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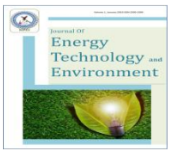

Techno-Economic Assessment of Associated Gas Fueled Fleets of Reheat Gas Turbine Plants

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Abstract

There are various advantages in investing in the commercialization of associated gas for power generation via gas turbines. Some of these advantages include massive energy generation, a high economic return, and a reduction in pollution and environmental deterioration. This paper provides a model and method for optimizing the techno-economics of gas turbine fleets that use associated gas as fuel. The methodology has the potential to be beneficial as a decision-making tool for investors and governments interested in investing in connected gas economic exploitation. The in-house gas turbine performance software (TURBOMATCH) from Cranfield University was used to model a hypothetical but realistic 296MW reheat engine. According to the study, compressor degradation reduced overall optimal power by 3.42%, 2.19%, and 1.09% for three distinct fleets. The research was carried out for one clean fleet and three degraded fleets (optimistic, medium, and pessimistic). The net present value of the clean, optimistic, medium, and pessimistic degraded fleets is 3.03, 2.97, 2.84, and 2.75 billion US dollars, respectively. The effect of the deterioration in the optimistic, medium and pessimistic fleets is 1.86, 6.05%, and 9.02% reductions in the net present values of the project, respectively. The study would be extremely valuable in decision making for associated gas investors and governments.

1. Introduction

Associated gas contains huge source of energy due to the presence of methane. Some parts of the globe waste this enormous energy resource, thereby causing environmental pollution, and deterioration. On an annual basis, about 150-170 billion cubic meters (bcm) of natural gas are been flared or vented around the globe from upstream petroleum operations [1]. Clark Energy reportedly generated approximately 3.6 million megawatt-hours of energy per year in 2013. This was accomplished through the employment of General Electric Jenbacher gas turbine engines that were powered by associated gas fuel [2].

According to Siemens, using associated gas more efficiently would result in lower emissions [1]. A 6.75 MW engine used wellhead gas to generate energy for production activities in the Tyanskoye Oil field [1]. According to Shonin et al. [3], "the most advanced and energy-efficient method of APG usage is to use it as a fuel in gas-turbine power plants (GTPP)’.According to Shayan et al. [4], using flare gas as fuel generated 1.442e+006, 4.350e+5, and 7.323e+5 kW by combined cycle power plant, electricity and heat generation, and steam turbine, respectively. The authors achieved investment return rates of 31.97, 25.79, 19.76, and 18.66 for combined cycle, electricity and heat cogeneration, steam turbine, and high-pressure steam generation, respectively. According to Iora et al. [5], feeding industrial gas turbines with related gas yielded a yearly profit of $480e+006. In terms of economic and environmental performance, Nezhadfard and Khalili-Garakani [6] studied four power generation scenarios, one of which is the gas turbine cycle for flare gas recovery.

Flare gas samples were used as fuel for the performance evaluation including associated gas in all of these power generation scenarios. Anosike et al. [7] investigated the performance implications of gas turbine engines powered by associated gas, using Nigeria as a case study. Their findings indicate that utilizing related gas as fuel in gas turbines could yield massive amounts of energy. Allison et al. [8] investigate the use of flare gas in a gas turbine for electricity generation in Nigeria, as well as the impact on the turbine hot end components. Their findings indicate that utilising related gas as fuel in gas turbines for power generation has a high potential. Allison [9] investigated the economic utilization of associated gas as well as the impact of degradation on economic returns. He suggested looking into the effect of gas turbine degradation on the time it takes to divest surplus engine units in a fleet. Obhuo et al. [10, 11] investigated the impact of gas turbine degradation on the economic consumption of related gas and the timeline for divesting redundant engines. Ighodaro and Osikhuemhe [12] assessed the thermo-economic of a heat recovery steam generator combined cycle. In their research, a retrofitted performance assessment of integrating a steam power cycle to the already existing gas turbine cycle in Delta IV power station was carried out. Results from these authors’ work show a further increase of the power output by 51.5MW, and consequently a 41.85% increase in the overall combined cycle efficiency. Rahim et al. [13] carried out an energy assessment of a gas turbine Brayton cycle which was incorporated to a refrigeration cycle, results promise an increase in the power output with a small reduction in the thermal efficiency.

A thermo-economic assessment for a trigeneration system incorporated by an absorption chiller, a gas microturbine, and a heat recovery steam generation subsystem was carried out by Guillermo et al [14]. Results from the authors’ work show that the combustor of the gas microturbine had the highest exergy destruction (29.24%), and this was followed by 26.25% for the generator of the absorption refrigeration chiller. Oyedepo et al [15] carried out a thermo-economic and environmental analysis of specific gas turbine power plants in Nigeria, results reveal that the combustor had the highest cost of exergy destruction. It was also observed that an increase in the turbine entry temperature of the gas turbine causes a reduction in the cost of exergy destruction. Sheng et al [16] proposed a novel power generation system which integrated a natural gas expansion plant with a geothermal organic rankine cycle. Dominique et al [17] researched on thermo-economic analysis of a natural gas liquefaction plant. The simplified version of ConocoPhillips Optimized Cascade process was employed in the research. This work also carried out sensitivity analyses to consider market price alterations and estimation errors due to the assumptions made. The conclusions of the authors are limited because they were estimated for a specific type of engine, and the results cannot be applied to other gas turbine engines with varied cycle configurations, performance characteristics, maintenance requirements, and applicability.

This research looks at the techno-economic assessment of a fleet of reheat engines that use related gas throughout a 20-year project life.

2. Methodology

2.1 Materials used for the techno-economic assessment of associated gas

2.1.1 The associated gas availability

The fuel resource for this project is associated gas. The associated gas availability for this study is shown in Figure 1. Associated gas resource decline was implemented on the Global Gas Flaring Reduction (GGFR) code for a single well which gave rise to the associated gas decline curve of Figure 1 [9]. The data from this figure is the fuel availability for the gas turbines and this data also served as the optimization constraints for the various years of the project.

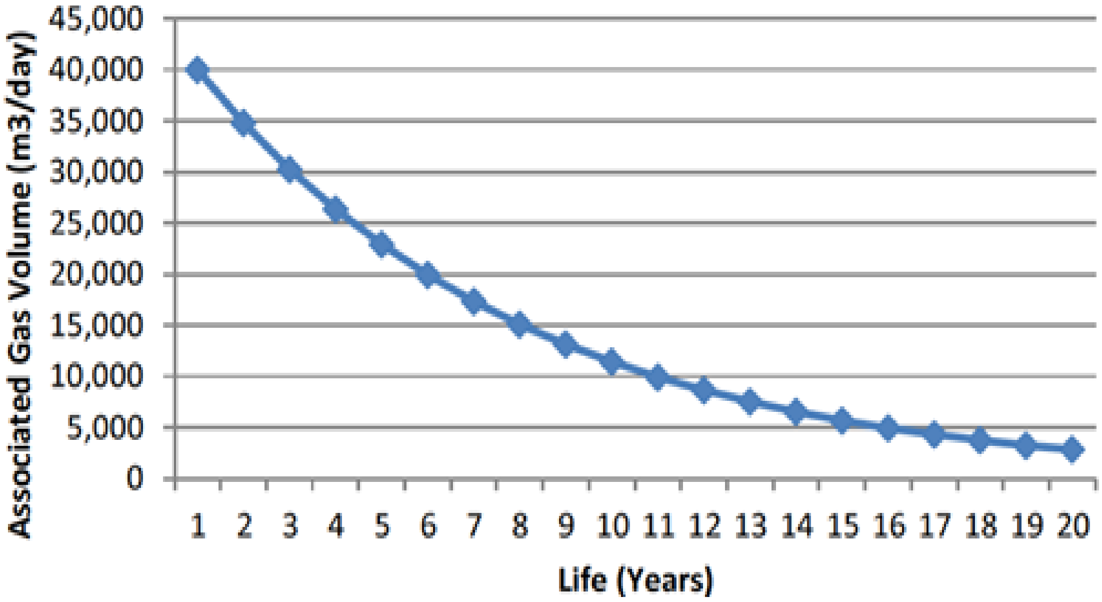

Figure 1: Associated gas availability for the techno-economic assessment of the various fleets [9]

When associated gas and clean natural gas were utilized as fuel for the same modeled engine, the findings showed no significant difference for the majority of the simulated parameters [7]; [18].Also, associated gas of three different gas quality was implemented as fuel for the same modeled engines, no significant change was observed for the lower heating values (LHV) of the three fuels, the power output and the efficiencies of the modeled engines also had the same observation [9]. Consequently, clean natural gas was used in place of associated gas in the simulations done in this study.

2.1.2 The study engine and performance parameters

The study engine for this paper is the RH296 engine. It is inspired by the Alstom GT-26 engine, a 296MW reheat engine with a thermal efficiency of about 39.6%. Other parameters of the study engine are overall pressure ratio of 33.3 and exhaust mass flow of 644kg/s [19-21]. The public domain is the source of the performance parameters of the real engine [19-21]. Figure 2 below shows a schematic representation of the study engine. The engine is made up of components such as the compressor (COMP), annular environmental combustor (Comb 1), a high-pressure turbine (HPT), annular sequential environmental combustor (Comb 2), and a low-pressure turbine (LPT).

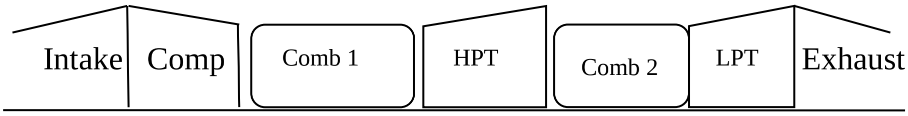

Figure 2: Schematic presentation of the RH296 engine

2.2 Methods employed for the techno-economic assessment of associated gas

Figure 3 depicts the methods used for the techno-economic assessment of various fleets using associated gas. The project will last for 20 years. The number of engines in the starting fleet is calculated by dividing the fuel available for the first year of the project by the engine's design point fuel flow, which yields the value 4, meaning that 4 units of RH296 engine were present in the starting fleet. In this study, four different scenarios are considered: the clean scenario and the deteriorated scenarios, which are optimistic (slow deterioration), medium, and pessimistic (fast degradation).

TURBOMATCH, a gas turbine performance simulation program developed by Cranfield University, was utilized to simulate both the clean and deteriorated engines. The TURBOMATCH engine performance results were used as the database (search domain) for the Genetic algorithm optimizer. The optimizer seeks the best fleet composition, maximum fleet power, and optimal divestment time for redundant engines. As shown in Figure 3, if an engine unit (s) is sold, the proceeds are included in the economic analysis of the optimized fleet. From the remaining fleet composition, the optimizer's optimized power is used to calculate the energy generated by the optimized fleet. The generated energy is sold to the national grid, providing revenue that is also factored into the fleet's economic analysis. Hephaestus, a FORTRAN-based program developed by Cranfield University for analyzing gas turbine emissions, is used to assess fleet emissions. The provided emissions data and the expected emission levy are used to calculate the fleet's emission tax; this value is also included in the economic analysis of the optimized fleet.
Maintenance analysis is also performed on the optimized fleet, from which the operations and maintenance expenses for this project of economic related gas use are estimated. The costs of operations and maintenance are also included in the fleet's economic analysis, as shown in Figure 3. This technique is performed throughout the duration of the project.

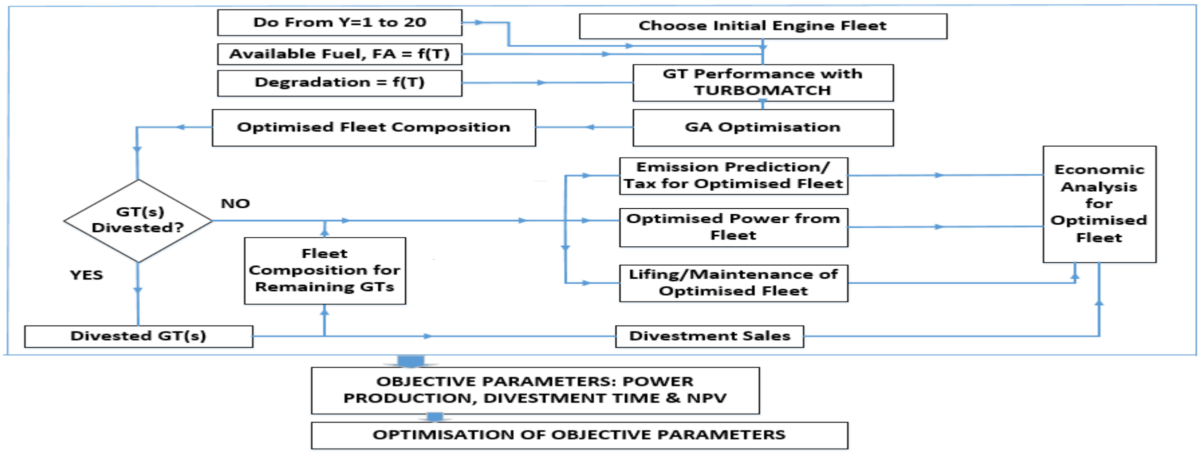

Figure 3: Methodology adopted for the techno-economic optimization of associated gas using gas turbines [22]

2.3 The genetic algorithm code and the optimization functions

2.3.1 The objective of the optimization

The goal of the optimization is to maximize power generation from the various fleets of engines while associated gas availability was the constraint.

2.3.2 The objective/fitness function

At the start of the project, each fleet has four engines, as detailed in section 2.2 above. The objective function used for optimization is shown in Equation 1. 'pou' is the power output for the fleet's individual units of engines, while' sop' is the sum of the optimum power of all the fleet's individual units of engines. The evolutionary algorithm in Matlab by default minimizes, hence the necessity for '-1' in equation 1, since the optimization in this study involves maximizing.

$$sop = 1 \times (pou(1) + pou(2) + pou(3) + pou(4)) \qquad (1)$$

2.3.3 The constraints in the optimization and the constraint function

The optimization constraints are the corresponding gas availability statistics shown in Figure 1. The constraint function fluctuates from year to year in the project due to differences in related gas supplies at various years of the project as well as continual divestments of superfluous engine units.
Equation 2 depicts the constraint function for the pessimistic scenario in the second year of the project. 'Fuel U' is the volume of fuel consumed by the fleet's individual engine units. To satisfy the constraint required in the optimization, 'U' must be zero, implying that the fuel has been full consumed. The observed value of 51.6361 as seen in equation 2 is the data for the associated gas availability for the second year of the project, which is 51.6361kg/s.

$$\mathrm{U} = \mathrm{Fuel\ U}(1) + \mathrm{Fuel\ U}(2) + \mathrm{Fuel\ U}(3) + \mathrm{Fuel\ U}(4) - 51.6361 \qquad (2)$$

2.3.4 The optimization variables

The optimization variables are the turbine inlet temperatures of the fleet’s engine units. The number of variables in the optimization code used is determined by the number of engine units at the start of the project, which is four.

2.4 Evaluating the viability of economically utilizing associated gas for power generation via gas turbines

The net present value (NPV) is the appraisal method utilized in this study to evaluate the economic feasibility of profitable use of this fuel resource for power generation using gas turbines. Equation 3 depicts the relationship employed in this study to estimate the net present value (NPV) of the various scenarios (fleets).

$$\mathrm{NPV} = \sum_{t=1}^{n} \frac{\mathrm{D_t}}{(1+\mathrm{u})^{\mathrm{t}}} - \mathrm{Do} \qquad (3) \qquad [23\text{-}25]$$

In equation 3, ‘Do’ represents the project's initial cost, which is the loan obtained. ‘D_t’ is the net cash-flow for the year under consideration, and ‘u’ is the assumed discount rate, and ‘t’ being the year being considered. The cost elements (cash outflows) implemented in equation 3 are capital investment, fleet emission tax, fleet operations and maintenance expenditures, loan repayment, and personnel compensation. While the revenue gained from the sold electricity and the divestment sales represent the cash inflows into the project, these were also included in equation 3.

3.0 Results and discussion

3.1 The effect of compressor degradation on the total optimized power

The total optimized power generated by the pessimistic, medium, optimistic and clean fleets are 7074.4, 7164.0, 7245.1 and 7324.6MW respectively. As shown in Figure 4; degradation in the compressor of the engine resulted to 3.42%, 2.19%, and 1.09% decrease in the total optimized power for the pessimistic, medium, and optimistic degraded fleets respectively

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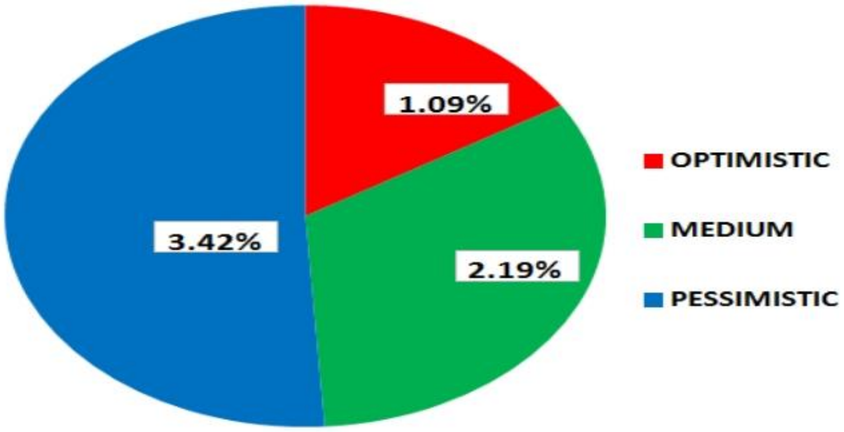

Figure 4: Effect of compressor degradation on the total optimized power of the reheat engine fleets

3.2 Optimized divestment schedule for the redundant units of engines in fleets

Due to the falling trend in the fuel available for the project, as shown in Figure 1, at some time during the project's lifespan, the fuel available would not be sufficient for all of the engines in the fleet. As a result, some engine units would be redundant, and these redundant engine units would be sold. The ideal timing to sell a redundant engine is a vital decision in the profitable use of associated gas by gas turbines.

Good timing in the sale of an engine can result in additional profits worth billions of dollars. As a result, there is a requirement to optimize the divestment time (schedule) of the fleet's redundant unit (s) of engines. The influence of engine degradation on the divestment sequence for the redundant unit (s) of RH296 engines is an important concern in this study. This is why the study analyzed three engine deterioration scenarios: optimistic, medium, and pessimistic. Figure 5 depicts the optimal divestment sequence for the various fleets (scenarios) of the RH296 engine, with the consequence of engine deterioration depicted by the degraded scenarios. Degradation delays the divestment of engine units in a fleet. As shown in Figure 5, the effect of degradation on the divestment schedule is minimal.This is linked to the level of degradation applied in the gas turbine performance software, the quantity of defective engine components, and the number of engine units in the fleet. Only compressor deterioration was used in this investigation.An increase in any of the aforementioned elements would amplify the effect of degradation.

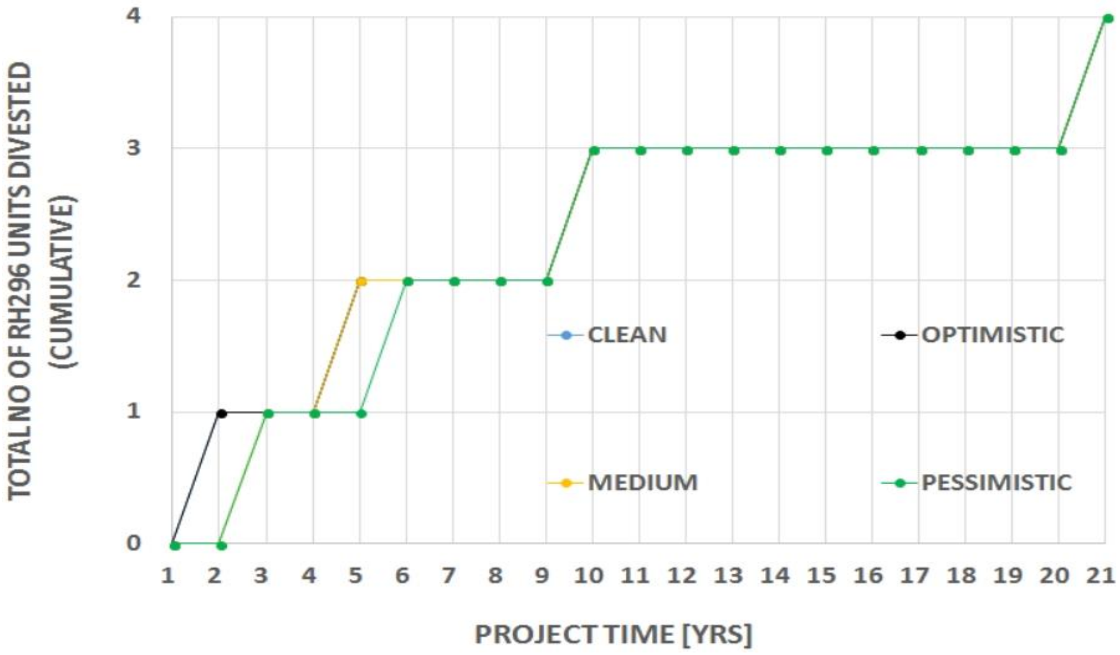

Figure 5: Optimized divestment schedule and the effect of compressor degradation on the divestment schedule of the RH296 fleets.

3.3 Divestment sales

Figure 6 depicts the proceeds from the sale of the redundant engines. In addition, any residual engine (s) was divested at the end of the project. The divestment sales for the clean, optimistic, medium, and pessimistic fleets are 609.8, 562.5, 507, and 460.3 million dollars, respectively, as shown in the Figure. The time the engine was sold and the condition of the engine at the time of sale were factors that influenced the divestment sales. The engines in the clean fleet were in better condition, and a unit of an engine in the clean fleet was sold earlier than in the other three fleets, this explains why the clean fleet had the largest divestment sales. For the degraded fleets, as shown in Figure 6, the higher the level of deterioration of the fleet, the lower the quality of the state of the unit of engine at the point of divestment, resulting in fewer divestment sales for the fleets with higher degradation.

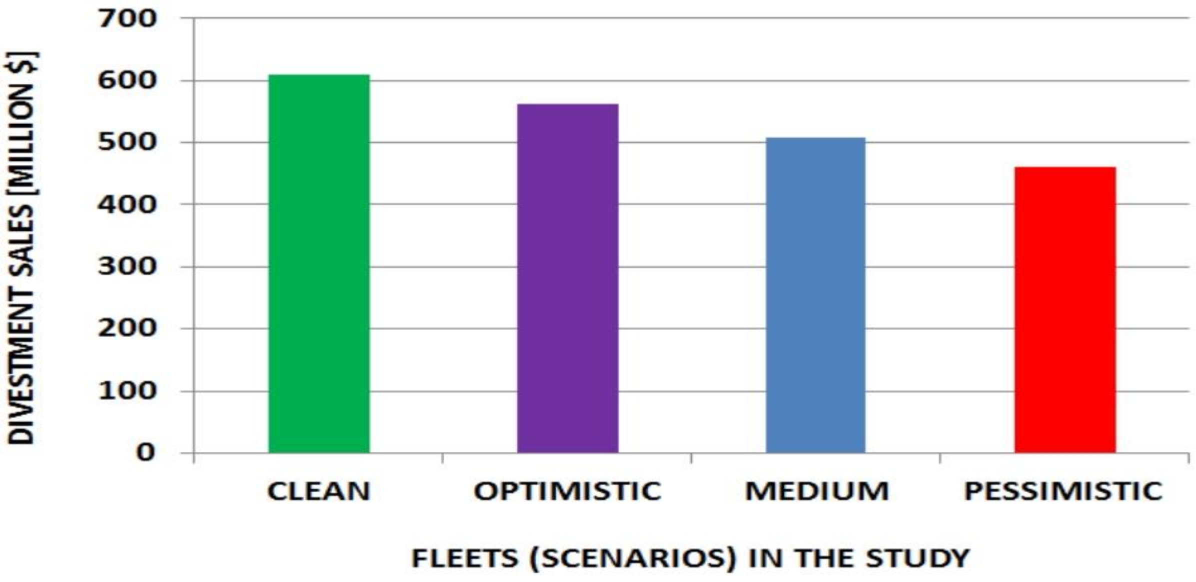

Figure 6: Sales realized from the divested fleets

3.4 The net present value (NPV) of the various optimal fleets

Figure 7 depicts the economic return (NPV) from the various optimized fleets. The results demonstrate that the net present value of the clean, optimistic, medium, and pessimistic degraded fleets is 3.03, 2.97, 2.84, and 2.75 billion US dollars, respectively. These enormous economic returns should persuade investors and governments to enter the business of economically utilizing associated gas via gas turbines.

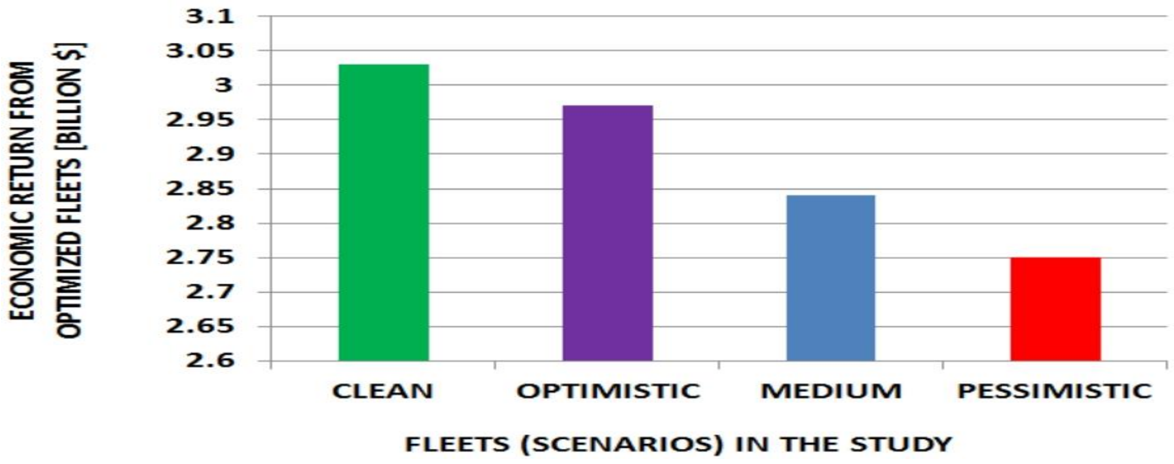

Figure 7: Economic return (NPV) in the economic utilization of associated gas for power generation using gas turbine

3.5 The impact of compressor deterioration on fleet economic returns

Engine deterioration, as projected, would have an influence on the economic returns of deteriorated fleets. The effect of engine degradation on the economic consumption of this fuel utilizing the 296MW reheat engine is depicted in Figure 8.

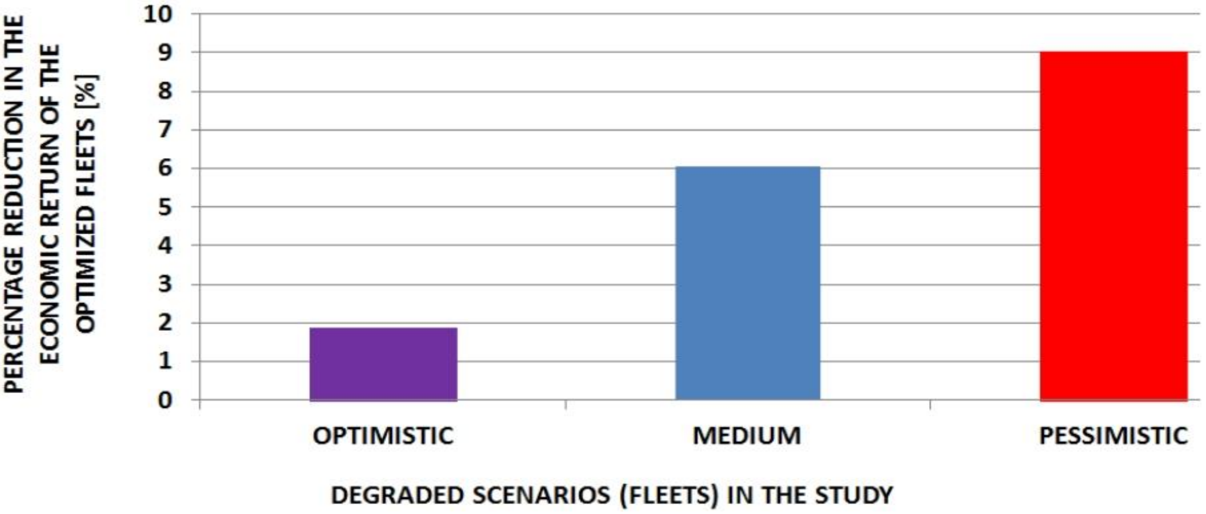

Figure 8: The impact of compressor degradation on the economic return (NPV) of the optimized fleets

According to Figure 8, the deterioration in the optimistic, medium, and pessimistic deteriorated fleets resulted in 1.86%, 6.05%, and 9.02% reductions in the net present value of the project of economic exploitation of associated gas respectively. The data and contents of this study are from the lead author's doctoral research [22].

4. Conclusion

Some researchers have shown that associated gas can be used to power industrial gas turbines and create electricity and energy. This paper offered a model and approach for optimizing the techno-economics of fleets of a 296MW reheat engine fueled by associated gas. Cranfield University's in-house gas turbine performance software was used to develop a hypothetical but realistic 296MW reheat engine (TURBOMATCH).

A multi-dimensional analysis of the economic consumption of associated gas with the RH296 reheat engine was performed using the Techno-Economic and Environmental Risk Assessment (TERA) approach. The study was conducted for four alternative scenarios: one with a clean fleet and three with degraded fleets (optimistic, medium, and pessimistic). Genetic algorithm was used to optimize the fleets in order to produce the best power and the highest economic return. A model that optimizes the best divestment schedule for the redundant unit (s) of engines for associated gas utilization is also included in this work. This model and the results presented would be tremendously useful to associated gas investors who use the Alstom GT-26 engine. Degradation of the engine's compressor resulted in 3.42%, 2.19%, and 1.09% reductions in total optimized power for the pessimistic, medium, and optimistic degraded fleets, respectively. The net present value of the clean, optimistic, medium, and pessimistic degraded fleets is 3.03, 2.97, 2.84, and 2.75 billion US dollars, respectively. Degraded fleets in the optimistic, medium, and pessimistic scenarios reduced the project's net present value by 1.86%, 6.05%, and 9.02%, respectively. The technique and results stated in this study would be extremely valuable in the economic exploitation of associated gas, as well as in associated gas investment and government decision making.

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Declaration of conflicting interests

The authors acknowledge that there is no conflict of interest.

Data availability

The data used for this work are available on request.

Authors' Contribution Statement

This is to affirm that all authors whose names appear in the title page of this manuscript have contributed to the contents of the manuscript.

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