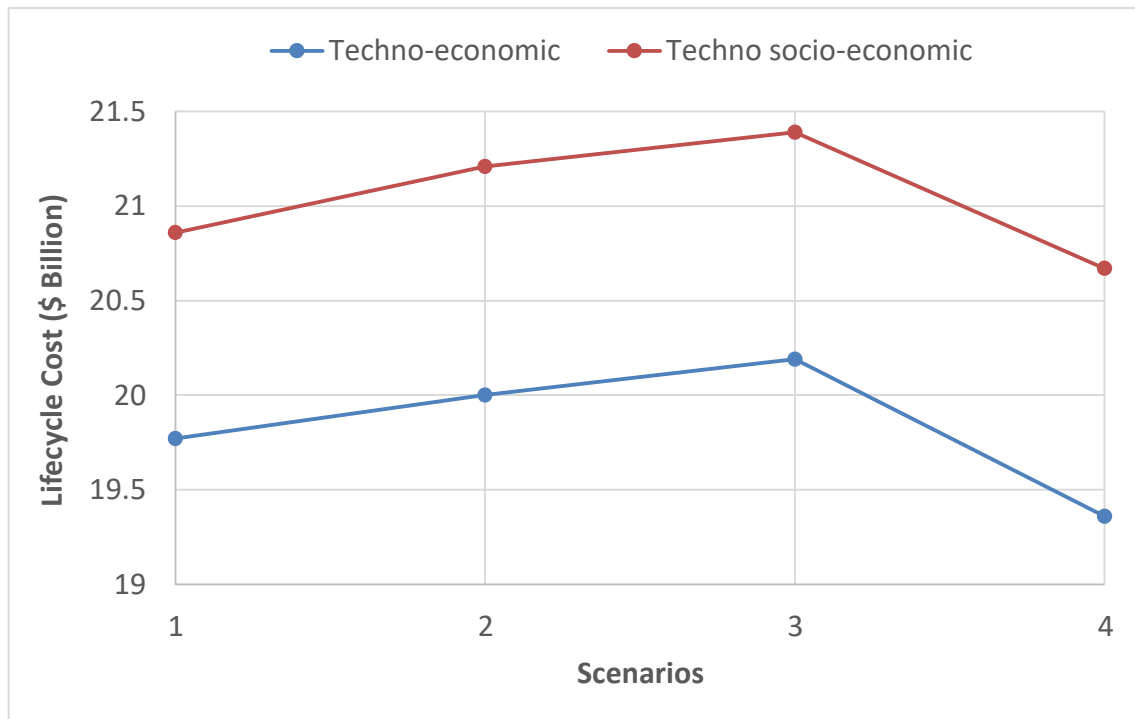


Figure 8-19 Comparison of Optimised Lifecycle Cost

In both cases, the lowest lifecycle cost is obtained for scenario 4 consisting of one number of installed intercooled aero-derivative gas turbine of 117 MW capacity driving one gas compressor per compressor station. This might be because scenario 4 has fewer number of compressor station locations along the pipeline route leading to low capital and operating cost. Furthermore, scenario 3 has the highest lifecycle cost estimation. Nonetheless, it is tempting to make a selection on the best scenario alternatives based on the lifecycle cost alone. The sensitivity analysis result based on a discounted cash flow method will guide the final selection of the best scenario among all the considered cases for this study.

Figure 8-20 and Figure 8-21 show the pipeline pressure profiles showing compressor station locations for the considered scenarios and the baseline case for the 419 segments Trans-Saharan gas pipeline.

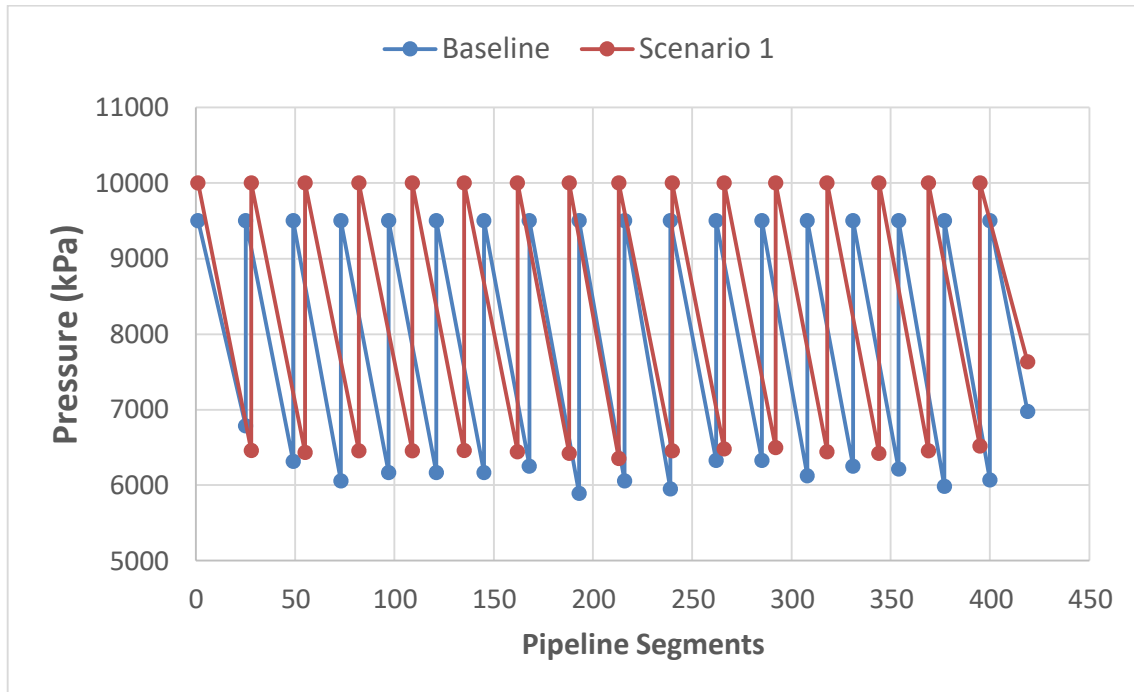


Figure 8-20 Pipeline Pressure Profile showing Compressor Station Locations

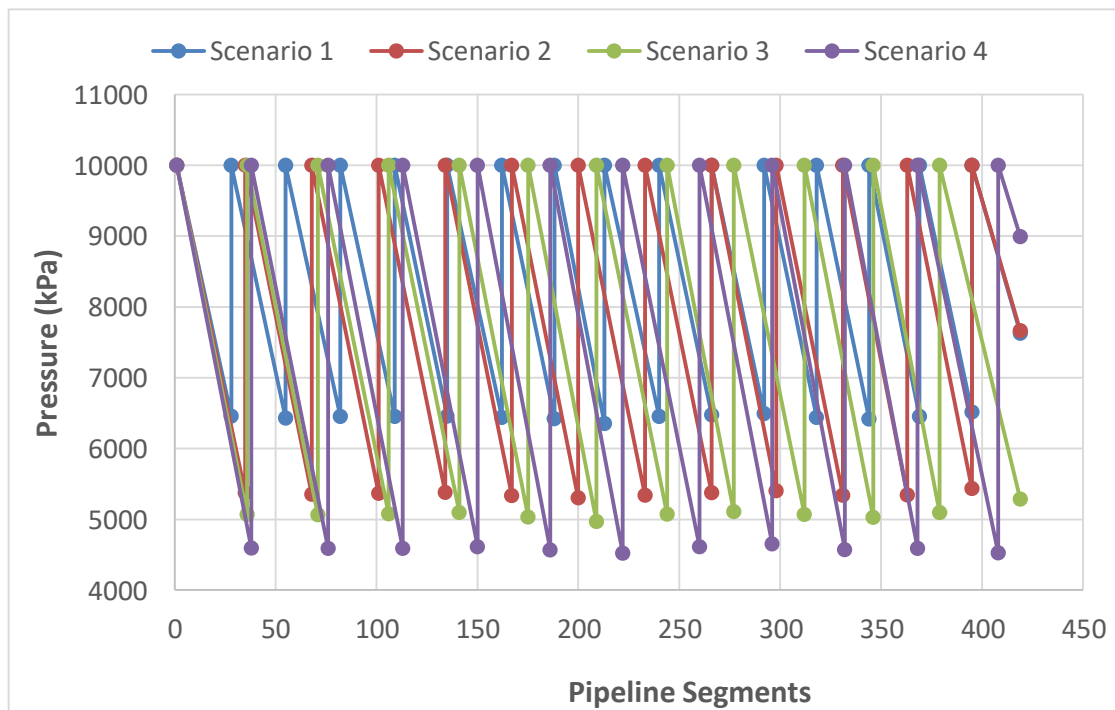


Figure 8-21 Pressure Profile showing Optimised Compressor Station Locations

Considering Figure 8-20, the maximum allowable operating pressures of the pipeline are 9500 kPa and 10000kPa for the baseline and scenario 1, respectively. At the 25th and 28th pipeline segments, these discharge pressures

drop to 6785 kPa and 6456.7 kPa, respectively. Thus, a second compressor station is needed at these pipeline segment locations since the first station has attained its maximum compression ratio required to compress the natural gas to the maximum distance. Considering Figure 8-21, the pipeline discharge pressure is fixed at 10000 kPa for all considered scenarios. This pressure drops to 5373.6 kPa, 5066.3 kPa, and 4589.6 kPa at pipeline segments 35, 36, and 38 for scenarios 2, 3, and 4, respectively. These are the maximum pipeline segment locations the installed gas compressors can compress the natural gas. Thus, a second compressor station is needed at these locations since the first station has attained its maximum compression ratio required to compress the gas to the maximum distance. This optimisation process continues until the required number of compressor stations needed to compress the given amount of natural gas through the 419 pipeline segments is attained. It is important to note that identical unit's configurations were utilised for this scenario-based techno-economic and techno socio-economic optimisation studies. This will lead to spare part management and a reduction in the frequency of maintenance required.

The exceptions occur at the last compressor station location for each scenario. This location requires smaller gas compressor power to compress the natural gas through the pipeline to the delivery point of 4180 km. Scenario 1 requires two units of installed simple cycle triple-shafts aero-derivative gas turbine of 15.2 MW capacity driving two gas compressors arranged in parallel at the last compressor station location. Scenario 2 requires one unit of installed simple cycle two-shafts gas turbine of 30.1 MW capacity driving one gas compressor at the last compressor station location. Scenario 3 requires one unit each of installed simple cycle two-shafts gas turbine of 50 MW and 30.1 MW capacity driving one gas compressor at the last compressor station location. Finally, scenario 4 requires one unit of installed simple cycle two-shafts gas turbine of 13.4 MW capacity driving one gas compressor at the last compressor station location.

The results obtained for the net present value analysis show that at a 15% discount rate, scenario 1 has a net present value of \$16.07 billion and \$15.70 billion for the techno-economic and techno socio-economic cases, respectively. At the same discount rate, the net present values are \$21.58 billion and \$20.41 billion for scenario 2, \$24.97 billion and \$24.38 billion for scenario 3, \$28.77 billion and \$28.60 billion for scenario 4, respectively. All project alternatives have positive net present value. At a 15% discount rate, scenario 4 consisting of one unit of installed intercooled aero-derivative gas turbine of 117 MW capacity driving one gas compressor per compressor station should be selected since it is the project with the highest net present value among the considered scenarios.

Sensitivity analyses are carried out to determine the effect of the discount rate on the net present value. Figure 8-22 and Figure 8-23 show the variation of the net present value with discount rates for techno-economic and techno socio-economic cases, respectively.

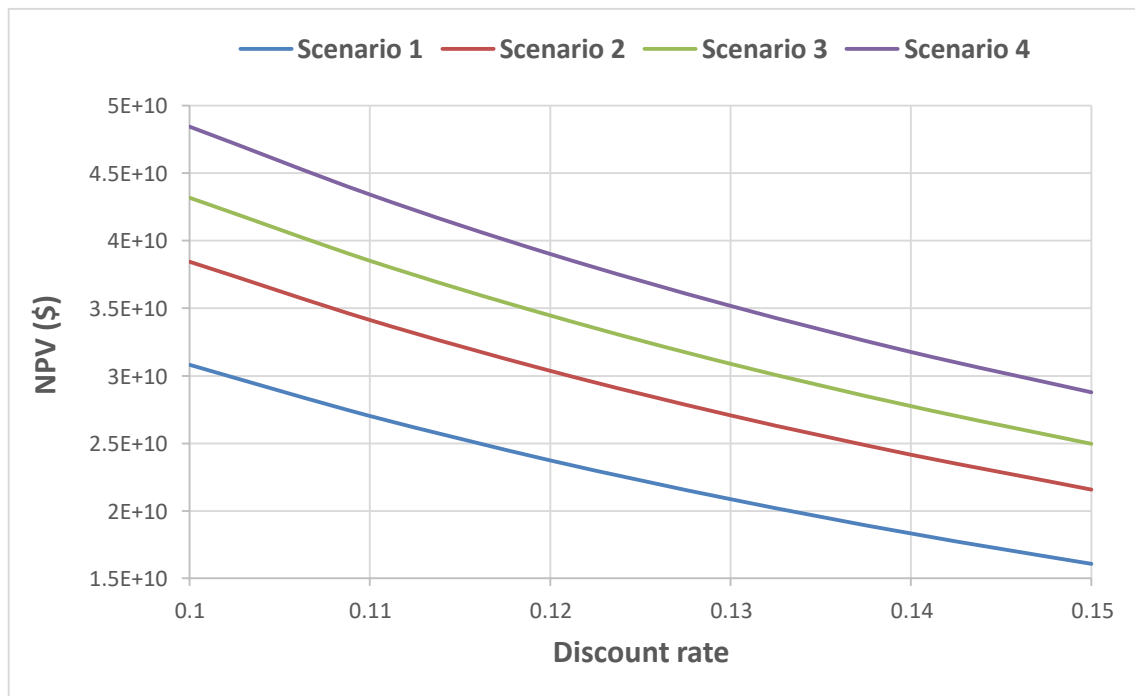


Figure 8-22 Variation of NPV with discount rate for techno-economic case

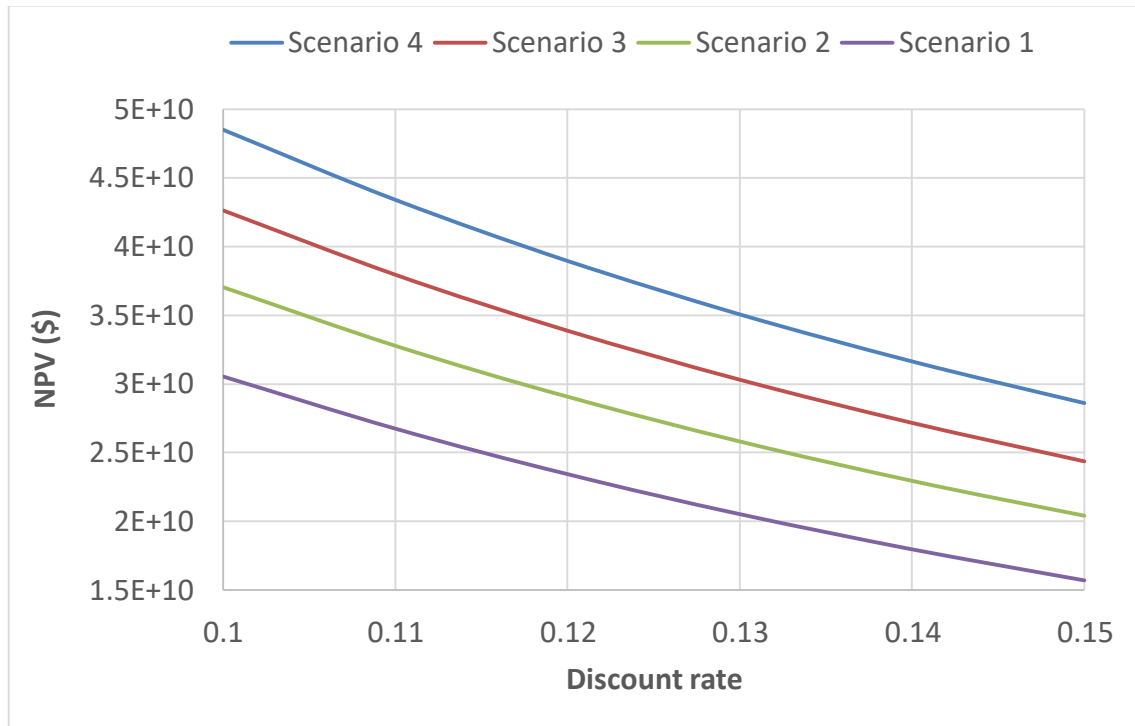


Figure 8-23 Variation of NPV with discount rate for techno socio-economic case

Sensitivity analyses show an increase in net present value with decreasing discount rate for all scenarios and cases. Scenario 4 has the highest net present value at all discount rates. Results show a preference for the selection of **scenario 4 in both cases** with the lowest lifecycle cost and highest net present value among all the project alternatives. Although the net present value of scenario 4, techno-economic case A is higher than techno socio-economic case B at all discount rates. The additional socio-economic benefits make scenario 4, case B, the preferred choice for the proposed Trans-Saharan gas pipeline and any pipeline projects.

The results obtained have shown the inherent advantages of the developed models and the significance of the proposed optimisation approaches utilised in this research for station location optimisation of the integrated pipeline TERA.

8.4 Summary

The objectives of this study were to evaluate the economic optimisation of the compressor station and pipeline system lifecycle cost as a function of the

compressor station location, pipeline characteristics, availability, and social context.

This study has performed a techno-economic optimisation of the compressor stations and pipeline systems using the SIMULINK optimisation procedure. The techno socio-economic optimisation was analysed using a genetic algorithm and a computer code developed in MATLAB. The optimisation problems are formulated considering compressor station location and lifecycle cost of the compressor stations and pipeline systems. Scenarios-based techno-economic and techno socio-economic optimisation studies are performed to illustrate the most usual compressor stations and pipeline systems network configurations that could be found in real life situations. Sensitivity analyses were carried out to determine the effect of the discount rate on the net present value. As evident in the public domain, this is the first time this research aspect has been done on optimising the natural gas transmission pipeline system using the compressor station location as a decision variable.

The evaluated techno-economic optimisation using the SIMULINK method agrees with the genetic algorithm optimisation approach. The challenges encountered during modelling and optimisation are due to the complexities of the compressor station and pipeline system, station location characteristics, and the non-linearity of the optimisation problem. However, they were effectively resolved. The validated results show the same number of compressor station locations and lifecycle cost estimation for each scenario. They demonstrate the benefits of the SIMULINK optimisation method since this is the first time this optimisation technique is applied to compressor station location optimisation. The validated results form the basis for further analysis of the techno socio-economic optimisation. They illustrate the novelty of the developed integrated TERA and optimisation model in this study. The results show significant savings in the optimised lifecycle cost estimation for the considered scenarios compared to the baseline case. The sensitivity analyses on net present value show a preference for the selection of techno socio-economic scenario 4, case B, among the considered scenarios and cases.

The results have shown the inherent advantages of the developed models and the significance of the proposed optimisation approaches utilised in this research for station locations optimisation of the integrated pipeline TERA. They show the potential of the modelling and optimisation approaches in guiding decision-makers on the ultimate selection of engine configurations that will give the optimum lifecycle cost and socio-economic benefits at the optimised station location. This will maximise profits and bring about improved economic performance. The analysed optimisation techniques form the basis for exploring sophisticated network configurations and for future research in these interesting aspects of compressor station and pipeline system optimisation studies.

9 CONCLUSION AND RECOMMENDATION

9.1 Conclusion

This thesis aimed to investigate the impact of the social context opportunities and engine availability on the specification, with a first step on the socioeconomics, and techno-economics of natural gas transportation in pipelines while focusing on compressor station location optimisation.

This thesis has developed a method for evaluating the integrated pipeline and gas compressor models analytically, considering the variation in the ambient temperature and location characteristics. The pipeline characteristics and pressure drop, gas compressor power requirements and performance curves at design and off-design conditions were evaluated considering segmented pipe length, elevation, and ambient temperature variation at varying flow conditions. The gas compressor and gas turbine models were selected based on the analysed gas compressor power requirements. The design and off-design points performance of the selected gas turbine models were simulated using Turbomatch to draw out essential performance data required for the economic analysis. The design point performance simulation results were validated with available original equipment manufacturers' data. The off-design performances of the selected gas turbine models were simulated at varying ambient conditions at each compressor station location with the objective that the gas turbine prime mover can supply the power required by the gas compressor under all flow conditions. The ambient temperature variation under all flow conditions and the gas turbine entry temperature were considered for the simulation.

The gas compressor, gas turbine, and turbo-compressor units' availability were evaluated based on a developed local maintenance schedule and failure rate retrieved from literature studies. The analysis considered the impact of compressor station subsystem configuration on the whole compressor station system availability. A scenarios-based approach was performed to show the sensitivities of the compressor station systems to availabilities in terms of the number of installed standby units. The economic assessment of the project was

achieved using a discounted cash flow method based on the lifecycle cost and net present value. The techno-economic model was developed using SIMULINK block diagrams and a developed code in MATLAB environment. This is based on the variation in compressor station location ambient temperatures at varying flow conditions. The gas compressor powers at isothermal, intermediate and non-isothermal flow conditions were considered. Their corresponding gas turbine shaft power, fuel flow, and turbine entry temperatures required to drive the gas compressor, which is expected to have a major impact on the projects fuel consumption and engine availability-based maintenance costs, were also considered in the analysis. These represent a contribution to the pipeline TERA literature. The author could not find any public studies that have adapted TERA by applying a typical original equipment manufacturer maintenance schedule to determine the impact of turbo-compressor availability on the whole compressor station and pipeline system investments.

For the first time, the analysis considered the potential social impacts and social benefits of gas turbine compressor station locations. The predicted jobs creation was quantified by the number of local jobs created and the equivalent employment cost and benefits in monetary units of employees' salaries and income taxes generated. Road infrastructures are quantified in terms of road benefits, road construction cost, and road tax. A scenario-based techno socio-economic analysis was performed to show the sensitivities of compressor stations and pipeline systems to social and technical aspects of the project in terms of social benefits and availabilities. The techno socio-economic assessment of the project was achieved using a discounted cash flow method based on the lifecycle cost and net present value. The techno socio-economic model was developed using a code written in MATLAB environment based on social benefit algorithms and the variation in compressor station location ambient temperatures at varying flow conditions.

For the first time, the techno-economic optimisation of the compressor stations and pipeline systems was performed using the SIMULINK optimisation procedure. The techno socio-economic optimisation was analysed using genetic

algorithm and a computer code developed in MATLAB environment. The optimisation problems were formulated considering compressor station location and lifecycle cost of the compressor stations and pipeline systems. A scenarios-based economic optimisation studies were performed to illustrate the most usual compressor station and pipeline system network configurations that could be found in real life situations. Sensitivity analyses were carried out to determine the effect of the discount rates on the net present value. As evident in the public domain, this is the first time this research aspect has been done on optimising the natural gas transmission pipeline system using the compressor station location as a decision variable.

Results show that the gas compressor inlet temperature and compressor station location characteristics, including the prevailing ambient temperature, distance, and elevation, have a strong influence on the gas compressor power requirements and affect the selection of the most appropriate turbo-compressor models. Comparison of results shows good agreement between the present study and Aspen HYSYS. The maximum absolute percentage difference between the gas compressor powers is equivalent to 0.048% at all compressor station locations except for compressor station location 18 with a percentage difference of 0.348%. Nevertheless, this difference is negligible and could be applied in the pipeline natural gas industry.

Comparison of performance results at design point show good agreement between the Turbomatch simulation and the literature. The off-design performance results show an increase in power output and efficiency with increasing turbine entry temperature due to increasing fuel flow into the engine. As the ambient temperature increases, the power output and efficiency decrease with a consequent reduction in the fuel flow. For the isothermal and intermediate flow conditions with constant ambient temperatures, the power output, efficiency, and fuel flow are constant at fixed turbine entry temperatures, respectively. The results show that the gas turbine power output is enough for the gas compressor power requirements at all flow conditions even for the worst case of the locations' ambient temperature.

The evaluated units' availability was in good agreement with literature reports and was within the recommended original equipment manufacturer operational requirement. Results show that increasing the compressor station availability demonstrated through scenarios-based study has a great impact on the compressor station system availability and the techno-economics of the proposed Trans-Saharan gas pipeline project. These findings represent one of the major contributions to knowledge in this research. Therefore, the availability analysis of compressor station components, subsystems, and systems could be beneficial in the techno-economic assessment of the compressor station and pipeline system. This is because the profitability of the project is greatly dependent on turbo-compressor availability. Considering the installation of standby turbo-compressor units at some or all compressor station locations could enhance the system availability and mitigate potential risk or uncertainties associated with the proposed Trans-Saharan gas pipeline and any gas pipeline projects.

The evaluated gas turbine impact area aligns with literature reports. The differences observed present no serious implications since this is the first-time direct land-use impact is applied to compressor station and pipeline system. The potential social benefits created is expected to bring about the socio-economic development of the local communities. This may be through human skills and resources development brought about by technological training of the local employees and the incomes generated. Results show promising improved stakeholder engagement. This will minimise potential future delays and conflict of interests by creating cooperation, stable long-term policies and trust relationship between the organisation and stakeholders due to the resulting positive social benefits obtained from the installation and operation of the gas turbine compressor stations and pipeline project.

The evaluated techno-economic optimisation using SIMULINK method aligns with the genetic algorithm optimisation approach. The validated results show the same number of compressor station locations and lifecycle cost estimation for each scenario. Thus, demonstrating the benefits of the SIMULINK optimisation method since this is the first time this optimisation technique is applied to

compressor station location optimisation. The results show significant savings in the optimised lifecycle cost estimation for the considered scenarios compared to the baseline case. The sensitivity analysis on net present value show preference for the selection of techno socio-economic scenario 4, case B, among the considered scenarios and cases.

The accuracy of the results obtained depended on the relevant assumptions made based on literature studies. The adopted methodology will provide the decision-maker with better insight into the expected risks and uncertainties associated with investment into the proposed Trans-Saharan gas pipeline and any gas pipeline projects. It will guide the selection of appropriate strategies needed to mitigate them. The results obtained could help in forecasting the lifecycle cost, expected performance of the compressor station system, the economic and social impacts. This could assist policymakers in decision-making and the feasibility of the proposed Trans-Saharan gas pipeline project. The models developed will aid in evaluating the social impacts of any compressor station and pipeline projects for the first time and the benefits of compressor station locations to the remote communities along the pipeline route. These will lead to faster and more economical pipeline system specifications. They will serve as useful decision-making tools for potential investors in compressor stations and pipeline systems and the Nigerian government on developing the proposed Trans-Saharan gas pipeline project.

The results have shown a novel contribution investment in the proposed Trans-Saharan gas pipeline project will have through potential local jobs and new roads creations. This could serve as an indicator of the quality of life of the local communities. The developed method can guide in the quantification of social impacts and socio-economic benefits during the design and development stage of any compressor station for pipelines application and other related projects. The results obtained have shown the inherent advantages of the developed models and significance of the proposed optimisation approaches utilised in this research for station locations optimisation of the integrated pipeline TERA. They show the potential of the modeling and optimisation approaches in guiding decision-

makers on the ultimate selection of engine configurations that will give the optimum lifecycle cost and socio-economic benefits at the optimised station locations. This will maximise profits and bring about an improved economic performance. The developed social benefit algorithms will open a new field of research closely aligned to the evolution of organisational goals to encompass stakeholders. It is hoped that the considered social benefit algorithms will serve as a useful methodological basis for further studies in the techno socio-economic benefits and an important driver for the implementation of the proposed Trans-Saharan gas pipeline and any pipeline projects.

The challenges encountered during modelling and optimisation are due to the complexities of the compressor station and pipeline system, station location characteristics, and the non-linearity of the optimisation problem. However, they were effectively resolved. The analysed optimisation techniques form the basis for exploring sophisticated network configurations and for future research in these interesting aspects of compressor station and pipeline system TERA and optimisation studies.

In summary, the main contributions to knowledge of this research work are:

1. Development of a model and method for evaluating gas turbine availability on pipeline TERA
2. Development of a model and method based on pipeline TERA for evaluating the social impacts and social benefits of compressor station locations along the pipeline route
3. Novel combination of TERA with socio-economic considerations in a first step
4. An economic optimisation analysis using the compressor station location as a decision variable

9.2 Recommendation for Future Work

The following shows potential areas for future work:

1. It was not easy to find data primarily for the social aspects of this research. However, the limited available data obtained from the literature, relevant assumptions and informed engineering judgement were utilised in this thesis and provided accurate results. Nonetheless, it is anticipated that data collection and use would need to be improved in future work.
2. The benefits examined focus primarily on direct benefits. Thus, they are an underestimate. Indirect benefits need to be included and should be the focus of more research.
3. This research considered two positive social impacts and benefits. Other positive social impacts of compressor station locations along pipeline route, such as water infrastructure impact and provision of electricity, could be explored. The water use associated with the construction, installation, and operation of the compressor station and pipeline system and its impacts on the local communities could be examined. The detailed analysis of water usage in each compressor station location along the pipeline route could help alleviate local water stress, thus providing socioeconomic benefits. The socioeconomic implications of supplying electricity from the gas turbine compressor stations to the local communities could be evaluated in future research. The willingness-to-pay approach based on the revealed preference method and stated preference method could be explored in future studies for the value of travel time savings estimation of road benefits.
4. In addition to other positive social impacts, negative social impacts such as accident fatalities, including the potential death of employees over the lifecycle of the proposed project, could be investigated using different methods. The subsequent interference in the local communities' socioeconomic activities arising because of their displacement from the social influence areas within the station locations could also be explored.
5. Unplanned downtimes were excluded from the developed local maintenance schedule. Although engine failure rates were integrated with

- the developed maintenance schedule, the effects of unplanned downtime on the availability of the system deserve further attention in future work.
6. The maintenance cost analysis could be improved by conducting statistical analysis to find the correlations between engine availability and maintenance cost for each selected engine model. This analysis could be based on engine availability and maintenance database retrieved from further literature studies or the developed maintenance schedule incorporating unplanned downtimes. The outcome of this additional investigation would be some developed trendline equations to estimate maintenance costs. In this, trendline equation or curve at any availability factor will give an equivalent maintenance factor, which can further be included in the availability-based maintenance cost models developed in this thesis.
 7. The optimisation aspects could be further improved by performing a multi-objective optimisation study combining two objective functions simultaneously while maintaining station location as the decision variable. The project's techno-economic and socio-economic costs may be the two competing objectives to be optimised. The inclusion of compressor station size as another decision variable under varying pipeline thickness could be considered in future work.
 8. The transmission pipeline could be integrated with the gas distribution network, and the model could be enhanced by employing varying natural gas compositions. Future work could encompass more simulation and optimisation models to cater for the increased complexity due to the additional gas distribution network and varying gas composition.

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APPENDICES

Appendix A Ambient Temperature at Station Locations

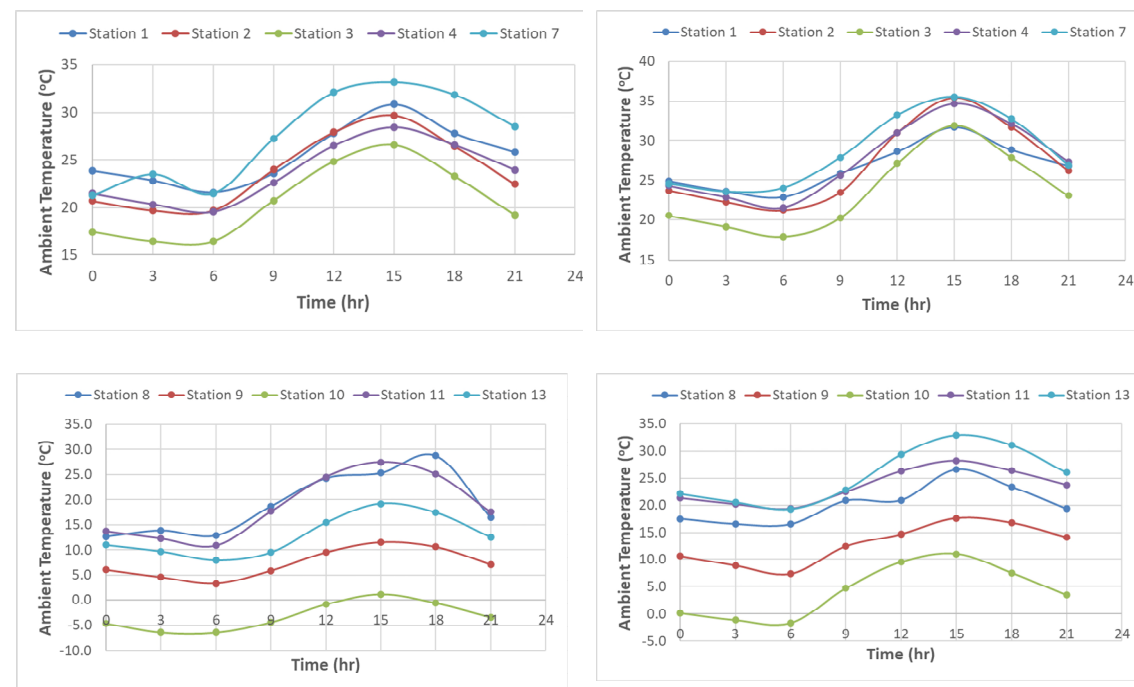


Figure A-1 Ambient Temperature at Stations 1-7 (Dry & Hot) & 8-13 (Winter & Dry)

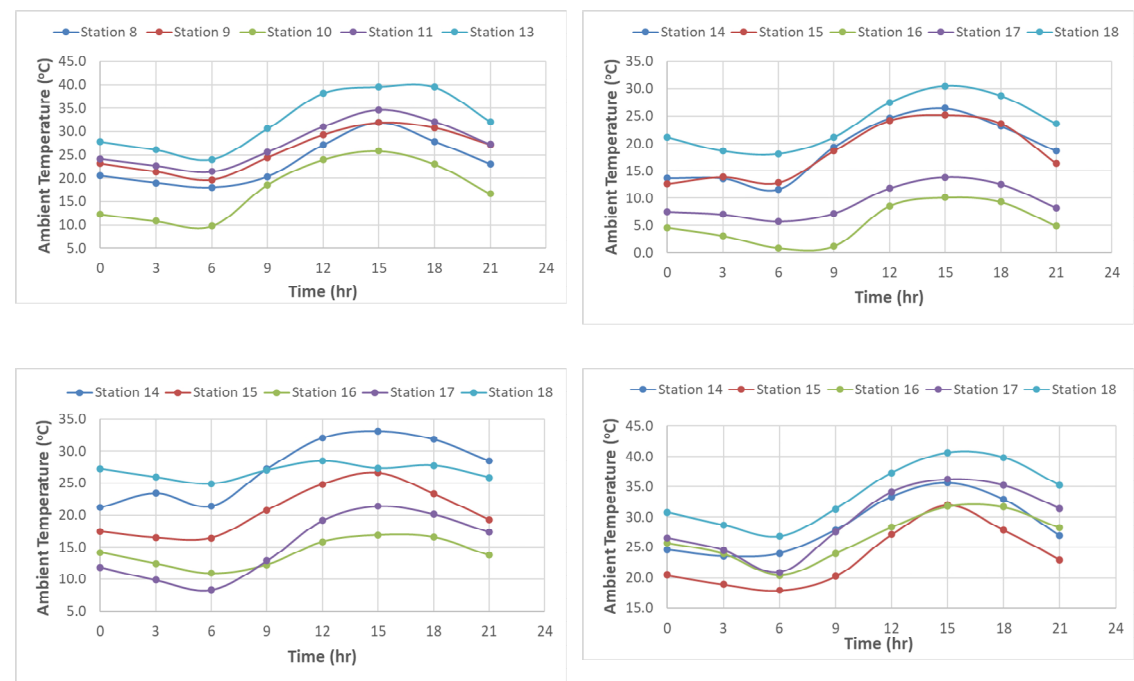


Figure A-2 Ambient Temperature at Stations 8-13 (Hot) & 14-18 (Winter, dry & hot)

Appendix B Gas Compressor Curves from Original Equipment Manufacturer

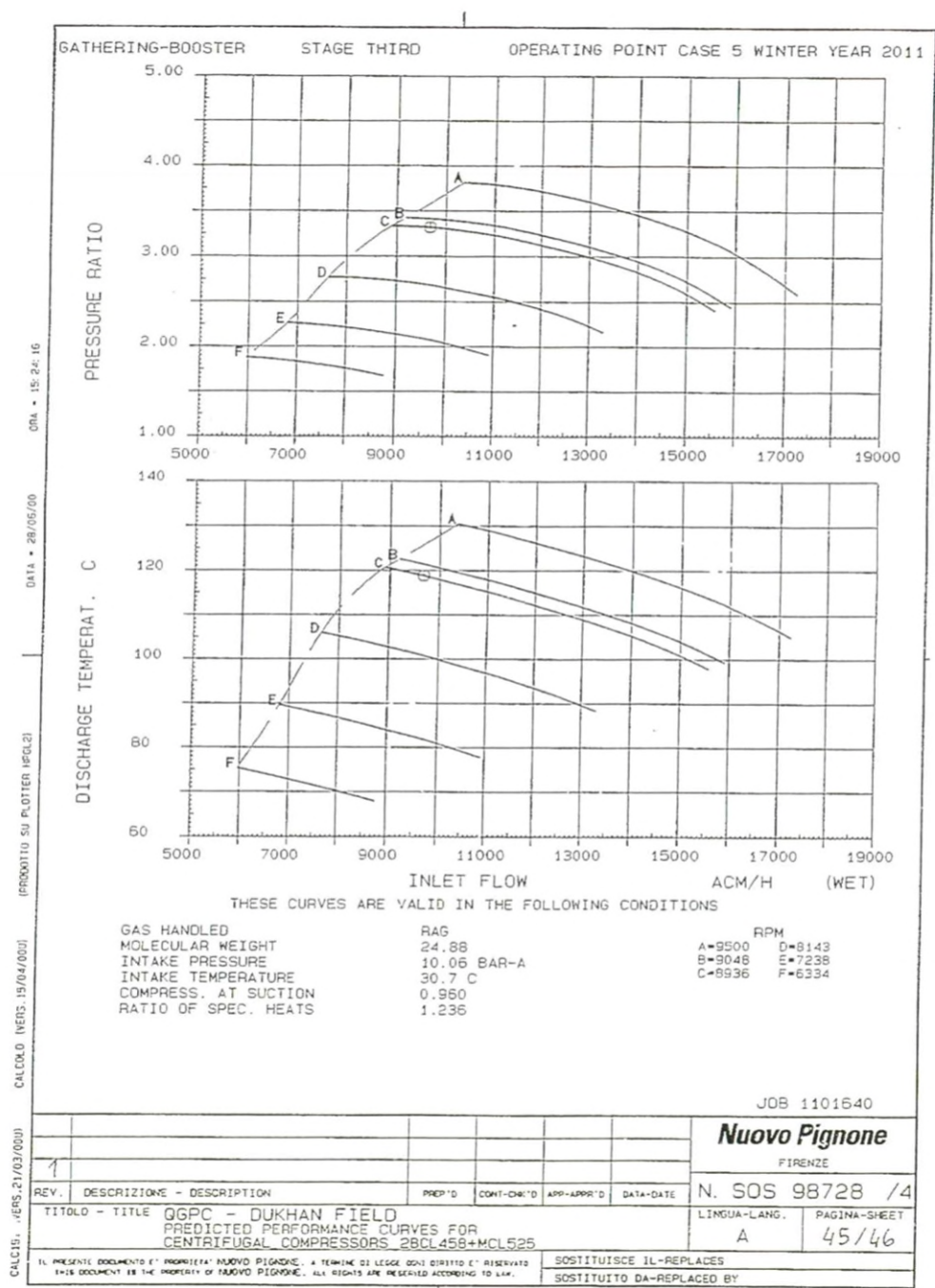


Figure B-1 Pressure Ratio and Discharge Temperature Curves

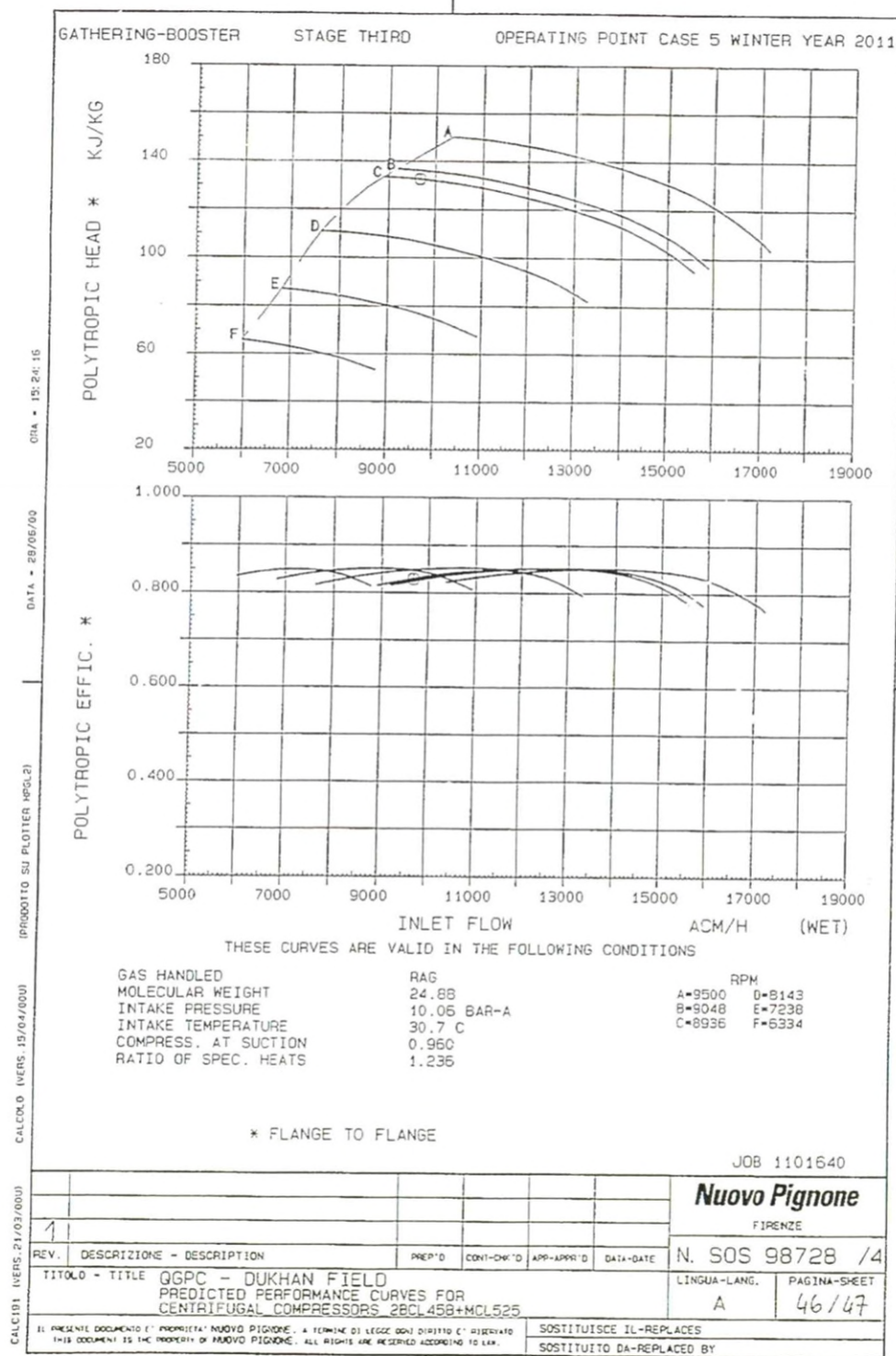


Figure B-2 Polytropic Head and Polytropic Efficiency Curves

Appendix C Gas Compressor Suction Pressures and Pressure Ratios at Non-Isothermal Conditions

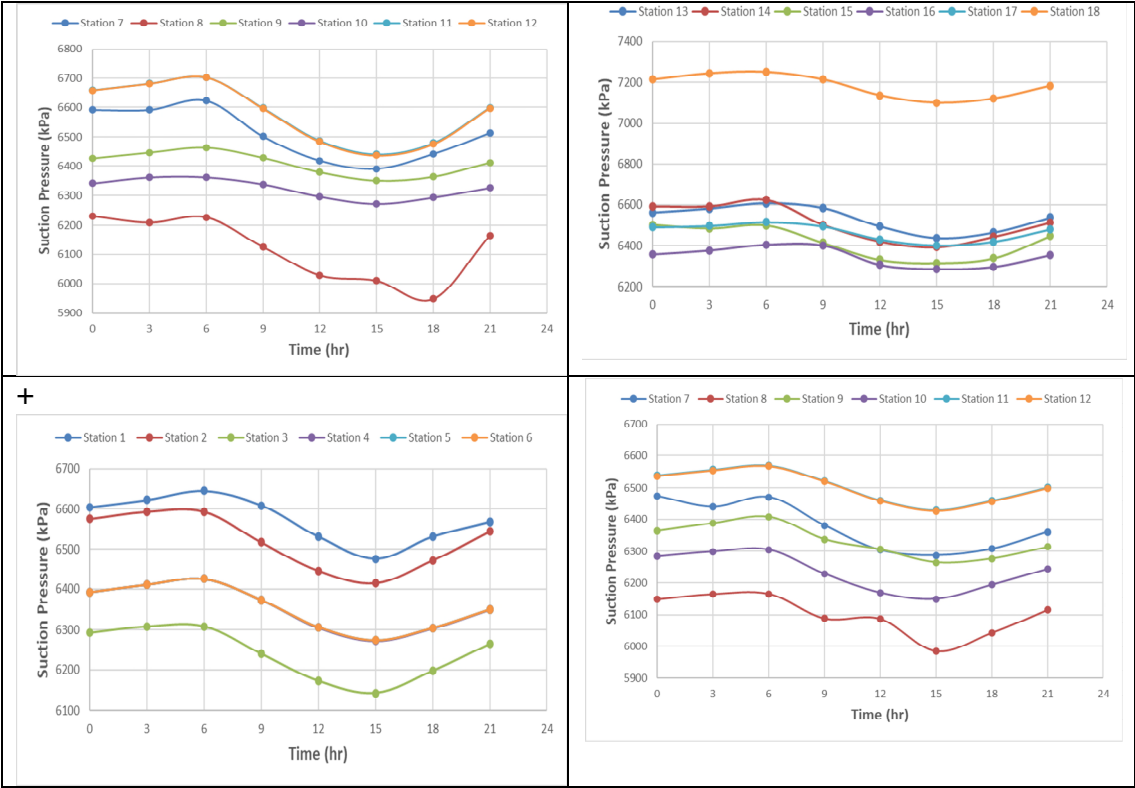


Figure C-1 GC Suction Pressures for Stations 7-18 (Winter) & 1-12 (Dry)

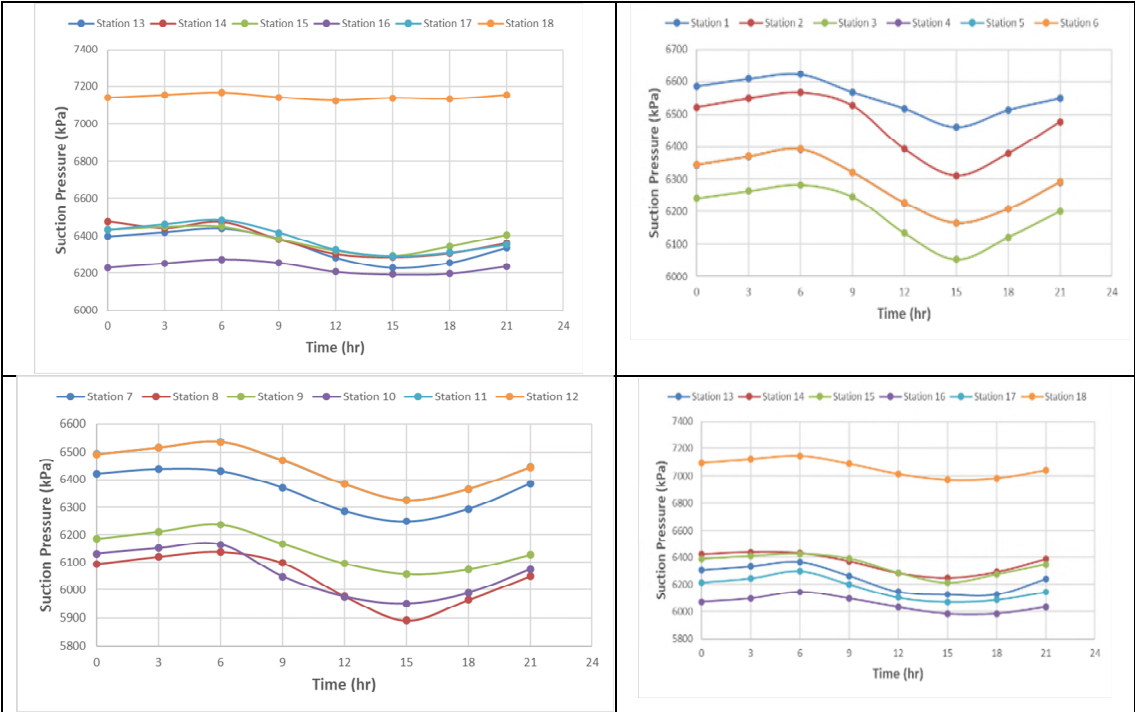


Figure C-2 GC Suction Pressures for Stations 13-18 (Dry) & 1-18 (Hot)

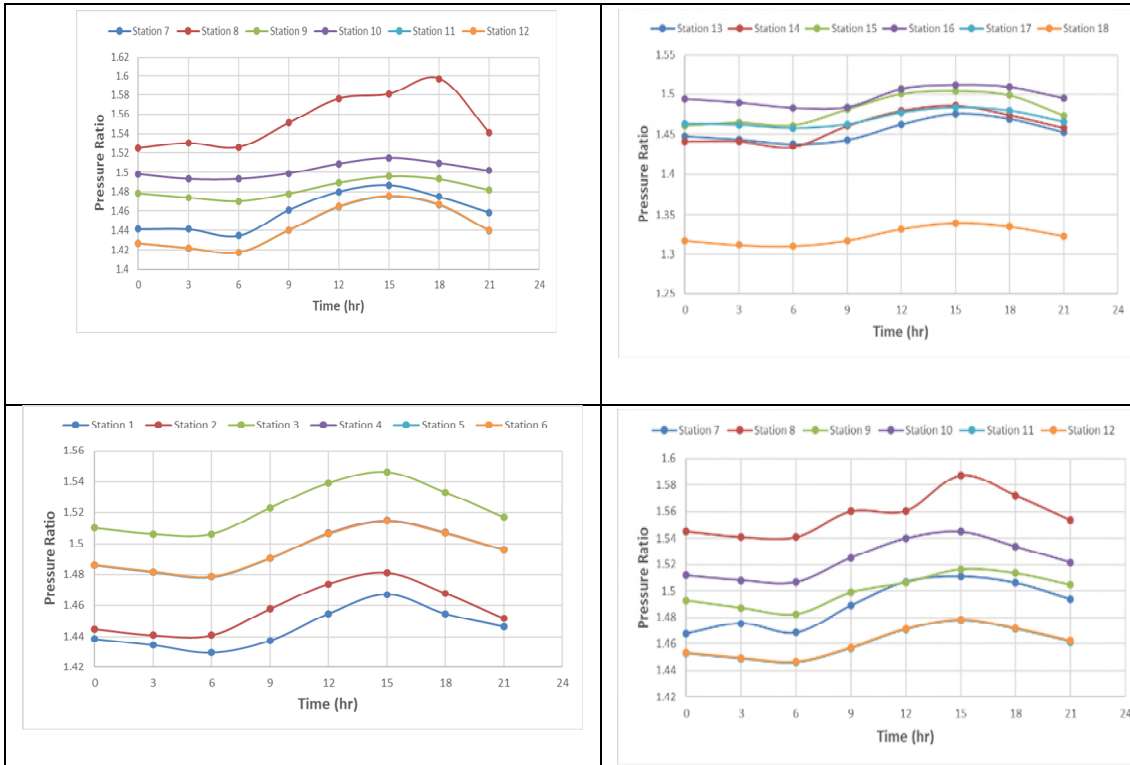


Figure C-3 GC Pressures Ratio for Stations 7-18 (Winter) & 1-12 (Dry)

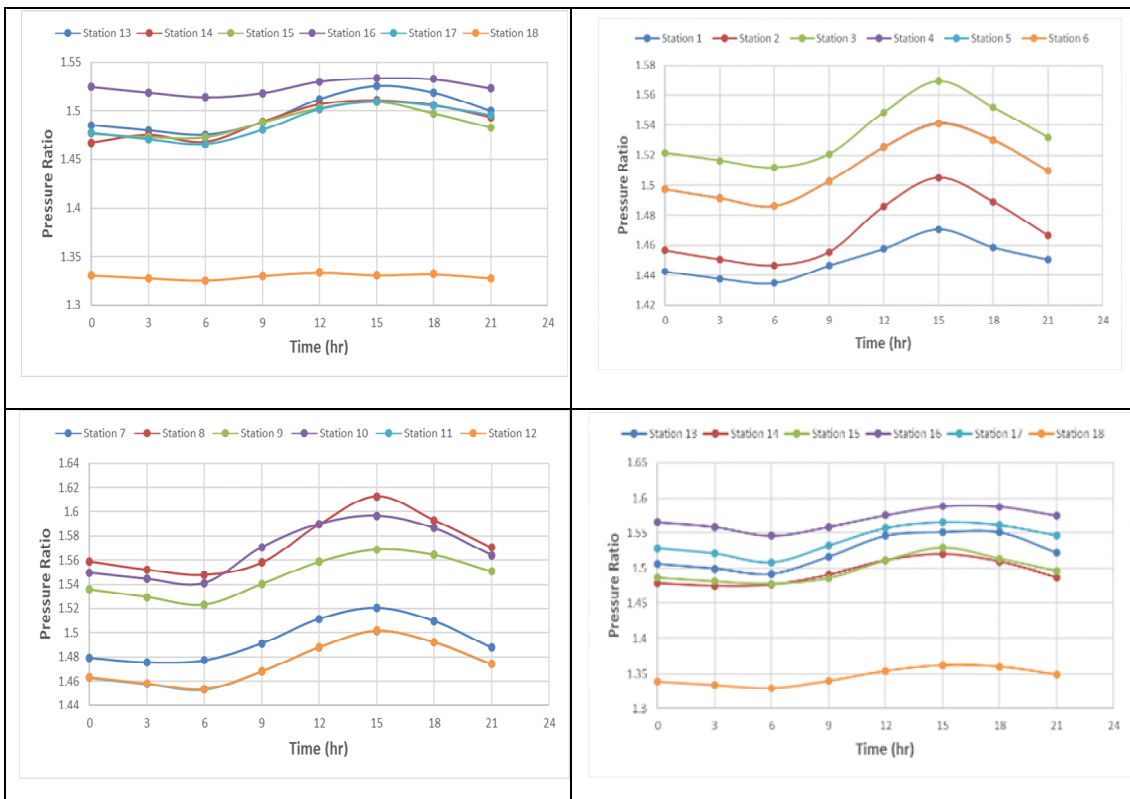


Figure C-4 GC Pressures Ratio for Stations 13-18 (Dry) & 13-18 (Hot)

Appendix D Gas Compressor Discharge Temperature at Non-Isothermal Conditions

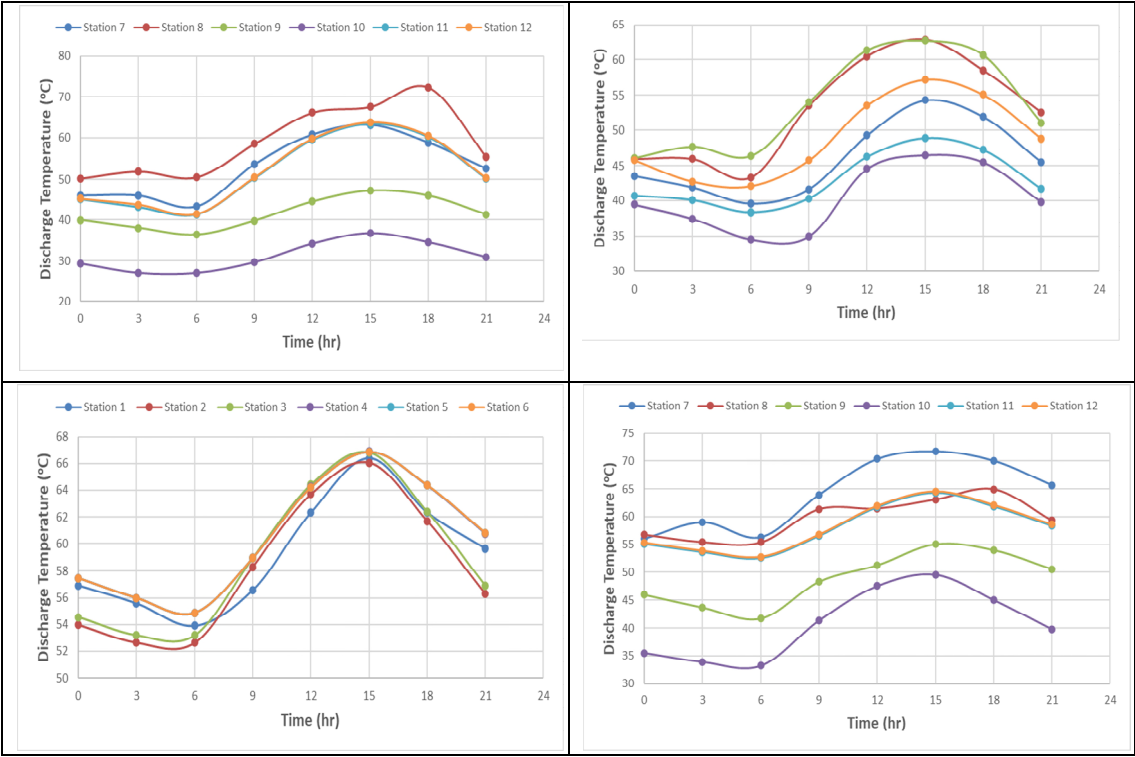


Figure D-1 GC Discharge Temperature for Stations 7-18 (Winter) & 1-12 (Dry)

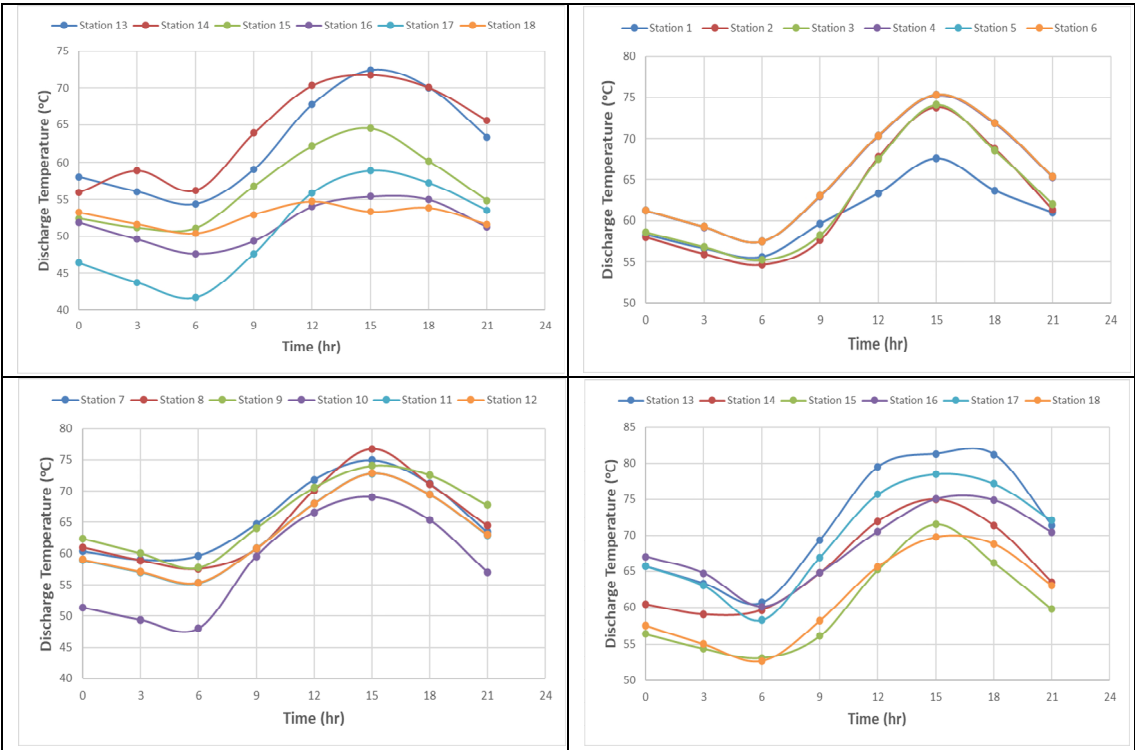


Figure D-2 GC Discharge Temperature for Stations 13-18 (Dry) & 1-18 (Hot)

Appendix E Gas Compressor Power Requirement at Non-Isothermal Conditions

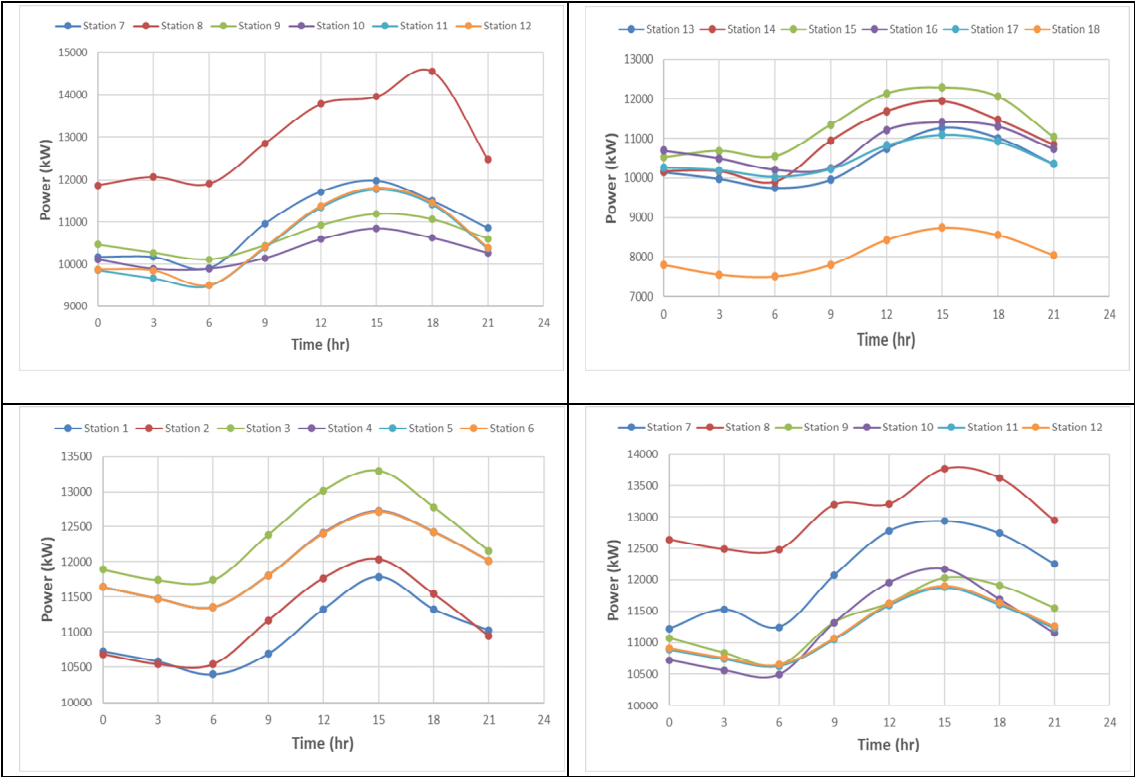


Figure E-1 GC Power for Stations 7-18 (Winter) & 1-12 (Dry)

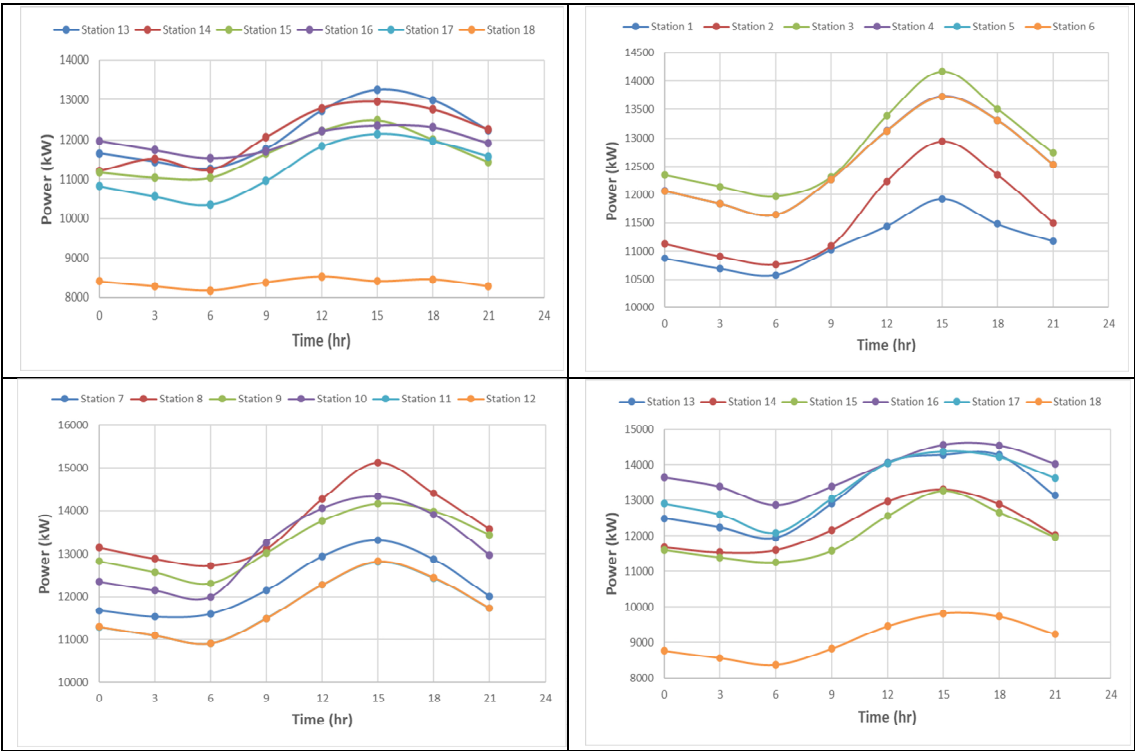


Figure E-2 GC Power for Stations 13-18 (Dry) & 1-18 (Hot)

Appendix F Mixture Properties

Table F-1 Natural Gas Mixture Properties

j	Gas Components	MW	y_j	$MW * y_j$	P_c	T_c	w	μ	k
1	Methane (C1)	16.04	0.9218	14.78567	46.04	190.58	0.0115	0.000107	1.31
2	Ethane (C2)	30.07	0.0493	1.482451	48.8	305.32	0.0995	0.000089	1.19
3	Propane (C3)	44.1	0.0056	0.24696	42.5	369.83	0.1523	0.000075	1.13
4	Iso-Butane (IC4)	58.12	0.0031	0.180172	36.4	407.8	0.1835	0.000071	1.09
5	N-Butane (nC4)	58.12	0.0011	0.063932	37.97	425.12	0.2002	0.000073	1.1
6	Iso-Pentane (IC5)	72.15	0.0011	0.079365	33.8	460.4	0.2279	0.000066	1.08
7	N-Pentane (nC5)	72.15	0.0004	0.02886	33.69	469.7	0.2515	0.000066	1.07
8	N-Hexane (nC6)	86.18	0.0005	0.04309	30.12	507.6	0.3013	0.000063	1.06
9	N-Heptane (nC7)	100.2	0.0003	0.03006	27.4	540.2	0.3495	0.000059	1.05
10	N-Octane	114.23	0.0001	0.011423	24.9	568.7	0.3996	0.00005	1.05
11	Nitrogen (N2)	28.01	0.0091	0.254891	34	126.2	0.0377	0.000173	1.4
12	Carbon dioxide (CO2)	44.01	0.0076	0.334476	73.83	304.21	0.2236	0.000147	1.3
	Mixture Properties		1.0000	17.5414	46.18505	199.1592	0.019837	0.000106295	1.302328

Appendix G Turbomatch Design Point Input Files

G.1 Design Point Input Files for SGT-400 Gas Turbine

Design Point Simulation for SGT-400 Industrial Gas Turbine

Inspired by Siemens SGT-400

BY OJO, OLUWATAYO BABATOPE

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DP SI GM VA FP

-1

-1

INTAKE	S1,2	D1-6	R200	
COMPRES	S2,3	D7-18	R205	V7 V8
PREMAS	S3,10,4	D19-22		
BURNER	S4,5	D23-30	R215	
MIXEES	S5,10,6			
TURBIN	S6,7	D31-45		V32
TURBIN	S7,8	D46-60		V46 V47
NOZCON	S8,9,1	D61-62	R220	
PLOTBD		D50,57		
PERFOR	S1,0,0	D46,64-66,220,200,215,0,0,0,0		
CODEND				

DATA ITEMS ////

1 0.0	! INTAKE: Altitude [m]
2 0.0	! Deviation from ISA temperature [K]
3 0.0	! Mach number
4 0.995	! Pressure recovery, according to USAF
5 0.0	! Deviation from ISA pressure [atm]
6 60.0	! Relative humidity [%]
7 -1.0	! COMPRESSOR I: $Z = (R-R[\text{choke}]) / (R[\text{surge}] - R[\text{choke}])$
8 0.876	! Relative rotational speed PCN
9 16.8	! DP Pressure ratio
10 0.87	! DP ETA
11 0.0	! Error selection
12 3.0	! Compressor map number
13 1.0	! Shaft number
14 1.0	! PR degradation scaling factor
15 1.0	! NDMF degradation scaling factor
16 1.0	! ETA degradation scaling factor
17 0.0	! Effective component volume [m ³] (only for transient)
18 0.0	! Stator angle (VSV) relative to DP
19 0.01	! PREMAS: LAMDA W Cooling bypass (Wout1/Win)
20 0.0	! DELTA W
21 1.0	! LAMBDA P
22 0.0	! DELTA P
23 0.05	! COMBUSTOR: Pressure loss (=DP/P inlet total)
24 0.999	! Combustion efficiency
25 -1.0	! Fuel flow (if -1.0, TET must be defined)
26 0.0	! (>0) Water flow [kg s ⁻¹ or lb s ⁻¹] or (<0) WAR
27 288	! Temperature of water stream [K]
28 0.0	! Phase of water (0=liquid, 1=vapour)
29 1.0	! ETA degradation scaling factor
30 -1.0	! Effective component volume [m ³] (only for transient)
31 0.0	! COMPRESSOR TURBINE: Auxiliary or power output [W]

32 0.8 ! Relative to max enthalpy drop to temperature ratio:ZT
 33 1.0 ! Relative non-dim speed CN
 34 0.90 ! DP ETA
 35 -1.0 ! Relative non-dim PCN (= -1 for compressor turbine)
 36 1.0 ! Shaft Number (for power turbine, the value 0 is used)
 37 4.0 ! Turbine map number
 38 -1.0 ! Power law index "n" (POWER = PCN^n)
 39 1.0 ! TF degradation scaling factor
 40 1.0 ! DH degradation scaling factor
 41 1.0 ! ETA degradation scaling factor
 42 0.0 ! Rotor rotational speed [RPS] (only for transient)
 43 0.0 ! Rotor moment of inertia [kg.m^2] (only for transient)
 44 0.0 ! Effective component volume [m^3] (only for transient)
 45 0.0 ! NGV angle, relative to D.P.

 46 13400000.0 ! FPT TURBINE: Auxiliary or power output [W]
 47 -1.0 ! Relative to max enthalpy drop to temperature ratio:ZT
 48 -1.0 ! Relative non-dim speed CN
 49 0.90 ! DP ETA
 50 1.0 ! Relative non-dim PCN (= -1 for compressor turbine)
 51 0.0 ! Shaft Number (for power turbine, the value 0 is used)
 52 4.0 ! Turbine map number
 53 -1.0 ! Power law index "n" (POWER = PCN^n)
 54 1.0 ! TF degradation scaling factor
 55 1.0 ! DH degradation scaling factor
 56 1.0 ! ETA degradation scaling factor
 57 200 ! Rotor rotational speed [RPS] (only for transient)
 58 20.0 ! Rotor moment of inertia [kg.m^2] (only for transient)
 59 -1.0 ! Effective component volume [m^3] (only for transient)
 60 0.0 ! NGV angle, relative to D.P.

 61 -1.0 ! CONVERGENT NOZZLE: = "-1" exit area is fixed
 62 1.0 ! Scaling factor

 63 1.0 ! ENGINE RESULTS: Power output - Power or Power turbine
 64 0.0 ! Propeller efficiency (= -1 for turbojet/turbofan)
 65 0.0 ! Scaling index ("1" = scaling needed, "0" = no scaling)
 66 0.0 ! Required DP shaft power (no scaling is needed)

 -1
 1 2 38.6 ! item 2 at station 1 = Mass flow(kg/s)
 5 6 1450 ! item 6 at station 5 = Total temperature (K)
 -1 ! End of DP data
 -3

G.2 Design Point Input Files for LM1600 Gas Turbine

Design Point Simulation for LM1600 Industrial Gas Turbine

Inspired by GE LM1600

BY OJO, OLUWATAYO BABATOPE

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DP SI GM VA FP

-1

-1

INTAKE	S1,2	D1-6	R200		
COMPRES	S2,3	D7-18	R205	V7	V8
COMPRES	S3,4	D19-30	R205	V19	V20
PREMAS	S4,25,5	D31-34			
PREMAS	S5,26,6	D35-38			
BURNER	S6,7	D39-46	R215		
MIXEES	S7,26,8				

TURBIN	S8,9	D47-61	V48
MIXEES	S9,25,10		
TURBIN	S10,11	D62-76	V63
TURBIN	S11,12	D77-91	V77 V78
NOZCON	S12,13,1	D92,93	R220
PERFOR	S1,0,0	D77,94-96,220,200,215,0,0,0,0,0	
CODEND			

DATA ITEMS ///

1 0.0	! INTAKE: ALTITUDE [m]
2 0.0	! DEVIATION FROM ISA TEMPERATURE [K]
3 0.0	! MACH NO
4 0.9954	! PRESSURE RECOVERY ACCORDING TO USAF
5 0.0	! DEVIATION FROM ISA PRESSURE [atm]
6 60.0	! RELATIVE HUMIDITY [%]
7 -1.0	! COMPRESSOR - FAN: SURGE MARGIN
8 -1.0	! RELATIVE ROTATIONAL SPEED PCN
9 2.509	! DESIGN POINT PRESSURE RATIO
10 0.87	! ISENTROPIC EFFICIENCY
11 0.0	! ERROR SELECTION
12 5.0	! COMPRESSOR MAP NO
13 1.0	! SHAFT NO
14 1.0	! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
15 1.0	! SCALING FACTOR OF NON-DIM MASS FLOW - DEGRADATION FACTOR
16 1.0	! SCALING FACTOR OF ISENTROPIC EFFICIENCY - DEGRADATION FACTOR
17 1.5	! EFFECTIVE COMPONENT VOLUME [m^3]
18 0.0	! STATOR ANGLE (VSV) RELATIVE TO DP
19 -1.0	! COMPRESSOR - HP: SURGE MARGIN
20 -1.0	! RELATIVE ROTATIONAL SPEED PCN
21 8.784	! DESIGN POINT PRESSURE RATIO
22 0.87	! ISENTROPIC EFFICIENCY
23 1.0	! ERROR SELECTION
24 5.0	! COMPRESSOR MAP NO
25 2.0	! SHAFT NO
26 1.0	! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
27 1.0	! SCALING FACTOR OF NON-DIM MASS FLOW - DEGRADATION FACTOR
28 1.0	! SCALING FACTOR OF ISENTROPIC EFFICIENCY - DEGRADATION FACTOR
29 -1.0	! EFFECTIVE COMPONENT VOLUME [m^3]
30 0.0	! STATOR ANGLE (VSV) RELATIVE TO DP
31 0.085	! PREMAS: BYPASS (Wout/Win)
32 0.0	! DELTA W
33 1.0	! LAMBDA P
34 0.0	! DELTA P
35 0.0725	! PREMAS: BYPASS (Wout/Win)
36 0.0	! DELTA W
37 1.0	! LAMBDA P
38 0.0	! DELTA P
39 0.05	! BURNER PRESSURE LOSS
40 0.999	! COMBUSTION EFFICIENCY
41 -1.0	! FUEL FLOW (IF -1, TET MUST BE DEFINED)
42 0.0	! (>0) WATER FLOW [kgs-1 OR lb s-1] OR (<0) WATER TO AIR RATIO
43 288.0	! TEMPERATURE OF WATER STREAM [K]
44 0.0	! PHASE OF WATER (0=LIQUID, 1=VAPOUR)
45 1.0	! SCALING FACTOR OF ETAb (COMBUSTION EFFICIENCY)-DEGRADATION FACTOR
46 -1.0	! EFFECTIVE COMPONENT VOLUME [M^3]

47 0.0 ! COMPRESSOR TURBINE: AUXILIARY OR POWER OUTPUT [W]
 48 -1 ! RELATIVE ENTHALPY DROP TO TEMPERATURE RATIO: ZT
 49 -1 ! RELATIVE NON-DIMENSIONAL SPEED CN
 50 0.88 ! DESIGN ISENTROPIC EFFICIENCY
 51 -1.0 ! RELATIVE NON-DIMENSIONAL SPEED PCN (= -1 FOR COMPRESSOR TURBINE)
 52 2.0 ! SHAFT NO
 53 3.0 ! TURBINE MAP NO
 54 -1.0 ! POWER LAW INDEX "n" (POWER=PCN^n) IF = -1, POWER IS ASSUMED TO BE A CONSTANT
 55 1.0 ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW)-DEGRADATION FACTOR
 56 1.0 ! SCALING FACTOR OF DH (ENTHALPY CHANGE)-DEGRADATION FACTOR
 57 1.0 ! SCALING FACTOR OF η_{ac} IS (TURBINE ISENTROPIC EFFICIENCY)-DEGRADATION FACTOR
 58 200 ! ROTOR ROTATIONAL SPEED [RPS]
 59 15.0 ! ROTOR MOMENT OF INERTIA [kg.m^2]
 60 -1.0 ! EFFECTIVE COMPONENT VOLUME [m^3]
 61 0.0 ! NGV ANGLE, RELATIVE TO DP

 62 0.0 ! COMPRESSOR TURBINE: AUXILIARY OR POWER OUTPUT [W]
 63 0.8 ! RELATIVE ENTHALPY DROP TO TEMPERATURE RATIO: ZT
 64 0.6 ! RELATIVE NON-DIMENSIONAL SPEED CN
 65 0.89 ! DESIGN ISENTROPIC EFFICIENCY
 66 -1.0 ! RELATIVE NON-DIMENSIONAL SPEED PCN (= -1 FOR COMPRESSOR TURBINE)
 67 1.0 ! SHAFT NO
 68 3.0 ! TURBINE MAP NO
 69 -1.0 ! POWER LAW INDEX "n" (POWER=PCN^n) IF = -1, POWER IS ASSUMED TO BE A CONSTANT
 70 1.0 ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW)-DEGRADATION FACTOR
 71 1.0 ! SCALING FACTOR OF DH (ENTHALPY CHANGE)-DEGRADATION FACTOR
 72 1.0 ! SCALING FACTOR OF η_{ac} IS (TURBINE ISENTROPIC EFFICIENCY)-DEGRADATION FACTOR
 73 200 ! ROTOR ROTATIONAL SPEED [RPS]
 74 15.0 ! ROTOR MOMENT OF INERTIA [kg.m^2]
 75 -1.0 ! EFFECTIVE COMPONENT VOLUME [m^3]
 76 0.0 ! NGV ANGLE, RELATIVE TO DP

 77 15200000 ! POWER TURBINE: AUXILIARY OR POWER OUTPUT [W]
 78 -1 ! RELATIVE ENTHALPY DROP TO TEMPERATURE RATIO: ZT
 79 -1 ! RELATIVE NON-DIMENSIONAL SPEED CN
 80 0.89 ! DESIGN ISENTROPIC EFFICIENCY
 81 1.0 ! RELATIVE NON-DIMENSIONAL SPEED PCN (= -1 FOR COMPRESSOR TURBINE)
 82 0.0 ! SHAFT NO (FOR POWER TURBINE, THE VALUE "0" IS USED)
 83 3.0 ! TURBINE MAP NO
 84 -1.0 ! POWER LAW INDEX "n" (POWER=PCN^n) IF = -1, POWER IS ASSUMED TO BE A
 CONSTANT
 85 1.0 ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW)-DEGRADATION FACTOR
 86 1.0 ! SCALING FACTOR OF DH (ENTHALPY CHANGE)-DEGRADATION FACTOR
 87 1.0 ! SCALING FACTOR OF η_{ac} IS (TURBINE ISENTROPIC EFFICIENCY)-DEGRADATION
 FACTOR
 88 200 ! ROTOR ROTATIONAL SPEED [RPS]
 89 20.0 ! ROTOR MOMENT OF INERTIA [kg.m^2]
 90 -1.0 ! EFFECTIVE COMPONENT VOLUME [m^3]
 91 0.0 ! NGV ANGLE, RELATIVE TO DP

 92 -1.0 ! CONVERGENT NOZZLE: = "-1" EXIT AREA IS FIXED
 93 1.0 ! SCALING FACTOR

 94 1.0 ! PERFORMANCE-ENGINE RESULTS- PERFOR: POWER OUTPUT
 95 0.0 ! SCALING INDEX ("1"= SCALING NEEDED, "0"= NO SCALING)
 96 0.0 ! REQUIRED DP NET THRUST (TURBOJET/TURBOFAN) OR SHAFT POWER
 (TURBOPROP/TURBOSHAFT)(=0 IF SCALING INDEX=0)

 -1
 1 2 46.0 ! ITEM 2 AT STATION 1 = MASS FLOW (kg/s)
 7 6 1560 ! ITEM 6 AT STATION 7 = TOTAL TEMPERATURE (k)
 -1 ! END OF DP DATA
 -3

Appendix H Gas Turbine Off-Design Performance
Results at each Compressor Station Location

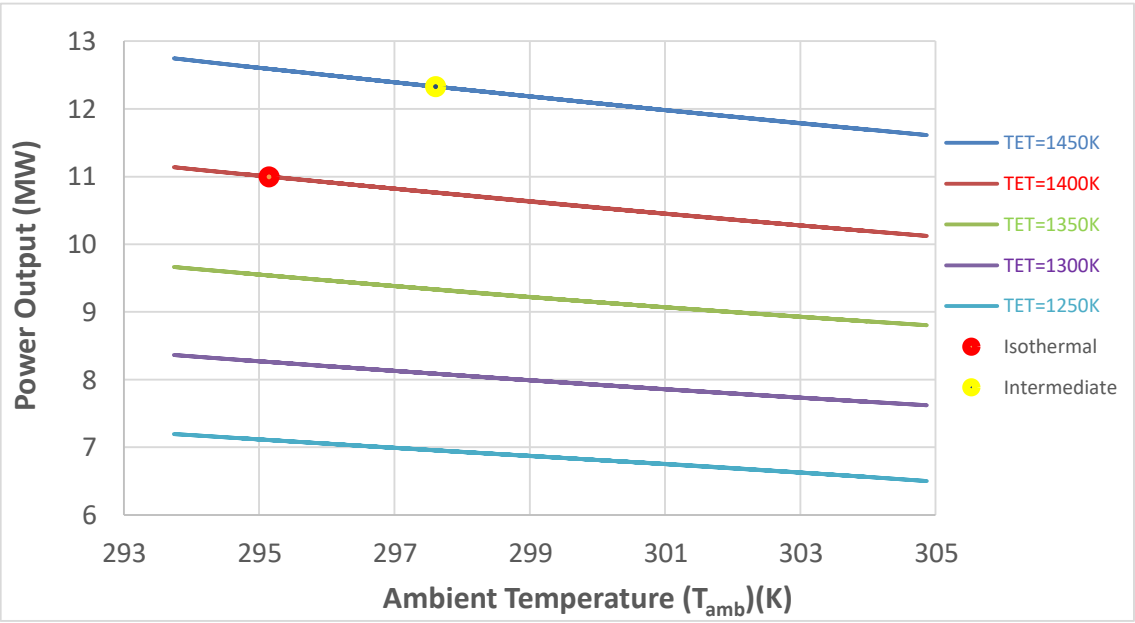


Figure H-1 Power Output against T_{amb} at different TET for Station 1

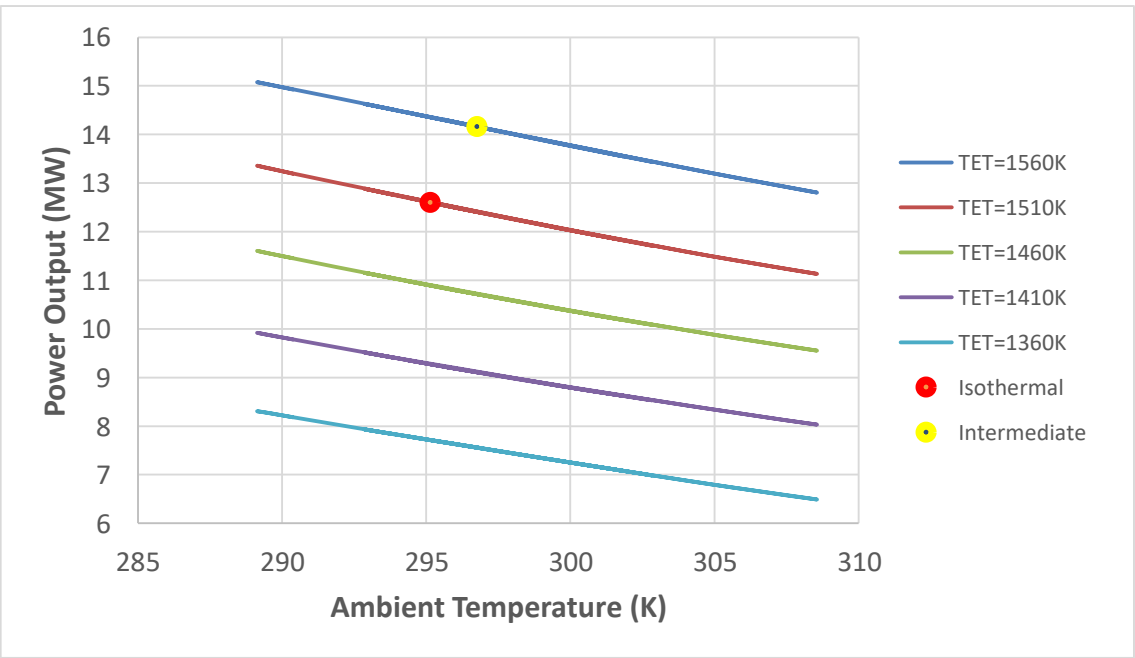


Figure H-2 Power Output against T_{amb} at different TET for Station 2

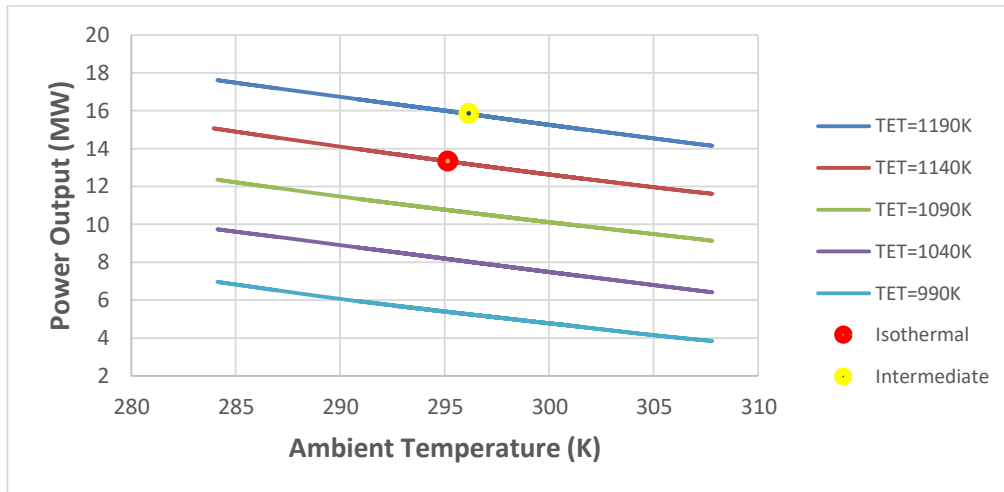


Figure H-3 Power Output against T_{amb} at different TET for Station 4

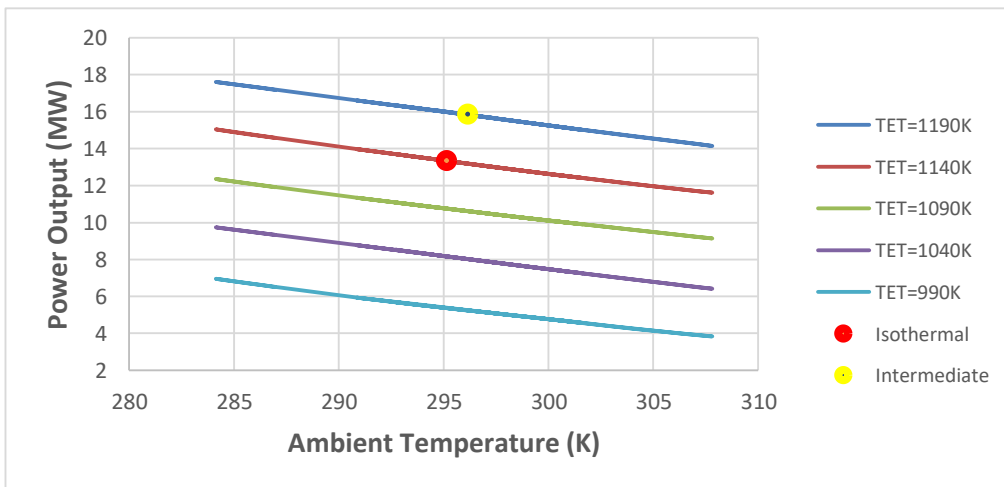


Figure H-4 Power Output against T_{amb} at different TET for Station 5

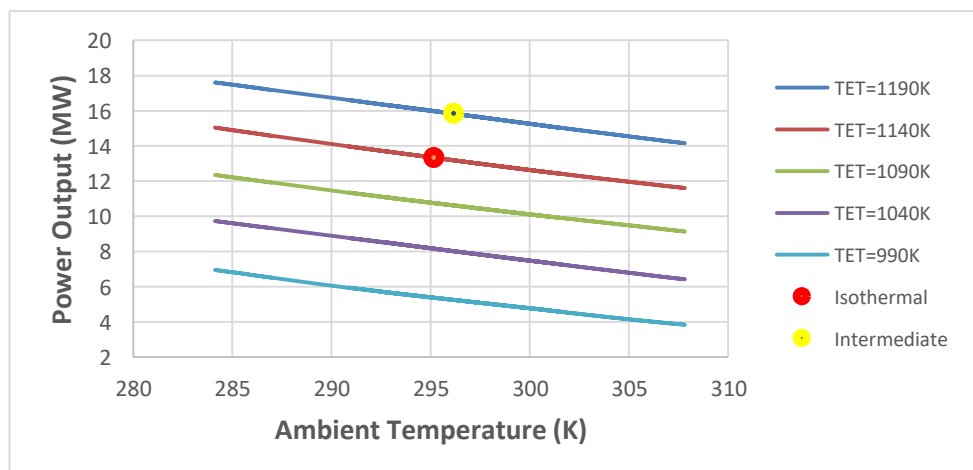


Figure H-5 Power Output against T_{amb} at different TET for Station 6

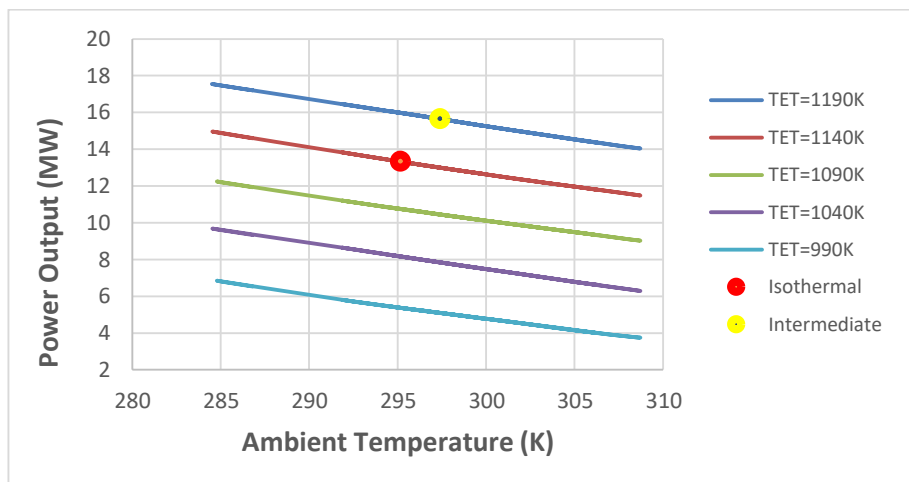


Figure H-6 Power Output against T_{amb} at different TET for Station 7

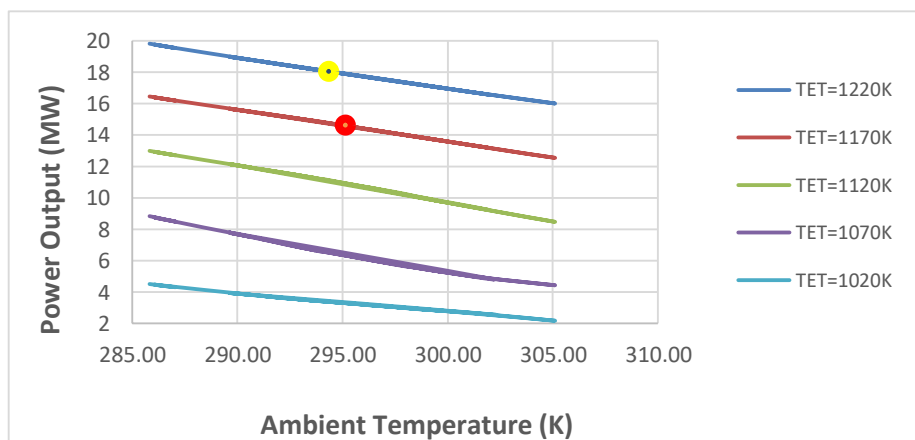


Figure H-7 Power Output against T_{amb} at different TET for Station 8

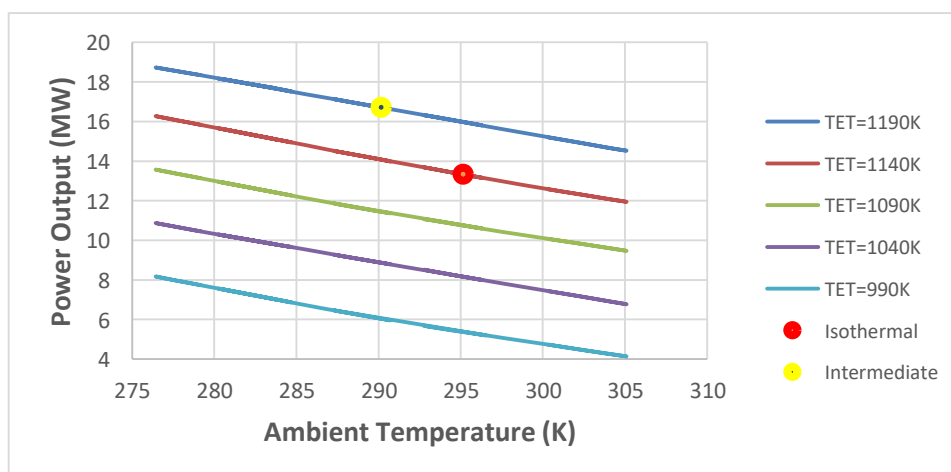


Figure H-8 Power Output against T_{amb} at different TET for Station 9

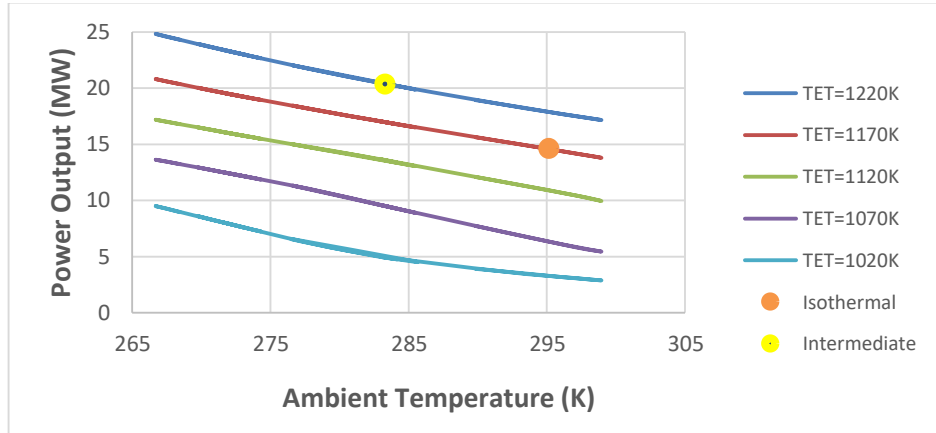


Figure H-9 Power Output against T_{amb} at different TET for Station 10

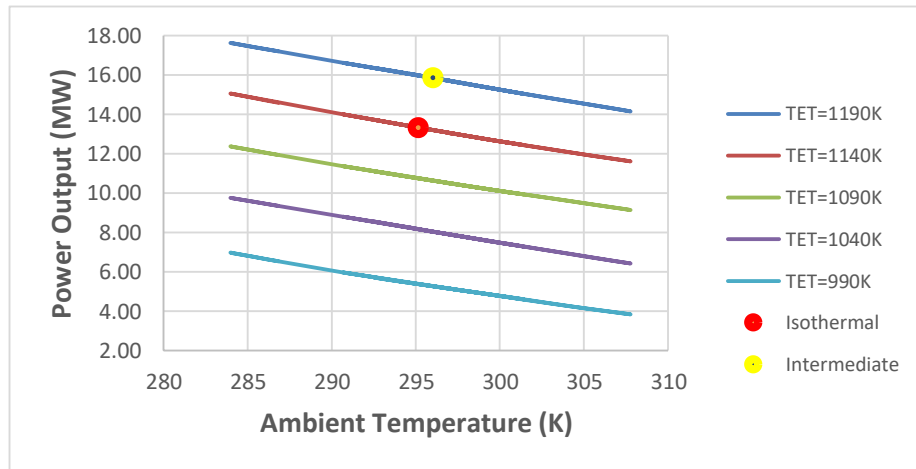


Figure H-10 Power Output against T_{amb} at different TET for Station 11

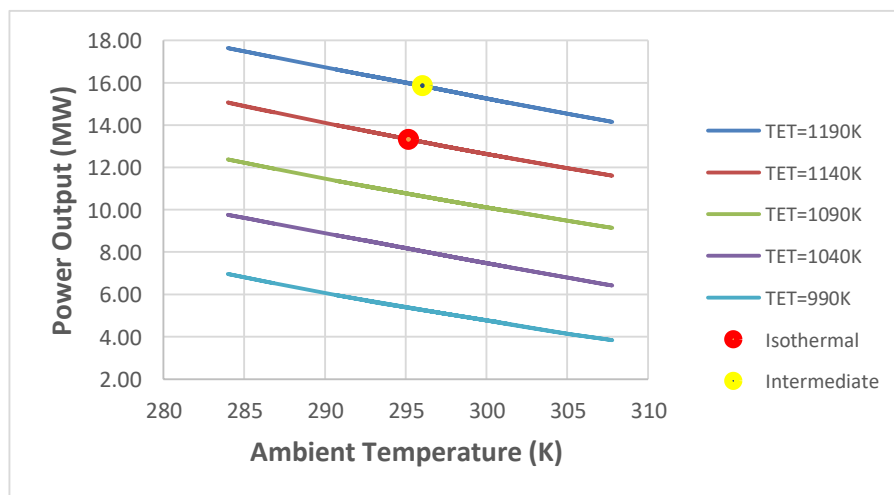


Figure H-11 Power Output against T_{amb} at different TET for Station 12

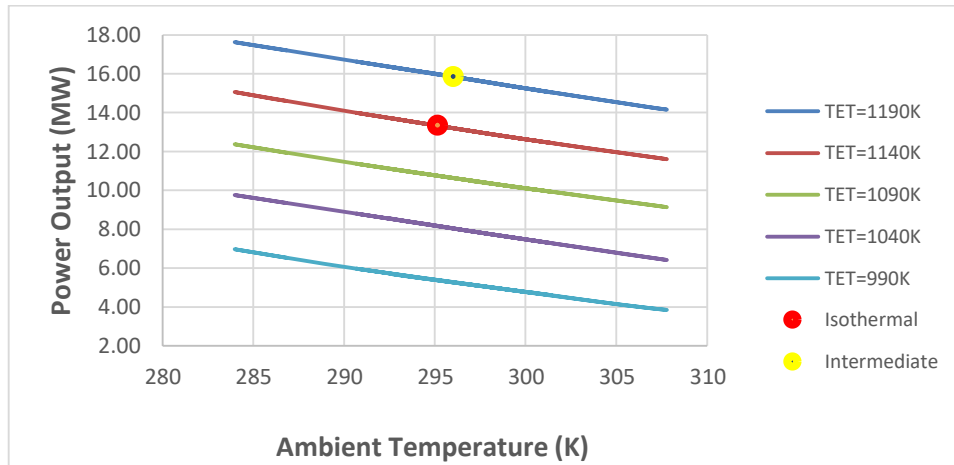


Figure H-12 Power Output against T_{amb} at different TET for Station 13

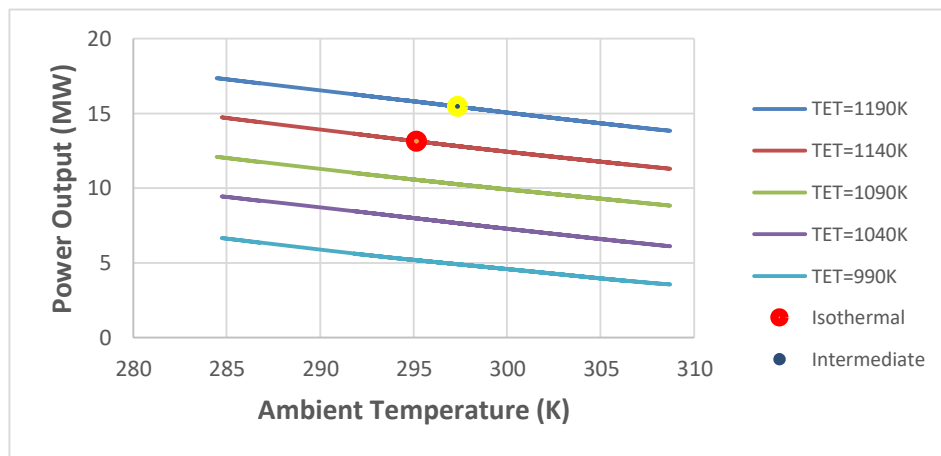


Figure H-13 Power Output against T_{amb} at different TET for Station 14

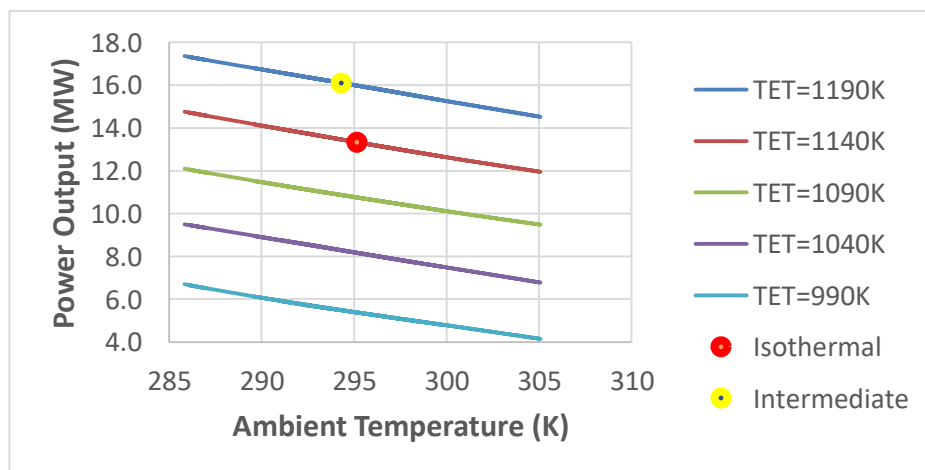


Figure H-14 Power Output against T_{amb} at different TET for Station 15

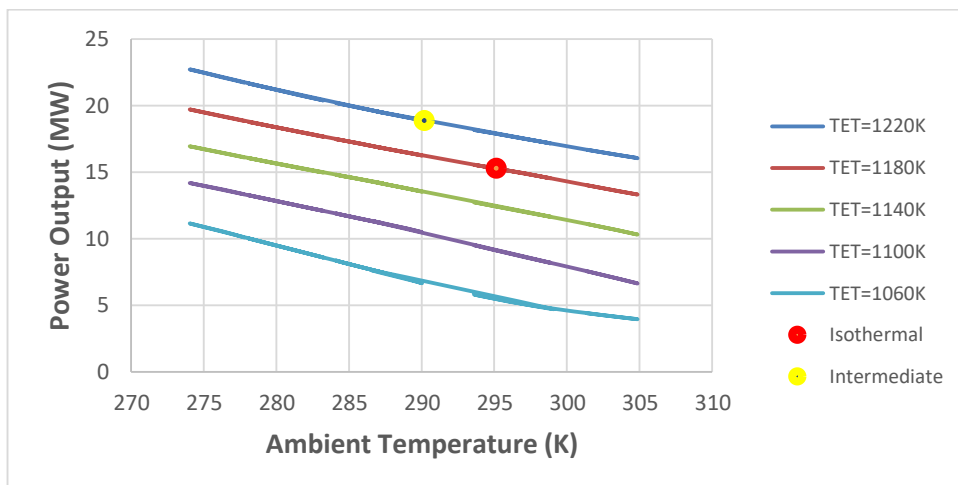


Figure H-15 Power Output against T_{amb} at different TET for Station 16

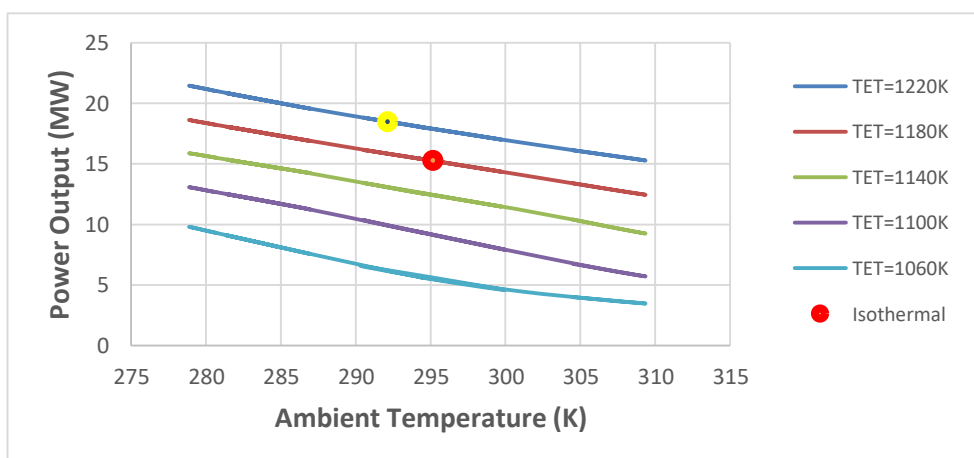


Figure H-16 Power Output against T_{amb} at different TET for Station 17

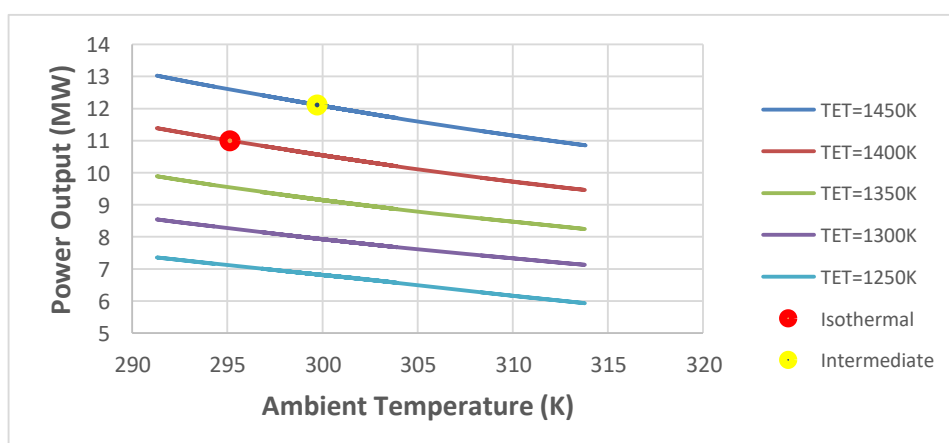


Figure H-17 Power Output against T_{amb} at different TET for Station 18

Appendix I Gas Turbine Shaft Power, Fuel Flow and TET Required by Gas Compressor at Non-Isothermal Flow

Table I-1 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 1 at 100 m Altitude, 0 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	295.49	1400	10.508	10.607	0.67914
	03:00	294.49	1400	10.362	10.714	0.68392
	06:00	293.74	1390	10.254	10.407	0.67086
	09:00	295.24	1400	10.471	10.633	0.6803
	12:00	298.49	1420	10.951	11.06	0.69837
	15:00	300.87	1440	11.309	11.583	0.72117
	18:00	298.99	1430	11.026	11.389	0.71288
	21:00	297.24	1410	10.765	10.813	0.6876
Dry						
	00:00	296.99	1410	10.728	10.839	0.68877
	03:00	295.99	1410	10.581	10.948	0.6934
	06:00	294.74	1400	10.398	10.687	0.68271
	09:00	296.74	1410	10.691	10.869	0.6899
	12:00	300.99	1440	11.328	11.573	0.72071
	15:00	303.99	1460	11.789	12.023	0.74112
	18:00	300.99	1440	11.328	11.571	0.72062
	21:00	298.99	1430	11.026	11.389	0.71286
Hot						
	00:00	297.99	1420	10.877	11.118	0.70103
	03:00	296.74	1410	10.691	10.871	0.69002
	06:00	295.99	1410	10.581	10.948	0.6934
	09:00	298.99	1430	11.026	11.389	0.71288
	12:00	301.74	1440	11.442	11.495	0.71721
	15:00	304.87	1460	11.926	11.937	0.73726
	18:00	301.99	1450	11.481	11.848	0.73306
	21:00	299.99	1430	11.176	11.294	0.70851

Table I-2 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 2 at 200 m Altitude, 240 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	290.38	1430	10.180	10.438	0.64908
	03:00	289.13	1420	10.003	10.254	0.63903
	06:00	289.38	1420	10.038	10.227	0.63781
	09:00	295.12	1460	10.868	10.895	0.6753
	12:00	300.6	1510	11.692	11.96	0.73369
	15:00	301.85	1520	11.884	12.16	0.7451
	18:00	300.1	1500	11.616	11.679	0.71891
	21:00	292.87	1450	10.539	10.817	0.66972
Dry						
	00:00	293.87	1450	10.685	10.702	0.66475
	03:00	292.87	1450	10.539	10.816	0.6697
	06:00	292.87	1450	10.539	10.816	0.6697
	09:00	297.11	1480	11.164	11.345	0.69938
	12:00	301.1	1510	11.769	11.9	0.73128
	15:00	302.84	1520	12.039	12.049	0.74041
	18:00	299.6	1500	11.540	11.729	0.72123
	21:00	295.62	1470	10.941	11.169	0.68968
Hot						
	00:00	296.86	1480	11.127	11.37	0.70058
	03:00	295.37	1470	10.904	11.202	0.69092
	06:00	294.37	1460	10.758	10.98	0.67899
	09:00	296.61	1480	11.089	11.404	0.70194
	12:00	304.09	1530	12.234	12.254	0.7521
	15:00	308.56	1570	12.950	13.153	0.8035
	18:00	304.83	1540	12.352	12.513	0.76635
	21:00	299.36	1500	11.502	11.762	0.72246

Table I-3 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 5 at 400 m Altitude, 960 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	286.97	1070	10.524	10.88	0.8286
	03:00	285.52	1060	10.319	10.56	0.81094
	06:00	284.13	1050	10.124	10.25	0.7931
	09:00	291	1090	11.107	11.32	0.85617
	12:00	297.99	1130	12.157	12.39	0.92154
	15:00	300.97	1150	12.622	13.01	0.95903
	18:00	298.52	1130	12.239	12.32	0.91819
	21:00	290.85	1090	11.084	11.34	0.85716
Dry	00:00	294.62	1110	11.644	11.84	0.88756
	03:00	293.51	1100	11.477	11.48	0.86713
	06:00	292.7	1100	11.357	11.59	0.87243
	09:00	295.76	1120	11.816	12.19	0.90805
	12:00	299.67	1140	12.417	12.68	0.93898
	15:00	301.63	1150	12.725	12.92	0.95489
	18:00	299.74	1140	12.429	12.66	0.93854
	21:00	297.07	1130	12.016	12.52	0.92742
Hot	00:00	297.42	1130	12.070	12.47	0.92518
	03:00	295.95	1120	11.845	12.17	0.90698
	06:00	294.65	1110	11.648	11.83	0.88734
	09:00	298.74	1130	12.273	12.29	0.91678
	12:00	304.16	1170	13.129	13.61	0.99635
	15:00	307.82	1190	13.727	14.15	1.0322
	18:00	305.28	1170	13.311	13.47	0.98987
	21:00	300.46	1140	12.541	12.57	0.93401

Table I-4 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 7 at 480 m Altitude, 1440 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	286.81	1060	10.181	10.389	0.80244
	03:00	286.79	1060	10.178	10.389	0.80256
	06:00	284.78	1050	9.913	10.155	0.7888
	09:00	292.61	1090	10.965	11.096	0.8457
	12:00	297.99	1120	11.720	11.879	0.89373
	15:00	299.80	1130	11.981	12.141	0.91019
	18:00	296.51	1110	11.509	11.569	0.87535
	21:00	291.86	1090	10.862	11.2	0.85054
Dry						
	00:00	294.43	1100	11.217	11.347	0.86118
	03:00	296.65	1110	11.529	11.549	0.87453
	06:00	294.64	1100	11.247	11.316	0.85983
	09:00	300.43	1140	12.072	12.569	0.9342
	12:00	305.25	1160	12.783	12.946	0.9614
	15:00	306.29	1170	12.940	13.328	0.98386
	18:00	305.00	1160	12.746	12.978	0.96286
	21:00	301.70	1140	12.257	12.392	0.92639
Hot						
	00:00	297.73	1120	11.683	11.916	0.89538
	03:00	296.70	1110	11.536	11.541	0.87413
	06:00	297.17	1120	11.603	11.997	0.89905
	09:00	301.00	1140	12.154	12.491	0.93066
	12:00	306.36	1170	12.951	13.317	0.9834
	15:00	308.71	1180	13.309	13.52	0.99848
	18:00	305.90	1170	12.881	13.378	0.98614
	21:00	300.04	1130	12.015	12.111	0.90874

Table I-5 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 8 at 600 m Altitude, 1670 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	285.82	1110	11.874	12.243	0.88041
	03:00	287.06	1120	12.071	12.697	0.90346
	06:00	286.05	1110	11.910	12.208	0.8788
	09:00	291.87	1140	12.844	13.11	0.92845
	12:00	297.44	1170	13.777	14.107	0.9834
	15:00	298.47	1180	13.954	14.611	1.0093
	18:00	301.91	1190	14.555	14.611	1.0143
	21:00	289.62	1130	12.478	12.86	0.91415
Dry						
	00:00	290.65	1140	12.645	13.406	0.94086
	03:00	289.68	1130	12.487	12.85	0.91364
	06:00	289.65	1130	12.483	12.85	0.91386
	09:00	293.98	1150	13.192	13.399	0.94466
	12:00	294.06	1150	13.207	13.399	0.94408
	15:00	299.82	1180	13.768	14.322	0.99723
	18:00	296.55	1170	13.626	14.296	0.99139
	21:00	292.50	1140	12.948	12.971	0.92251
Hot						
	00:00	293.69	1150	13.145	13.466	0.94754
	03:00	292.18	1140	12.895	13.038	0.92552
	06:00	291.18	1140	12.732	13.269	0.93524
	09:00	293.49	1150	13.112	13.516	0.94968
	12:00	300.33	1190	14.277	14.95	1.0284
	15:00	305.12	1210	15.131	15.375	1.0571
	18:00	301.07	1190	14.407	14.789	1.0217
	21:00	296.22	1160	13.570	13.649	0.95946

Table I-6 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 9 at 800 m Altitude, 1920 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	279.17	1050	10.466	10.983	0.82753
	03:00	277.69	1040	10.274	10.675	0.81036
	06:00	276.42	1030	10.110	10.337	0.79179
	09:00	279.03	1040	10.448	10.471	0.80095
	12:00	282.65	1060	10.926	10.987	0.83064
	15:00	284.68	1070	11.199	11.204	0.84403
	18:00	283.76	1070	11.074	11.34	0.85033
	21:00	280.24	1050	10.606	10.82	0.81991
Dry						
	00:00	283.76	1070	11.074	11.34	0.85033
	03:00	281.99	1060	10.838	11.083	0.83517
	06:00	280.49	1050	10.639	10.784	0.8182
	09:00	285.58	1080	11.321	11.593	0.86539
	12:00	287.84	1090	11.631	11.778	0.87749
	15:00	290.73	1110	12.033	12.399	0.91371
	18:00	289.90	1110	11.916	12.526	0.91945
	21:00	287.30	1090	11.556	11.857	0.88128
Hot						
	00:00	296.30	1140	12.833	13.156	0.96084
	03:00	294.52	1130	12.575	12.891	0.94439
	06:00	292.76	1120	12.321	12.623	0.92793
	09:00	297.55	1150	13.017	13.505	0.98127
	12:00	302.46	1170	13.753	13.845	1.0068
	15:00	305.09	1190	14.158	14.525	1.0488
	18:00	303.97	1180	13.985	14.156	1.0263
	21:00	300.35	1160	13.433	13.625	0.9918

Table I-7 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 10 at 1050 m Altitude, 2150 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	268.47	1040	10.112	10.92	0.80347
	03:00	266.71	1030	9.892	10.46	0.78194
	06:00	266.70	1030	9.890	10.46	0.78201
	09:00	268.73	1040	10.144	10.838	0.80007
	12:00	272.28	1050	10.593	10.752	0.79904
	15:00	274.31	1060	10.855	11.076	0.81542
	18:00	272.54	1050	10.628	10.677	0.79587
	21:00	269.74	1040	10.271	10.53	0.78727
Dry						
	00:00	273.28	1060	10.723	11.319	0.82596
	03:00	272.01	1050	10.559	10.835	0.80239
	06:00	271.49	1050	10.493	10.965	0.80808
	09:00	277.81	1080	11.316	11.804	0.85227
	12:00	282.60	1100	11.961	12.227	0.8764
	15:00	284.15	1110	12.175	12.606	0.89635
	18:00	280.63	1090	11.694	11.914	0.85997
	21:00	276.59	1070	11.153	11.314	0.82841
Hot						
	00:00	285.50	1120	12.362	13.053	0.91867
	03:00	283.96	1110	12.148	12.657	0.89826
	06:00	282.93	1100	12.006	12.153	0.87334
	09:00	291.77	1150	13.256	13.885	0.96537
	12:00	297.13	1170	14.053	14.174	0.98623
	15:00	298.96	1180	14.330	14.503	1.0049
	18:00	296.18	1170	13.909	14.375	0.99475
	21:00	289.84	1140	12.977	13.579	0.9484

Table I-8 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 12 at 400 m Altitude, 2610 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	286.93	1050	9.9	9.9	0.77533
	03:00	285.45	1050	9.851	10.071	0.78489
	06:00	284.06	1040	9.504	9.759	0.76733
	09:00	290.93	1080	10.411	10.85	0.83065
	12:00	297.93	1110	11.378	11.407	0.86804
	15:00	300.94	1130	11.810	12.02	0.9049
	18:00	298.47	1120	11.456	11.843	0.89226
	21:00	290.81	1080	10.395	10.866	0.83136
Dry						
	00:00	294.62	1100	10.916	11.346	0.86111
	03:00	293.51	1090	10.762	10.994	0.84105
	06:00	292.69	1090	10.649	11.107	0.84627
	09:00	295.73	1100	11.070	11.185	0.85389
	12:00	299.64	1120	11.622	11.675	0.88452
	15:00	301.60	1130	11.906	11.925	0.90047
	18:00	299.75	1120	11.638	11.663	0.88399
	21:00	297.09	1110	11.260	11.514	0.87298
Hot						
	00:00	297.44	1110	11.310	11.451	0.87
	03:00	295.97	1100	11.103	11.148	0.85206
	06:00	294.66	1100	10.921	11.325	0.86021
	09:00	298.79	1120	11.501	11.768	0.88869
	12:00	304.21	1150	12.287	12.575	0.93952
	15:00	307.84	1170	12.831	13.133	0.97552
	18:00	305.34	1160	12.455	12.942	0.96126
	21:00	300.50	1130	11.746	12.059	0.90642

Table I-9 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 13 at 560 m Altitude, 2840 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	284.13	1050	10.148	10.247	0.79309
	03:00	282.86	1050	9.982	10.432	0.80173
	06:00	281.10	1040	9.754	10.164	0.78647
	09:00	282.69	1050	9.959	10.456	0.80292
	12:00	288.55	1080	10.738	11.162	0.8452
	15:00	292.36	1100	11.260	11.64	0.87466
	18:00	290.56	1090	11.011	11.383	0.85911
	21:00	285.68	1060	10.353	10.542	0.80985
Dry						
	00:00	295.23	1110	11.661	11.748	0.88357
	03:00	293.71	1110	11.448	11.966	0.8936
	06:00	292.45	1100	11.272	11.627	0.87408
	09:00	296.00	1100	11.770	12.157	0.90658
	12:00	302.55	1150	12.723	12.792	0.94925
	15:00	306.08	1170	13.254	13.354	0.98508
	18:00	304.29	1160	12.984	13.074	0.96708
	21:00	299.26	1140	12.240	12.732	0.94155
Hot						
	00:00	301.01	1150	12.496	13.005	0.95876
	03:00	299.24	1140	12.237	12.734	0.94173
	06:00	297.22	1120	11.945	11.984	0.89864
	09:00	303.78	1160	12.907	13.145	0.97016
	12:00	311.36	1200	14.074	14.208	1.0416
	15:00	312.70	1210	14.287	14.56	1.0639
	18:00	312.63	1210	14.275	14.56	1.0639
	21:00	305.31	1170	13.137	13.457	0.98952

Table I-10 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 14 at 480 m Altitude, 3070 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	286.77	1060	10.175	10.388	0.80256
	03:00	286.75	1060	10.173	10.388	0.80268
	06:00	284.74	1050	9.908	10.161	0.78905
	09:00	292.50	1090	10.949	11.111	0.84641
	12:00	297.80	1120	11.693	11.905	0.89492
	15:00	299.60	1130	11.951	12.169	0.91143
	18:00	296.33	1110	11.484	11.594	0.8765
	21:00	291.78	1090	10.850	11.212	0.85109
Dry						
	00:00	294.40	1100	11.213	11.352	0.86138
	03:00	296.62	1110	11.525	11.553	0.87467
	06:00	294.60	1100	11.242	11.322	0.8601
	09:00	300.39	1140	12.066	12.575	0.93445
	12:00	305.25	1160	12.783	12.945	0.96138
	15:00	306.32	1170	12.945	13.324	0.98367
	18:00	305.03	1160	12.751	12.974	0.96268
	21:00	301.69	1140	12.256	12.392	0.92644
Hot						
	00:00	297.74	1120	11.684	11.914	0.89532
	03:00	296.71	1110	11.538	11.541	0.87411
	06:00	297.17	1120	11.603	11.996	0.89904
	09:00	301.04	1140	12.160	12.485	0.9304
	12:00	306.45	1170	12.964	13.305	0.98289
	15:00	308.73	1180	13.313	13.517	0.99836
	18:00	305.99	1170	12.895	13.367	0.98562
	21:00	300.07	1130	12.020	12.107	0.90855

Table I-11 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 16 at 900 m Altitude, 3530 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	277.78	1070	10.692	11.035	0.81636
	03:00	276.30	1060	10.499	10.536	0.7926
	06:00	274.03	1050	10.208	10.228	0.77727
	09:00	274.37	1060	10.251	11.061	0.8148
	12:00	281.73	1090	11.214	11.658	0.84898
	15:00	283.25	1100	11.420	12.077	0.87013
	18:00	282.46	1090	11.314	11.484	0.84159
	21:00	278.09	1070	10.732	10.962	0.81321
Dry						
	00:00	287.35	1110	11.983	12.815	0.90521
	03:00	285.59	1110	11.739	12.296	0.88264
	06:00	284.09	1100	11.534	11.889	0.86196
	09:00	285.42	1110	11.715	12.335	0.88428
	12:00	289.00	1120	12.213	12.275	0.88519
	15:00	290.04	1130	12.360	12.77	0.91027
	18:00	289.72	1130	12.315	12.844	0.91332
	21:00	286.89	1110	11.919	12.016	0.87049
Hot						
	00:00	298.87	1170	13.650	13.81	0.97078
	03:00	297.10	1160	13.385	13.462	0.9517
	06:00	293.60	1150	12.871	13.486	0.94834
	09:00	297.13	1160	13.390	13.456	0.95131
	12:00	301.51	1190	14.051	14.695	1.0178
	15:00	304.87	1200	14.571	14.729	1.0245
	18:00	304.76	1200	14.555	14.751	1.0255
	21:00	301.41	1190	14.036	14.716	1.0187

Table I-12 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 17 at 700 m Altitude, 3760 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	280.68	1080	10.260	11.131	0.82335
	03:00	280.18	1070	10.195	10.372	0.78849
	06:00	278.87	1070	10.025	10.756	0.80447
	09:00	280.38	1070	10.219	10.313	0.78603
	12:00	284.95	1090	10.824	10.913	0.81693
	15:00	286.97	1100	11.097	11.23	0.83378
	18:00	285.71	1100	10.926	11.516	0.84588
	21:00	281.41	1080	10.354	10.965	0.81609
Dry						
	00:00	285.0255	1090	10.834	10.894	0.8161
	03:00	283.0006	1090	10.564	11.366	0.83641
	06:00	281.4809	1080	10.364	10.948	0.81531
	09:00	285.9997	1100	10.965	11.45	0.84307
	12:00	292.299	1130	11.834	12.283	0.8893
	15:00	294.5632	1140	12.155	12.526	0.90355
	18:00	293.3068	1130	11.976	12.076	0.88041
	21:00	290.5123	1120	11.583	11.954	0.87138
Hot						
	00:00	299.72	1170	12.905	13.64	0.96358
	03:00	297.68	1160	12.605	13.326	0.94619
	06:00	294.12	1140	12.091	12.621	0.90757
	09:00	300.67	1170	13.047	13.442	0.95531
	12:00	307.26	1200	14.051	14.253	1.0051
	15:00	309.35	1210	14.379	14.563	1.024
	18:00	308.34	1210	14.220	14.76	1.0318
	21:00	304.51	1190	13.626	14.086	0.99247

Table I-13 Gas Turbine Shaft Power, Fuel Flow, and TET Required by Gas Compressor for Station 18 at 240 m Altitude, 3990 km from Origin

Seasons	Time of the Day	Average Ambient Temperature (K)	TET (K)	GC Power (MW)	Shaft Power (MW)	Fuel Flow (Kg/s)
Winter	00:00	294.31	1330	7.804	8.357	0.57842
	03:00	291.82	1330	7.562	8.464	0.58531
	06:00	291.29	1330	7.512	8.485	0.58729
	09:00	294.3	1330	7.804	8.396	0.57655
	12:00	300.62	1360	8.432	8.681	0.59456
	15:00	303.64	1370	8.741	8.794	0.59838
	18:00	301.88	1360	8.560	8.574	0.59005
	21:00	296.81	1330	8.051	8.149	0.56665
Dry						
	00:00	300.38	1360	8.408	8.7	0.59543
	03:00	299.09	1350	8.278	8.444	0.58564
	06:00	298.06	1330	8.175	8.233	0.56557
	09:00	300.16	1360	8.386	8.715	0.5961
	12:00	301.61	1360	8.532	8.597	0.591
	15:00	300.46	1360	8.416	8.694	0.59515
	18:00	300.9	1360	8.461	8.657	0.59354
	21:00	299.07	1350	8.276	8.445	0.58571
Hot						
	00:00	303.91	1370	8.768	8.772	0.59745
	03:00	301.84	1360	8.556	8.577	0.5902
	06:00	299.95	1350	8.365	8.385	0.58259
	09:00	304.44	1380	8.823	9.069	0.61009
	12:00	310.45	1410	9.454	9.612	0.63455
	15:00	313.78	1430	9.812	10.071	0.6548
	18:00	312.99	1420	9.726	9.773	0.64172
	21:00	308.34	1400	9.230	9.427	0.62633

Appendix J Local Maintenance Schedule

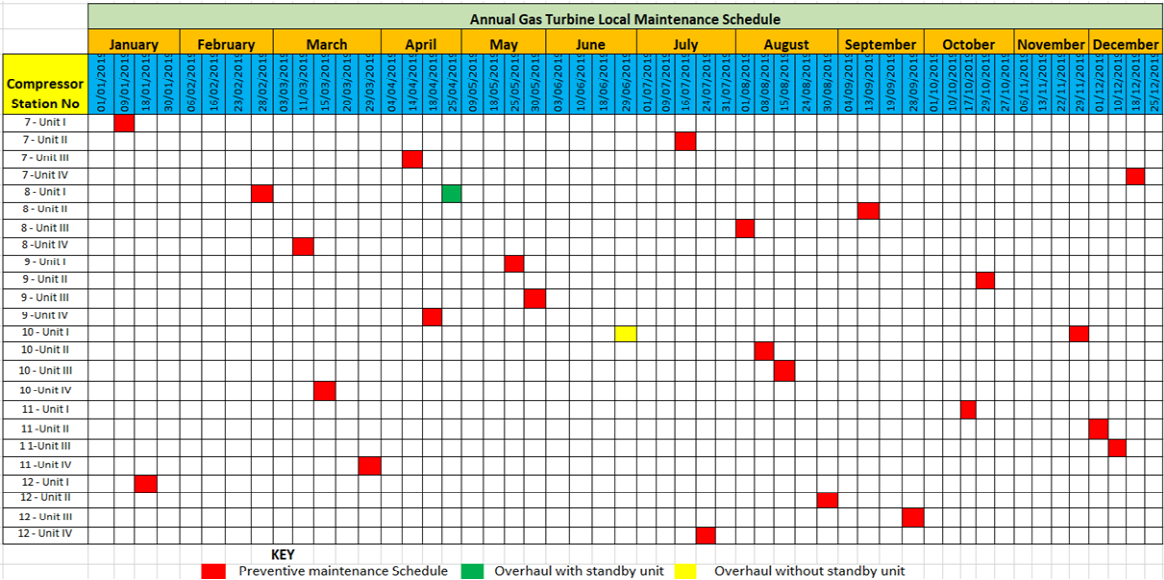


Figure J-1 Annual Gas Turbine Local Maintenance Schedule for Station 7-12

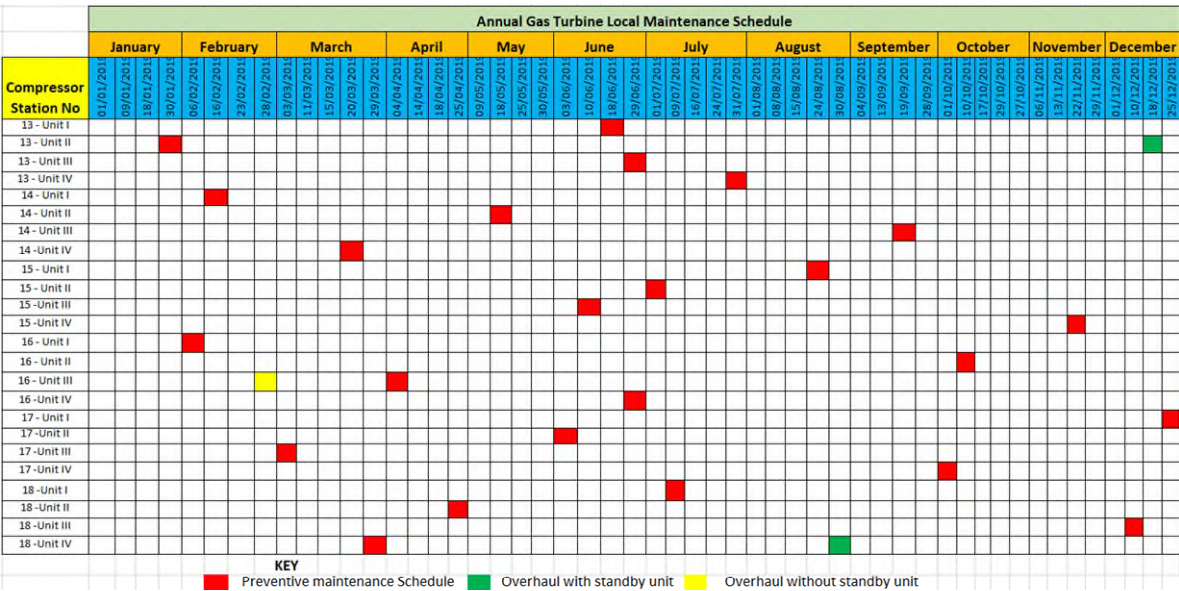


Figure J-2 Annual Gas Turbine Local Maintenance Schedule for Station 13-18

[illegible]

Figure J-3 Annual Gas Compressor Local Maintenance Schedule for Station 1-7

[illegible]

Figure J-4 Annual Gas Compressor Local Maintenance Schedule for Station 7-12

Appendix K Breakdown of Project Cost for Availability Scenarios

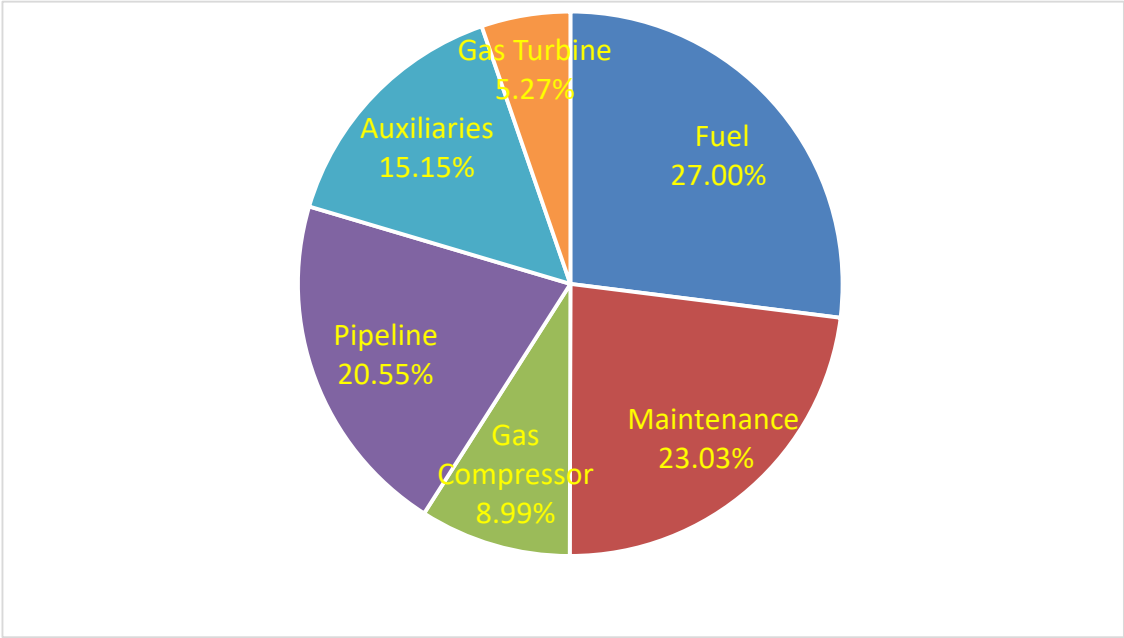


Figure K-1 Breakdown of Project Cost for Availability Scenario 1

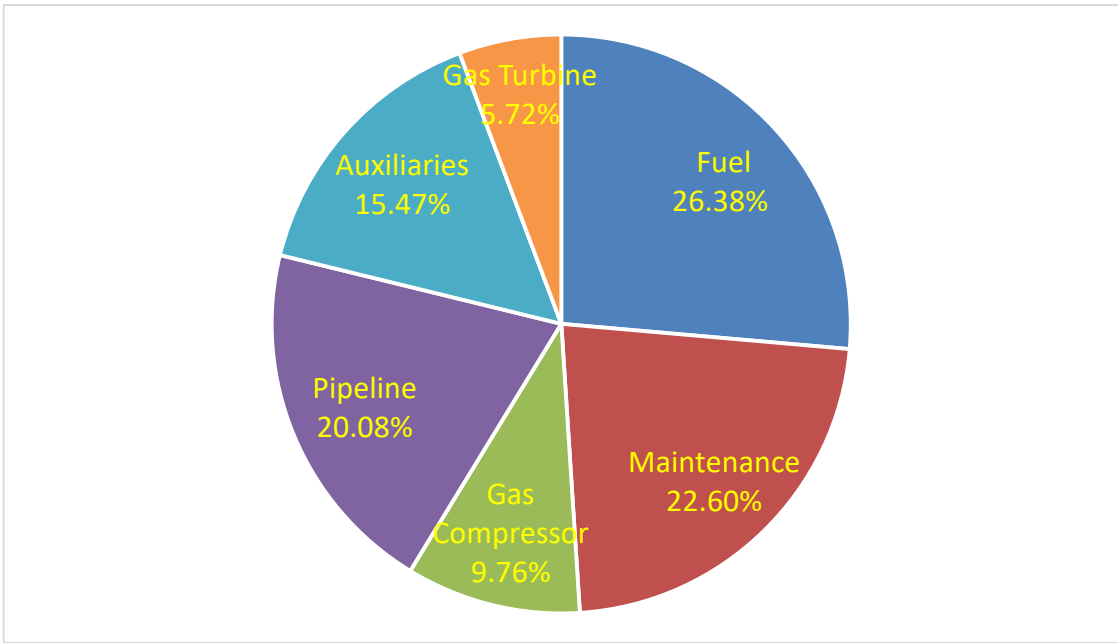


Figure K-2 Breakdown of Project Cost for Availability Scenario 2

Appendix L Breakdown of Project Cost for Techno socio-economic Scenarios

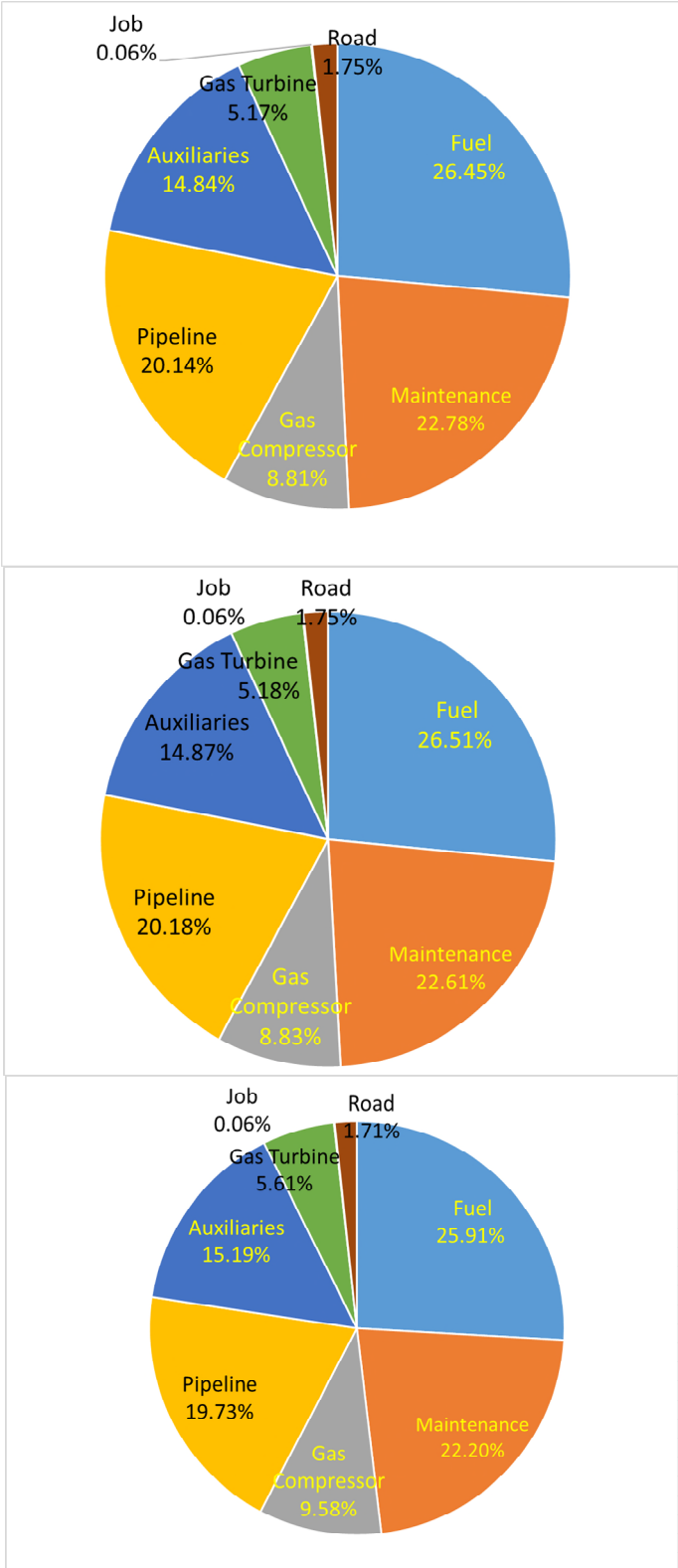


Figure L-1 Breakdown of Project Cost for Techno socio-economic Scenario 1,2,3

Appendix M MATLAB and Genetic Algorithm Optimisation Code for Objective Function

MATLAB R2019a - academic use

HOME	PLOTS	APPS	EDITOR	PUBLISH	VIEW
New Script New Live Script	New Open	Find Files Compare	Import Data Save Workspace	New Variable Open Variable Clear Workspace	Analyze Code Run and Time Clear Commands
FILE		VARIABLE		CODE	

Editor - C:\Users\s302885\OneDrive - Cranfield University\Documents\Techno socio-economic Optimisation\fitness_function

```
1 % Modelled by OLUWATAYO BABATOPE OJO, 2022
2
3 % Objective function
4 function Lifecycle_cost = fitness_function(L)
5
6 filename = 'cstation1.csv';
7 cstation1 = csvread(filename);
8
9 filename = 'cstation2.csv';
10 cstation2 = csvread(filename);
11
12 filename = 'cstation3.csv';
13 cstation3 = csvread(filename);
14
15 filename = 'cstation4.csv';
16 cstation4 = csvread(filename);
17
18 filename = 'cstation5.csv';
19 cstation5 = csvread(filename);
20
21 filename = 'cstation6.csv';
22 cstation6 = csvread(filename);
23
24 filename = 'cstation7.csv';
25 cstation7 = csvread(filename);
26
27 filename = 'cstation8.csv';
28 cstation8 = csvread(filename);
29
30 filename = 'cstation9.csv';
31 cstation9 = csvread(filename);
32
33 filename = 'cstation10.csv';
34 cstation10 = csvread(filename);
35
36 filename = 'cstation11.csv';
37 cstation11 = csvread(filename);
```



```

39 - for i = 1:length(cstation1)
40 -     cstation1_L(i) = cstation1(i,5);
41 -     cstation1_P1(i) = cstation1(i,3);
42 -     cstation1_P2(i) = cstation1(i,4);
43 -     cstation1_rp(i) = cstation1(i,6);
44 -     cstation1_Hp(i) = cstation1(i,9);
45 -     cstation1_Power(i) = cstation1(i,10);
46 -     cstation1_Ds(i) = cstation1(i,11);
47 -     cstation1_S(i) = cstation1(i,12);
48 -     cstation1_Unew(i) = cstation1(i,13);
49 -     cstation1_Vnew(i) = cstation1(i,14);
50 -     cstation1_Uexist(i) = cstation1(i,15);
51 -     cstation1_Vexist(i) = cstation1(i,16);
52 - end
53 - for i = 1:length(cstation2)
54 -     cstation2_L(i) = cstation2(i,5);
55 -     cstation2_P1(i) = cstation2(i,3);
56 -     cstation2_P2(i) = cstation2(i,4);
57 -     cstation2_rp(i) = cstation2(i,6);
58 -     cstation2_Hp(i) = cstation2(i,9);
59 -     cstation2_Power(i) = cstation2(i,10);
60 -     cstation2_Ds(i) = cstation2(i,11);
61 -     cstation2_S(i) = cstation2(i,12);
62 -     cstation2_Unew(i) = cstation2(i,13);
63 -     cstation2_Vnew(i) = cstation2(i,14);
64 -     cstation2_Uexist(i) = cstation2(i,15);
65 -     cstation2_Vexist(i) = cstation2(i,16);
66 - end
67 - for i = 1:length(cstation3)
68 -     cstation3_L(i) = cstation3(i,5);
69 -     cstation3_P1(i) = cstation3(i,3);
70 -     cstation3_P2(i) = cstation3(i,4);
71 -     cstation3_rp(i) = cstation3(i,6);
72 -     cstation3_Hp(i) = cstation3(i,9);
73 -     cstation3_Power(i) = cstation3(i,10);
74 -     cstation3_Ds(i) = cstation3(i,11);
75 -     cstation3_S(i) = cstation3(i,12);
76 -     cstation3_Unew(i) = cstation3(i,13);
77 -     cstation3_Vnew(i) = cstation3(i,14);
78 -     cstation3_Uexist(i) = cstation3(i,15);
79 -     cstation3_Vexist(i) = cstation3(i,16);
80 - end
81 - for i = 1:length(cstation4)
82 -     cstation4_L(i) = cstation4(i,5);
83 -     cstation4_P1(i) = cstation4(i,3);
84 -     cstation4_P2(i) = cstation4(i,4);
85 -     cstation4_rp(i) = cstation4(i,6);
86 -     cstation4_Hp(i) = cstation4(i,9);
87 -     cstation4_Power(i) = cstation4(i,10);
88 -     cstation4_Ds(i) = cstation4(i,11);
89 -     cstation4_S(i) = cstation4(i,12);
90 -     cstation4_Unew(i) = cstation4(i,13);
91 -     cstation4_Vnew(i) = cstation4(i,14);
92 -     cstation4_Uexist(i) = cstation4(i,15);
93 -     cstation4_Vexist(i) = cstation4(i,16);
94 - end
95 - for i = 1:length(cstation5)
96 -     cstation5_L(i) = cstation5(i,5);
97 -     cstation5_P1(i) = cstation5(i,3);
98 -     cstation5_P2(i) = cstation5(i,4);
99 -     cstation5_rp(i) = cstation5(i,6);
100 -     cstation5_Hp(i) = cstation5(i,9);
101 -     cstation5_Power(i) = cstation5(i,10);
102 -     cstation5_Ds(i) = cstation5(i,11);
103 -     cstation5_S(i) = cstation5(i,12);
104 -     cstation5_Unew(i) = cstation5(i,13);
105 -     cstation5_Vnew(i) = cstation5(i,14);
106 -     cstation5_Uexist(i) = cstation5(i,15);
107 -     cstation5_Vexist(i) = cstation5(i,16);
108 - end
109 - for i = 1:length(cstation6)
110 -     cstation6_L(i) = cstation6(i,5);
111 -     cstation6_P1(i) = cstation6(i,3);
112 -     cstation6_P2(i) = cstation6(i,4);
113 -     cstation6_rp(i) = cstation6(i,6);
114 -     cstation6_Hp(i) = cstation6(i,9);
115 -     cstation6_Power(i) = cstation6(i,10);
116 -     cstation6_Ds(i) = cstation6(i,11);
117 -     cstation6_S(i) = cstation6(i,12);
118 -     cstation6_Unew(i) = cstation6(i,13);
119 -     cstation6_Vnew(i) = cstation6(i,14);
120 -     cstation6_Uexist(i) = cstation6(i,15);
121 -     cstation6_Vexist(i) = cstation6(i,16);
122 - end

```

```

123 - for i = 1:length(cstation7)
124 -     cstation7_L(i) = cstation7(i,5);
125 -     cstation7_P1(i) = cstation7(i,3);
126 -     cstation7_P2(i) = cstation7(i,4);
127 -     cstation7_rp(i) = cstation7(i,6);
128 -     cstation7_Hp(i) = cstation7(i,9);
129 -     cstation7_Power(i) = cstation7(i,10);
130 -     cstation7_Ds(i) = cstation7(i,11);
131 -     cstation7_S(i) = cstation7(i,12);
132 -     cstation7_Unew(i) = cstation7(i,13);
133 -     cstation7_Vnew(i) = cstation7(i,14);
134 -     cstation7_Uexist(i) = cstation7(i,15);
135 -     cstation7_Vexist(i) = cstation7(i,16);
136 -
137 - end
138 - for i = 1:length(cstation8)
139 -     cstation8_L(i) = cstation8(i,5);
140 -     cstation8_P1(i) = cstation8(i,3);
141 -     cstation8_P2(i) = cstation8(i,4);
142 -     cstation8_rp(i) = cstation8(i,6);
143 -     cstation8_Hp(i) = cstation8(i,9);
144 -     cstation8_Power(i) = cstation8(i,10);
145 -     cstation8_Ds(i) = cstation8(i,11);
146 -     cstation8_S(i) = cstation8(i,12);
147 -     cstation8_Unew(i) = cstation8(i,13);
148 -     cstation8_Vnew(i) = cstation8(i,14);
149 -     cstation8_Uexist(i) = cstation8(i,15);
150 -     cstation8_Vexist(i) = cstation8(i,16);
151 -
152 - end
153 - for i = 1:length(cstation9)
154 -     cstation9_L(i) = cstation9(i,5);
155 -     cstation9_P1(i) = cstation9(i,3);
156 -     cstation9_P2(i) = cstation9(i,4);
157 -     cstation9_rp(i) = cstation9(i,6);
158 -     cstation9_Hp(i) = cstation9(i,9);
159 -     cstation9_Power(i) = cstation9(i,10);
160 -     cstation9_Ds(i) = cstation9(i,11);
161 -     cstation9_S(i) = cstation9(i,12);
162 -     cstation9_Unew(i) = cstation9(i,13);
163 -     cstation9_Vnew(i) = cstation9(i,14);
164 -     cstation9_Uexist(i) = cstation9(i,15);
165 -     cstation9_Vexist(i) = cstation9(i,16);
166 -
167 - end
168 - for i = 1:length(cstation10)
169 -     cstation10_L(i) = cstation10(i,5);
170 -     cstation10_P1(i) = cstation10(i,3);
171 -     cstation10_P2(i) = cstation10(i,4);
172 -     cstation10_rp(i) = cstation10(i,6);
173 -     cstation10_Hp(i) = cstation10(i,9);
174 -     cstation10_Power(i) = cstation10(i,10);
175 -     cstation10_Ds(i) = cstation10(i,11);
176 -     cstation10_S(i) = cstation10(i,12);
177 -     cstation10_Unew(i) = cstation10(i,13);
178 -     cstation10_Vnew(i) = cstation10(i,14);
179 -     cstation10_Uexist(i) = cstation10(i,15);
180 -     cstation10_Vexist(i) = cstation10(i,16);
181 -
182 - end
183 - for i = 1:length(cstation11)
184 -     cstation11_L(i) = cstation11(i,5);
185 -     cstation11_P1(i) = cstation11(i,3);
186 -     cstation11_P2(i) = cstation11(i,4);
187 -     cstation11_rp(i) = cstation11(i,6);
188 -     cstation11_Hp(i) = cstation11(i,9);
189 -     cstation11_Power(i) = cstation11(i,10);
190 -     cstation11_Ds(i) = cstation11(i,11);
191 -     cstation11_S(i) = cstation11(i,12);
192 -     cstation11_Unew(i) = cstation11(i,13);
193 -     cstation11_Vnew(i) = cstation11(i,14);
194 -     cstation11_Uexist(i) = cstation11(i,15);
195 -     cstation11_Vexist(i) = cstation11(i,16);
196 -
197 - end
198 -
199 - % interpolate
200 - P2(1) = interp(cstation1_L,cstation1_P2,L(1),'spline');
201 - P2(2) = interp(cstation2_L,cstation2_P2,L(2),'spline');
202 - P2(3) = interp(cstation3_L,cstation3_P2,L(3),'spline');
203 - P2(4) = interp(cstation4_L,cstation4_P2,L(4),'spline');
204 - P2(5) = interp(cstation5_L,cstation5_P2,L(5),'spline');
205 - P2(6) = interp(cstation6_L,cstation6_P2,L(6),'spline');
206 - P2(7) = interp(cstation7_L,cstation7_P2,L(7),'spline');
207 - P2(8) = interp(cstation8_L,cstation8_P2,L(8),'spline');
208 - P2(9) = interp(cstation9_L,cstation9_P2,L(9),'spline');
209 - P2(10) = interp(cstation10_L,cstation10_P2,L(10),'spline');
210 - P2(11) = interp(cstation11_L,cstation11_P2,L(11),'spline');
211 - P2(12) = interp(cstation12_L,cstation12_P2,L(12),'spline');

```

```

209 - Hp(1) = interp1(cstation1_L,cstation1_Hp,L(1),'spline');
210 - Hp(2) = interp1(cstation2_L,cstation2_Hp,L(2),'spline');
211 - Hp(3) = interp1(cstation3_L,cstation3_Hp,L(3),'spline');
212 - Hp(4) = interp1(cstation4_L,cstation4_Hp,L(4),'spline');
213 - Hp(5) = interp1(cstation5_L,cstation5_Hp,L(5),'spline');
214 - Hp(6) = interp1(cstation6_L,cstation6_Hp,L(6),'spline');
215 - Hp(7) = interp1(cstation7_L,cstation7_Hp,L(7),'spline');
216 - Hp(8) = interp1(cstation8_L,cstation8_Hp,L(8),'spline');
217 - Hp(9) = interp1(cstation9_L,cstation9_Hp,L(9),'spline');
218 - Hp(10) = interp1(cstation10_L,cstation10_Hp,L(10),'spline');
219 - Hp(11) = interp1(cstation11_L,cstation11_Hp,L(11),'spline');
220 - Hp(12) = interp1(cstation12_L,cstation12_Hp,L(12),'spline');
221
222 - rp(1) = interp1(cstation1n_L,cstation1_rp,L(1),'spline');
223 - rp(2) = interp1(cstation2_L,cstation2_rp,L(2),'spline');
224 - rp(3) = interp1(cstation3_L,cstation3_rp,L(3),'spline');
225 - rp(4) = interp1(cstation4_L,cstation4_rp,L(4),'spline');
226 - rp(5) = interp1(cstation5_L,cstation5_rp,L(5),'spline');
227 - rp(6) = interp1(cstation6_L,cstation6_rp,L(6),'spline');
228 - rp(7) = interp1(cstation7_L,cstation7_rp,L(7),'spline');
229 - rp(8) = interp1(cstation8_L,cstation8_rp,L(8),'spline');
230 - rp(9) = interp1(cstation9_L,cstation9_rp,L(9),'spline');
231 - rp(10) = interp1(cstation10_L,cstation10_rp,L(10),'spline');
232 - rp(11) = interp1(cstation11_L,cstation11_rp,L(11),'spline');
233 - rp(12) = interp1(cstation12_L,cstation12_rp,L(12),'spline');
234
235 - Power(1) = interp1(cstation1_L,cstation1_Power,L(1),'spline');
236 - Power(2) = interp1(cstation2_L,cstation2_Power,L(2),'spline');
237 - Power(3) = interp1(cstation3_L,cstation3_Power,L(3),'spline');
238 - Power(4) = interp1(cstation4_L,cstation4_Power,L(4),'spline');
239 - Power(5) = interp1(cstation5_L,cstation5_Power,L(5),'spline');
240 - Power(6) = interp1(cstation6_L,cstation6_Power,L(6),'spline');
241 - Power(7) = interp1(cstation7_L,cstation7_Power,L(7),'spline');
242 - Power(8) = interp1(cstation8_L,cstation8_Power,L(8),'spline');
243 - Power(9) = interp1(cstation9_L,cstation9_Power,L(9),'spline');
244 - Power(10) = interp1(cstation10_L,cstation10_Power,L(10),'spline');
245 - Power(11) = interp1(cstation11_L,cstation11_Power,L(11),'spline');
246
247 - Ds(1) = interp1(cstation1_L,cstation1_Ds,L(1),'spline');
248 - Ds(2) = interp1(cstation2_L,cstation2_Ds,L(2),'spline');
249 - Ds(3) = interp1(cstation3_L,cstation3_Ds,L(3),'spline');
250 - Ds(4) = interp1(cstation4_L,cstation4_Ds,L(4),'spline');
251 - Ds(5) = interp1(cstation5_L,cstation5_Ds,L(5),'spline');
252 - Ds(6) = interp1(cstation6_L,cstation6_Ds,L(6),'spline');
253 - Ds(7) = interp1(cstation7_L,cstation7_Ds,L(7),'spline');
254 - Ds(8) = interp1(cstation8_L,cstation8_Ds,L(8),'spline');
255 - Ds(9) = interp1(cstation9_L,cstation9_Ds,L(9),'spline');
256 - Ds(10) = interp1(cstation10_L,cstation10_Ds,L(10),'spline');
257 - Ds(11) = interp1(cstation11_L,cstation11_Ds,L(11),'spline');
258
259 - S(1) = interp1(cstation1_L,cstation1_S,L(1),'spline');
260 - S(2) = interp1(cstation2_L,cstation2_S,L(2),'spline');
261 - S(3) = interp1(cstation3_L,cstation3_S,L(3),'spline');
262 - S(4) = interp1(cstation4_L,cstation4_S,L(4),'spline');
263 - S(5) = interp1(cstation5_L,cstation5_S,L(5),'spline');
264 - S(6) = interp1(cstation6_L,cstation6_S,L(6),'spline');
265 - S(7) = interp1(cstation7_L,cstation7_S,L(7),'spline');
266 - S(8) = interp1(cstation8_L,cstation8_S,L(8),'spline');
267 - S(9) = interp1(cstation9_L,cstation9_S,L(9),'spline');
268 - S(10) = interp1(cstation10_L,cstation10_S,L(10),'spline');
269 - S(11) = interp1(cstation11_L,cstation11_S,L(11),'spline');
270
271 - Unew(1) = interp1(cstation1_L,cstation1_Unew,L(1),'spline');
272 - Unew(2) = interp1(cstation2_L,cstation2_Unew,L(2),'spline');
273 - Unew(3) = interp1(cstation3_L,cstation3_Unew,L(3),'spline');
274 - Unew(4) = interp1(cstation4_L,cstation4_Unew,L(4),'spline');
275 - Unew(5) = interp1(cstation5_L,cstation5_Unew,L(5),'spline');
276 - Unew(6) = interp1(cstation6_L,cstation6_Unew,L(6),'spline');
277 - Unew(7) = interp1(cstation7_L,cstation7_Unew,L(7),'spline');
278 - Unew(8) = interp1(cstation8_L,cstation8_Unew,L(8),'spline');
279 - Unew(9) = interp1(cstation9_L,cstation9_Unew,L(9),'spline');
280 - Unew(10) = interp1(cstation10_L,cstation10_Unew,L(10),'spline');
281 - Unew(11) = interp1(cstation11_L,cstation11_Unew,L(11),'spline');
282
283 - Vnew(1) = interp1(cstation1_L,cstation1_Vnew,L(1),'spline');
284 - Vnew(2) = interp1(cstation2_L,cstation2_Vnew,L(2),'spline');
285 - Vnew(3) = interp1(cstation3_L,cstation3_Vnew,L(3),'spline');
286 - Vnew(4) = interp1(cstation4_L,cstation4_Vnew,L(4),'spline');
287 - Vnew(5) = interp1(cstation5_L,cstation5_Vnew,L(5),'spline');
288 - Vnew(6) = interp1(cstation6_L,cstation6_Vnew,L(6),'spline');
289 - Vnew(7) = interp1(cstation7_L,cstation7_Vnew,L(7),'spline');
290 - Vnew(8) = interp1(cstation8_L,cstation8_Vnew,L(8),'spline');
291 - Vnew(9) = interp1(cstation9_L,cstation9_Vnew,L(9),'spline');
292 - Vnew(10) = interp1(cstation10_L,cstation10_Vnew,L(10),'spline');
293 - Vnew(11) = interp1(cstation11_L,cstation11_Vnew,L(11),'spline');
294
295 - Uexist(1) = interp1(cstation1_L,cstation1_Uexist,L(1),'spline');
296 - Uexist(2) = interp1(cstation2_L,cstation2_Uexist,L(2),'spline');

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297 - Uexist(3) = interp1(cstation3_L,cstation3_Uexist,L(3),'spline');
298 - Uexist(4) = interp1(cstation4_L,cstation4_Uexist,L(4),'spline');
299 - Uexist(5) = interp1(cstation5_L,cstation5_Uexist,L(5),'spline');
300 - Uexist(6) = interp1(cstation6_L,cstation6_Uexist,L(6),'spline');
301 - Uexist(7) = interp1(cstation7_L,cstation7_Uexist,L(7),'spline');
302 - Uexist(8) = interp1(cstation8_L,cstation8_Uexist,L(8),'spline');
303 - Uexist(9) = interp1(cstation9_L,cstation9_Uexist,L(9),'spline');
304 - Uexist(10) = interp1(cstation10_L,cstation10_Uexist,L(10),'spline');
305 - Uexist(11) = interp1(cstation11_L,cstation11_Uexist,L(11),'spline');
306 -
307 - Vexist(1) = interp1(cstation1_L,cstation1_Vexist,L(1),'spline');
308 - Vexist(2) = interp1(cstation2_L,cstation2_Vexist,L(2),'spline');
309 - Vexist(3) = interp1(cstation3_L,cstation3_Vexist,L(3),'spline');
310 - Vexist(4) = interp1(cstation4_L,cstation4_Vexist,L(4),'spline');
311 - Vexist(5) = interp1(cstation5_L,cstation5_Vexist,L(5),'spline');
312 - Vexist(6) = interp1(cstation6_L,cstation6_Vexist,L(6),'spline');
313 - Vexist(7) = interp1(cstation7_L,cstation7_Vexist,L(7),'spline');
314 - Vexist(8) = interp1(cstation8_L,cstation8_Vexist,L(8),'spline');
315 - Vexist(9) = interp1(cstation9_L,cstation9_Vexist,L(9),'spline');
316 - Vexist(10) = interp1(cstation10_L,cstation10_Vexist,L(10),'spline');
317 - Vexist(11) = interp1(cstation11_L,cstation11_Vexist,L(11),'spline');
318 -
319 - M_S = 1638.2; % Marshall and Swift Cost
320 - Fc = 1.15; % Correction factor for t
321 - w1 = 1;
322 - bhp1 = (Power(1).*1.341).^0.82;
323 - GC_purchased_cost1 = (M_S/280)*517.5.*bhp1.*Fc; % Gas compressor pu
324 - GC_installed_cost1 = (M_S/280)*517.5.*bhp1.*(2.11+Fc); % Gas compress
325 -
326 - w2 = 1;
327 - bhp2 = (Power(2).*1.341).^0.82;
328 - GC_purchased_cost2 = (M_S/280)*517.5.*bhp2.*Fc; % Gas compressor pu
329 - GC_installed_cost2 = (M_S/280)*517.5.*bhp2.*(2.11+Fc);
330 -
331 - w3 = 1;
332 - bhp3 = (Power(3).*1.341).^0.82;
333 - GC_purchased_cost3 = (M_S/280)*517.5.*bhp3.*Fc;
334 - GC_installed_cost3 = (M_S/280)*517.5.*bhp3.*(2.11+Fc);
335 -
336 - w4 = 1;
337 - bhp4 = (Power(4).*1.341).^0.82;
338 - GC_purchased_cost4 = (M_S/280)*517.5.*bhp4.*Fc;
339 - GC_installed_cost4 = (M_S/280)*517.5.*bhp4.*(2.11+Fc);
340 -
341 - w5 = 1;
342 - bhp5 = (Power(5).*1.341).^0.82;
343 - GC_purchased_cost5 = (M_S/280)*517.5.*bhp5.*Fc;
344 - GC_installed_cost5 = (M_S/280)*517.5.*bhp5.*(2.11+Fc);
345 -
346 - w6 = 1;
347 - bhp6 = (Power(6).*1.341).^0.82;
348 - GC_purchased_cost6 = (M_S/280)*517.5.*bhp6.*Fc;
349 - GC_installed_cost6 = (M_S/280)*517.5.*bhp6.*(2.11+Fc);
350 -
351 - w7 = 1;
352 - bhp7 = (Power(7).*1.341).^0.82;
353 - GC_purchased_cost7 = (M_S/280)*517.5.*bhp7.*Fc;
354 - GC_installed_cost7 = (M_S/280)*517.5.*bhp7.*(2.11+Fc);
355 -
356 - w8 = 1;
357 - bhp8 = (Power(8).*1.341).^0.82;
358 - GC_purchased_cost8 = (M_S/280)*517.5.*bhp8.*Fc;
359 - GC_installed_cost8 = (M_S/280)*517.5.*bhp8.*(2.11+Fc);
360 -
361 - w9 = 1;
362 - bhp9 = (Power(9).*1.341).^0.82;
363 - GC_purchased_cost9 = (M_S/280)*517.5.*bhp9.*Fc;
364 - GC_installed_cost9 = (M_S/280)*517.5.*bhp9.*(2.11+Fc);
365 -
366 - w10 = 1;
367 - bhp10 = (Power(10).*1.341).^0.82;
368 - GC_purchased_cost10 = (M_S/280)*517.5.*bhp10.*Fc;
369 - GC_installed_cost10 = (M_S/280)*517.5.*bhp10.*(2.11+Fc);
370 -
371 - w11 = 1;
372 - bhp11 = (Power(11).*1.341).^0.82;
373 - GC_purchased_cost11 = (M_S/280)*517.5.*bhp11.*Fc;
374 - GC_installed_cost11 = (M_S/280)*517.5.*bhp11.*(2.11+Fc);
375 -
376 - w12 = 1;
377 - Power_12=10274.7;
378 - bhp12 = (Power_12.*1.341).^0.82;
379 - GC_purchased_cost12 = (M_S/280)*517.5.*bhp12.*Fc;
380 - GC_installed_cost12 = (M_S/280)*517.5.*bhp12.*(2.11+Fc);

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382 - GC_Cost = w.*(GC_purchased_cost + GC_installed_cost)
383 - d = 56;
384 - D_d = d*25.4; % Pipe outer diameter inches converted to metre
385 - to = 0.81*25.4; % Pipe wall thickness inches converted to metre
386 - material = 1312; % Pipe material cost $ per metric ton
387 - pipe_material_cost = 0.0246*(D_d-to)*to*material*4180; % Pipe material cost $
388 - C_W = 5; % Coating and Wrapping cost $ per feet
389 - Coating_Wrapping = C_W * 4180* 3280.8399; % Coating and Wrapping cost $
390 - installation = 343.21 * d^2 + 2073.9*d + 170013; %This is the installation cost
391 - pipe_installation_cost = installation*4180*0.621371192; % pipe installation cost
392 -
393 - Pipeline_cost = pipe_material_cost + Coating_Wrapping + pipe_installation_cost;
394 -
395 - n = 11; % no of installed gas turbine less last
396 - GT_IC = 117000; % Gas turbine selected capacity KW
397 - hp1 = (GT_IC.*1.341); %Horsepower Conversion
398 - equipment_cost1 = 8118*(hp1^-0.294); % Gas turbine equipment cost $ per hp
399 - GT_equipment_cost1 = equipment_cost1*hp1; % Gas turbine equipment cost $
400 -
401 - KW2 = 13400; % Gas turbine selected capacity KW for 1
402 - hp2 = (KW2.*1.341); %Horsepower Conversion
403 - equipment_cost2 = 8118*(hp2^-0.294); % Gas turbine equipment cost $ per hp
404 - GT_equipment_cost2 = equipment_cost2*hp2; % Gas turbine equipment cost $
405 - installation_factor = 2; % Factor accounting for installation cost
406 - shipping_cost = 1.38; % Factor accounting for shipping cost
407 - GT_CAPEX = n*(GT_equipment_cost1*installation_factor*shipping_cost);
408 -
409 - D_r = 0.15; % Assumed fixed discount rate over the period
410 - time = 1:1:30;
411 - F_c = 227741540.6; % Annual Fuel cost obtained from Turboma
412 - fuel_cost = F_c./(1+D_r).^time;
413 - M_c = 278831121.7; % Annual Maintenance cost obtained from
414 - m_cost = M_c./(1+D_r).^time;
415 - Fuel_cost = sum(fuel_cost); % This is the discounted lifecycle fuel cost
416 - O_M_cost = sum(m_cost); % This is the discounted O&M cost determined
417 -
418 - PPIC = (GC_Cost + Pipeline_cost + GT_CAPEX); % This is the Pipeline project initial
419 -
420 - mainline_valve = 0.005*PPIC; % cost of mainline valve, $
421 - SCADA = 0.02*PPIC; % Supervisory control and data acquisition
422 - Env_Permit = 0.1*PPIC; % Environmental and permitting cost
423 - ROW = 0.06*PPIC; % Right of Way cost, $
424 - Engr_const_Mgt = 0.15*PPIC; % Engineering construction and management
425 - contingency = 0.1*PPIC; % contingency cost, $
426 -
427 -
428 - Auxiliaries = mainline_valve + SCADA + Env_Permit + ROW + Engr_const_Mgt + contingency; % Au
429 -
430 -
431 - Lifecycle_cost = -1*(GC_Cost + Pipeline_cost + GT_CAPEX + Fuel_cost + O_M_cost + Auxiliaries)
432 - end

```

Appendix N MATLAB and Genetic Algorithm Optimisation Code for Constraint Function

MATLAB R2019a - academic use

HOME PLOTS APPS EDITOR PUBLISH VIEW

New Script New Live Script New Open Find Files Compare Import Data Save Workspace New Variable Open Variable Clear Workspace Favorites Analyze Code Run and Time Clear Commands

FILE VARIABLE CODE

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fitness_function.m x const.m x main.m x +

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1 % Modelled by OLUWATAYO BABATOPE OJO, 2022
2
3 % Constraint function
4 function [c, ceq] = const(L)
5
6 Power(1) = interp(cstations1_L, cstations1_Power, L(1), 'spline');
7 Power(2) = interp(cstations2_L, cstations2_Power, L(2), 'spline');
8 Power(3) = interp(cstations3_L, cstations3_Power, L(3), 'spline');
9 Power(4) = interp(cstations4_L, cstations4_Power, L(4), 'spline');
10 Power(5) = interp(cstations5_L, cstations5_Power, L(5), 'spline');
11 Power(6) = interp(cstations6_L, cstations6_Power, L(6), 'spline');
12 Power(7) = interp(cstations7_L, cstations7_Power, L(7), 'spline');
13 Power(8) = interp(cstations8_L, cstations8_Power, L(8), 'spline');
14 Power(9) = interp(cstations9_L, cstations9_Power, L(9), 'spline');
15 Power(10) = interp(cstations10_L, cstations10_Power, L(10), 'spline');
16 Power(11) = interp(cstations11_L, cstations11_Power, L(11), 'spline');
17 Power(12) = interp(cstations12_L, cstations12_Power, L(12), 'spline');
18
19 c(1) = [Power(1) - 106363.6];
20 c(2) = [Power(2) - 106363.6];
21 c(3) = [Power(3) - 106363.6];
22 c(4) = [Power(4) - 106363.6];
23 c(5) = [Power(5) - 106363.6];
24 c(6) = [Power(6) - 106363.6];
25 c(7) = [Power(7) - 106363.6];
26 c(8) = [Power(8) - 106363.6];
27 c(9) = [Power(9) - 106363.6];
28 c(10) = [Power(10) - 106363.6];
29 c(11) = [Power(11) - 106363.6];
30 c(12) = [Power(12) - 10274.7];
31
32 c = [c(1) c(2) c(3) c(4) c(5) c(6) c(7) c(8) c(9) c(10) c(11) c(12)];
33
34 ceq = [];
35 end

```

Appendix O MATLAB Code and Genetic Algorithm Optimisation Solver used in Optimising Station Location

MATLAB R2019a - academic use

HOME PLOTS APPS EDITOR PUBLISH VIEW

New Script New Live Script New Open Find Files Import Data Save Workspace New Variable Open Variable Analyze Code Run and Time Clear Commands

FILE VARIABLE CODE

Editor - C:\Users\s302885\OneDrive - Cranfield University\Documents\Techno socio-economic Optimisation\techno-econo

fitness_function.m x const.m x main.m x +

```

1 - clc
2 - clear all
3
4 - Lifecycle_cost = @fitness_function;
5 - nvar = 12; %number of variable
6
7 - LB = [200 580 960 1330 1690 2060 2420 2800 3160 3520 3880 4080];%Lowerbound
8 - UB = [390 770 1150 1520 1880 2250 2610 2990 3350 3710 4090 4180];%Upperbound
9
10 - constraint = @const
11
12 - options = optimoptions(@ga,'PlotFcn',...
13     {@gaplotbestf,@gaplotbestindiv,@gaplotscores,@gaplotdistance},...
14     'populationSize',500,'Generations',25,'FunctionTolerance',1e-9,...
15     'ConstraintTolerance', 1e-9,'display','iter');
16
17
18 - [x,fval] = ga(Lifecycle_cost,nvar,[],[],[],[],LB,UB,constraint,options);

```

Solver: ga - Genetic Algorithm

Problem

Fitness function: @obj_function

Number of variables: 12

Constraints:

Linear inequalities: A: b:

Linear equalities: Aeq: beq:

Bounds: Lower: [200 580 960 1330 1690 2060 2420 2800 3160] Upper: [390 770 1150 1520 1880 2250 2610 2990 3350]

Nonlinear constraint function: @const

Integer variable indices:

Run solver and view results

☐ Use random states from previous run

Start Pause Stop

Current iteration: 8 Clear Results

Optimization running.

Objective function value: -3.2235520724414467E10

Optimization terminated: average change in the fitness value less than options.FunctionTolerance and constraint violation is less than options.ConstraintTolerance.

Final point:

1	2	3	4	5	6	7	8	9	10	11	12
379.824	751.801	1,131.802	1,496.924	1,853.404	2,225.968	2,591.761	2,960.295	3,327.457	3,675.843	4,078.891	4,180

Population

Population type: Double vector

Population size: ☐ Use default: 50 for five or fewer variables ☒ Specify: 400

Creation function: Constraint dependent

Initial population: ☒ Use default: [] ☐ Specify:

Initial scores: ☒ Use default: [] ☐ Specify:

Initial range: ☒ Use default: [-10;10] ☐ Specify:

Fitness scaling

Scaling function: Rank

Selection

Selection function: Roulette

Reproduction

Elite count: ☐ Use default: 0.05*PopulationSize ☒ Specify: 2

Crossover fraction: ☐ Use default: 0.8 ☒ Specify: 0.7

Mutation

Mutation function: Adaptive feasible

Appendix P Temperature, Pressure, Polytropic Head, and Power Relationship for Compressor Station 2

L (km)	Elevation(m)	Tf (K)	MW	Z	P1	P2	rp	Q	m	Hp	GC_Power
200	160	305.31	17.54	0.85	10000	7673	1.3	40578	3E+06	34.3	31695.9
210	170	308.32	17.54	0.86	10000	7495	1.3	42237	3E+06	38.2	35237.5
220	180	308.65	17.54	0.86	10000	7347	1.4	43204	3E+06	41.1	37917.4
230	190	308.62	17.54	0.86	10000	7201	1.4	44119	3E+06	43.9	40575.2
240	200	308.56	17.54	0.86	10000	7053	1.4	45082	3E+06	47	43354.5
250	50	309.50	17.54	0.86	10000	7018	1.4	45529	3E+06	47.9	44229.2
260	100	309.14	17.54	0.86	10000	6834	1.5	46729	3E+06	51.7	47755.6
270	150	308.78	17.54	0.86	10000	6647	1.5	48020	3E+06	55.8	51484.5
280	200	308.42	17.54	0.86	10000	6457	1.6	49417	3E+06	60	55440.2
290	250	308.05	17.54	0.86	10000	6262	1.6	50929	3E+06	64.6	59643.7
300	300	307.69	17.54	0.87	10000	6062	1.7	52584	3E+06	69.5	64144.6
310	290	307.72	17.54	0.87	10000	5901	1.7	54085	3E+06	73.7	68031.4
320	280	307.75	17.54	0.87	10000	5735	1.7	55724	3E+06	78.2	72209.2
330	270	307.78	17.54	0.87	10000	5563	1.8	57523	3E+06	83.1	76719
340	260	307.81	17.54	0.87	10000	5384	1.9	59509	3E+06	88.4	81611.2
350	250	307.84	17.54	0.87	10000	5198	1.9	61718	3E+06	94.2	86947.6
360	240	307.87	17.54	0.87	10000	5005	2	64194	3E+06	101	92806.2
370	230	307.89	17.54	0.87	10000	4802	2.1	66988	3E+06	108	99269.2
380	220	307.92	17.54	0.87	10000	4590	2.2	70194	3E+06	115	106498
390	210	307.95	17.54	0.87	10000	4365	2.3	73913	3E+06	124	114651

Appendix Q Road benefit – Test case

This test case illustrates the benefits of new road infrastructure creation in a way easy to understand. The mode of transportation for the existing and new road infrastructure routes is bus mode. Both routes have the same origin and destination. The origin could be denoted as point A, for example, a location in Cranfield. The destination could be denoted as point B, for example, a location in Bedford.

The road benefit is a function of the travel time, road infrastructure impact, performance characteristics, road width, population characteristics, and the travel speed (see Equations (7-35) to (7-44) on pages 192-193). By assuming the following values for the existing route:

Bus speed = 3 mph; road infrastructure impact = 0.004 km²/MW per 10000 populations; gas turbine performance characteristics = 40 MW; road width = 0.011 km; social influence area population density = 5.8 persons/km²; social benefit width = 100 km. Assuming the compressor station is located on a pipeline segment of 10 km in length. This is equivalent to a social benefit area of 1000 km². Utilising the above information and employing Equation (7-40), the travel time (t_e) for the existing route is estimated as:

$$t_e = 0.004 \frac{\text{km}^2}{\text{MW}} * \frac{1000 \text{km}^2}{10000 \text{ persons}} * \frac{5.8 \text{ persons}}{\text{km}^2} * \frac{40 \text{MW}}{0.011 \text{km}} * \frac{1}{(3 * 1.60934)} \frac{\text{hr}}{\text{km}}$$

$$t_e = 1 \text{ hour } 45 \text{ minutes}$$

Therefore, travel time for existing route is 1 hour 45 minutes.

For the new road infrastructure route, improvements in the new road are reflected by an increased bus speed. Assuming a 20-mph bus speed with all other conditions remaining the same. Employing Equation (7-43), the travel time (t_n) for the new route is estimated as:

$$t_n = 0.004 \frac{\text{km}^2}{\text{MW}} * \frac{1000 \text{km}^2}{10000 \text{ persons}} * \frac{5.8 \text{ persons}}{\text{km}^2} * \frac{40 \text{MW}}{0.011 \text{km}} * \frac{1}{(20 * 1.60934)} \frac{\text{hr}}{\text{km}}$$

$$t_n = 16 \text{ minutes}$$

Therefore, travel time for new route is 16 minutes.

The travel time savings is the difference between the travel times for the existing and the new road infrastructure routes. It is equivalent to 1 hour 29 minutes (1.483 hour).

Employing the value of travel time savings (VTTS) values of \$4.74 per hour for the middle-income groups as shown in Table 7-4. The travel time cost savings between the existing and the new road infrastructure routes is estimated as:

$$(T_e - T_n) = 1.483 \text{ hr} * \frac{\$}{\text{hr}} 4.74 = \$7.03 \text{ per road trip per job}$$

The annual road benefit for one job assuming 248 road trips per job are made per year is estimated as:

$$R_B = (T_e - T_n)N_t J_t = \frac{\$}{\text{trip.job}} 7.03 * 248 \text{ trips} * 1 \text{ job} = \$1743.4$$

By assuming the same values of annual road benefits over the project lifecycle. This annual road benefits would be discounted over the project lifecycle to the reference year at the beginning of the project using the assumed social discount rate of 5%.

Appendix R Direct Employment benefit – Test case

This section uses two hypothetical compressor station locations scenarios to illustrate the employment benefit in a manner easy to understand. It is assumed that the compressor station locations under scenario 1 is at Abuja. The compressor station locations under scenario 2 is at Niger-Delta.

The compressor station locations under scenario 1 is characterised by urban area with high standard of living, high population density, and a higher existing level of wealth. Conversely, the compressor station locations under scenario 2 is characterised by rural area with low standard of living, low population density, and a lower existing level of wealth compared to scenario 1.

The employment benefit is a function of the annual jobs created, the population characteristics, and the income level. It depends on the compressor station locations.

Scenario 1

By assuming the following values for scenario 1:

Annual jobs produced = 0.1 jobs per 10000 population; average annual salaries per jobs according to income level = \$43,704/job; social influence area population density = 415 persons/km²; social discount rate = 5%; social benefit width = 100 km. Assuming the compressor station is located on a pipeline segment of 10 km in length. This is equivalent to a social benefit area of 1000 km². Project life is 30 years. Utilising the above information and employing Equation (7-18), the employment benefit (S_N) for scenario 1 is estimated as:

$$S_N = \sum_{i=1}^{i=30} \frac{0.1 \text{ job}}{10000 \text{ persons}} * \frac{415 \text{ persons}}{\text{km}^2} * 1000 \text{ km}^2 * 43704 \frac{\$}{\text{job}}}{(1.05)^i}$$

$$S_N = \$ 2.79 \text{ million}$$

Therefore, the employment benefit for scenario 1 is about \$2.79 million.

Existing level of wealth is defined as the product of the population and the average salaries according to income groups for the 10 km pipeline segment where the compressor station is located. The existing level of wealth is estimated for scenario 1 as:

$$S_E = \frac{415 \text{ persons}}{\text{km}^2} * 1000 \text{ km}^2 * 43704 \frac{\$}{\text{person}}$$

$$S_E = \$ 18.14 \text{ billion}$$

The employment benefit ratio is the ratio of the employment benefit and the existing level of wealth. It represents the degree of social uplift from the jobs created within the social influence area of the compressor station location. The employment benefit ratio is estimated for scenario 1 as:

$$EBR = \frac{\$ 2.79 \text{ million}}{\$ 18.14 \text{ billion}}$$

$$EBR = 0.0002$$

Scenario 2

By assuming the following values for scenario 2:

Annual jobs produced = 2 jobs per 10000 population; average annual salaries per jobs according to income level = \$4,380/job; social influence area population density = 11.2 persons/km²; social discount rate = 5%; social benefit width = 100 km. Assuming the compressor station is located on a pipeline segment of 10 km in length. This is equivalent to a social benefit area of 1000 km². Project life is 30 years. Utilising the above information and employing Equation (7-18), the employment benefit (S_N) for scenario 2 is estimated as:

$$S_N = \sum_{i=1}^{i=30} \frac{\frac{2 \text{ job}}{10000 \text{ persons}} * \frac{11.2 \text{ persons}}{\text{km}^2} * 1000 \text{ km}^2 * 4380 \frac{\$}{\text{job}}}{(1.05)^i}$$

$$S_N = \$151,000$$

Therefore, the employment benefit for scenario 2 is about \$151,000.

The existing level of wealth is estimated for scenario 2 as:

$$S_E = \frac{11.2 \text{ persons}}{km^2} * 1000km^2 * 4380 \frac{\$}{person}$$

$$S_E = \$ 49.06 \text{ million}$$

The employment benefit ratio is estimated for scenario 2 as:

$$EBR = \frac{\$ 151,000}{\$ 49.06 \text{ million}}$$

$$EBR = 0.0031$$

Discussion

It is observed that the employment benefit for scenario 1 is considerably higher than scenario 2. However, the employment benefit ratio which represent the degree of social uplift derived from scenario 2 is about ten times higher than the EBR of scenario 1. This indicate that high social uplifts are obtained from the jobs created under scenario 2 associated with rural communities compared to scenario 1 which is associated with urban dwellers.