The Effect of Compressor Degradation on the Optimised Divestment Schedule of an Intercooled Gas Turbine Utilising Associated Gas

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ABSTRACT

Associated gas flaring has not only amounted to compounding environmental problems but has also resulted in huge economic loss. Due to the rich methane content of this fuel resource, it is a viable source of fuel for energy generation using gas turbines. This study presents a model and methodology which would serve as a guide while evaluating the impact of degradation on the divestment of redundant units of the LMS100 gas turbine engine and the economic utilisation of associated gas. The Cranfield University performance simulation tool, TURBOMATCH was used in modelling hypothetical but realistic intercooled gas turbine engines. Economic models were generated by implementing the performance results in three degradation scenarios within the Techno-Economic and Environmental Risk Assessment (TERA) framework. Optimised divestment schedule results from Genetic algorithm showed that degradation delays the divestment time of redundant intercooled engines. This implies that the level of compressor degradation is directly proportional to the divestment time.

Results from the optimisation of the fleets show the clean, optimistic, medium, and pessimistic degraded fleets having total energy values of 74.2, 73.6, 72.9, and 72.2 billion kWh respectively. Costs analysis showed that the pessimistic degraded fleet incurred the highest total operations and maintenance costs of (1.45 billion US dollars) whereas, the clean fleet had the least (1.34 billion dollars). Compressor degradation resulted to 1.6%, 3.5%, and 8.4% increase in the operations and maintenance costs for the optimistic, medium, and pessimistic fleets respectively. The economic return (net present value - NPV) for the clean fleet is the highest, and it is estimated to be 3.24 billion US dollars. Compressor degradation reduced the NPV of the optimistic, medium, and pessimistic fleets by 4.3%, 8.1%, and 16.6% respectively.

Keywords:

Energy, Clean engine, Engine degradation, Fleet composition

NOMENCLATURE

CO_2	Carbon dioxide
DP	Design point
GA	Genetic algorithm
GE	General Electric
GT (s)	Gas turbine (s)
IC100	Intercooled engine (100MW)
kg/s	Kilogram per second
kW	Kilowatt
kWh	Kilowatt-hour
LMS100	General Electric Land Marine Supercharged 100MW engine
MW	Megawatt
NPV	Net present value
Nm3/h	Newton metre-cube per hour
O & M costs	Operations and maintenance costs
TERA	Techno-economic and environmental risk assessment
TET (s)	Turbine entry temperature (s)
TURBOMATCH	Cranfield University gas turbine performance simulation software
ΣF(N-1) ENGINES	Sum of fuel requirements for the undivested engines
$	United States Dollars
US	United States

1. INTRODUCTION

Associated gas is natural gas found in a mixture with crude oil in a reservoir [1]; [2]. During routine processes of oil and gas exploration, associated gas flaring is been carried out; and this is the controlled burning of natural gas formed in conjunction with crude oil [3].

Associated gas flaring is a huge economic loss and a great source of environmental pollution. This fuel resource has great potential as a fuel for power generation using industrial gas turbine engines. The great potential of this fuel as a fuel resource is due to its high methane content.

The assumed project life for this associated gas utilisation project is 20 years. Degradation of engine components would usually be observed in gas turbines after a series of usage. Due to the limited availability of the associated gas, over time some units of engines would become redundant because of lack of enough fuel. The best economic decision at such time would be to divest the redundant engines. Associated gas investors would therefore need a model or methodology for evaluating the effect of gas turbine deterioration on the divestment sequence for the redundant units of engines.

The engine used in this study is a 100 megawatt intercooled engine denoted as IC100 gas turbine engine.

It is inspired by the General Electric (GE) land marine supercharged 100.2MW engine (LMS100 engine), its thermal efficiency is about 0.44 [4]. Its higher pressure ratio and increased mass flow are a result of its intercooling system [5].

Power and electricity have been successfully generated by gas turbines running on associated gas [6]. It was reported in 2013 by Clark Energy that the General Electric Jenbacher gas turbine engines generated about 3.6 million megawatt-hours of electricity annually [6].

Ancona et al [7] studied "optimum sizing of cogeneration plants by means of a genetic algorithm optimization: a case stusy". This research explored the possibility of estimating the best power plant configuration, energy, and return on investment (ROI) of varying scenarios of co-generation plants that mostly ran on natural gas fuel. This author used a genetic algorithm tool for the minimisation of the cost of energy generation. The project lifespan of the author's work (20 years) should have necessitated the indepth analysis of the degradation of engine components, and its effect on the energy generated, this is lacking in the author's work. Also, the divestment and divestment sequence of the plants either at the point of being redundant or at the end of the project were not considered.

Iora et al [8] reported on 'flare gas reduction through electricity production'. This work explored the potential energy recovery from a small flow of associated gas (1150 Nm3/h). An indepth degradation analysis was not done on the engine components used for this study. Zolfaghari et al [9] worked on the recovery of flare gas and its economic use, his findings show an annual profit of 480e+006 $ when gas turbines running on flare gas are employed for power generation. A major limitation in the work is the absence of engine degradation and its effect on the economic return of his research. Shayan et al [10] worked on the technological and economic assessment of varying flare recovery methods. The work also compared varying steam and power generation systems. Results show that by using flare gas as fuel, electric power of the magnitude of 7.323e+5, 4.350e+5, and 1.442e+006 kW were generated by a steam turbine, electricity and heat generation, and combined cycle power plant respectively. 18.66, 19.76, 25.79, and 31.97 are reported to be the rate of investment return for the high-pressure steam generation, steam turbine, electricity and heat cogeneration, and combined cycle respectively. However, a detailed assessment of the degradation of the plant's components and its effect was not properly explored by the author. Divestment and divestment sequence of redundant plants or all plants at the end of the project were not also considered.

Nezhadfard et al [11] studied 'power generation as a useful option for flare gas recovery: enviro-economic evaluation of different scenarios'. Four power generation scenarios were considered by this study, one of which is the gas turbine cycle. Gas turbine components degradation and the effect of the degradation on the power generated was not satisfactorily evaluated. Mousavi et al [12] worked on 'technical, economic, and environmental assessment of flare gas recovery system: a case study'. This work explored three major scenarios of flare gas recovery to reduce energy utilization and control environmental pollution. One of the scenarios explored is the generation of power through a combined heat and power system (CHP) and an internal combustion engine. Results reveal that flare gas pressurizing and injection to oil wells is one of the most efficient means of reducing gas flare, an internal investment rate of 117% and a payback period of 1.02 years was achieved. However, the author's work lacked the vital elements of in-depth components degradation assessment and also the divestment of redundant engines. Kurz et. al. [13] researched on the degradation of gas turbine performance in natural gas service. The authors investigated the causes of gas turbine components degradation and the effect of degradation on the performance of the gas turbine. However, the authors did not consider the economic implication of the degradation of components of the engine. Divestment of engines was also not considered.

Anosike et. al. [14] studied associated gas use by gas turbine engines, however, the authors did not take into account the influence of engine deterioration on the economic utilisation of associated gas. Allison [1] researched on the influence of gas turbine deterioration on the economic utilisation of associated gas and showed the onset of resource decline and palliative divestment protocol. He recommended that the influence of engine deterioration on divestment time should be analysed. Allison et. al. [15] researched on gas turbine degradation in the techno-economic environmental and risk analysis of flare gas utilisation in Nigeria. Their research analysed the performance of some engines when running on clean and degraded modes using associated gas as fuel. However, they didnot consider the economic implication of the performance of the engines nor the effect of engine degradation on the economic use of associated gas. Obhuo et. al. [16] investigated the delaying influence of degradation on the divestment of gas turbines for associated gas utilisation. In another study, Obhuo et. al. [17] researched on economic optimisation from fleets of aero-derivative gas turbines utilising flared associated gas. Obhuo et. al. [16, 17] findings are true for the General Electric LM6000 gas turbine engine but cannot be used for other gas turbine engines. Obhuo et al. [16, 17] studied the economic feasibility of using associated gas as fuel for the AD43 engine (inspired by the GE LM6000 engine), together with the effect of degradation on divestment and on the economic return. Thus, more research involving other engines are needed to better guide investors on associated gas investment planning.

As evident in the public domain, the following are lacking: (1) no work has been published on the effect of engine degradation on the divestment schedule of redundant intercooled engines in the economic utilisation of associated gas; and (2) no work has been published on the effect of degradation on the economic utilisation of associated gas when using an intercooled gas turbine engine. Therefore, this current research aimed at assessing the effect of degradation on the divestment schedule of redundant units of IC100 engines in the economic use of associated gas. The outcome of this study would guide both governments and investors in the project of economic utilisation of associated gas when using the General Electric LMS100 engine. The findings on the optimised fleet composition and total energy of the fleets are all very useful decision-making tools for associated gas investment planning.

Apart from the aforementioned deficiencies pointed out to be addressed in the current study, the following are additional areas distinguishing the current study from previous studies in this field of research : (1) different gas turbine was used as against [16, 17]. Thus the engines have different cycle configurations, different performance characteristics, different economic performance, different emission characteristics among others, (2) investigation of the effect of engine degradation on the optimised divestment schedule of an intercooled gas turbine, and (3) the Genetic algorithm optimisation models adopted in the current. Readers are referred to [16, 17] for more details.

Gas turbine engines and machine components usually experience wear and tear over time. This could be due to friction between moving parts, fouling, environmental factors, the effect of the fuel used, foreign objects damage, etc. Since the assumed life span of this associated gas utilisation project is 20 years, it is very imperative to consider the influence of engine deterioration on the performance and on the economic return of the various fleets.

2. MATERIALS AND METHOD

2.1 Data acquisition

The associated gas availability data was gotten from the work of Allison [1]. He implemented the Global Gas Flaring Reduction (GGFR) code on associated gas resource data. This code and the associated gas resource data were provided by a team of World Bank experts in the process of researching associated gas resource decline. The research of Allison [1] resulted in Figure 1.

Figure 1 shows the associated gas fuel availability for the project for an assumed project life of 20 years. Associated gas and clean natural gas were both used as fuel in the performance simulation of the same modelled engines, results show that the performance of the modelled engines was very similar and that there was no significant difference in the results when both fuels were used separately [18]; [14]. Therefore, the results presented in this paper are assumed the same for either fuel.

The performance data for the LMS100 gas turbine engine were gotten from the public domain [4].

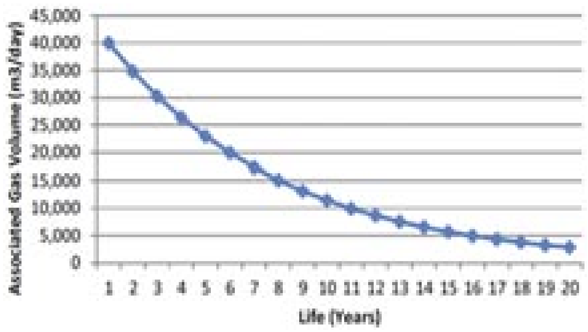


Figure 1: Associated Gas Availability and Decline over 20 Years Period [1]

2.2 Assumed levels of engine degradation considered

The gas turbine engine component that degrades most is the compressor [1]. Therefore, this paper considered just the degradation (decrease in the flow capacity, pressure ratio, and isentropic efficiency) in the compressor of the gas turbine system. Varying degrees of degradation were effected for the decrease in isentropic efficiency, compressor pressure ratio, and non-dimensional mass flow. This was effected in the model used for the performance simulation of the degraded fleets. The basis for the consideration of the isentropic efficiency, compressor pressure ratio, and the non-dimensional mass flow is because degradation in the compressor negatively influences the efficiency, compressor pressure ratio, and flow capacity [1]. The varying levels of degradation considered are designated as optimistic (slow), medium, and pessimistic (fast) degradation. Table 1 and Figure 2 show the levels of degradation considered for the various years of the project. At the beginning of the project, that is, year 1, all engines are new, and as such are all clean (zero degradation).

Partial overhauling is effected at the end of every 3 years of the project lifespan, hence the reason for the decrease in the rate of implemented degradation as observed in years 4, 7, 10, 13, 16, and 19 as shown in Table 1.

Table 1: Rate of Degradation Effected [16]

Year	Optimistic (%)	Medium (%)	Pessimistic (%)
1	0	0	0
2	1.333	2.666	4.0
3	2.0	4.0	6.0
4	0.667	1.333	2.0
5	1.333	2.666	4.0
6	2.0	4.0	6.0
7	0.667	1.333	2.0
8	1.333	2.666	4.0
9	2.0	4.0	6.0
10	0.667	1.333	2.0
11	1.333	2.666	4.0
12	2.0	4.0	6.0
13	0.667	1.333	2.0
14	1.333	2.666	4.0
15	2.0	4.0	6.0
16	0.667	1.333	2.0
17	1.333	2.666	4.0
18	2.0	4.0	6.0
19	0.667	1.333	2.0
20	1.333	2.666	4.0

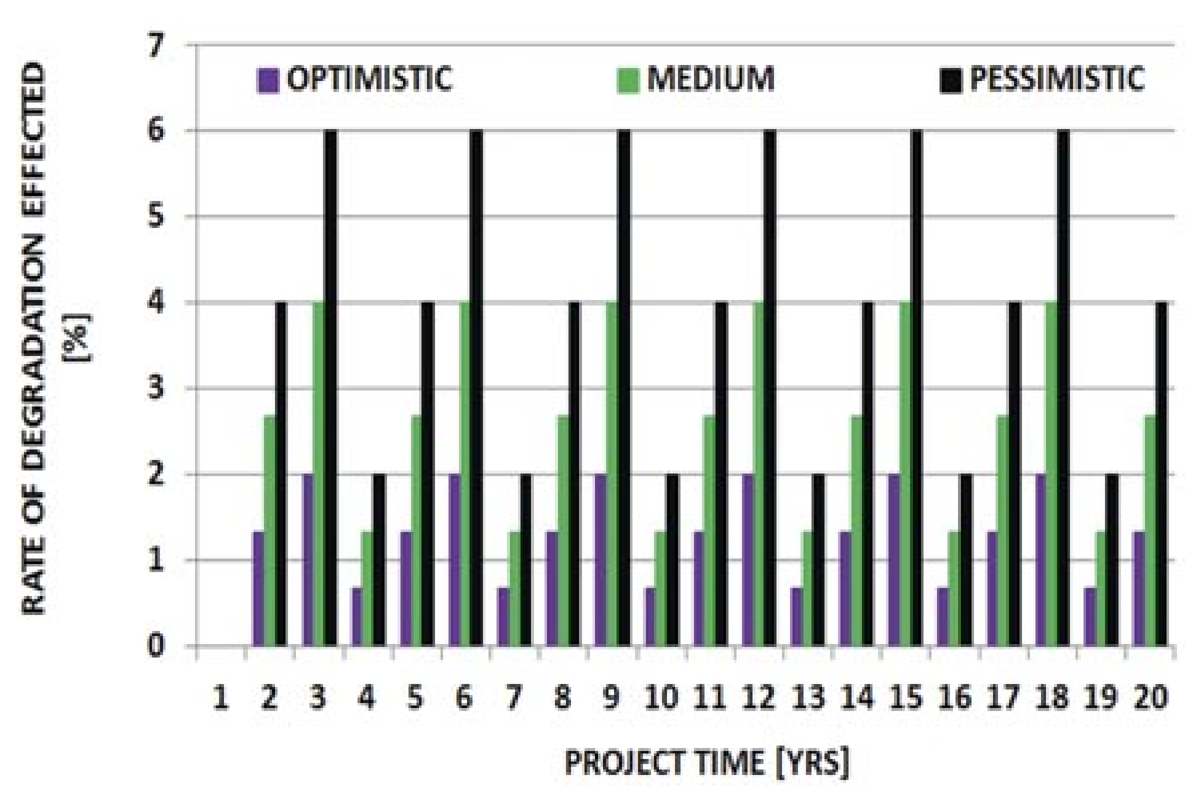


Figure 2: Rate of degradation effected in the project

2.3 Methodology adopted for the techno-economic optimisation

The Cranfield University techno-economic and environmental risk assessment (TERA) framework was adopted to evaluate the economic utilisation of associated gas when gas turbines are used. The various components of this TERA framework are demonstrated in Figure 3. The framework comprises the performance, the emission, the lifing/maintenance, and the economic modules. All these various modules are captured in Figure 3. The sequence of activities commences with the performance module. The initial number of engines in the fleet is determined by dividing the associated gas availability in the first year of the project by the fuel flow of the engine when operated at the design point. TURBOMATCH; a Cranfield University tool [19-24] was used in carrying out the performance simulations of both the clean and degraded engines. Genetic Algorithm has been successfully utilised on many occasions to get the solutions to Turbomachinery problems [25-32]. For this paper, the Genetic Algorithm optimisation code written in Matlab uses the performance data and generates results of annual optimised power, optimised fleet compositions, and best divestment time (schedule). This optimised fleet composition is the fleet composition that would give the best economic return from the fleet. The optimiser recommends the unit(s) of engine(s) for divestment, and the effect of engine degradation on the divestment sequence is effected as shown in Figure 3. The divested unit(s) of engine(s) generate some income which is added as divestment sales for the economic analysis of the fleet. This is shown in Figure 3.

As described in Figure 3, on achieving the optimised fleet composition; a Cranfield University emission prediction code called Hephaestus was is used in predicting the engine emissions. This code is FORTRAN-based and has been used by other authors for the prediction of gas turbine engine emissions [20]; [33-35]. The costs incurred as a result of the CO_2 emission from the engines were estimated using the emission results and the assumed emission tax value. This emission cost was also incorporated into the economic analysis of the fleets. The optimiser gives the optimum power possible from the fleets, this power generated is sold to the national grid, the revenue realised is also added for the economic assessment of the fleets. Creep life assessment is carried out to estimate the useful life of the unit(s) of engine(s), this led to maintenance assessment evaluation. Results from the maintenance analysis were used in evaluating the annual operations and maintenance (O & M) costs of the fleets. These operations and maintenance costs are also effected in the broad economic analysis of the fleets as shown in Figure 3. The process illustrated in Figure 3 is repeated annually for the entire life span (20 years) of this economic utilisation of associated gas

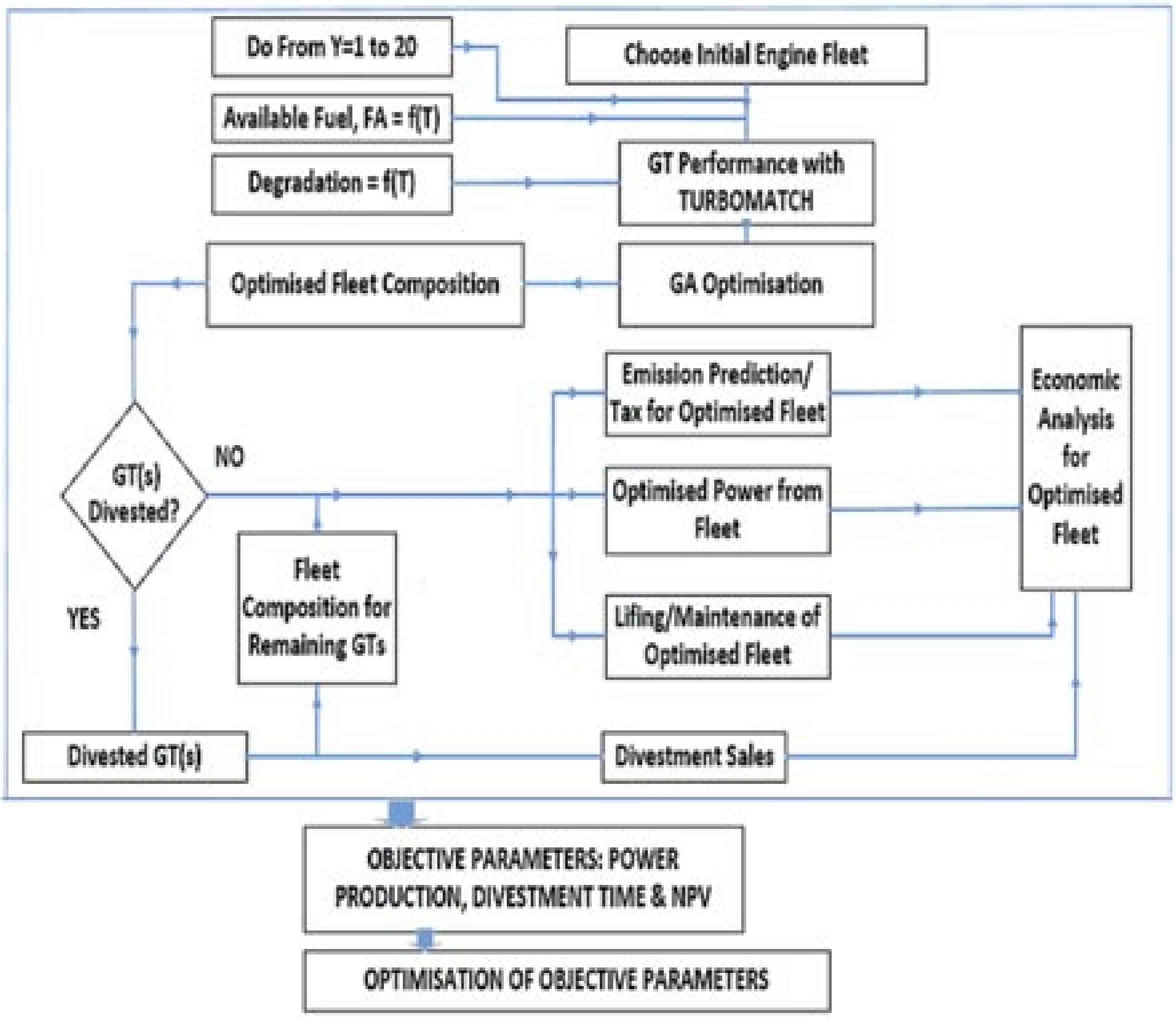


Figure 3: Techno-Economic Optimisation of Gas Turbine Fleets for Associated Gas Utilisation [16].[1]

project. This model yields the optimum economic return from the fleets in terms of Net Present Value (NPV). The effect of compressor degradation on divestment time is evaluated and also effected in the economic utilisation of the associated gas. This same methodology has been adopted by [16], however, for a different type of engine.

2.4 The gas turbine performance model

The gas turbine performance model used for simulating the clean and degraded engines is the Cranfield University in-house code, TURBOMATCH, a FORTRAN-based code. The performance parameters of the study engine were gotten from the public domain and then implemented in the model. Figure 4 shows the schematic of the study engine. See the footnote below for the names of the engine components abbreviations.

Figure 4: Schematic of the IC100 engine [36]

[1] *GA (genetic algorithm), TERA (techno-economic and environmental risk assessment), GT(s) (gas turbines), DP (design point), FA (fuel available), ΣF (sum of fuel consumption for the engines), Y (year), FL (fuel requirement for the last unit of engine), f(T) (function of time), ΣF(N-1) ENGINES (Sum of Fuel Requirements for the Undivested Engines), NPV (net present value)*

2.5 The genetic algorithm optimisation model

2.5.1 The aim of the optimisation

The optimisation aims to get the optimum power generation from the fleets and the best divestment time for the redundant engines, subject to the quantity of fuel available for that year.

2.5.2 The fitness (objective function)

The fitness (objective) function adopted in the optimisation is shown in equation 1 [36].

$$TPO=-1\times[PO(1)+PO(2)+PO(3)+PO(4)+PO(5)+PO(6)+PO(7)+PO(8)+PO(9)+PO(10)+PO(11)+PO(12)] \quad (1)$$

Where TPO is the total optiminised power, and the ‘PO’ is the optimised power from the unit of engine.

2.5.3 The constraints and constraints equation

The constraint for the optimisation is the associated gas availability values for the various years of the project. These values are shown in Figure 1; however, their equivalents in kg/s were used because the fuel flow of the engine is given in kg/s. Equation 2 [36] shows the constraint equation used by the optimiser in the first year of the project.

$$C=\text{Fuel } C(1)+\text{Fuel } C(2)+\text{Fuel } C(3)+\text{Fuel } (4)+\text{Fuel } C(5)+\text{Fuel } C(6)+\text{Fuel } C(7)+\text{Fuel } C(8)+\text{Fuel } C(9)+\text{Fuel } C(10)+\text{Fuel } C(11)+\text{Fuel } C(12) - 59.3519 \quad (2)$$

‘C’ must be zero for the constraint requirement to be satisfied. ‘Fuel C’ is the fuel consumption for the unit of engine. The value 59.3519kg/s is the associated gas availability for the first year of the project.

2.5.4 The optimisation variables

The optimisation variables are the turbine entry temperatures of the engines. The number of variables is dependent on the number of units of engines in the starting fleet. As such, the number of variables is 12.

2.6 The maintenance model

The annual operations and maintenance costs were evaluated using the relationship in equation 3 [36] below.

$$\text{Annual}_{\text{O \& M Cost}} = \text{Fixed}_{\text{O \& M Cost}} + \text{Variable}_{\text{O \& M Cost}} + \text{Major}_{\text{Maintenance Cost}} \quad (3)$$

2.7 The emission model

Hephaestus, a Cranfield University Fortran-based code for gas turbine emission evaluation was used in getting estimates (not the exact quantity of CO_2 emissions of the real engine) of the CO_2 emissions from the fleets. Currently, CO_2 emission is not tasked, but as part of the risk assessment in this work, an emission levy of 0.02$/kg was assumed. The annual emission tax was calculated using the relationship in equation 4 [36].

$$\text{Annual Emission tax} = \text{Emission released} \times CO_{2\,\text{emission tax}} \quad (4)$$

2.8 The overall economic model

The overall economic model incorporated various technical and economic factors needed for the economic utilisation of associated gas when using gas turbines. The net present value is used for the economic appraisal of this project. The cost factors considered are capital investment, emission tax, operations and maintenance cost, staff salaries, and loan repayment. The revenues generated from the project are from the electricity sold and from the sales gotten from the divested engines.

The net present value of the project was calculated using the relation in equation 5 [37-39].

$$NPV=\sum_{t=1}^{n}\frac{C_t}{(1+r)^t}-C_o \quad (5)$$

Where C_o is the initial cost of the project, and this is the loan taken, C_t is the net cash-flow for the year under consideration, and r is the discount rate assumed, t is the year under consideration.

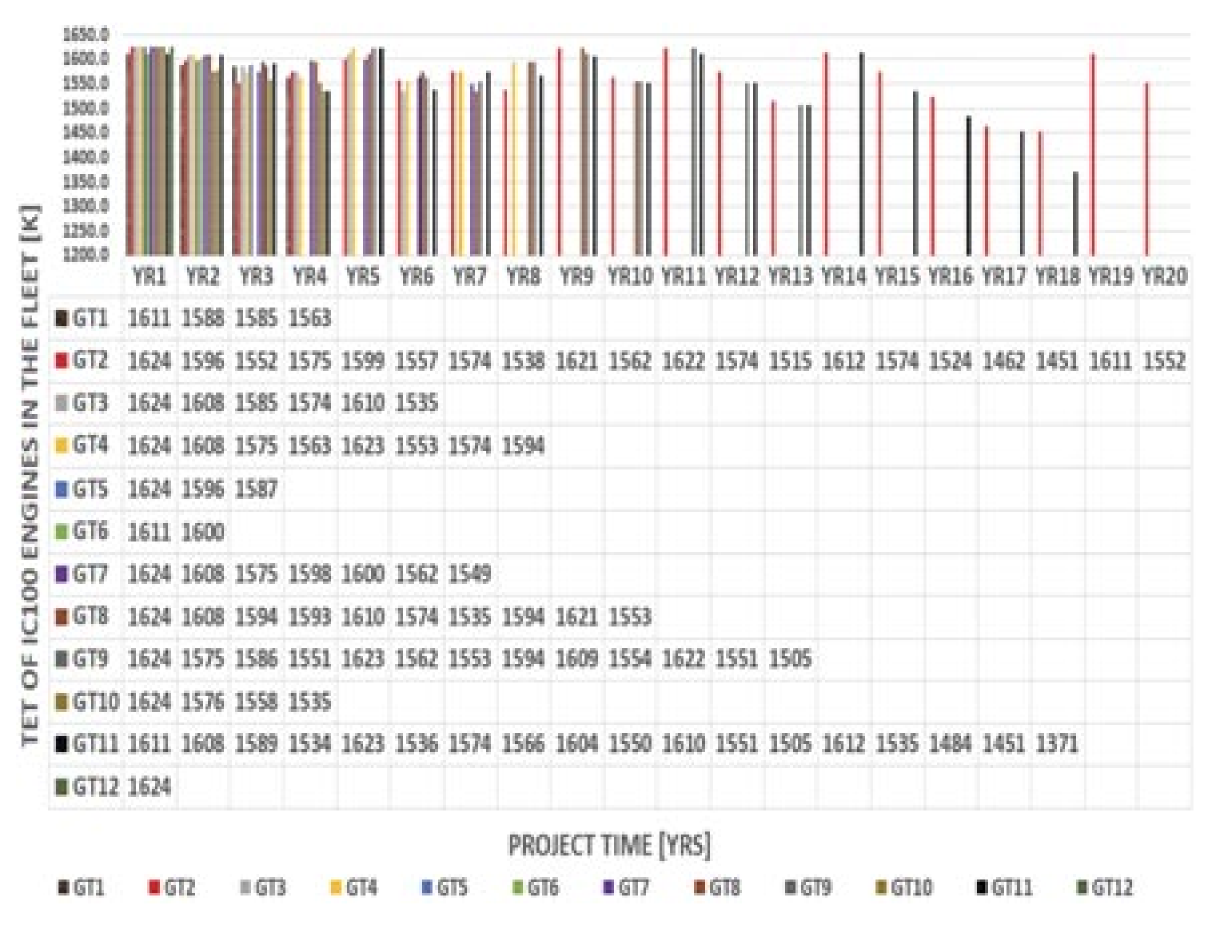
3. RESULTS AND DISCUSSION

3.1 Design point performance results

Table 2 shows the design point performance simulation results for the IC100 engine and their corresponding data as found in the public domain for the General Electric LMS100 engine. TURBOMATCH software was used in carrying out the performance simulation.

Table 2: Performance parameters for the Real Engine and Engine Model
Source of data for the Real Engine [4]

Parameters	Real data	Engine model
Exhaust mass flow [kg/s]	222.0	221.0
Turbine Entry Temperature, TET [K]	Not available	1630.0
Shaft power [MW]	100.2	100.0
Thermal efficiency [%]	44	44
Overall pressure ratio	42.0	42.0
Fuel flow [kg/s]	Not available	5.0401



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1611	1588	1585	1563																
GT2	1624	1596	1552	1575	1599	1557	1574	1538	1621	1562	1622	1574	1515	1612	1574	1524	1462	1451	1611	1552
GT3	1624	1608	1585	1574	1610	1535														
GT4	1624	1608	1575	1563	1623	1553	1574	1594												
GT5	1624	1596	1587																	
GT6	1611	1600																		
GT7	1624	1608	1575	1598	1600	1562	1549													
GT8	1624	1608	1594	1593	1610	1574	1535	1594	1621	1553										
GT9	1624	1575	1586	1551	1623	1562	1553	1594	1609	1554	1622	1551	1505							
GT10	1624	1576	1558	1535																
GT11	1611	1608	1589	1534	1623	1536	1574	1566	1604	1550	1610	1551	1505	1612	1535	1484	1451	1371		
GT12	1624																			

Figure 5: Optimised Fleet Composition for the IC100 Clean Fleet

3.2 Optimised fleet composition for the clean fleet

The optimised fleet composition for the clean fleet of the intercooled gas turbine engine is shown in Figure 5. This optimised fleet composition gives the optimised number of units of engines running in the project and their corresponding turbine entry temperatures. This is presented on an annual basis. This fleet composition yields the optimised power production, the optimum economic benefit, and the best divestment time for the redundant units of the engines in the fleet. The number of units of the redundant engines that have been divested is represented by the empty spaces in Figure 5.

3.3 Optimised power production for all fleets in the project

3.3.1 Annual Optimised power production for all fleets in the project

Figure 6 shows the results for the optimised power for the IC100 engine when running on associated gas. The figure illustrates the results for all the various scenarios considered in the paper – clean, optimistic, medium, and pessimistic degraded fleets. All fleets have the same value for the total optimised power (1177.9MW) at the 1st year of the project, this is because all fleets are considered clean at the commencement year of the project. As observed in Figure 6, after every 3 years of the project lifespan, the values for the total optimised power for the degraded fleets approach that of the clean fleet nearer as compared to other years of the project. This is as a result of the partial overhauling that takes place as explained in section 2.2. On comparing the values for the total optimised power of all the fleets on an annual basis, the clean fleet has the highest, followed by the optimistic degraded fleet, then the medium, and the pessimistic degraded fleet has the least. Although in some of the years, this difference in the results for the various fleets is very small. This small difference in the effect of the various scenarios as seen in Figure 6 and Figure 7 is a result of the level of degradation implemented in the gas turbine performance simulation model. Also, this degradation was implemented for the compressor of the engine only, hence the small effect of change in scenarios. In Figure 6, it should be noted that the difference in the values for the various scenarios at some years of the project appears minimal due to the large size of the drawing scale when compared with the difference in scenarios.

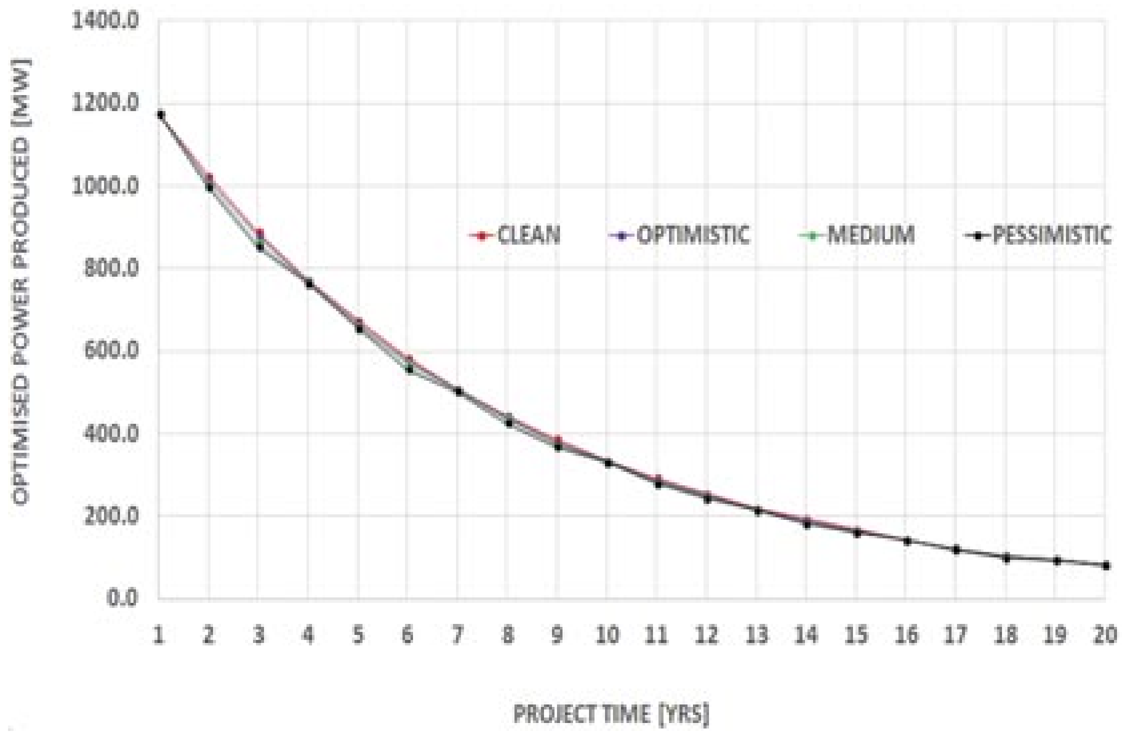


Figure 6: Optimised Power Production for all the IC100 Fleets

3.3.2 Total energy production from optimised fleets

Figure 7 shows the total energy that was obtained from the optimised fleets when running on associated gas as fuel. This total energy value is the sum of the various energy values for the entire project lifespan. The total energy for the clean fleet is 74.2 billion kWh. As expected, engine degradation had a negative effect on the energy derivable from the degraded fleets. The optimistic degraded fleet has an energy value of 73.6, the medium 72.9, and the pessimistic degraded fleet 72.2 billion kWh. The results show that investing in the economic utilisation of associated gas would be a very profitable means of power/energy generation and immense economic advancement for countries that are given to associated gas flaring.

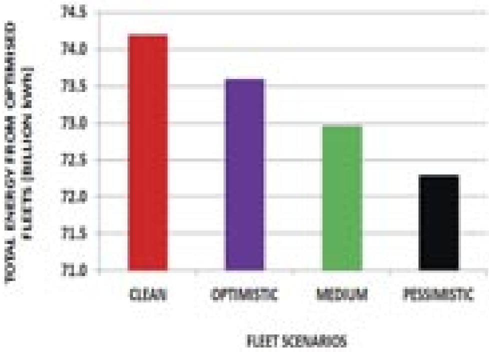


Figure 7: Total Energy from Optimised Fleets

It should be noted that in the process of correcting the content of this manuscript after one of its review; Figure 6 was corrected which resulted to the correction of Figures 7 and 10. However, the influences of these corrections were not effected in the other parts of this study.

3.4 Total operations and maintenance cost assessment for all fleets

Maintenance of equipment and machine parts is a key activity in an engineering firm. In this project of associated gas utilisation, maintenance of gas turbine

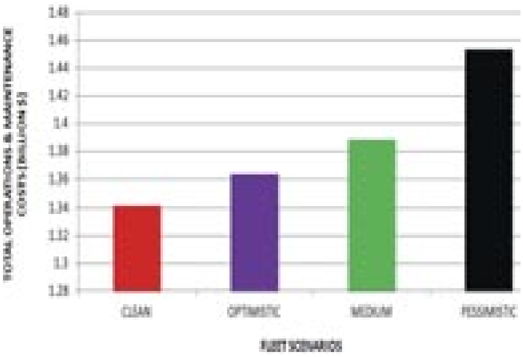


Figure 8: Total Operations and Maintenance Costs Assessment for all Fleets

components is very essential as the engine components would be given to wear and tear after some time of usage. The operations and maintenance (O & M) of engines, their consumables, and the overall progress of this associated gas utilisation project is expensive. As can be seen in Figure 8, the pessimistic degraded fleet incurred the highest total O & M cost (1.45 billion US dollars) whereas, the clean fleet had the least (1.34 billion US dollars). Engine degradation resulted to 1.6%, 3.5%, and 8.4% increase in the O & M costs for the optimistic, medium, and pessimistic fleets respectively.

3.5 Effect of compressor degradation on the economic utilisation of associated gas

Various techno-economic factors were incorporated into the model used for the project (Figure 3). Some of these factors are the optimised power/energy, the revenue from the generated electricity, the operations and maintenance costs of the project, etc. Compressor degradation had a significant impact on these factors and the overall economic return of the project. The economic return (NPV) for the clean fleet is estimated to be about 3.24 billion US dollars. Compressor degradation resulted to 4.3%, 8.1%, and 16.6% decrease in the NPV for the optimistic, medium, and pessimistic degraded fleets, respectively. This is shown in Figure 9. Despite the effect of degradation, the results show that investing in the economic utilisation of associated gas would not only amount to a reduction in environmental pollution but would also enhance economic advancement.

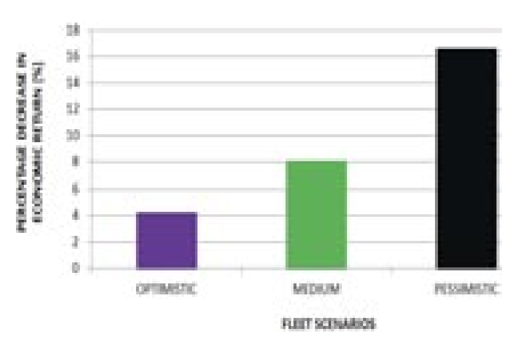


Figure 9: Assessment on the Effect of Compressor Degradation of an Intercooled Engine on the Economic Utilisation of Associated Gas

3.6 Optimised divestment schedule and t he influence of compressor degradation on the divestment schedule for redundant units of engines

The effect of engine degradation on the divestment schedule for the redundant units of engines is very central in the economic use of associated gas with gas turbines. Due to the declining availability of the associated gas, some units of engines would be getting redundant. The best economic decision would then be to divest the redundant engines, and the effect of this intercooled engine degradation on the divestment schedule is very important. When known, the effect of engine degradation on divestment schedule would help associated gas investors in making wise decisions on the units of engines to divest, the number of units to divest, and the timing for the divestment. When these decisions are optimally taken, additional economic returns worth billions of US dollars would be gained by investors. As can be seen in Figure 10, compressor degradation extends the divestment time

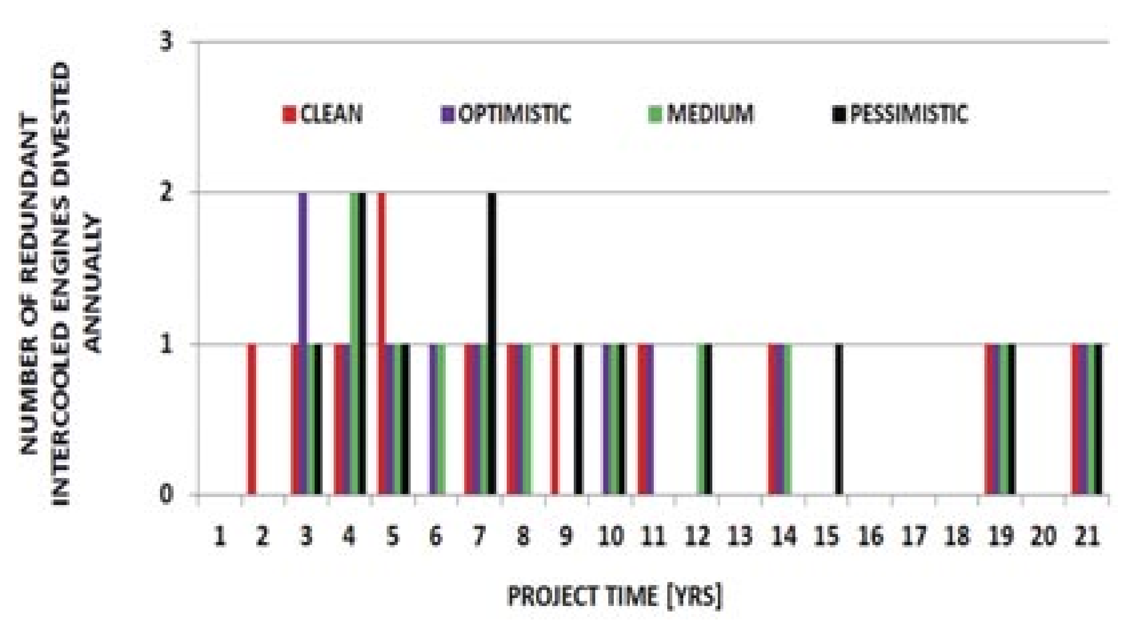


Figure 10: Compressor Degradation in an Intercooled Engine (IC100) and its Effect on the Divestment Schedule of Redundant Units of the Engine

for the redundant engines. For instance, in the 1st year of the project, there was no divestment. In the 2nd year, while in the degraded fleets there was no divestment, 1 unit of engine was divested in the clean fleet. At the 16th, 17th, and 18th year of the project, the cumulative number of units divested was least for the most degraded fleet (pessimistic fleet).

It is necessary to state that the contents of this paper are extracts from the Ph.D. research of the lead author [36].

4. LIMITATIONS AND RECOMMENDATIONS

The scope of this study was limited to the effect of compressor degradation on the optimised divestment schedule of an intercooled gas turbine utilising associated gas. The study did not consider the effect of degradation of other engine components. It is therefore recommended that the effect of degradation in more engine components be explored.

5. CONCLUSION

Associated gas is wasted on a large scale in various parts of the world. As a result of its high methane content, this fuel can be used for power and energy generation using gas turbines. The techno-economic and environmental risk assessment (TERA) framework has been employed for holistic and multi-dimensional optimisation of the economic return of varying fleets of a 100MW intercooled engine using associated gas. The effect of engine degradation on the divestment schedule for the redundant units of engines and the overall economic use of associated gas were explored. This was done using 3 degradation scenarios – optimistic, medium, and pessimistic fleets.

TURBOMATCH code was used in carrying out the performance simulations for the various fleets of the study engine. Genetic algorithm was successfully used in optimising the divestment schedule of the redundant engines. Results revealed that degradation in this intercooled engine would extend the divestment time of the units of the engines, which implies that the level of engine degradation is in direct proportion to the divestment time.

Furthermore, results from the optimised fleets show that the clean, optimistic, medium, and pessimistic degraded fleets while running on associated gas generated energy values of 74.2, 73.6, 72.9, and 72.2 billion kWh respectively. Also, results on the operations and maintenance costs analyses showed that the pessimistic degraded fleet incurred the highest total O & M cost (1.45 billion US dollars) whereas, the clean fleet had the least (1.34 billion dollars). Engine degradation resulted to 1.6%, 3.5%, and 8.4% increase in the operations and maintenance costs for the optimistic, medium, and pessimistic fleets respectively. The economic return (net present value - NPV) for the clean fleet is the highest, and it is estimated to be 3.24 billion US dollars. Engine degradation reduced the NPV of the optimistic, medium, and pessimistic fleets by 4.3%, 8.1%, and 16.6% respectively. It is therefore recommended that for optimum economic return, engine overhauling should be carried out frequently. ■

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Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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