CRANFIELD UNIVERSITY

OBHUO MAFEL

TECHNO-ECONOMIC AND ENVIRONMENTAL RISK ASSESSMENT OF GAS TURBINES FOR USE WITH FLARED ASSOCIATED GASES

SCHOOL OF AEROSPACE, TRANSPORT & MANUFACTURING
Department of Power and Propulsion

DOCTOR OF PHILOSOPHY
Academic Year: 2016- 2017

Supervisor: Professor Pericles Pilidis
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ABSTRACT

Investing in the economic use of associated gas for power generation using gas turbines would require a model for evaluating the effect of gas turbine degradation on the divestment time of the redundant units of engines.

The Techno-Economic and Environmental Risk Assessment (TERA) framework is adopted for a broad and multidimensional analysis of the problem. Due to the limited availability of the associated gas, the fleet composition is optimised to obtain the maximum power, economic returns and best divestment time. The performance, emission, creep life, economic returns and risk associated with the optimised fleets are all analysed. Four different study engines are considered – an aero-derivative, an aero-derivative with intercool, a single shaft, and a reheat engine. Turbomatch, Hephaestus, and Genetic Algorithm in Matlab are among the tools used.

As expected, results show that engine degradation extends the divestment time. For example, at the 2nd year of the project; 0, 1, 2, 3, 3 are the respective number of units of engines divested in the pessimistic degraded, medium degraded, optimistic degraded, clean (optimised) and baseline fleets of the aero-derivative engine. An increase of 1.0% and 1.6% respectively in the power and NPV of the optimised clean aero-derivative fleet as against the baseline are achieved. The economic performance of the fleets show the optimised fleet (clean) of the aero-derivative intercooled engine having the highest NPV of $3.24b and the pessimistic degraded fleet of the (43.3MW) aero-derivative engine having the least NPV of $2.39b. Degradation reduced the NPV of the project for the degraded fleets. As an example, a reduction by 4.0%, 9.1% and 15.8% for the optimistic, medium and pessimistic degraded fleets of the 43.3MW aero-derivative engine is observed.

The novel technical contribution of this research is the development of a model and methodology for evaluating the effect of degradation on divestment time, which serves as a guide to associated gas investors. Other contributions are the development of models for best divestment time evaluation, improvement of the economic performance of different fleets of different gas turbine cycles and the assessment of the impact of engine degradation on the economic use of associated gas. The results of the optimised divestment time, fleet compositions, power and improved economic returns from the project are also a big contribution to knowledge.

This research has proposed a model that can be used for the profitable economic utilisation of associated gas.

Keywords: divestment time, degradation, fleet optimisation, power generation

ACKNOWLEDGEMENTS

It's a long journey that began some years ago. It had good times and challenging times. At all times, a man was there to help and guide, he is a father, a mentor and an inspirer, he is my amiable Supervisor, Prof. Pericles Pilidis. His words of encouragement gave me hope during the rough times of the journey. His technical and professional foresight on my research was superb, I'm very grateful for his guidance and counsels all through this PhD studies journey. The part Mrs Gillian Hargreaves played towards the success of my PhD studies is highly acknowledged, she did her best to make sure I see Peri even at very short notice, she helped in many other ways, thanks Gill. Thanks to Dr Goulos I. and Prof. Kalfas A. for their useful comments.

The funding for this research and my up keep while doing the research was made possible by the Government of Nigeria, I'm very grateful to the Nigerian Government and the Petroleum Technology Development Fund (PTDF) for sponsoring both my MS.c and PhD studies.

I sincerely and deeply appreciate the gracious input of Dr Isaiah Allison, Dr Dodeye Igbong, Dr Dawid Bosak and Dr Aziaka Silas Duabari, the contributions of these four guys gave wings to my PhD research. I want to show my gratitude to Dr Bobby Sethi, Dr Uyi. Igie, Dr Eric Goodger, Dr Nikolaidis Theoklis, Dr Tosin Somorin and Dr Natan Zawadzki, I really appreciate the input you guys have put into my research. Thanks to Mrs Emma Turner and Mr Keith, they helped greatly in my use of Mendeley and in formatting the thesis.

A big thanks to my friends Dr Emmanuel Osigwe, Dr Musa Gali, Dr Nasiru Tukur, Dr Mosab, Dr Alozie Okechukwu. A big thanks to all the brethren of Deeper Life Bible Church, Burkinghamshire Region, your encouragement and prayers are well appreciated.

Thanks to my extended family members and in-laws, thanks for your prayers. Thanks especially to my Dad and Mum, they were always calling to know my progress. Words cannot express my gratitude to my Beloved Friend and Wife, our Daughter Gracious and our coming Son, we have all received this PhD

degree together, it was a joint effort. THANK YOU JESUS FOR YOUR FAITHFULNESS!

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NOMENCLATURE

ACARE	Advisory Council for Aeronautics Research in Europe
ADNOC	Abu Dhabi National Oil Company
ADCO	Abu Dhabi Company for Onshore Oil Operations
AG	Associated Gas
Bcfd	Billion Cubic Feet per Day
BSCM	Billion Standard Cubic Meters
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DP	Design Point
DPR	Directorate of Petroleum Resources
GA	Genetic Algorithm
GAs	Genetic Algorithms
GE	General Electric
GGFR	Global Gas Flaring Reduction
GT	Gas Turbine
GTs	Gas Turbines
GTU	Gas Treating Unit
KWh	Kilo Watt Hour
KW	Kilo Watt
Kg/s	Kilogram per Second
LANatGas	Lean Associated Natural Gas
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MANatGas	Medium Associated Natural Gas
MM scfd	Million Standard Cubic Feet per Day
MM scf	Million Standard Cubic Feet
MDEA	Methyl Diethanolamine
MW	Mega Watts
MED	Medium Degraded Fleet
NEWAC	New Aero Engine Core Concepts
NGC	Nigeria Gas Company
NNPC	Nigerian National Petroleum Company
NLNG	Nigeria Liquefied Natural Gas Limited
NO	Nitrogen Monoxide
NO_X	Oxides of Nitrogen
NO_2	Nitrogen Dioxide
NPV	Net Present Value

O & M	Operations and Maintenance
OPT	Optimistic Degraded Fleet
PES	Pessimistic Degraded Fleet
RANatGas	Rich Associated Natural Gas
SO_2	Sulphur Dioxide
$	United States Dollars
TERA	Techno-Economic and Environmental Risk Assessment
TET	Turbine Entry Temperature
TETs	Turbine Entry Temperatures
URR	Ultimate Recoverable Reserve

1 INTRODUCTION AND PROBLEM STATEMENT

1.1 Overview

The use of flared associated gas (AG) for power generation in the oil and gas industry has been attracting a growing interest given the environmental and energy benefits associated with this approach. The flared gases which are hydrocarbon rich can be converted into methane based fuel for combustion in gas turbines. However, the employment of gas turbines as part of this process requires investigation in terms of the architecture of the cycles, the integration of the different components, the economics of the process and the attending environmental impact. This project will employ the techno-economic and environmental risk assessment framework (TERA), developed in Cranfield University, to investigate the suitability of a range of approaches to exploit these existing sources of energy.

Natural gas found in conjunction with crude oil within the reservoir is referred to as associated gas (AG) [1, p.1]; [2]. AG flaring is the controlled burning of natural gas produced in association with oil in the process of routine oil and gas production activities. The practice of disposing natural gas to the atmosphere by flaring is an integral practice in oil and gas production, primarily for safety reasons [3, p.ii].

Flaring of AG does not only amount to great economic waste but it also results in life-threatening environmental impact. Huge amount of energy (Kilo Watts Hour, kWh) and economic return would be gotten when AG is used as fuel in industrial gas turbines.

1.2 Research Background and Problem Statement

Nigeria, a West African country, is among the countries currently having a very high level of AG flaring. Because of the enormous amount of energy that can be generated from the use of this AG, and the environmental benefits derivable due to the reduced emissions, the Nigerian government therefore needs a decision-making guide for investment in the economic use of AG for power generation (Mega Watts, MW).

This research seeks to develop a model and methodology that will provide useful decision-making guide on investment in the economic use of AG for power generation. The model and methodology will be useful to the government of any country that is flaring AG.

In this research, this AG utilisation project has a time span of 20 years, this is because of the decline in the availability of natural gas which is the source of the AG.

Fleets of four different types of gas turbine engines to make use of the AG as fuel for power generation are used in the model. As a result of the limited quantity of AG at various times in the years of the project, there is therefore the need for an optimisation model that gives the fleet composition that maximises power production and fuel utilisation. This is called the optimised fleet composition.

Gas turbines exhibit the effect of wear and tear over time, therefore degradation of the gas turbine components will set in during the life span of this project.

At some point during the life span of the project, due to the decline in the availability of associated gas, some of the gas turbine engines in the fleets would be redundant, and would therefore need to be divested. Hence, the need for an optimisation model that would evaluate the best divestment time for the redundant units of engines in the fleet. Investors (governments) who want to invest in the economic use of associated gas using gas turbines need to know the effect of engine degradation on the best divestment time for the redundant units of engines in the fleet, this would also serve as a decision-making guide.

1.3 Research Aim

The aim of this research is to explore the effect of gas turbine degradation on the optimum divestment time for the redundant units of engine in a fleet. This is a key element that would be needed by investors who want to invest in the economic utilisation of associated gas for power generation. Knowing the effect of degradation on divestment time would serve as a useful decision-making guide for associated gas investors. As evident in the public domain, this has not previously been done.

1.4 Research Objectives

The objectives of this research are as follows;

- To simulate engine performance at varying operating conditions of the study engines at clean and degraded modes using Turbomatch
- To generate a baseline fleet composition given the fuel availability as constraint
- To optimise the fleet composition of the various fleets using Genetic Algorithms (GA) in Matlab
- To optimise the power generated (MW) by the various fleets given the constraint of limited fuel availability (using GA in Matlab)
- To carry out a simple lifing model for maintenance cost estimation for all the various fleets in the study
- To carry out emission assessment for the various fleets in the study using Hephaestus
- Assessment on the impact of gas turbine degradation on divestment time and on the economic use of associated gas (using GA in Matlab)
- Optimising the economic performance of the various fleets of gas turbines for power generation using GA in Matlab and TERA modules acting as external solver

1.5 Contribution to Knowledge

1.5.1 Development of a model for evaluating the effect of engine degradation on the divestment time for redundant units of engine

After doing a detailed literature review on the economic utilisation of AG using gas turbines, the research gap as evident in public domain is the lack of literature that show the effect of gas turbine degradation on the divestment time for redundant units of engines in a fleet.

This research has successfully developed a model for evaluating the effect of gas turbine degradation on the divestment time for redundant units of engines. This model serves as a guide for investors who would want to invest in the economic utilisation of AG using gas turbines.

1.5.2 Development of a model and methodology for investing in AG utilisation

AG is being wasted to flaring in many countries. A robust model and methodology has been developed in this research which would serve as a guide for investing in AG utilisation.

1.5.2.1 Development of a model for the assessment of the impact of engine degradation on the economic use of AG

As seen in the public domain, the models already provided for the economic utilisation of AG lack robustness due to the absence of the effect of degradation on the divestment time for redundant units of engines, which is a key element. The effect of engine degradation on divestment time and cost have been integrated into the model presented in this research. The robustness of the economic model proposed by this research makes it useful as a guide for investing in AG utilisation.

1.5.2.2 Development of a model for the improvement of the economic performance of a fleet of gas turbines for power generation

As a result of the depletion of natural gas, AG which is a form of natural gas is also gradually depleting. Investing in the economic utilisation of AG will require a model for optimising the fleet composition, the power and economic return (NPV) from the fleets subject to the constraint of depleting AG availability.

This research has successfully produced a GA model for the optimisation of gas turbine fleet composition, power and improvement of the economic return from the fleet (NPV) given the constraint of limited AG availability.

1.5.3 Reliable results for AG investment planning

The results of the optimised divestment times for the degraded fleets are a novel contribution to knowledge. The optimised divestment times, fleet compositions, power and the improved economic returns from the project are also a big contribution to knowledge. These results can be used as estimates of expected returns on investing in AG utilisation.

1.6 Structure of Thesis

This section gives a brief description of the contents of the various chapters of this research. This thesis report is made up of 7 chapters, each ends with a brief chapter summary.

Chapter 1: Introduction and Problem Statement

This introductory chapter gives an overview on associated gas wastage and the opportunity of harnessing it as a source of energy. The research background and statement of the problem that prompted the need to carry out this research were also identified. The research aim, objectives and contribution to knowledge were all described in this introductory chapter of the research.

Chapter 2: Literature Review

This chapter contains a detailed literature review on the economic utilisation of associated gas for power generation using gas turbine engines.

The literature review exposed the effects of associated gas flaring. It also emphasised the current trend in associated gas decline and the reason for this decline. A detailed review on degradation in gas turbine components, the causes and the effects on engine performance is also presented. Previous studies on the economic utilisation of associated gas and engine units' divestment are also surveyed and the research gap highlighted. Case studies on associated gas recovery and utilisation are cited. Some previous applications of the Techno-Economic and Environmental Risk Assessment (TERA) framework are outlined.

The engines selected for the research and the reasons for their selection are carefully described. Literature review are also carried out on the tools used in this research. Different project appraisal methods are highlighted and the one to be adopted in this research is explained.

Chapter 3: Research Methodology

Having identified the research aim and objectives in the first chapter of the research, this chapter describes in a chronological order the steps and tools utilised to achieve the aim and objectives.

The associated gas availability data used by the fleets is also shown in this chapter. A brief and introductory explanation as regards the engine degradation aspect of the research is done.

The fleet composition for the baseline fleet and the economic utilisation of the associated gas by the baseline fleet is analysed for the entire duration of the project as seen in this chapter. The robust model developed for the economic utilisation of associated gas using gas turbines and the several technical and economic factors integrated into the model are all described.

Chapter 4: Genetic Algorithms, Matlab and the Optimisation Process

This chapter describes the Genetic Algorithm tool and its operators when used for optimisation purposes. The aim of the optimisation, the objective function to be maximised and the optimisation constraints are also explained in this chapter. This chapter describes the Genetic Algorithm in Matlab code developed and employed in this study. The chapter explains how the database (search domain) for the optimiser was generated. The effects of some Genetic Algorithm parameters on the optimisation results are also highlighted.

Chapter 5: Optimisation Results and their Integration into the TERA Model

This chapter shows the results of the optimisation for the various fleets.

The chapter begins with the verification of the optimisation model and its results.

The results from the optimisation such as the optimised fleet composition, power, divestment time and efficiencies for the units of engines in the fleets are all presented in this chapter.

The effect of engine degradation on divestment time, which is the aim and main contribution to knowledge in this research is also evaluated as seen in this chapter.

In this chapter, the process of integrating the optimisation results into the TERA model is initiated by estimating the emissions and creep life of the various optimised fleets.

Chapter 6: Economic Evaluation of the Optimised Fleets

This chapter contains the economic evaluation of the various optimised fleets. The robust economic model developed was used in the assessment of the impact of gas turbine degradation on the economic use of associated gas. The chapter also considers the optimised economic performance of the various fleets of gas turbines for power generation. A sensitivity analysis showing the effects of some technical and economic factors on the economic return (NPV) of the project are also highlighted.

Chapter 7: Conclusions and Recommendations for Future Work

The final chapter shows the conclusions drawn from the research and the recommendations made for improving future studies on the economic utilisation of associated gas using gas turbines.

2 LITERATURE REVIEW

2.1 Introduction

The Niger Delta region of Nigeria is suffering from the negative effects of the frequent flaring of associated gas. These associated gases are natural gases with impurities.

Although the conventional fuel used by industrial gas turbines in generating electricity is natural gas, associated gases can also be harnessed as fuel for power generation.

Harnessing associated gases for power generation will not only help in solving the problem of lack of constant power supply, but it will also add to the volume of fuel for our industrial gas turbines while at the same time eliminating the negative effects that would have been caused by the unused flared associated gases.

2.2 Effects of associated gas flaring

The negative effects of associated gas flaring are numerous. The hazardous effects of associated gas flaring range from land to sea and air, thus its negative effects are experienced by humans, terrestrial and aquatic animals, plants, etc. Underneath are some examples of the negative effects of associated gas flaring.

2.2.1 Emission of greenhouse gas (GHG)

The burning of fossil fuel produces greenhouse gases which lead to global warming. The carbon dioxide emitted during associated gas flaring results in high global warming potential. Associated gas flaring also contributes considerably to the release of emissions of carbon monoxide (CO) and oxides of nitrogen (NO_X), which are gases that aid the formation of tropospheric ozone (another greenhouse gas). In the stratosphere, methane is available as a greenhouse gas; whereas in the troposphere (ground level), methane aids the photochemical process of formation of ground level ozone and smog [1, p.14]; [4].

2.2.2 Air pollution

Chemically, ambient air is composed of gaseous mixture of 21% Oxygen, 78% Nitrogen, 0.04% Carbon dioxide, with Water vapour and Rare gases such as Helium and Argon. Ambient air composition is affected when the concentrations of the components are altered and this causes pollution of the air. Gas flaring is one of the main causes of air pollution. CO_2 emissions is expected to reduce by about 15 million tonnes in various oil production facilities, especially in Nigeria, this is as a result of the serious effort made towards ending continuous flaring [1, p.14]; [5].

Figure 2-1: Associated Gas Flaring in Rumuekpe, Rivers State (Nigeria) [6]

2.2.3 Health threat

The implications of gas flaring on human health all have to do with the exposure of those toxic air pollutants generated in the process of partial combustion of gas flare. These pollutants are linked with various serious health cases such as cancer, neurological, reproductive and developmental effects. It is also reported that skin sicknesses, lung damage and deformities in children can also be linked to these toxic pollutants [7, p.7]. Some serious changes in haematological parameters are said to be caused by hydrocarbon compounds, negatively affecting the blood and blood-forming cells, which can lead to anaemia, leukaemia and pancytopenia [7, p.7].

2.2.4 Formation of acid rain

Acid rain is reportedly associated with the activities of gas flaring [8, p.1, 2]; [9]. Reports from the Niger Delta region of Nigeria reveal that corrugated roofs are been corroded by the constituents of the rain that falls due to associated gas flaring [7, p.7]. Acid rain is primarily caused by the emissions of nitrogen oxides (NOx) and sulphur dioxide (SO_2) which in combination with atmospheric moisture form nitric acid and sulphuric acid respectively. The negative effects of acid rain are numerous; it acidifies aquatic habitats and damages vegetation. Also, acid rain increases the rate of decay of building materials and paints. Before falling to the earth, NO_2 and SO_2 gases and their particulate matter derivatives, nitrates and sulphates, aid visibility degradation and threaten public health [7, p.7].

2.2.5 Effect on agriculture

Gas flaring results in atmospheric contamination. These contaminants include oxides of Nitrogen, Carbon and Sulphur (NO_2, CO_2, CO, SO_2), hydrocarbons and ash, particulate matter, hydrogen sulphide (H_2S) and photochemical oxidants [10]; [11]. These contaminants acidify the soil, which leads to depletion of soil nutrient. Reports have shown that the nutritional values of crops planted around that location are reduced [12]. In some instances, there is no vegetation at all in the vicinity surrounding the flare resulting from the intensity of the heat that is produced and the acid nature of the soil pH [7, p.7]; [13].

2.2.6 Economic loss

Apart from the health and environmental effects of gas flaring, billions of dollars' worth of gas is literally burnt off on regular basis in some part of the world, including Nigeria. According to the Directorate of Petroleum Resources (DPR) in Nigeria, the 1.4bcfd (billion cubic feet per day) flared gas was costing the Federal Government $4.9m (million) daily at $3.50/1,000 standard cubic feet, when put together, the nation loses $1.79bn (billion) yearly to gas flaring [14]. This can be converted for electricity generation and many other useful means.

2.3 Associated gas flaring in Nigeria

Gas flaring in Nigeria dates back to when oil exploration commenced in the nation in the 1950s. Laws have been put in place since 1984 and several attempts have been made by various government regimes to put an end to gas flaring but complete success is yet to be achieved [14].

According to the Directorate of Petroleum Resources (DPR), the 1.4bcfd flared gas was costing the Federal Government $4.9m daily at $3.50/1,000 standard cubic feet, when put together, the nation loses $1.79bn yearly to gas flaring [14].

2.3.1 Past gas gathering efforts in Nigeria

Natural gas is a vital component of global energy supply, being one of the most useful and safest sources of fuel. It is clean burning, yields less toxic fumes during combustion, and can also be harnessed as feedstock for the petrochemical industry. In 1988, the Nigeria Gas Company (NGC) was created as a section of the Nigerian National Petroleum Company (NNPC) and with the objective of transporting and marketing gas in Nigeria and West Africa [1, p.16,17]. Many attempts have been made and continue to be made to gather associated gas, this is explained in the sections below.

2.3.2 Field data

Examined below is a literature review of field data obtained from the Niger Delta region of Nigeria. Data on associated gas (AG) usage was collected from the Directorate of Petroleum Resources (DPR), while the data on AG composition was gotten from the Nigeria Liquefied Natural Gas (NLNG) Limited [1, p.37,38].

2.3.2.1 Data obtained from DPR

Data items gotten from the DPR, between the years 1999 to 2008, are as follows:

- Gas quantity in BSCM (billion standard cubic meters) produced from oil exploration activities
- Gas quantity utilised
- Gas quantity flared

Details are as shown in Table 2-1 below.

Table 2-1: Natural Gas Produced, Utilised and Flared, 1999-2008

Year	Production (BSCM)	Gas Used (BSCM)	% Used	Gas Flared (BSCM)	% Flared
1999	39.05	14.57	37.32	24.48	62.68
2000	48.73	22.39	45.96	26.33	54.04
2001	55.04	27.27	49.54	22.26	50.50
2002	49.59	26.21	52.85	23.38	47.15
2003	53.90	31.20	57.89	22.70	42.11
2004	59.75	35.64	59.64	24.12	40.36
2005	60.47	37.66	62.28	22.81	37.72
2006	64.84	41.61	64.17	23.23	35.83
2007	73.82	53.41	72.35	23.12	31.33
2008	72.27	53.42	73.91	18.85	26.09

Source of Data [DPR, Nigeria]

The gas usage above includes its usage as fuel, for domestic sales, re-injection for Enhanced Oil Recovery (EOR), processing to Liquefied Natural Gas (LNG) or Liquid Petroleum Gas (LPG) [1, p.38].

2.3.2.2 Data obtained from the NLNG

Data obtained from the NLNG Company cover the compositions of three constituents of AG, characterised in Table 2-2.

- Lean Associated Natural Gas (LANatGas)
- Medium Associated Natural Gas (MANatGas)
- Rich Associated Natural Gas (RANatGas)

The different AG composition above represents different degrees of gas quality [1, p.43,44].

Table 2-2: AG Compositions from Three Locations

Constituents	LANatGas	MANatGas	RANatGas
Methane, CH4	0.88748	0.84734	0.82483
Ethane, C2H6	0.04402	0.06300	0.07026
Propane, C3H8	0.02572	0.04185	0.04819
iso-Butane, C4H10	0.00553	0.01158	0.01332
n-Butane, C4H10	0.00843	0.01161	0.01332
iso-Pentane, C5H12	0.00265	0.00335	0.00405
n-Pentane, C5H12	0.00195	0.00336	0.00405
Hexane, C6H14	0.00174	0.00182	0.00224
Heptane+, C7H16	0.00178	0.00198	0.00233
Carbondioxide, CO2	0.01957	0.01297	0.01579
Nitrogen, N2	0.00113	0.00114	0.00163
Total	1	1	1

Source of Data [NLNG, Nigeria]

Currently, the NLNG is processing, transporting and marketing Nigeria's gas resources and hopes to mitigate gas flaring. As regards the NLNG Plant at Bonny, AG is gotten from onshore concession locations in the Niger Delta region and also from offshore pipelines and conveyed to the plant. NNPC/Shell, NNPC/Agip, NNPC/Elf are the three production ventures from where the gas is being supplied and has Soku, Obiafu and Obite respectively as major gas fields in Rivers State which serve as transfer points [1, p.44].The supply of associated gas to the NLNG is further explained in Figure 2-2.

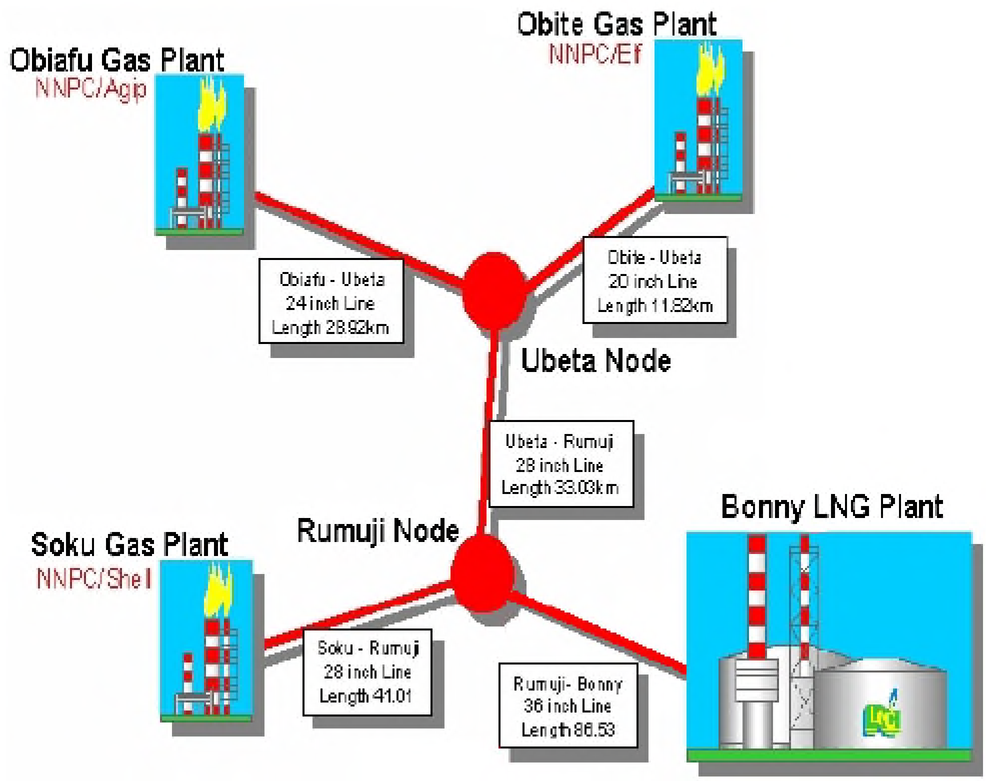


Figure 2-2: Supply of AG to the NLNG [1, p.44]

2.4 AG as a fuel for gas turbines

AG has properties which makes it suitable for combustion in gas turbines after its purification. Because AG is gotten from pure natural gas, it has most of the properties of natural gas.

The high methane content in AG makes it a possible fuel for power generation and industrial use.

2.4.1 Natural gas and its chemistry

The primary constituent of natural gas is methane. Fuels and chemicals could be gotten from methane either through synthesis gas or directly into C_2 hydrocarbons or methanol. Although other processes for the conversion of methane do exist, most large scale commercial conversion of natural gas uses the synthetic gas approach. The method mostly used in producing synthetic gas is steam reforming. Other methods employed in the production of synthetic gas from methane are direct partial oxidation and the direct conversion of methane approach [15, p.2-4]; [16, p.249, 250].

2.4.2 Industrial gas turbine fuel requirements

For combustion to take place in the combustion chamber of a gas turbine, the fuel must be injected, vaporised, and then mixed with air. The influence of these processes on combustion is a function, to a great extent, on the physical properties of the fuel [17, p.456]. The important properties of the fuel are distillation range, vapour pressure, flash point, volatility point, viscosity, surface tension, calorific value, sensible enthalpy, limits of flammability, and smoke point [17, p.458-471]; [18, p.11-15].

2.4.3 Impurities in AG

Allison [1, p.19] reported that impurities in the use of AG as fuel for gas turbines could come from the fuel gas, air, fuel oil or water.

Having these impurities in excess quantity could result in poor combustion of the fuel, which leads to poor engine performance. The presence of H_2S in the AG also reduces the quality of this fuel source.

Lefebvre and Ballal [17, p.449] highlighted some contaminants that can be found in distillate fuels. They posit that apart from sulphur and sulphur compounds, other contaminants in distillate fuels are gum, water, and trace amounts of metal particles. AG may also contain some of these contaminants, although in less quantities.

2.4.4 Examples of AG utilisation

AG has been successfully utilised as fuel in gas turbines to generate power. Detailed below are case studies of AG utilisation in various localities.

2.4.4.1 AG utilisation by the General Electric (GE) Jenbacher gas engine

Clarke Energy [19] reported that the earliest GE's Jenbacher systems utilising AG were installed in 1998 in Italy. By 2013, there are more than 330 units worldwide operating on AG, having a total electrical output of more than 450MW.

About 3.6 million MWh of electricity is generated yearly by these plants, as reported in 2013 [19].

2.4.4.2 AG utilisation in Abu Dhabi

According to Misellati and Ghassnawi [20, p.1-2], and Wasfi [21, p.1], the Abu Dhabi National Oil Company (ADNOC) has for long set the goal of zero flaring for the companies operating under its group. The Zakum Development Company (ZADCO) and the Abu Dhabi Company for Onshore Oil Operations (ADCO) have made several efforts in the recovery of flared gas.

In the early 1970's, ZADCO recorded large amounts of gas flaring while carrying out its operations. However, due to the zero flaring mandate, a flare gas recovery compressor was integrated into its system, which help in recovering some of the gas flared [20, p.1-3].

Wasfi [21, p.1] reported that ADCO has made several efforts in carrying out projects in all its Fields to reduce flaring to the minimum and to recover the AG. ADCO adopted a zero flaring strategy which led to a 90% decrease in one of its field's total daily process flaring, from about 2.8 to 0.3 million standard cubic feet per day (MM scfd). The resulting increase in gas availability of approximately 900 million standard cubic feet (MM scf) has an annual beneficial value of $1.4m (million dollars), equating to $22m as an NPV in a 25 year basis.

2.4.4.3 AG utilisation in Qatar

Ferdrin [22] highlighted the improvement achieved in Qatar in its efforts to minimise AG flaring and recovering AG for other useful purposes.

Gas production commenced in Qatar in 1949, this was used in field work that had to do with oil production. In the 1960's, the State commenced utilising gas for power generation, while the use of onshore AG to produce Natural Gas Liquid (NGL) started in 1974. In the early 1970's, a project was executed to transport onshore AG to Umm Said and Doha from 5 different oil/gas separation stations which are situated between Khatiyah and Jaleha. This transported AG were used in a Cement and Fertilizer plants at Umm Bab and Umm Said respectively. The transported AG was used in the RAA power station in Doha. While the above project was going on, another project of recovering Natural Gas Liquids (NGL) from the onshore AG was also executed.

As at the time Ferdrin reported, the Qatar government has made several efforts both to minimise flaring and to recover the flared AG for other useful purposes such as fuelling of power plants. Ferdrin [22] also reported that gas utilisation in the State has been well optimised.

2.4.4.4 AG utilisation in Iran

Zadakbar et al., [23, p.51] posit that due to the enormous volume of gas flaring that was going on in the Khangiran gas refinery, investigations were carried out on the operational conditions. These investigations focussed on the units directly producing the flare gases [24]. From the existing data, it was discovered that the flash drum of the methyl diethanolamine (MDEA), the regenerator reflex drum of the MDEA, the regenerator column of the MDEA, the residue gas filter and the inlet gas separator which goes into the gas treating unit (GTU) were paramount when considering the production of flared gases.

From past research and experience, Zadakbar et al., [23, p.51] suggested some practical ways of minimising, recovering and reusing of flared gases. To minimise and/or reuse flared gases; improve the geometry of the MDEA flash drum. This helps in reducing H_2S and CO_2, thereby sending the gases to the fuel gas header. Equipment with envisaged streams should be upgraded, this will also help in sending the gases to the fuel gas header. The internals of the inlet gas separator should also be upgraded. For recovering and reusing of flared gases, the flare gas recovery system for the MDEA flash drum should be installed. The overall flare gas recovery system should also be installed.

2.5 AG production decline, gas turbine engine degradation and engine units divestment

A serious concern in this research is the decline in the production of fossil fuel which is the source of AG. Engine component deterioration must be put into consideration when researching on using AG as fuel for gas turbine power generation. Divestment of redundant engines will normally take place at some time in a gas turbine company, this will be necessary for the purpose of maximising the company's assets.

2.5.1 AG gas production decline

Due to the continuous consumption of fossil fuel on an industrial scale, it is certain that there is gradual depletion in its reserve [25, p.45]. It also implies that associated gas production is gradually declining since it is a fossil fuel. Decline may be as a result of politics, sabotage, malfunctions or depletion [1, p.86]. For the purpose of this research, decline as a result of depletion is the focus.

In 2002, the World Bank organised a Summit for Sustainable Development in South Africa where the Global Gas Flaring Reduction (GGFR) Initiative was launched. Its primary aim was to render a solution to the challenge of global gas flaring. In the study, a decline rate of -13% was used throughout the 20-year period of the life of the power plant, starting from year 2015. The plant was expected to have an annual operational hours of 8000, making use of AG as fuel (with a constant Lower Heating Value of 41MJ/Kg), and a daily Ultimate Recoverable Reserve (URR) of 40,000m3 per well as recommended by the team of World Bank experts. The resource decline was implemented on the GGFR Code for a single well which gave rise to the AG Decline Curve of Figure 2-3 [1, p.93-96], this was done by Isaiah Allison using the GGFR code [1]. This research utilised the same fuel availability as that used by Allison. His case study is Nigeria, this research is a follow-up of his. Also, Nigeria is a member of the World Bank GGFR partnership programme and is actively receiving assistance on reducing gas flaring. The World Bank GGFR partnership is helping some African countries (including Nigeria) in their effort to stop or reduce gas flaring [26, p.8, 10, 13]. The URR used for this research is as suggested by the World Bank experts, and Nigeria is the case study for this research. However, the model proposed by this research is applicable to any country flaring AG.

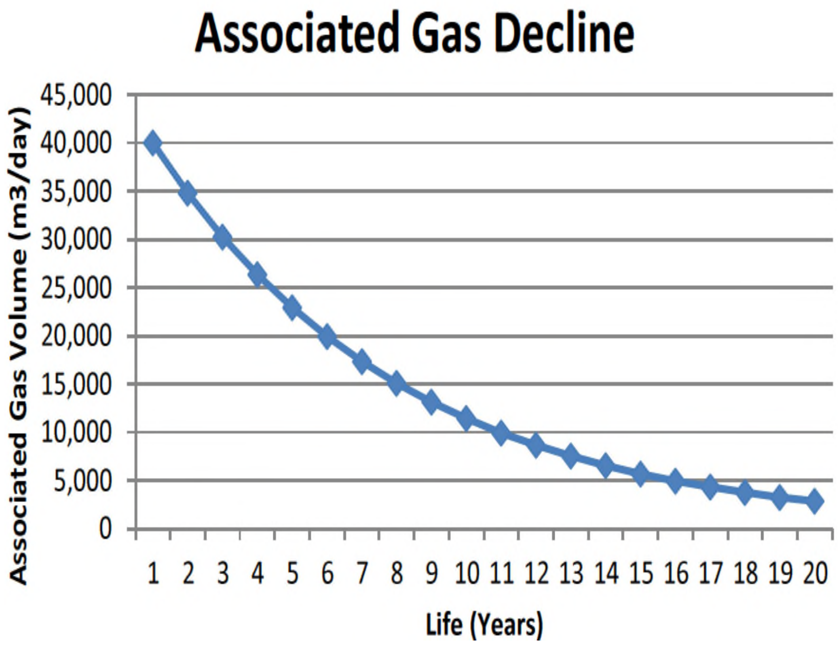


Figure 2-3: Associated Gas Decline over Time [1, p.95]

Shown in Figure 2-4 is the graphical illustration of the steady reduction in power as a result of the decline in AG supply. Figure 2-5 shows the steady increase in redundant power (undivested) capacity due to the decline in AG, which can be divested.

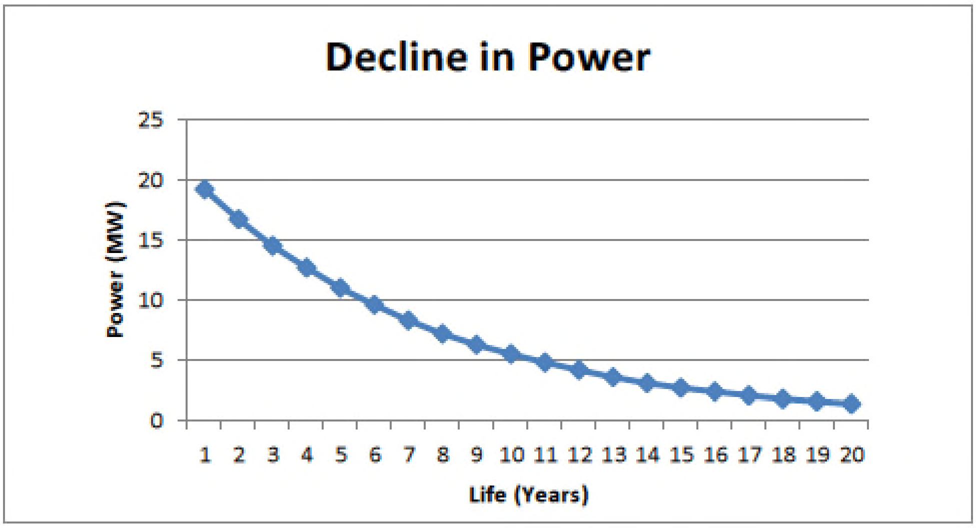


Figure 2-4: Decline in Power over Time [1, p.96]

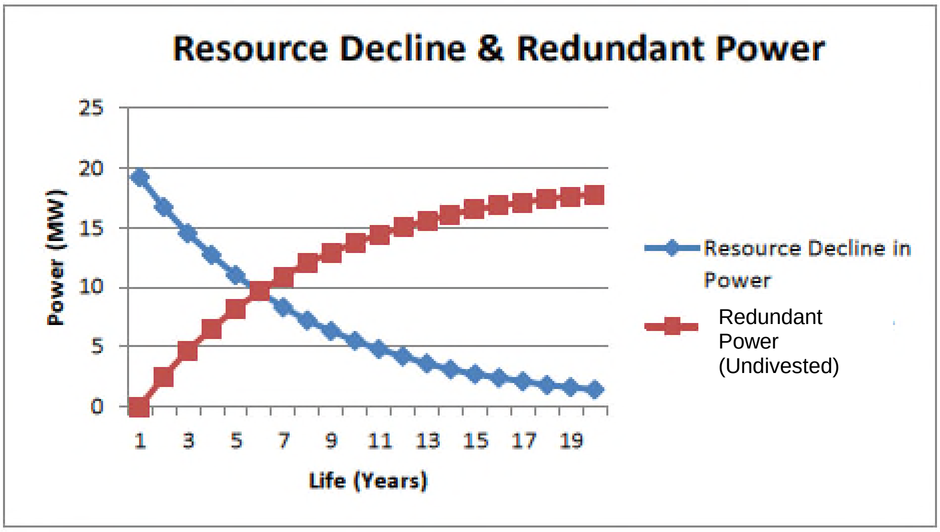


Figure 2-5: Resource Decline and Engine Redundancy [1, p.96]

2.5.2 Gas turbine units divestment

Fossil fuel which is the source of AG is continually undergoing depletion, as such, a gas turbine industry running its engines on AG needs to plan on divestment of redundant engines. The option of which gas turbine unit to divest involves selection of engine units and management of redundant engine units. For a selected fleet of engines and a given AG production profile, the timing of the withdrawal and the appropriate engine unit to be withdrawn is a major concern. The AG decline rate and the Ultimate Recoverable Resources are the two major factors that determine the number of redundant engine units [27, p.135].

In Anosike's [27] study on engine units' divestment, he adopted a methodology in which the gas turbine unit divestment algorithm relied on output from the AG production profile module in order to predict the power plant engine mix. Also, the prediction was based on the available engine within the eight gas turbine engines which were used as study engines. The performance and economic parameters served as the determinant factors for the estimation of the particular gas turbine unit due for divestment. The engine thermal efficiency and the fuel consumption are the performance parameter criteria considered whereas the purchased equipment cost (PEC) of the gas turbine unit was considered as the economic criterion. It was observed that achieving gas turbine engine operation with engine divestment option requires multiple mix of gas turbine units. The economic performance increase found as a result of the divestment stratagem was quite noticeable across the power plants considered [27].

Allison [1] analysed the influence of degradation on the economic use of AG, and demonstrated the onset of resource decline and palliative divestment protocol. He recommended that the effect of gas turbine degradation on divestment time should be explored.

On the economic utilisation of AG using gas turbines, the research gap as evident in public domain is the effect of gas turbine degradation on engine units' divestment time. This is key for investors who would want to invest in the economic utilisation of AG using gas turbines.

2.5.3 Degradation in gas turbine components

Wear and tear are usually observed in gas turbines after a period of usage, with this deterioration of an engine having a negative effect on the engine's overall performance. Therefore, the effect of deterioration on an engine and the attendant economic implication would be factors to be considered when using AG as fuel for industrial gas turbine engines for the purpose of power generation [1, p.22].

2.5.3.1 Causes of degradation in gas turbine components

The most important factors responsible for deterioration of gas turbine components are; fouling, hot corrosion, corrosion, erosion, damage, abrasion, creep, etc. [1, p.22-24]; [28, p.174-176].

Fouling is caused by the adherence of particles to airfoils and annulus surfaces in the presence of oil or water mists. This results in a build-up of material that leads to surface roughness and to some extent causes alteration in the shape of the airfoil. Sea salts, carbon, oil mists and smoke are common examples of particles that cause fouling and they are typically smaller than 2 to 10µm. An example of the adverse effect of fouling is the plugging of turbine blade cooling holes which is caused by submicron particles, this increases damage from overheating [28, p.174].

Hot corrosion is the loss or degradation of material from flow path components as a result of chemical reactions taking place between component and some contaminants such as reactive gases, salts and mineral acids (Figure 2-6).

Figure 2-6: Hot Corrosion on a Turbine Rotor [28, p.175]

Corrosion is mainly caused by inlet air contaminants, fuel contaminants and combustion-derived contaminants. Fuel-induced corrosion is more noticeable and severe with distillates and heavy fuel oils than with natural gas, as a result of the presence of additives and impurities in the liquid fuels which leave aggressive deposits after combustion. Corrosion could also be caused by impurities present in the air, which is as a result of the combustion of fuel in the combustion chamber [28, p.175].

The time-dependent deformation of components when loads are applied to them at high temperatures is called creep. This causes plastic deformation, it is time dependent and under favourable thermal conditions could lead to material deformation [1, p.23]; [29].

2.5.3.2 Effect of components deterioration on the engine performance

Deterioration in gas turbine engine components has a compounded effect on the performance of the entire gas turbine engine. The reason being that the alteration in component performance characteristics results in mismatch of these components both on the component level and on the entire gas turbine engine level [30, p.97].

2.5.3.2.1 Effect of compressor deterioration

Compressor deterioration is mostly caused by fouling and erosion. The main effect of compressor deterioration is a reduction in the thermal efficiency and power output of the gas turbine. Fouling results in a change to the geometry of the blading and also causes the rotor airfoils' smooth surfaces to become rougher. The outcome is a decrease in mass flow rate, compressor efficiency and pressure ratio [31, p.48]; [32].

Lakshminarasimha et al. [33] found that fouling resulted in a 5% decrease in compressor inlet mass flow, which led to a 10% and 2.5% decrease in power output and compressor efficiency respectively [31, p.48].

Zwebek [31, p.48] reported that test data of some sites show results that, in the case of large industrial gas turbines, compressor fouling caused a 5% decrease in inlet mass flow, which decreased the efficiency of the compressor by 1.8%. This level of fouling will decrease the power output of the engine and increase the heat rate by 7% and 2.5% respectively.

2.5.3.2.2 Effect of combustion system deterioration

According to Diakunchak [34, p.164], time-dependent engine performance degradation is unlikely to have been directly caused by degradation in the combustion system. Regardless of the fuel utilised (such as natural gas, distillate oil, or even crude oil) and even if deposits of carbon are stuck on the fuel nozzles, there will not be a reduction in the efficiency of the combustor, though deposits of carbon breaking off from the nozzles and soot formed due to the incomplete combustion of fuel will lead to performance deterioration. Temporary or permanent deformation of downstream components, which will lead to performance deterioration, can occur if there are alterations in the outlet pattern factor of the combustor.

2.5.3.2.3 Effect of turbine deterioration

Performance degradation is the outcome when there is fouling of the turbine airfoils and annulus, erosion of the turbine surface, blade tip and seal land rubs. Performance deterioration can also occur when the leakage and cooling flows increase beyond a certain level [34, p.164]. Bammert and Stobbe [35] reported that a test on a multi-stage axial turbine revealed a significant decrease in performance due to the effect of both increase in airfoil profile thickness (caused by surface deposits) and decrease in airfoil profile thickness (due to erosion) [34, p.164].

According to Zwebek and Pilidis [36] and Diakunchak [34], about 2.7% increase in heat rate and 3.7% reduction in power output is the resultant effect of 1% reduction in the overall turbine isentropic efficiency [31, p.49].

2.5.3.2.4 Effect on the overall engine

The overall engine degradation is a result of the combined effect of the degradation in the individual components of the engine. Experience in the use of gas turbines has revealed that under unfavourable conditions, the loss in power output could be as high as 20% while under most favourable conditions, it could be as low as 2% [31]; [37, p.50]. As an example, Diakunchak [34] reported a 5% reduction in inlet mass flow resulted in a 0.5% reduction in the efficiency of the turbine, and a 1.8% reduction in the efficiency of the compressor will lead to a 4.2% increase in the heat rate and a 10% reduction in power output.

2.5.3.3 Effect of performance deterioration due to associated gas combustion

Alteration of natural gas quality from pipeline gas quality will not only cause inefficient thermodynamic performance, but will also initiate the deterioration of the hot gas path of the gas turbine engine as a result of the contaminants in the fuel [1, p.76]; [38].

The composition of AG vary significantly and although the high methane content makes it desirable for generating power, the heat content of a gas could be affected by this variation in composition. For example, the heating value of a gas would be decreased by a high mass composition of Nitrogen, or the flame speed is affected by the Hydrogen content in the fuel, which could lead to uneven release of heat in the combustor [1, p.76-77]; [39].

2.6 TERA tool

Ogaji et al., [40] described the emergence and application of the tool called TERA – Techno-economic and Environmental Risk Assessment. TERA is a concept invented at Cranfield University, which was based on studies undertaken in power plant asset management, power plant multi-disciplinary optimisation and impact of power plant design and operation on atmospheric pollution. TERA was developed to provide a methodology to analyse the technological, economic and environmental risks of aircraft engines. The TERA software is integrated with a commercial optimiser (iSIGHT, a product of Engineous Software Ltd) and creates a framework for cycle studies [40].

Although TERA was originally invented for the aerospace field, it is currently being applied to other fields such as industrial and marine gas turbines.

2.6.1 Aviation application

The TERA concept was formulated as a decision-making tool to conceive and analyse gas turbine engines with respect to obtaining minimal global warming effect and minimum cost of ownership in the midst of various legislations on emissions, emission taxation policies, fiscal and Air Traffic Management environments [40]; [41, p. 15-16].

As part of the effort to meet the Advisory Council for Aeronautics Research in Europe (ACARE) goals, the TERA concept has been applied in the European projects – Environmentally Friendly Aero Engine (VITAL) and NEW Aero Engine Core Concepts (NEWAC) to evaluate advanced aircraft engine concepts [41, p.15-16].

Kyprianidis et al., [42] displayed sample results to show how the tool can be utilised to ascertain those gaseous pollutants and flight phases that maximally aid global warming. Colmenares Quintero et al., [43] illustrated an example on how to use the tool to analyse the trade-off between operating costs and environmental requirements of the future aero-engines for short range commercial aircrafts [41, p.17]. Figure 2-7 shows the TERA scheme for aviation application.

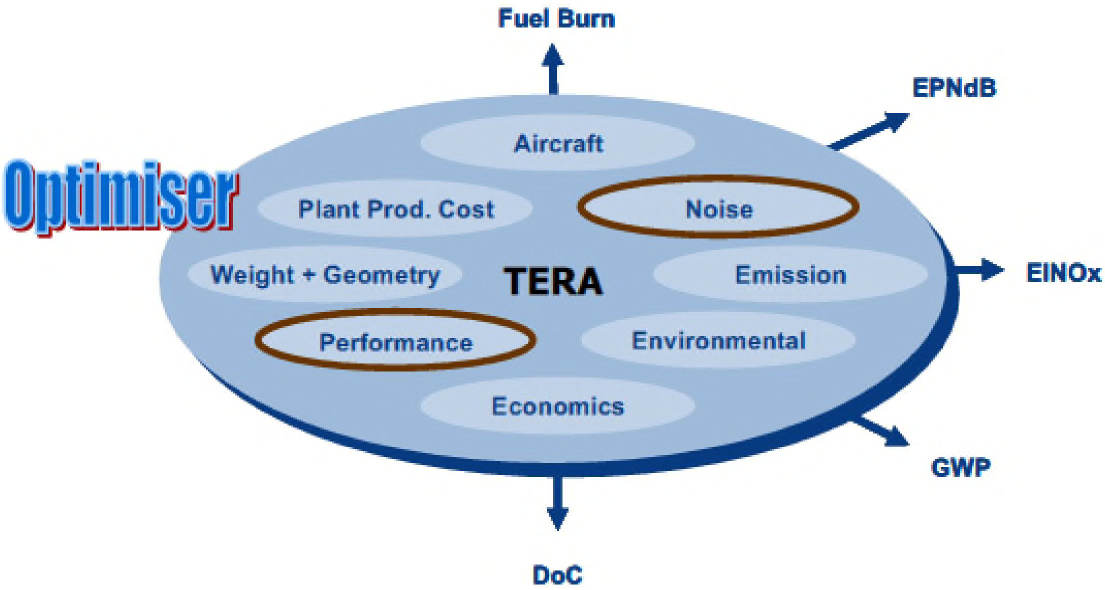


Figure 2-7: TERA scheme for Aviation [40, p.4]

2.6.2 Marine application

As a result of the AMEPS (Advanced Marine Electric Propulsion Systems) project, a TERA-based computational procedure has been developed for marine gas turbine-based power plants (Figure 2-8) [41, p.17-18]; [44].

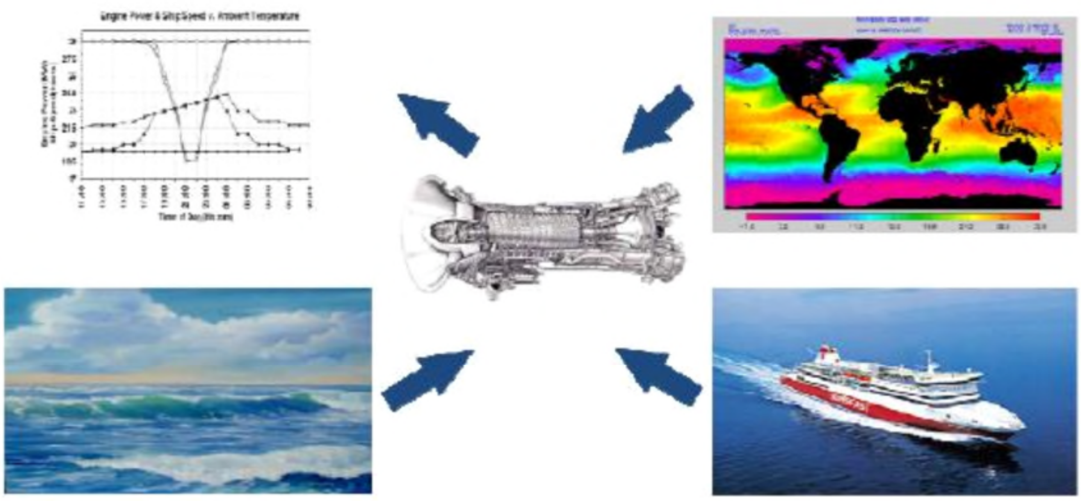


Figure 2-8: TERA for Marine Application [41, p.18]; [44]

Doulgeris et al., [45] developed a computational method for marine propulsion systems comprising various numerical models which simulate the life cycle operation of marine gas turbines installed on marine vessels. The authors also generated stochastic estimates of the power plant's life cycle net present cost. They illustrated this by carrying out TERA simulation of a 25MW marine gas turbine powering a RoPax fast ferry in an integrated full electric propulsion system [45].

2.6.3 Industrial application

Although TERA was initially conceived for aero gas turbine applications, research interests have also broadened to include industrial gas turbine engines. Gayraud [46]; [47]; [48] observed challenges encountered in gas turbine selection for power generation and proffered solutions using techno-economic assessments. His subsequent research [47]; [48] of more complicated systems helped him to provide the basis for a decision support system for combined cycle systems. Mucino [49] also developed techno-economic performance simulation and diagnostics computational system for the operations optimisation and risk management of a combined cycle gas turbine (CCGT) power station by applying TERA and using same route as Gayraud [41, p.18].

The cogeneration field is not left out in the fields that have experienced the successful application of the TERA tool [41, p.19]. TERA for LNG applications is another product of the Industrial version of TERA and its objective is to choose the optimum engines in terms of performance, emissions, economic investment, maintainability and reliability [50, p.18].

2.7 Selection of study engines

Four study engines were selected; designated as AD43, IC100, RH296, and SS296. These engines have been selected to represent a proper mix in gas turbine engine technology level and their wide industrial usage.

2.7.1 AD43 gas turbine

The AD43 gas turbine is a simple-cycle, two-shaft, high performance gas turbine engine. It is inspired from the GE LM6000 engine. It has modifications and additions designed to make it more fit for marine propulsion, marine power and industrial power generation use. These additional features include an expanded turbine section which converts thrust into shaft power, supports and struts for mounting on a steel or concrete deck, and upgraded controls packages for generating power [51].

2.7.1.1 Design & development

The AD43 gas turbine engine produces 43.4MW of power from either end of its low-pressure rotor system, which rotates at 3,600rpm. It has a twin spool configuration with the low pressure turbine operating at an electrical frequency of 60Hz, this helps it avoid the need for a conventional power turbine. It is designed to operate with natural gas [51].

2.7.1.2 Applications of AD43 engine

The AD43 gas turbine engine has proved its usefulness in many sectors. Some of its applications include power generation for combined cycle and peak power, combined heat and power for industrial and independent power producers. Typical users of the AD43 gas turbine engine are hospitals, airports, pulp and paper plants, cement plants, mining plants, gas pipelines, refineries, gas production, utilities, cruise ships and fast ferries [51].

2.7.2 IC100 gas turbine engine

The IC100 gas turbine is inspired from the GE LMS100 gas turbine engine. It has a thermal efficiency of about 0.44 and its power output is about 100.2MW [52]. It’s intercooling system results in higher pressure ratio and increased mass flow [53].

2.7.2.1 Components of the IC100 gas turbine engine

The IC100 gas turbine is an intercooled gas turbine engine. It has an intercooler, a low pressure compressor and a power turbine as part of its components. Its supercore is made up of a high pressure compressor, a burner, a high pressure turbine and an intermediate pressure turbine [53].

2.7.2.2 Applications of the IC100 gas turbine

The IC100 has various applications as it provides different solutions to various industries [54]:

- Utilities – peak power, combined cycle, distributed generation, grid stability
- Oil and Gas – mechanical drive, power generation
- Offshore power generation
- Industrial – combine heat and power
- Mobile power – emergency power, peak demand, mining, oil and gas applications
- Marine – power and propulsion

2.7.3 SS296 gas turbine engine

The SS296 gas turbine is inspired from the Siemens SGT6-8000H gas turbine engine. It is an engine model of high performance, efficiency and flexibility. It is a single-spool engine of 296MW power output, 40% efficiency and pressure ratio of 19.5. Due to its flexibility, it could be easily integrated in single-spool or multi-spool combined cycle plants [55, p.3-4].

2.7.3.1 Components of the SS296 gas turbine engine

The key features of the SS296 gas turbine engine are found in its rotor, compressor, bearings, turbine and combustor [55, p.4-5].

The rotor of this engine has features such as hirth serration, internal cooling air passages and central tie rod giving this engine the capability of fast (cold) start and hot restart [55, p.4-5].

The compressor has 4 stages of quick acting variable pitch guide vanes (VGV), which enables it to have better efficiency at part load and high load transients. The ability of replacing its rotating blades without rotor destack is an advantageous feature [55, p.4-5].

The bearings of this engine also have some good features. The hydraulic clearance has been optimised for the purpose of minimising clearance losses and the active clearance control using hydraulic clearance optimisation helps minimise deterioration in the clearances of the bearing [55, p.4-5].

The turbine has an internally air-cooled turbine section which provides the engine with high cycling ability. Its 3-dimensional 4 stage turbine is made with advanced materials and thermal barrier coating. Another good feature of this engine is the ability of replacing all of its turbine blades and vanes without lifting the rotor. The combustion system is the advanced can annular [55, p.4-5].

2.7.3.2 Applications of the SS296 gas turbine

The SS296 engine is a robust and flexible heavy-duty engine, manufactured for both simple and combined cycle power plants. And is suitable for peak, medium, or base load duty as well as cogeneration applications [55, p.4-5].

2.7.4 RH296 gas turbine engine

The RH296 gas turbine is inspired from the Alstom GT-26 gas turbine engine. It is a reheat gas turbine system with thermal efficiency of 0.396 and power output of 296MW [56]; [57]; [58, p.33]. Four features make this gas turbine engine desirable; Sequential Combustion Design, Industry-leading Burners, Welded Rotors and High Power Density. Its sequential combustion design helps it to provide increasing efficiency and power output without significantly increasing environmental emissions. Its sequential combustion concept also gives rise to a gas turbine system with very high power density making smaller blade dimensions possible. Its industry-leading burners help it to achieve low NO_X, its welded rotors helps to minimise stress cracking, thereby helping its maintenance process [59].

2.7.4.1 Components of the RH296 gas turbine

The gas generator of the RH296 gas turbine comprises of the compressor, an annular EV combustor, the high pressure turbine, an annular SEV combustor and the low pressure turbine. When fuel is injected into the two combustion systems in series, increased power output and thermal efficiency are achieved without significantly increasing the emissions and this can occur at both full and part load settings. This is possible because the firing temperature in the first combustor can be kept relatively low whereas the second combustor does not make a significant addition to the volume of engine NO_X emissions [59].

2.7.4.2 Applications of the RH296 gas turbine

The RH296 gas turbine engine finds application in many industries; such as simple-cycle, combined-cycle and co-generation applications [60]. This engine is also useful in applications that need repowering [61].

2.8 Engine performance simulations and engine emissions prediction

2.8.1 TURBOMATCH: Gas turbine performance simulation code

The performance analysis of gas turbine engines can be modelled using TURBOMATCH software; a Cranfield University in-house FORTRAN-based code for simulating both design point and off-design engine operating conditions. It can also be used in simulating the transient performance of gas turbine engines. In design point condition, the Turbomatch software gives engine performance and size data; whereas in off-design point mode, engine performance is estimated for various throttle setting (rotational speed, combustor exit temperature otherwise known as turbine entry temperature (TET), or fuel flow). The performance simulation of the engine at transient states is done by adjusting the fuel flow with the preferred rotational speed or time [62, p.3].

A Turbomatch engine model is built in a modular manner by employing various pre-programmed units called Bricks. The majority of the Bricks correspond to specific engine components, for example, INTAKE, COMPRE (compressor), BURNER (combustor), TURBIN (turbine), NOZCON (convergent nozzle). There are however, also Bricks for arithmetical operations (ARITHY) and the final calculation of the performance (PERFOR) when all the engine component processes have been calculated. Furthermore, there are bricks to produce additional output, either as Files (PLOTBD, PLOTSV) or as additional screen information (OUTPBD, OUTPSV) can also be used [62, p.5].

More importantly, the gas state at the inlet and outlet to all component bricks are expressed by a number of quantities known as Station Vectors. These gas states help in describing the thermodynamic processes that occur within the component. Each Station Vector is made up of the following nine quantities – fuel-air ratio, mass flow, static pressure, total pressure, static temperature, total temperature, velocity, area, water/air mass, water phase [62]; [63, p.24]; [64]; [65].

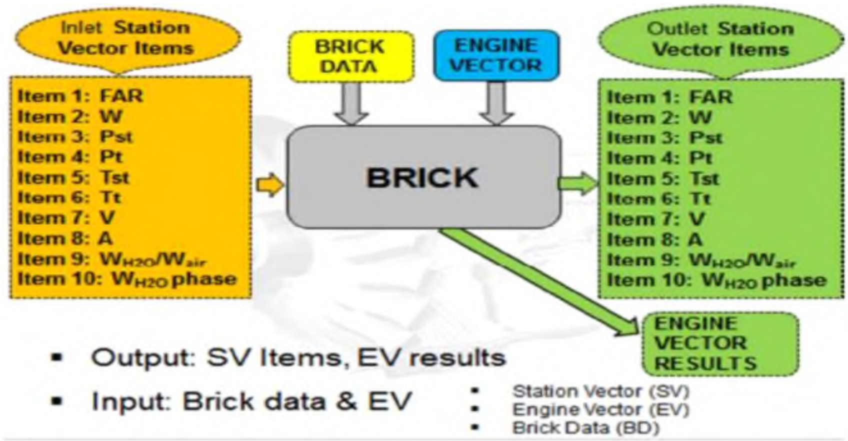


Figure 2-9: Brick Input / Output [62, p.6]

2.8.2 Design point and off design point Performance of gas turbines

The Design Point of a gas turbine engine is the particular point in the operating range of the engine when it is running at the particular speed, pressure ratio and mass flow for which the engine components where designed [66]. In determining the design point of an engine, the mass flow, pressure ratio and TET that result in an overall optimum thermal efficiency are usually determined from preliminary cycle calculations. After this has been done, then other appropriate design parameters of the gas turbine system may be allotted. The next step is to carry out a detailed design of various engine components; this will help to provide the specific requirements of the complete system when operating at the design point [67]; [68].

Apart from the design point performance of the gas turbine, it is also necessary to determine its general performance over the entire operating range of power output and speed; this is termed Off-Design (OD) performance [64].

2.8.3 Gas turbine emissions

Pollutant emissions generated from combustion processes are now of serious concern, as a result of their effect on health and the environment. The past decade has experienced vast improvements both in regulations for controlling gas turbine emissions and the technologies to be harnessed if the regulations are to be met. At the same time, during this era, fuel consumed by the civil aviation industry has escalated to the point that air transportation is presently seen as one of the world's fastest growing energy-consuming sectors [17, p.359].

Industrial gas turbines have also become strongly established as prime movers in the oil and gas industry, and a variety of new applications in combined cycle power plants and various areas of utility power generation. Due to all these developments, the combustion engineer is under increasing pressure to reduce gas turbine pollutant emissions. The emissions produced by industrial gas turbine engines are CO, NO_X, Unburned hydrocarbons (UHC), CO_2, Particulate matter, SO_X, and Water vapour (H_2O_{vapour}) [17, p.359-360]; [18, p.15-19]; [69].

2.8.4 Hephaestus – Engine emissions prediction code

Hephaestus is a FORTRAN-based code developed at Cranfield University and is adapted for industrial gas turbine engines. It is validated to carry out the engine emissions and environment module of TERA. The code simulates a single annular combustor, and introduces a technology factor for the calibration of the amounts of engine emissions to standards that apply to various technology combustors. The model has the ability of simulating combustion of various fuels, such as: natural gas, Jet-A, blended jatropha-jet A, and biofuels. Applying the Dry Low Emission (DLE) principle, the main input parameters to the code are: ambient temperature, ambient altitude, ambient relative humidity, air total pressure at combustor inlet, air total temperature at combustor inlet, total air mass flow rate, flame front air mass flow rate fraction, primary air mass flow rate fraction, intermediate air mass rate flow fraction, dilution air mass flow rate fraction, fuel mass flow rate, and fuel total temperature [42]; [63, p.27]; [70].

The scheme uses physics-based approach of the Stirred-reactors strategy for the estimation of emissions because this method combines some required features of both empirical correlations approach and computational fluid dynamics (CFD) calculations. The model employs three concepts of Stirred-reactors strategies; perfectly-stirred reactors, series of perfectly-stirred reactors, and partially-stirred reactors [63, p.27]; [71].

The scheme calculates the emission indices of the various gaseous products at various power settings and ambient temperatures, and the total quantity of each emission. These products of combustion are NO_X, CO, UHC, CO_2, and H_2O_{vapour} [42]; [63, p.27]; [70].

2.9 The use of Genetic Algorithm in optimisation

Optimisation is the act of making a process or design function as effectively as possible, thereby yielding the optimum benefit. In most occasions, optimisation is based on minimising or maximising a function known as the fitness function, or objective function, subject to some constraints applied on the variables of the function [72, p.145].

Genetic Algorithms (GAs) are search algorithms prompted by the natural selection and evolution theory proposed by Charles Darwin [73, p.102]. The GAs can also be said to be a set of search and optimisation methods appropriate in finding the solutions to complex problems. They are specifically suited to getting the optimal solutions to non-deterministic polynomial-time hard problems (complex problems whose solutions cannot usually be attained analytically) [74].

2.9.1 Areas of applications of GAs

GAs have been applied to solve problems in many fields of human endeavour such as; automatic programming, machine learning, economics and finance, immune systems, ecology, population genetics, evolution and learning, social systems, engineering, image processing, networking and communication, geometry and physics, data mining and data analysis, scheduling, chemistry. [75, p.15-16]; [76, p.124]; [77, p.142-143]. The list of applications is growing.

2.9.2 Applications of GAs to turbomachinery

GAs have been applied in many fields of human endeavour, however, this section focusses on the applications of genetic algorithms to turbomachinery.

Osama Lotfi [78] applied genetic algorithms methods for the optimisation of the aerodynamic shape of a 2-dimensional axial fan cascade. His approach began with a Navier-Stokes flow solver (which included a grid generator to give the right computational meshes). After which he developed specific interfaces to connect with a GA optimisation code written in FORTRAN programming language, this was done in an automated design loop [75, p.125].

Fujita et al., [79] applied GA based optimisation to get the solution to the planning problem of energy plant configurations. In this planning problem, the plant configuration, i.e, the types, models, and number of equipment, are estimated in order to meet the needed energy demand and to reduce the costs of plant facilities and input energy to the minimum.

Oyama et al., [80]; [81] made effort to redesign a 4-stage compressor by applying a multi-objective evolutionary algorithm for the maximisation of the overall isentropic efficiency and the total pressure ratio. The design parameters considered were the flow angles and solidities at the stator trailing edges, and the total pressure and solidities at the rotor trailing edges. The resulting design outperformed the original with a theoretical one percent increase in efficiency while keeping the pressure ratio constant [75, p.124].

Oksuz et al., [82] employed GA to evaluate the optimal aerodynamic performance of a turbine cascade. He did this by using a boundary layer coupled Euler algorithm and a GA which were connected within an automated design loop [83], with the tangential blade force as the basis for the multi-parameter objective function. The Sanz subcritical cascade was chosen to be the baseline turbine section. For a specified blade chord and inlet Mach number, the flow inlet and exit angles, the blade pitch and the blade thickness are optimised by a genetic algorithm model that is robust. The author claims that the highest tangential force is realised for a higher flow turning, a thicker cascade and a wider pitch.

Knight et al., [84] used GA to carry out economic optimisation of gas turbine power generation, the results show that they achieved remarkable financial benefits. Although, the economic benefits are dependent on the exact application, that is, the plant configuration, the economic input data for plant operation, and the reliability of the simulations applied for modelling [75, p.126].

2.10 Economic appraisal methods employed in projects

2.10.1 Examples of economic appraisal methods

Before the commencement of a project, it is necessary to carry out a feasibility study on the viability of that project. Different economic appraisal methods are employed. For example, net present value (NPV), internal rate of return (IRR), discounted pay-back period (DPP), and cost of electricity (COE) [85, p.192-193].

In this research, the NPV will be used as the appraisal method for exploring the viability of the economic utilisation of associated gas.

2.10.2 Net present value (NPV)

The net present value (NPV) of a project or a business is the difference between the values of the cash inflow and cash outflow occurring over the time of the project or business. The cash inflow and cash outflow are sometimes referred to as the benefit and cost cash flow streams respectively. The NPV is evaluated by dividing the expected income (net cash flow) of a project in each year by a term which is equal to 1 plus the discount rate raised to a power equal to the year considered in the project as illustrated by Equation **2-1**.

$$\boldsymbol{NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_o} \qquad \textbf{2-1}$$

C_t is the net cash-flow for the year considered in the project, C_o is the initial cost of the project which is also the loan taken, r is the discount rate assumed, and t is the project year under consideration [76]; [85, p.193]; [86]; [87].

2.11 Research Gap and Contribution to Knowledge

After doing a detailed literature review on the various elements relating to the economic utilisation of associated gas using gas turbines, the research gap as evident in public domain is the lack of literature that shows the effect of gas turbine degradation on engine units' divestment time. This is key for investors who would want to invest in the economic utilisation of AG using gas turbines.

Therefore, the main contribution to knowledge in this research is on exploring the effect of gas turbine degradation on engine units' divestment time.

3 RESEARCH METHODOLOGY

3.1 Methodology and Tools

The methodologies adopted for this research are presented in Figure 3-1, Figure 3-2 and Figure 3-3.

This research is about optimising the economic returns of different fleets of gas turbine engines for power generation and also to investigate the effect of gas turbine degradation on the divestment time of the redundant engines. The TERA and optimisation models from this research will serve as decision-making guide for the Nigerian government and the likes who want to invest in the economic use of associated gas for power generation using gas turbine engines.

The different engine types selected for this research and the reasons for their selection have been explained in section 2.7 of this research.

The engines used associated gas as the fuel. The life span of this project is 20 years. The fuel availability for the period of the project is shown in Figure 2-3 and Appendix A. Nigeria is the case study for this research.

For the purpose of verifying the accuracy of the results that were obtained from the optimised fleets, a baseline analysis for the same results expected from the optimiser. Because of the need of comparing the results of the baseline and the optimised fleet (of the same engine type), the same techno-economic and environmental risk assessment (TERA) approaches were adopted for the baseline and the optimised fleets. However, the methodology adopted for getting the fleet composition and best divestment time for the units of engines in the baseline fleet varies from that which was adopted for the optimised fleets. The fleet composition and engine units' divestment time for the baseline fleet are gotten by critical human judgement, while that for the optimised fleets are given by the optimiser.

3.1.1 Methodology adopted for the baseline fleet

For the baseline scenario, the fleet made up of units of AD43 engine would be used. The aim is to get the fleet composition that gives the maximum power (energy) and the best economic return. Also, to determine the best divestment time for the redundant units of engines in the fleet.

As shown in Figure 3-1, after choosing the initial number of engines in the fleet, the next action is to operate the engines using the quantity of fuel available for each year of the project. The performance analysis of the engines were done using TURBOMATCH software; a Cranfield University in-house FORTRAN-based code for simulating both design point and off-design engine operating conditions. The engines in the fleet are assumed to be operating 24 hours daily. The engines are to economically utilise the available fuel (FA) per year of the project.

Having known the fuel requirement for operating the AD43 engine at design point, the sum of the fuel requirements for all the units of engines in the fleet (ΣF) is calculated. The fuel requirement for the last unit of AD43 engine in the fleet will be designated as FL. As the project goes on progressively from one year to the next, the available fuel (FA) gradually decreases. As seen in Figure 3-1, for each year of the project the following conditions will be considered;

- Is $(\sum F - FL) > FA$? (Condition 1)

If a "NO" is the answer to condition 1, a second condition will be considered;

- Is $(\sum F) \leq FA$ or is $(\sum F) > FA$? (Condition 2)

In respect of condition 2, in the case of $(\sum F) \leq FA$, it implies that there is enough fuel to meet the fuel requirements of all the units of engines in the fleet when they are all operated at design point. Whereas, for the case of $(\sum F) > FA$, it implies that there is not enough fuel available to operate all engine units at design point and so the last engine will be operated at part-load.

If a "YES" is the answer to Condition 1, the last unit of engine in the fleet will be divested, it means the available fuel (FA) is no longer enough to meet the fuel need of all the engines in the fleet, even if the last engine in the fleet is operated at part-load condition. The redundant unit of engine is divested and the divestment sale is added into the economic analysis for the fleet as shown in Figure 3-1.

As seen in Figure 3-1, from the resulting fleet composition, an emission prediction is undertaken for the fleet using the Cranfield University emission prediction code – Hephaestus. The annual emission tax from the fleet is calculated using the emission results and the assumed emission tax value. The estimated annual emission tax is added into the economic analysis for the fleet. The power generated by the fleet is sold to the national grid and the revenue from the electricity sold is added into the economic analysis for the fleet. Results from the lifing and maintenance analysis of the fleet is used to calculate the annual operations and maintenance cost, this is also added into the economic analysis for the fleet as seen in Figure 3-1.

It is assumed that the starting capital for this project is gotten through loan taking. The number of staff to attend to the fleets, their annual salaries, and loan repayment are other factors considered in the economic analysis for the fleet.

This economic utilisation of AG described by Figure 3-1 is repeated annually for the entire duration of the project.

The above explanations forms the model used for the baseline fleet. The model gives the maximum power possible from the fleet, the best divestment time and the best economic return from the investment as an NPV, this is based on critical human judgement, not optimised.

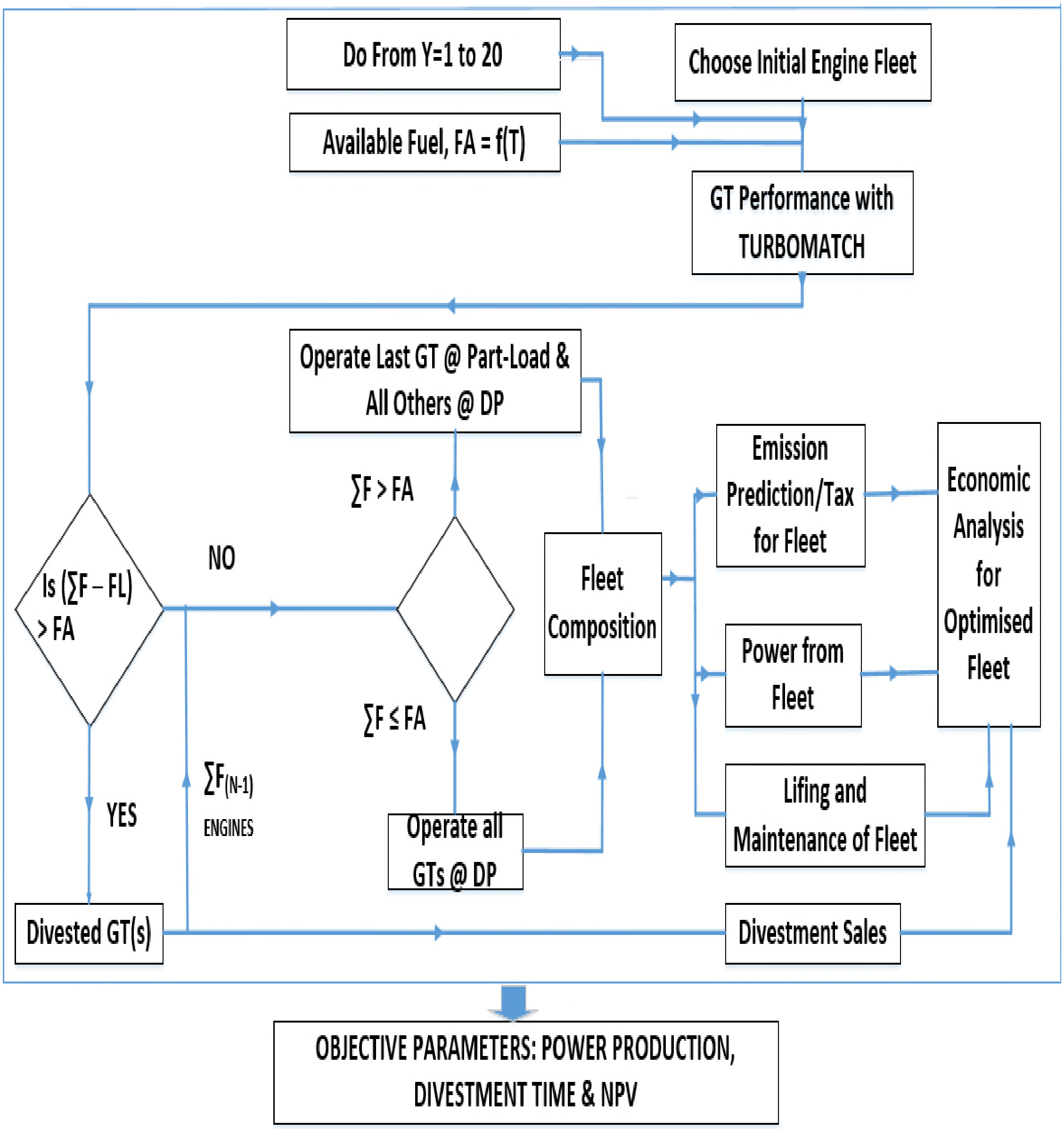


Figure 3-1: TERA Methodology for AG Utilisation (Baseline)

3.1.2 Methodology adopted for the optimised fleets

Figure 3-2 shows the methodology adopted for the optimised fleets. It is almost the same with that of the baseline fleet, except that for the case of the optimised fleets, the fleet composition and the best divestment time are given by the optimiser. Also, the influence of degradation is considered in this case. The optimiser gives the fleet composition that will yield the maximum power, a good economic return from the fleet and also gives the best divestment time for the redundant unit(s) of engines in the fleet. A key element in this research is the impact of degradation on the economic returns of the optimised fleets. The results of the optimised best divestment time for the units of engines in the degraded fleets will show the effect of gas turbine degradation on divestment time, this is the primary contribution to knowledge in this research.

Figure 3-2 shows how the TERA framework links with the optimisation model of the research. Figure 3-3 shows the GA optimisation flow chart employed in this research. As seen from Figure 3-1 and Figure 3-2, the model adopted for the baseline and optimised fleets are almost the same, their TERA approaches are exactly the same.

The aim of the optimisation exercise is to get the fleet composition that gives the maximum power and a good economic return (NPV). Another primary aim of the exercise is to optimise the best divestment time for the redundant engine units in the various fleets. The design variables for the optimisation are the initial fleet of engines and their TETs, whereas, the constraint for the optimisation is the fuel availability. The optimisation is done using GA in Matlab code with the TERA module acting as an external solver as shown in Figure 3-3.

As seen in Figure 3-3; selection, crossover and mutation are GA operators, they enable the algorithm to find the best solution to the optimisation problem within the search domain specified. Section 4-4 to 4-6 of this research report describes the optimisation settings in a more detailed manner, knowledge of these sections is recommended for full understanding of Figure 3-3. It should be noted that the performance data used by the optimiser are gotten from Turbomatch. This data served as the search domain (database) for the GA optimiser.

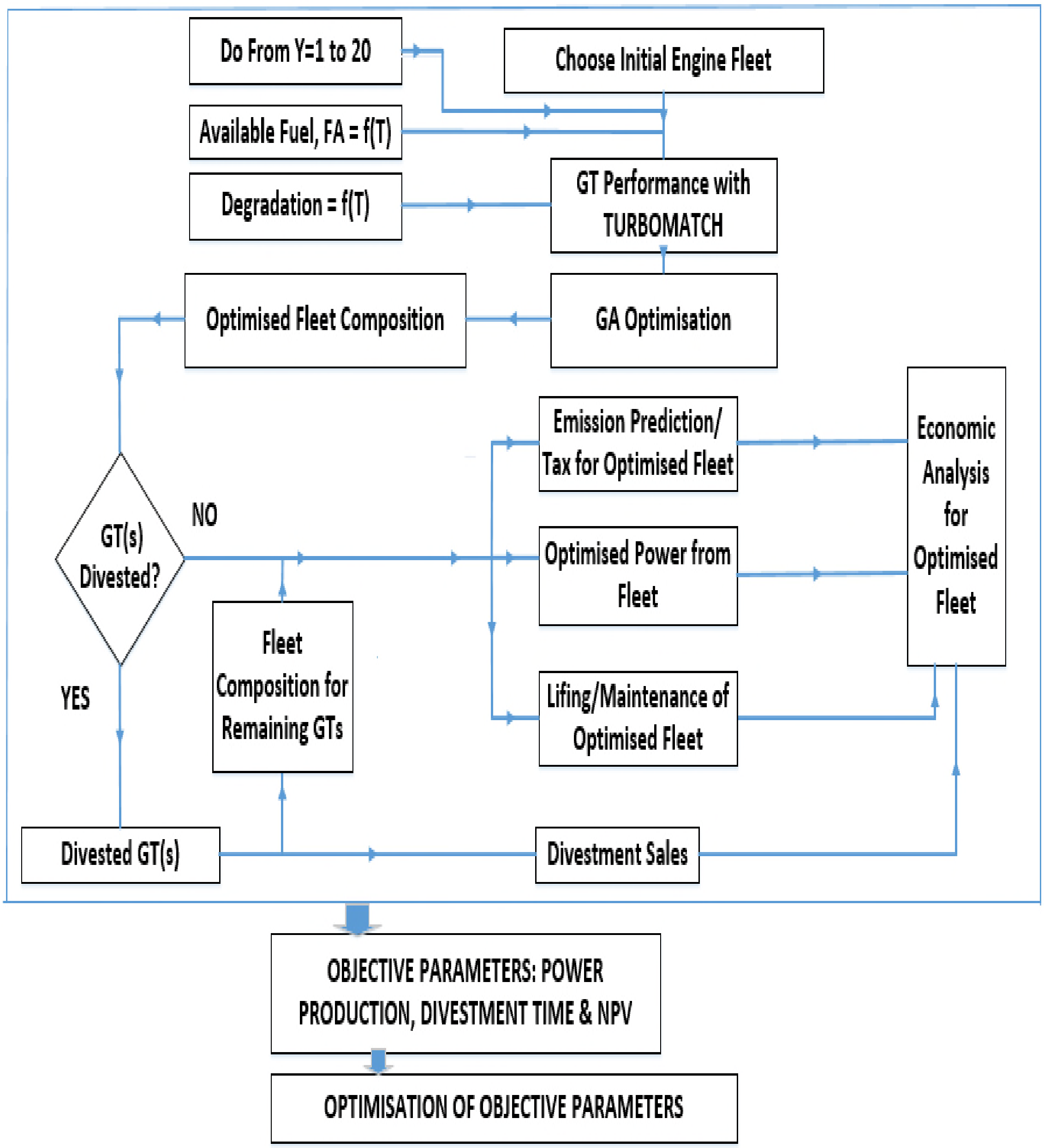


Figure 3-2: TERA & Optimisation Methodologies for AG Utilisation

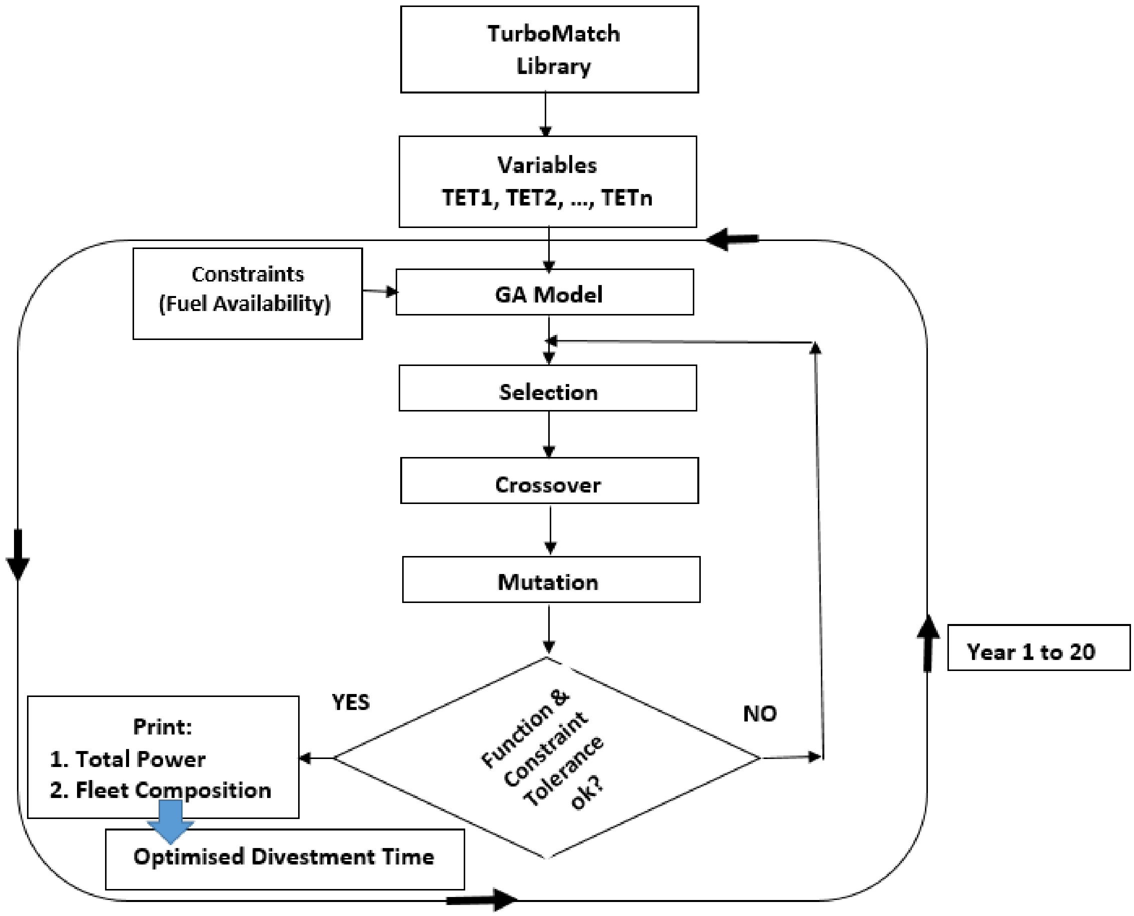


Figure 3-3: GA Optimisation Flow chart

3.2 Fuel resources and AG availability

Figure 2-3 shows the fuel availability for the project, which is also the constraint to be observed by the optimiser while trying to maximise the power production, the economic returns from the fleet and to optimise the best divestment time for the redundant units of engines. The graph shows the fuel (AG) available for the project for the period of 20 years, the decline is as a result of the gradual depletion in natural gas which is the source of the AG.

The AG data shown in Figure 2-3 was converted to the unit for gas turbine engine fuel flow (Kg/s), this gives rise to Figure 3-4, see Appendix A.2.

Clean natural gas was used in the actual performance simulations instead of AG, this was done on the basis of observations made in the simulated performance results when these two fuels were used for the same modelled engines. For most of the simulated performance parameters, there was no significant difference between the results for both fuels [27, p.60-71; 88, p.142, 144]. Also, AG of 3 varying degree of gas quality were used as fuel for different engines, results show that were no significant changes in the lower heating values (LHV) of these 3 fuels, the same observation was made for the power output and efficiencies of the engines used [1, p.49, 50]. Finally, implementing AG as a fuel in Turbomatch within the duration of this research is uncertain.

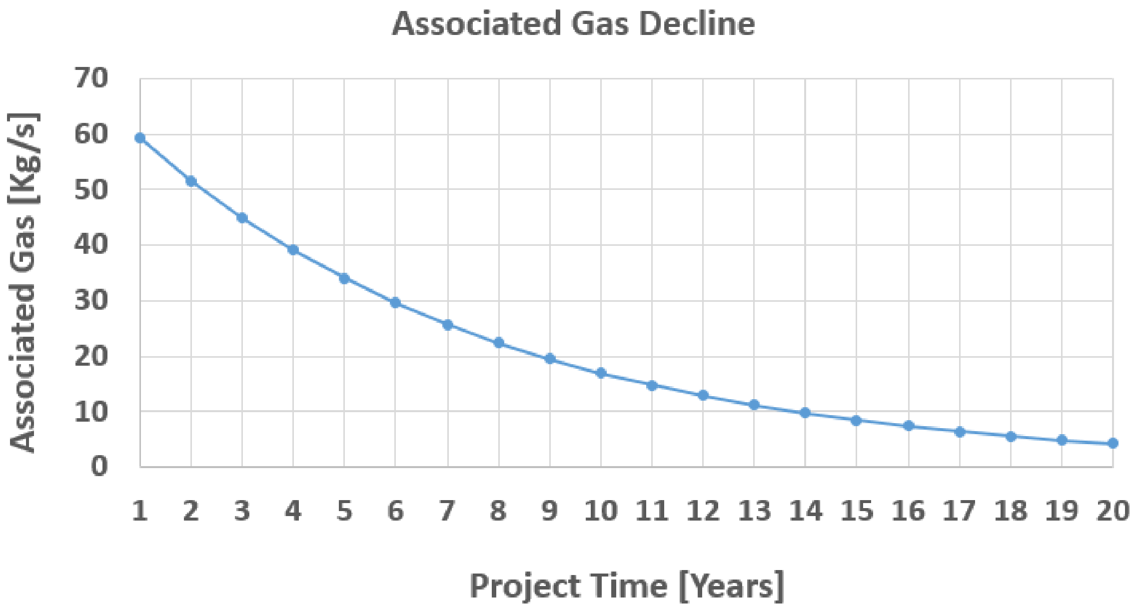


Figure 3-4: AG Availability for the Project (Kg/s)

3.3 Gas turbine engine degradation

Gas turbines exhibit the effects of wear and tear over time. The long duration of this AG utilisation project necessitated the need to consider the effect of degradation on the economic return from the fleets. The effect of degradation on engine divestment time is the key interest in this research.

This research only considered degradation in the compressor of the gas turbine, since this accounts for more than half the degradation that takes place in the gas turbine engine, with compressor fouling assumed as the cause of the degradation. In the performance simulation models used for the degraded engines, different levels of degradation were implanted for the compressor pressure ratio, non-dimensional mass flow and efficiency. This is because the degradation in the compressor affects the compressor pressure ratio, flow capacity and efficiency [1, p.25]. The effects of different rates of degradation on the project are considered. These different rates of degradation are designated as optimistic (OPT) (slow), medium (MED) and pessimistic (PES) (fast) degradation. Sub-section 4.5.2 gives a more detailed explanation on the degraded fleets, the engine simulation model used for the degraded engines and the optimisation database for the degraded engines.

3.4 Schematics, cycle parameters and component efficiencies of the study engines

3.4.1 Schematics, cycle parameters and component efficiencies for the AD43 engine

Shown in Figure 3-5 is the schematics and cycle parameters of the AD43 engine. In the Turbomatch model used for this engine, 0.85 was used as the isentropic efficiencies for both the low pressure compressor (LPC) and the high pressure compressor (HPC), whereas, 0.9 was used as the isentropic efficiency for both the high pressure turbine (HPT) and the low pressure turbine (LPT). The assumed combustion efficiency used is 0.999.

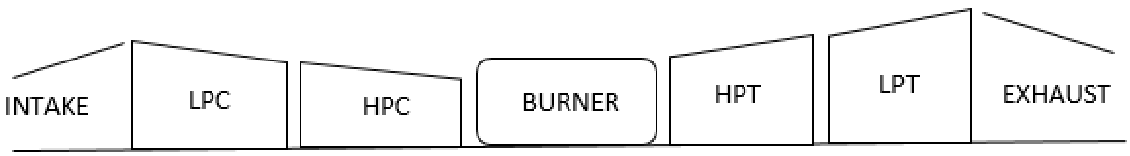


Figure 3-5: Schematics of the AD43 engine

3.4.2 Schematics, cycle parameters and component efficiencies for the SS296 engine

Figure 3-6 shows the schematics and cycle parameters of the SS296 engine. The assumed isentropic efficiency of the compressor (Comp) is 0.88, that of the turbine is 0.9, whereas, the combustion efficiency was assumed to be 0.999.

Figure 3-6: Schematics of the SS296 engine

3.4.3 Schematics, cycle parameters and component efficiencies for the IC100 engine

Shown in Figure 3-7 is the schematics and cycle parameters of the IC100 engine. 0.86 was used as the isentropic efficiencies for both the LPC and the HPC, whereas, 0.9 was used as the isentropic efficiency for the HPT, intermediate pressure turbine (IPT) and the power turbine (PT). The assumed combustion efficiency used is 0.999. “IC” refers to the intercooler.

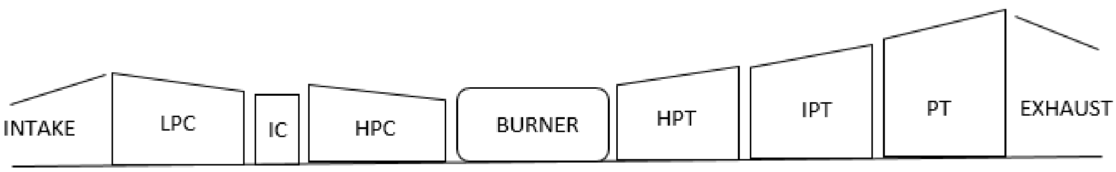


Figure 3-7: Schematics of the IC100 engine

3.4.4 Schematics, cycle parameters and component efficiencies for the RH296 engine

Figure 3-8 shows the schematics and cycle parameters of the RH296 engine. 0.85 was used as the isentropic efficiency for the compressor, whereas, 0.9 was used as the isentropic efficiency for both the HPT and the LPT. The assumed combustion efficiency for the two burners is 1.0, this is a wrong assumption, it was observed after the thesis oral examination.

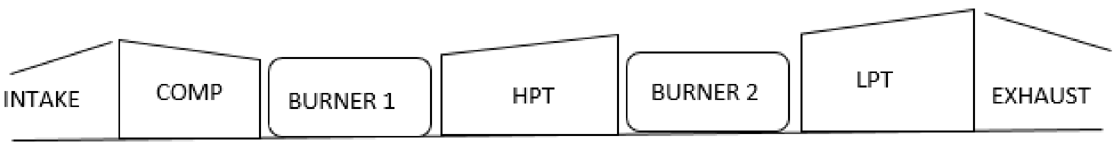


Figure 3-8: Schematics of the RH296 engine

3.4.5 Engine performance modelling

The cycle performance models used (AD43, SS296, RH296 and IC100) for this research were inspired by the commercial gas turbines LM6000, SGT6-8000H, GT26 and LMS100 respectively. The models used are simple models.

The input parameters used in the simulation models were taken from public domain information, others are from reasonable estimations. For the OD conditions, TET was used as the handle for the simulations. The OD simulations aimed to capture the effects on the power output, thermal efficiency and fuel flow, all at constant ambient temperature (288.15K).

The performance simulations were carried out both for clean and degraded modes of the study engines. The assumption is that the fleets are operated in the part of Nigeria that has relatively low temperatures, like Jos, which is located in the North Central region of Nigeria. The TETs, power outputs, fuel flows, and efficiencies data for the range of TET values considered formed the database (search domain) the optimiser worked with. For increased level of model fidelity and results accuracy, future researchers should specify an exhaust Mach number, in conjunction with an exhaust pressure loss to estimate the LPT back-pressure. Also, provisions should be made in the models to ensure sufficient turbomachinery stability at low-power settings to prevent LPT backflow and LPC surge. Conclusively, detailed engine modelling is recommended for future researchers.

3.5 TERA for power generation

This research adopted the Techno-Economic and Environmental Risk Assessment (TERA) framework. This implies that the baseline fleet and all optimised fleets were integrated into the TERA framework. Thus, the performance, the emissions, the creep life/maintenance and the different elements in the economic utilisation of the various fleets were all considered.

For the baseline fleet only the AD43 engine is considered, since this is sufficient for the purpose of comparison with the results from the optimisation.

3.5.1 Engine performance module

In order to achieve the performance module in the TERA framework, design point and off-design simulations have been carried out on each of the study engines.

3.5.1.1 Design point performance data

The design point performance data for the study engines - AD43, IC100, SS296 and RH296 gas turbine engines as derived from Turbomatch performance simulation are shown in Table 3-1 to Table 3-4 below. The variation in some of the parameters especially the exhaust gas temperature and exhaust mass flow are a bit large, this large discrepancies are as a result of the performance modelling approach used in Turbomatch. A more detailed performance modelling approach should be adopted by future researchers. The features of the real engines from which the study engines were inspired are explained in section 2.7.

Table 3-1: Engine Model Specifications (AD43 Engine)

Parameter	LM6000	Engine Model	%Diff.
Exhaust mass flow(Kg/s)	127.0	131.9	3.86
Exhaust temperature (K)	717.2	750.5	4.64
TET (K)	Not available	1550.0	–
Shaft power (MW)	43.4	43.3	0.23
Thermal efficiency (%)	0.41	0.40	2.44
Pressure ratio	29.1	29.1	0
Fuel flow (Kg/s)	Not available	2.3958	–

Source of LM6000 performance data [89]

Table 3-2: Engine Model Specifications (IC100 Engine)

Parameter	LMS100	Engine Model	%Diff.
Exhaust mass flow(Kg/s)	222.0	221.0	0.45
Exhaust temperature (K)	679.2	727.7	7.14
TET (K)	Not available	1630.0	–
Shaft power (MW)	100.2	100.0	0.20
Thermal efficiency	0.44	0.44	0
Pressure ratio	42.0	42.0	0
Fuel flow (Kg/s)	Not available	5.0401	–

Source of LMS100 performance data [52]

Table 3-3: Engine Model Specifications (SS296 Engine)

Parameter	SGT6-8000H	Engine Model	%Diff.
Exhaust mass flow(Kg/s)	640	666.6	4.16
Exhaust temperature (K)	903.2	912.0	0.97
TET (K)	Not available	1700	–
Shaft power (MW)	296	296	0
Thermal efficiency (%)	0.4	0.3921	1.975
Pressure ratio	19.5	19.5	0
Fuel flow (Kg/s)	Not available	16.5794	–

Source of SGT6-8000H performance data [55, p.4]

Table 3-4: Engine Model Specifications (RH296 Engine)

Parameter	GT26	Engine Model	%Diff.
Exhaust mass flow(Kg/s)	644	660.4	2.55
Exhaust temperature (K)		908.8	–
TET (K)	Not available	1543	–
Shaft power (MW)	296	296	0
Thermal efficiency	0.396	0.396	0
Pressure ratio	33.3	33.3	0
Fuel flow (Kg/s)	Not available	16.4153	–

Source of GT26 performance data [56]; [57]; [58, p.33]

3.5.1.2 Off-design performance of the study engines

Figure 3-9 to Figure 3-13 show the off-design behaviour of the AD43 engine. Graphs showing the off-design behaviour of the other engines used in this research can be seen in Appendix I. It should be noted that the exact off-design figures have not been validated, however, their trends have been checked against that of other engines in the public domain [90, p.5, 6; 91, p.203-228; 92, p.4, 5]. Different levels of degradation were implanted for the compressor pressure ratio, non-dimensional mass flow and efficiency, this is because compressor degradation accounts for more than half the degradation that takes place in gas turbines.

Figure 3-9 to Figure 3-11 show the changes in the fuel flow, power output and thermal efficiency of the engine as the TET changes. The results show the right trend as the fuel flow, power output and thermal efficiency increases with increase in the TET. The influence of degradation is also seen in the results, for a specific TET considered; the fuel flow, power output and thermal efficiency reduces with increase in the level of degradation as expected. Figure 3-12 and Figure 3-13 show the off-design behaviours of the LPC and the HPC respectively. The graphs show the changes in the pressure ratio against changes in the corrected mass flow. The engine design point, surge line and running line are also shown.

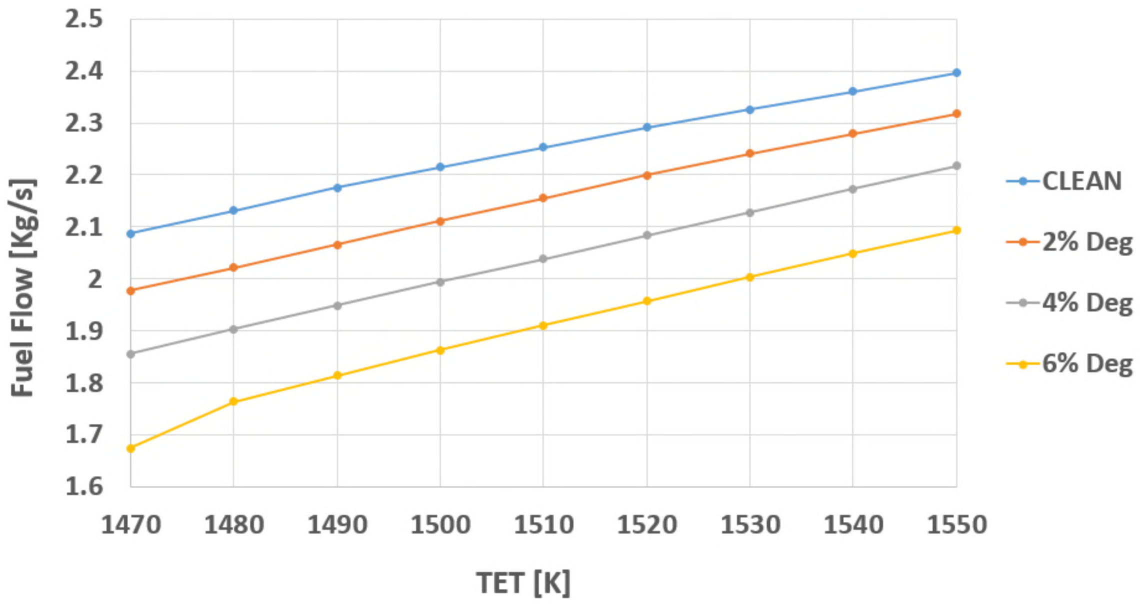


Figure 3-9: TET [K] versus Fuel flow [Kg/s]

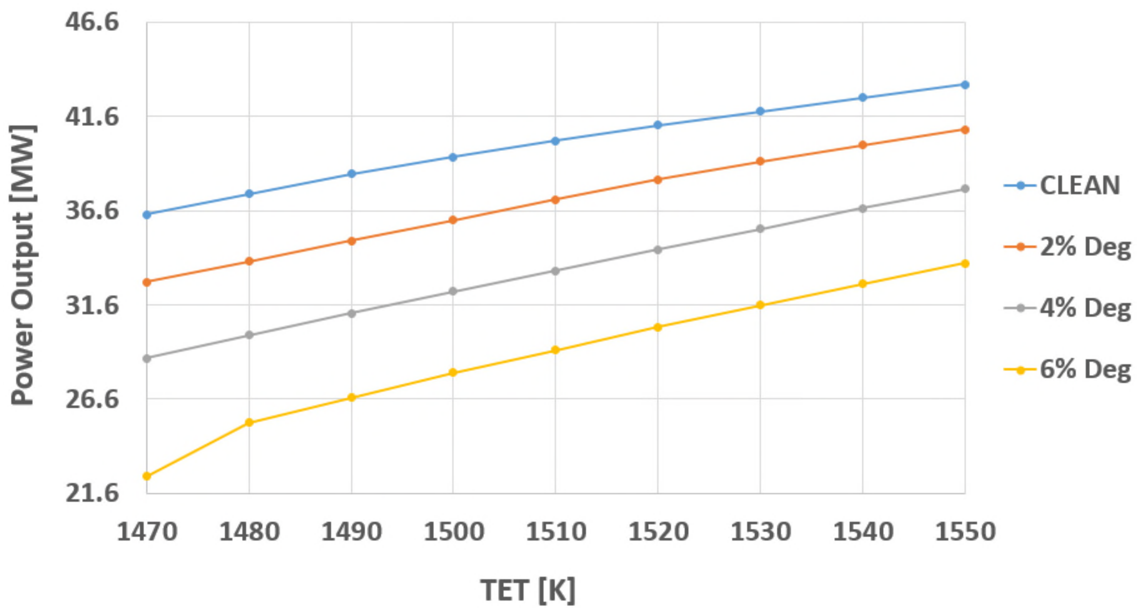


Figure 3-10: TET [K] versus Power output [MW]

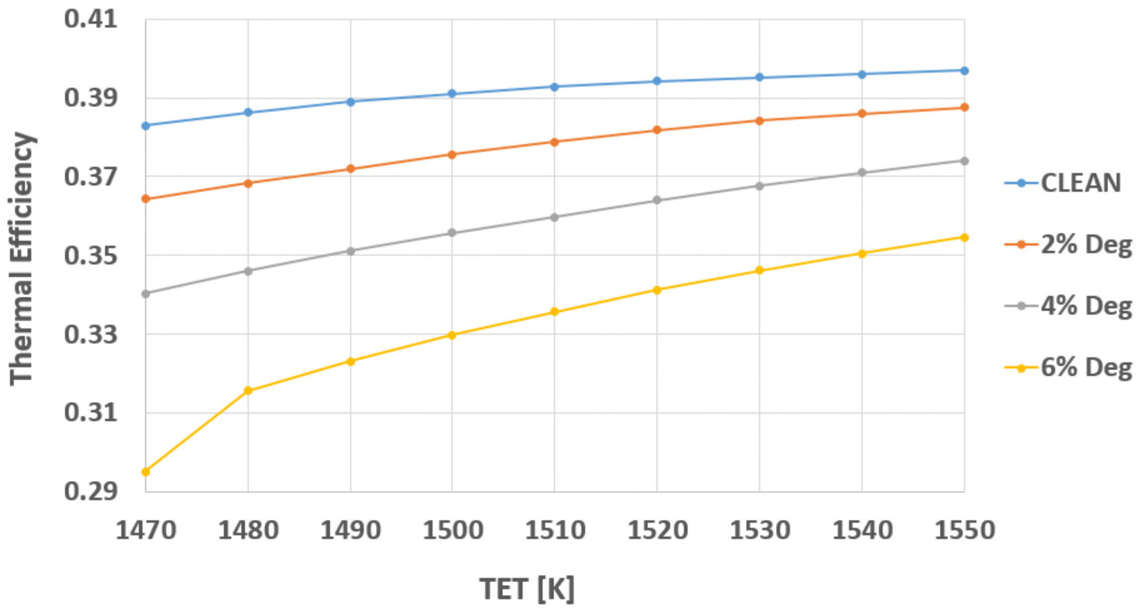


Figure 3-11: TET [K] versus Thermal efficiency

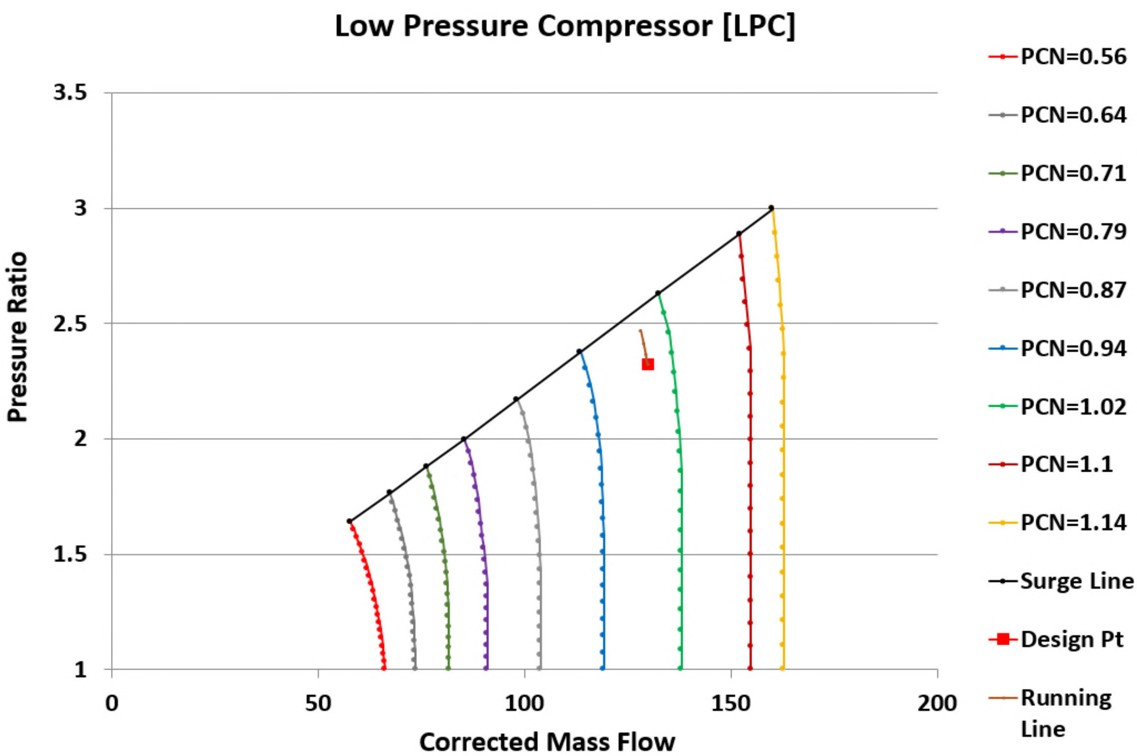


Figure 3-12: LPC Map showing Pressure Ratio versus Corrected Mass Flow

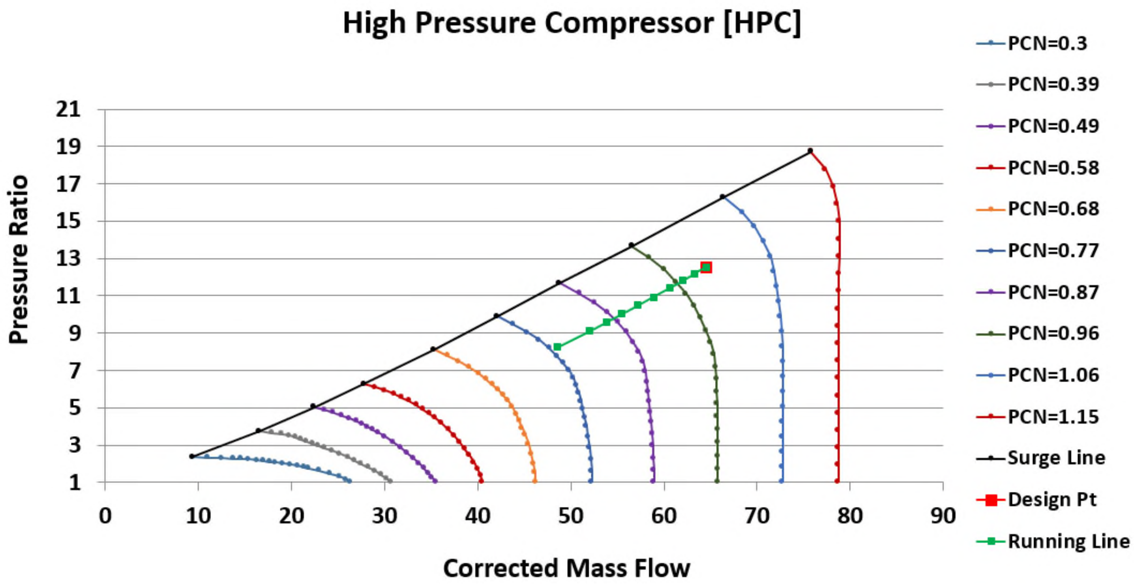


Figure 3-13: HPC Map showing Pressure Ratio versus Corrected Mass Flow

3.5.1.3 AD43 baseline fleet composition

The baseline fleet has a starting number of 25 units of AD43 engines. This number was gotten by dividing the fuel availability at the 1st year of the project (59.3519Kg/s) by the fuel consumption of the engine at design point (2.3958Kg/s). The fuel available at the 1st year can conveniently serve 24 units of the engine running at design point while the remaining fuel will be able to serve 1 more unit of the engine running at a part-load.

The baseline fleet composition is the fleet composition that would probably give the maximum power production from the fleet, based on critical human judgement. Using the principle in Figure 3-1, the annual fleet composition for the AD43 baseline fleet is given in Table 3-5 below.

Table 3-5: Fleet Composition for the Baseline Fleet (AD43 Engine)

YEAR	NUMBER OF AD43 ENGINES RUNNING AT DESIGN POINT TET [1550K]	PART-LOAD TET [K]
1	**24**	**1416.5**
2	**21**	**1354.1**
3	**18**	**1405.5**
4	**16**	**-**
5	**14**	**-**
6	**12**	**-**
7	**10**	**1401.2**
8	**9**	**-**
9	**8**	**-**
10	**7**	**-**
11	**6**	**-**
12	**5**	**-**
13	**4**	**1369**
14	**4**	**-**
15	**3**	**1352**
16	**3**	**-**
17	**2**	**1371.7**
18	**2**	**-**
19	**2**	**-**
20	**1**	**1408.5**

Table 3-5 shows the number of units of engines that were operated at design point and the part-load TET for the entire project time. As seen from the table, the starting fleet had 25 units of engines, out of which 24 units were operated at design point whereas the remaining 1 unit of engine was operated at a part-load of 1416.5K. At the 2nd year of the project, there is reduction in the fuel availability, 21 units of engines were operated at design point, 1 unit of engine was operated at a part-load of 1354.1K and 3 redundant units of engines were divested. The engine units' redundancy was caused by insufficient fuel availability. At the 3rd year, 18 units of engines were operated at design point, 1 unit of engine was operated at a part-load of 1405.5K and 3 redundant units of engines were divested. Redundant engine units' divestment continued over the years of the project. At the 20th year of the project, only 2 units of engines were left in the fleet, out of which 1 was operated at design point while the remaining 1 unit was operated at part-load of 1408.5K. These 2 remaining units of engines were also divested at the end of the project. The part-load TET(s) were determined by considering the quantity of fuel remaining, and then interpolating from the performance simulation results from Turbomatch. The Matlab code used in interpolating the performance data gives the TET, power and efficiency values corresponding to the quantity of fuel remaining. It should be noted that the fuel flow limit for divesting an engine when required to run at part-load is 1.26kg/s. This corresponds to an efficiency of about 0.21. This efficiency is already very low, an engine with efficiency below this is divested.

3.5.1.4 Gas turbine divestment sequence and time

There is a decline in associated gas availability as seen in Figure 3-4. Over time, the fuel available for the project will not be sufficient to meet the fuel requirement of all the units of engines in the fleet, as a result some units of engines will be left redundant. There is therefore need to divest the units of engines that are redundant.

For this baseline fleet, all the units of engines in the fleet were expected to be operated at design point using the fuel available for the various years, this is because the goal is to maximise power production and economic returns (NPV). However, in many of the years of the project, the fuel available could only serve some units of engines operated at design point and the remaining 1 unit of engine been operated at a part-load condition. When the fuel available cannot serve the fuel requirement of the remaining 1 unit of engine even at a part-load condition, this engine becomes redundant and the best option would be to divest it.

Figure 3-14 and Figure 3-15 show the number of units of the baseline fleet divested and their respective divestment time.

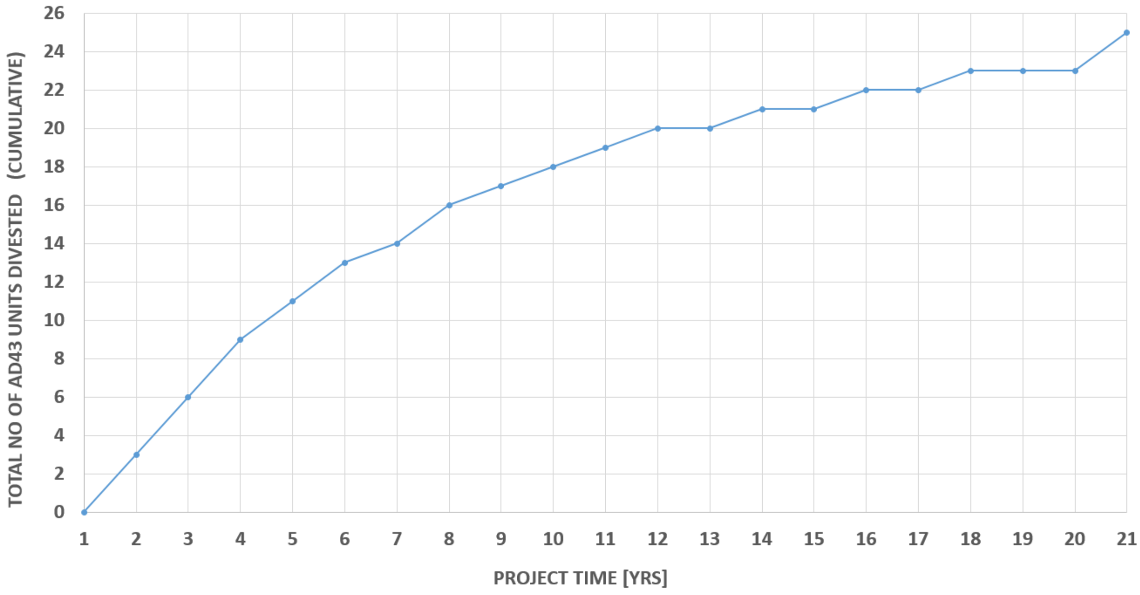


Figure 3-14: Total Number of Baseline Fleet Engine Units Divested (Cumulative)

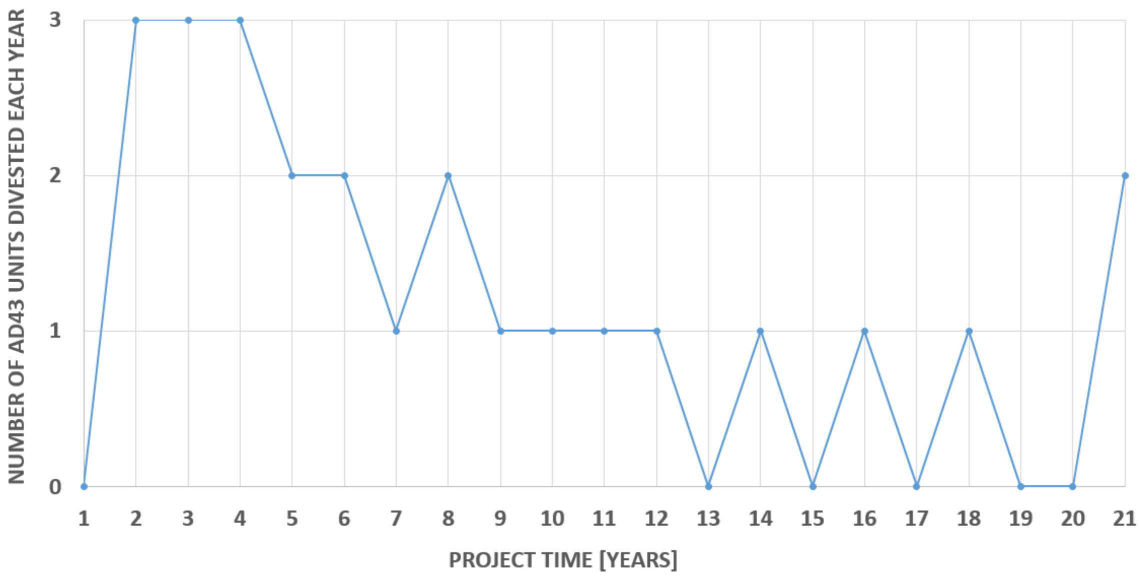


Figure 3-15: Number of Baseline Fleet Engine Units Divested Yearly

3.5.1.5 Total power and energy generated by the baseline fleet

The annual power and energy generated from the fleet are major elements in this economic use of AG model. The annual power and energy generated by the baseline fleet for the entire time of the project are shown in Figure 3-16 and Figure

3-17.The gradual reduction in the power and energy generated from the fleet is as a result of the decline in the fuel available for the project. The data used in plotting Figure 3-16 are the sum of the power output values of the units of engines corresponding to the baseline fleet composition shown in Table 3-5, with power output data from performance simulation of the engine using Turbomatch.

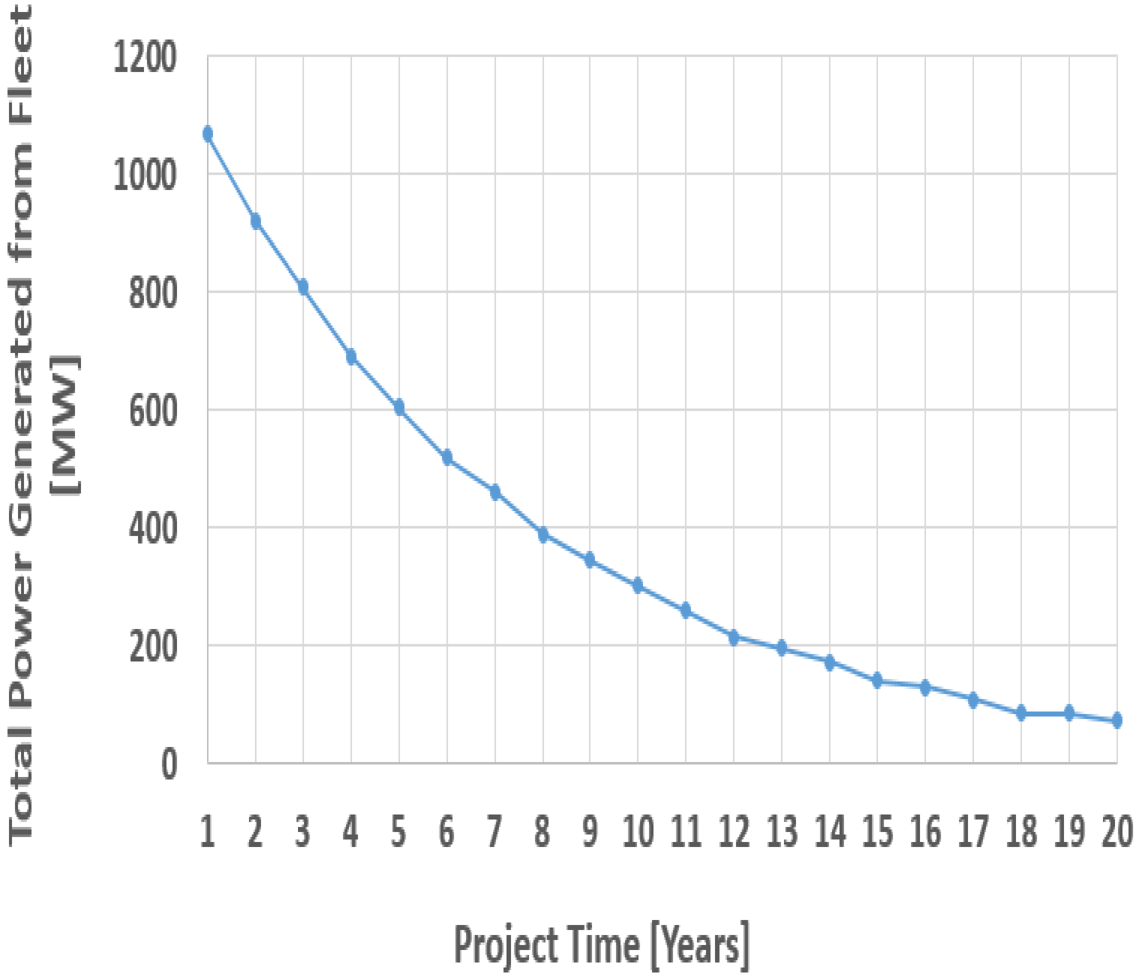


Figure 3-16: Annual Power Generated by the Baseline (AD43) Fleet

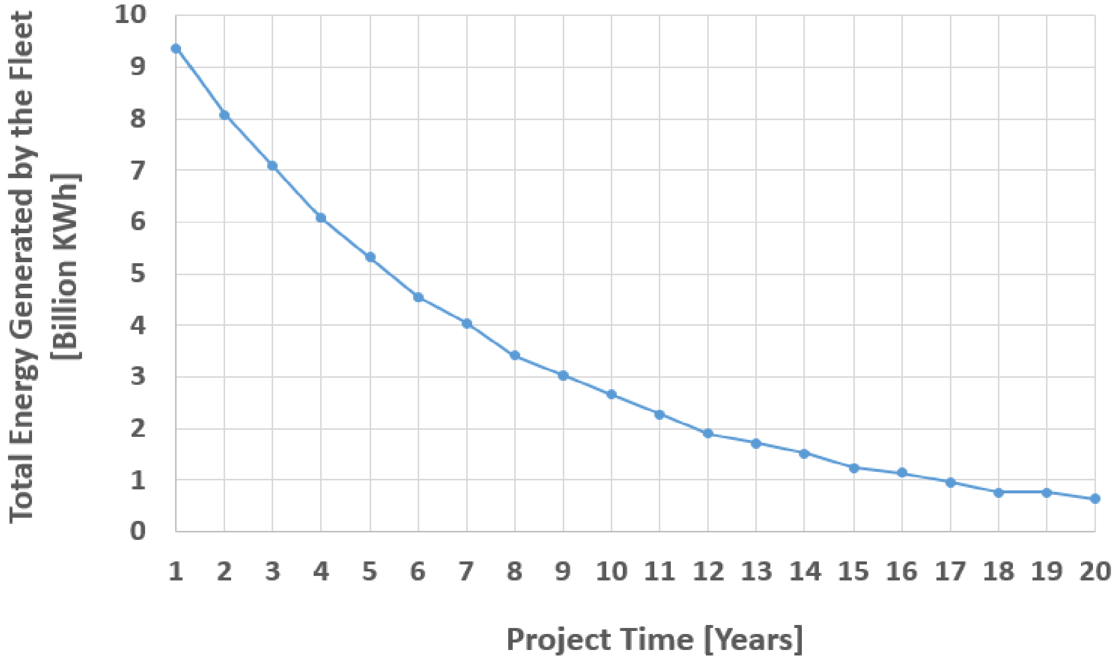


Figure 3-17: Annual Energy Generated by the Baseline (AD43) Fleet

In this research, the engines in the fleet are assumed to be running 24hours on a daily basis. The data for the energy generated by the fleet were gotten by multiplying the power generated by the fleet (MW) by the hours of engine operation, this was done annually for the entire time of the project.

As seen in Figure 3-17, the energy generated by the baseline fleet at the 1st and 20th year of the project are 9.4 billion kWh and 0.6 billion kWh respectively.

3.5.2 Engine emissions module

Another element of the model for the economic use of AG using gas turbines is the emissions generated by the fleet.

The emission prediction was done using Hephaestus, a FORTRAN-based code developed at Cranfield University for gas turbine emissions prediction.

3.5.2.1 Predicted emissions from the baseline fleet

The emission indices at design point are 2837.98, 2.028 and 0.08g/kg fuel for CO_2, NO_X and CO respectively. The NOx emission index for this engine when using natural gas (at DP) is 25ppm (approximately, 2g/kg fuel) [93]. It is noted that the emissions data gotten for the individual units of engines in the fleet at their various operating conditions do not represent the exact emission data for the real engines at the same operating cTonditions, due to the assumption of a generic combustor in the emission prediction code.

Figure 3-18 and Figure 3-19 show the predicted emissions generated by the baseline fleet for the entire duration of the project.

The gradual fall in the emission generated as seen in Figure 3-18 and Figure 3-19 is basically as a result of the divestments of units of engines in the fleet.

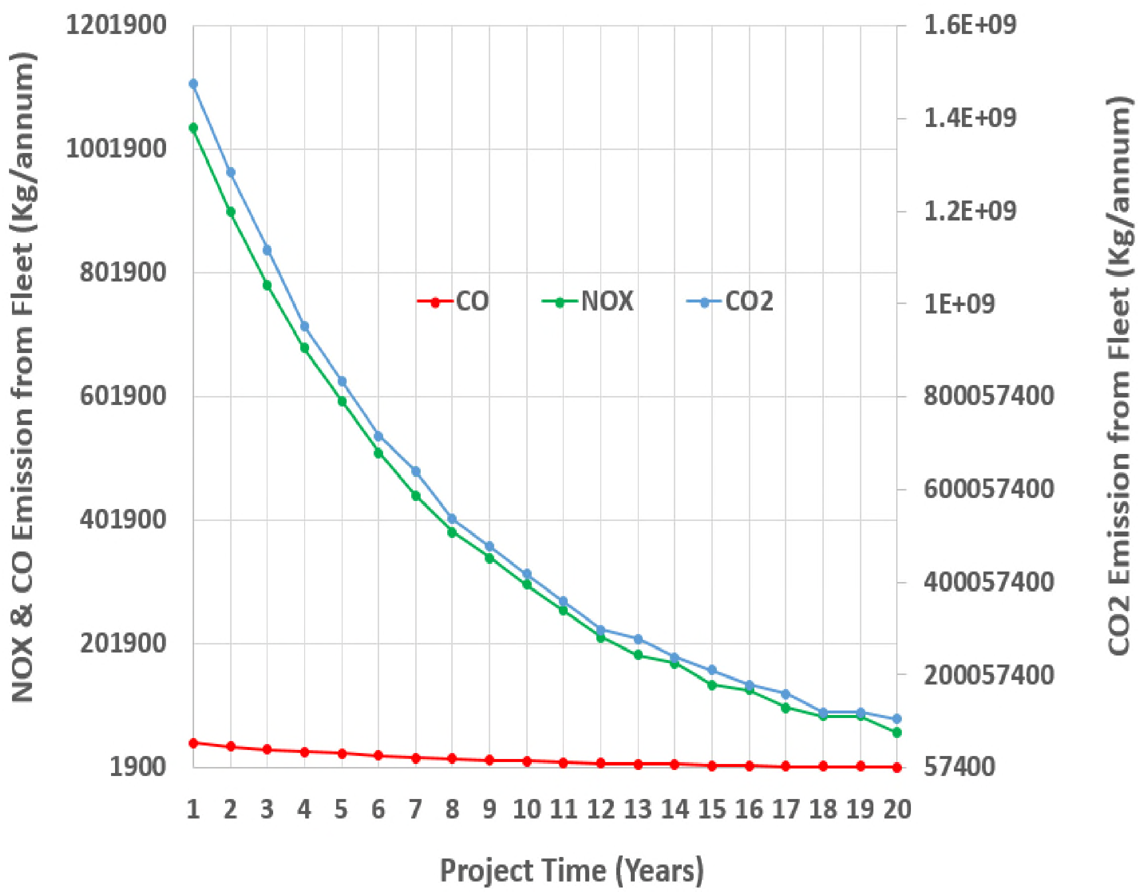


Figure 3-18: Emissions Generated by the Baseline Fleet

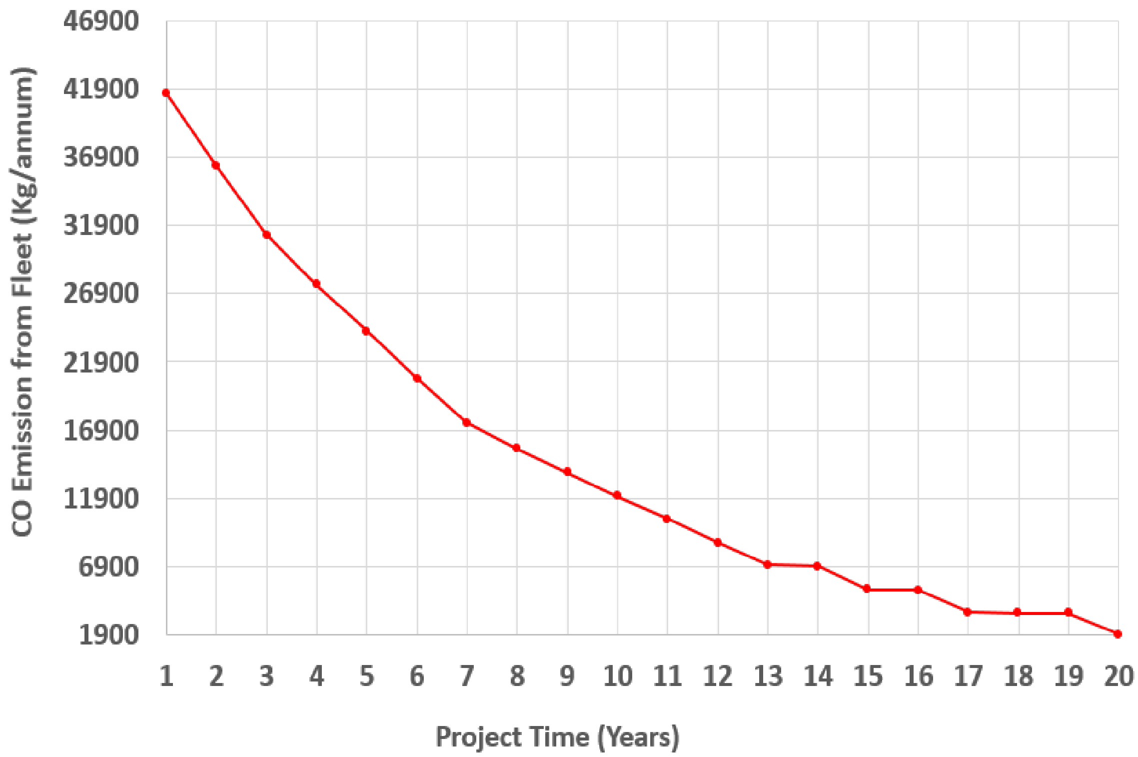


Figure 3-19: CO Emission Generated by the Baseline Fleet

3.5.3 Creep life/maintenance module

The creep life of the various engine units in the fleet were estimated at their various operating conditions throughout the duration of the project. These estimated creep life values were used to calculate the total maintenance cost of the fleet. The estimated annual maintenance cost served as a factor in the economic analysis of AG utilisation.

A simple creep life model was used in this research. The creep life values of the various engine units were estimated using a simple relationship between the TET of the engines and the engine creep life. This approach is taken because the creep life has a direct relationship with the TET of the engine [94, p.7].

The creep life reduces with increasing operational TETs and increases with reducing operational TETs. This simple model assumes that for every 20K rise in the TET, the creep life will reduce by 50%, whereas, for every 20K reduction in the operational TET, the creep life increases by 50%. The design point TET was taken as the reference TET. The results of the work of Gad-Briggs et al., [94, p.7] also showed this TET and creep life relationship.

It was assumed that at the design point TET, the creep life of the engine is 25,000hours. It was also assumed that in the case of decreasing operational TETs, in which case the creep life is expected to be increasing, the limit is 50,000hours.

3.5.3.1 Estimated creep life values for engines in the baseline fleet

For this baseline fleet, in order to avoid repetition of the same results, the creep life values for the various units of engines in the fleet are shown for all TETs represented in the fleet. The TETs of the baseline fleet are shown in Table 3-5 above. All TET values represented in the baseline fleet and their corresponding creep life values are shown in Table 3-6. The creep life values for the units of engines in the fleet are used in estimating the fleet operations and maintenance cost.

Table 3-6: Estimated Creep Life Values for the Representative Units of Engines in the Baseline Fleet

TET (K)	1550 DP	1416.5	1354.1	1405.5	1401.2	1369	1352	1371.7	1408.5
Creep Life (Hrs)	25000	50000	50000	50000	50000	50000	50000	50000	50000

3.5.4 Economic assessment of the baseline fleet

In order to have a robust model for the economic utilisation of AG, various factors have been identified and integrated into the economic model.

The cost elements under consideration are capital investment, operations and maintenance cost, emission tax, staff salaries and loan repayment. The revenues generated from the project are derived from the engine divestment sales and the revenue from generated electricity that is sold to the national grid. The economic feasibility of the project is then determined by the NPV when considering all of these factors.

The input data and assumptions for the economic assessment are contained in Table 3-7. The data were obtained from the open domain, reasonable estimates were made to get data that could not be found in the open domain.

Table 3-7: Input Data & Assumptions for the Economic Assessment of Associated Gas Utilisation [1]; [85]; [95]; [96]; [97]; [98]; [99]; [100]

S/N	Input Parameter	Value	IC100	SS296	AD43	RH296
1	**Engine Capital Cost ($/KW)**		**953**	**689**	**973**	**689**
2	**Fixed O&M cost ($/KW-yr)**		**7.33**	**7.34**	**7.34**	**7.34**
3	**Variable O&M cost ($/KWh)**		**0.01445**	**0.01545**	**0.01545**	**0.01545**
4	**Maintenance factor1 ($/KWh) -20% of variable O&M cost**		**0.00289**	**0.00309**	**0.00309**	**0.00309**
5	**Discount rate**	**10%**				
6	**Loan interest rate**	**2% - 14%**				
7	**CO_2 emission tax ($/Kg)**	**0 – 0.04**				
8	**Engine availability**	**100%**				
9	**Loan holiday**	**1 year**				
10	**Loan duration**	**10 years**				
11	**Operating hours**	**24 hrs daily**				
12	**Project Life**	**20 years**				
13	**GT Rate of Depreciation**	**0.0516/annum**				
14	**GT Life Depreciation Type**	**Straight Line**				
15	**Electricity Selling Tariff to Grid ($/KWh)**	**0.12**				

It should be noted that while the fixed O & M cost ($/KW-yr) and the variable O & M cost ($/KWh) values for the SS296 and RH296 engines should have been smaller than that of the IC100 engine. It was observed during the write-up stage of the research that these changes were not effected in the model used. However, all the assumed data used for the economic assessment are within acceptable limit.

3.5.4.1 Capital investment for the baseline fleet

It has been assumed that the required starting capital for the project would be obtained from a business loan.

The loans were taken differently for the various units of engines in the fleet, the exact amount taken as loan per engine was estimated using the relationship in Equation 3-1;

$$Loan\ per\ engine\ (\$) = Shaft\ power\ (KW) \times Engine\ capital\ cost\ (\$/KW) \quad \textbf{3-1}$$

From Equation 3-1, substituting in values, it implies that $42,130,900 is taken as loan for each unit of AD43 engine. Therefore the total starting capital (loan amount) required for the 25 units in the baseline fleet is $1,053,272,500.

3.5.4.2 Annual operation and maintenance costs for the baseline fleet

Operations and maintenance costs consists of engine overhauling and replacement of engine components [1, p.113].

Fixed operations and maintenance costs are expenses in the operation of the engine that do not change significantly with the amount of power generated, such as routine predictive and preventive maintenance. Whereas, variable operations and maintenance costs are those that are directly related with the amount of power generation, such as purchase of chemicals, consumables, lubricants, spare parts, etc [1, p.113].

Major maintenance costs are those incurred as a result of extended outages, such as scheduled major overhaul, which in most cases are undertaken once per year [1, p.113].

In this study, all costs incurred in the process of getting the associated gas are assumed to be embedded in the operations and maintenance cost, including the cost of the flare gas recovery system (FGRS). Fuel cost is not considered because the AG is assumed to be available free of charge since it is currently being wasted to flaring.

The annual operations and maintenance costs for the fleets of engines are estimated using the relationships 3-2 to 3-6;

$$Annual_{O\ \&\ M\ Cost} = Fixed_{O\ \&\ M\ Cost} + Variable_{O\ \&\ M\ Cost} + Major_{\ Maintenance\ Cost} \quad \textbf{3-2}$$

Where;

$$Fixed_{O\ \&\ M\ Cost} = GT_{Shaft\ power} \times Fixed_{O\ \&\ M\ Cost\ \ factor}\ (\$/KW\ \ -yr) \quad \textbf{3-3}$$

$$Variable_{O\ \&\ M\ Cost} = GT_{Shaft\ power} \times Hours_{GT\ operation} \times Variable_{\ O\ \&\ M\ Cost\ factor} \times Availability \quad \textbf{3-4}$$

$$Major_{Maintenance\ Cost} = GT_{Shaft\ power} \times Hours_{GT\ operation} \times Maintenance_{\ factor2} \times Availability \quad \textbf{3-5}$$

$$Maintenance_{factor2} = Maintenance_{factor1} \times \frac{(Unit\ expected\ life\ of\ engine)}{(Creep\ life\ of\ engine)} \quad \textbf{3-6}$$

The unit expected life of the engine used in Equation 3-6 [85] is the assumed creep life of the engine at design point (25,000hrs). All factors used in the above equations are all outlined in Table 3-7.

Figure 3-20 shows the estimated amount for the annual operation and maintenance costs for the baseline fleet. The data is calculated using Equation 3-2 for the various engine units in the fleet on an annual basis. To account for the effect of inflation on the cost of engine spare parts, chemicals, consumables, etc., an annual escalation of 2% increase was applied to the annual operations and maintenance costs.

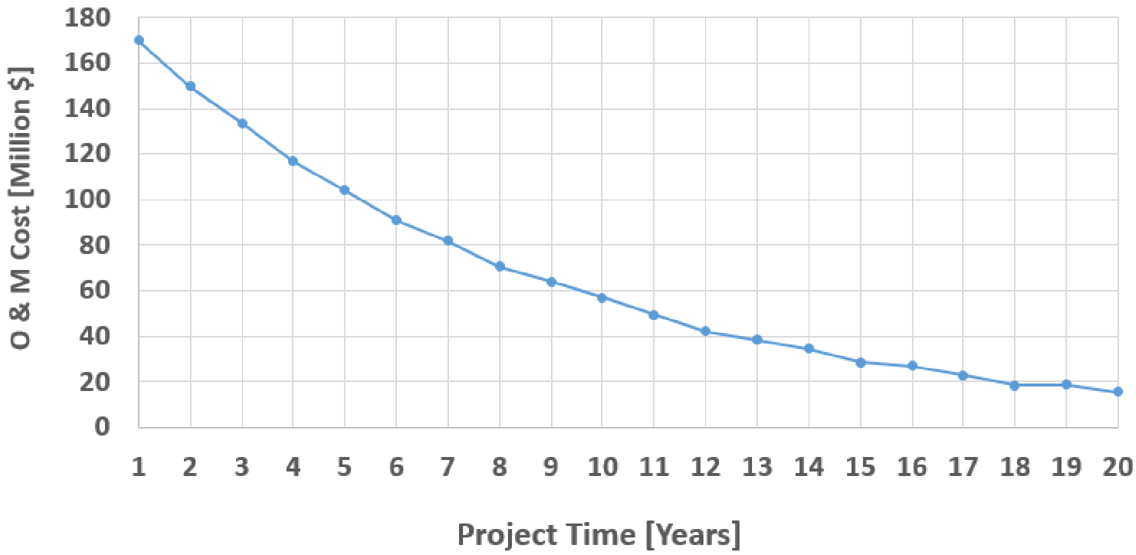


Figure 3-20: Annual Operations & Maintenance Cost for the Baseline (AD43) Fleet

The gradual decline seen in Figure 3-20 results from the divestment of engine units in the fleet and the continual fall in power due to reducing fuel availability. The annual operations and maintenance costs of the fleet depends on many factors, among which are the power produced and the creep life of the individual units of engines in the fleet.

3.5.4.3 Emission tax from baseline fleet

For the economic model used in this AG utilisation project to be robust, there is the need to include emission tax. As seen in Figure 3-18, emission prediction was done for CO, CO_2 and NOX emissions. However, for legislative reasons, the emission tax was only considered for CO_2 emission. At the moment, CO_2 emission is not being taxed, but as part of the risk assessment associated with this research, a CO_2 emission levy of 0.02$/kg has been assumed.

The annual emission tax was estimated using the relationship below;

$$Annual\ Emission\ tax = Emission\ released\ \times GT_{emission\ tax} \quad \textbf{3-7}$$

Figure 3-21 shows the annual emission tax for the baseline fleet, calculated using the emissions derived in section 3.5.2.1 and shown in Figure 3-18.

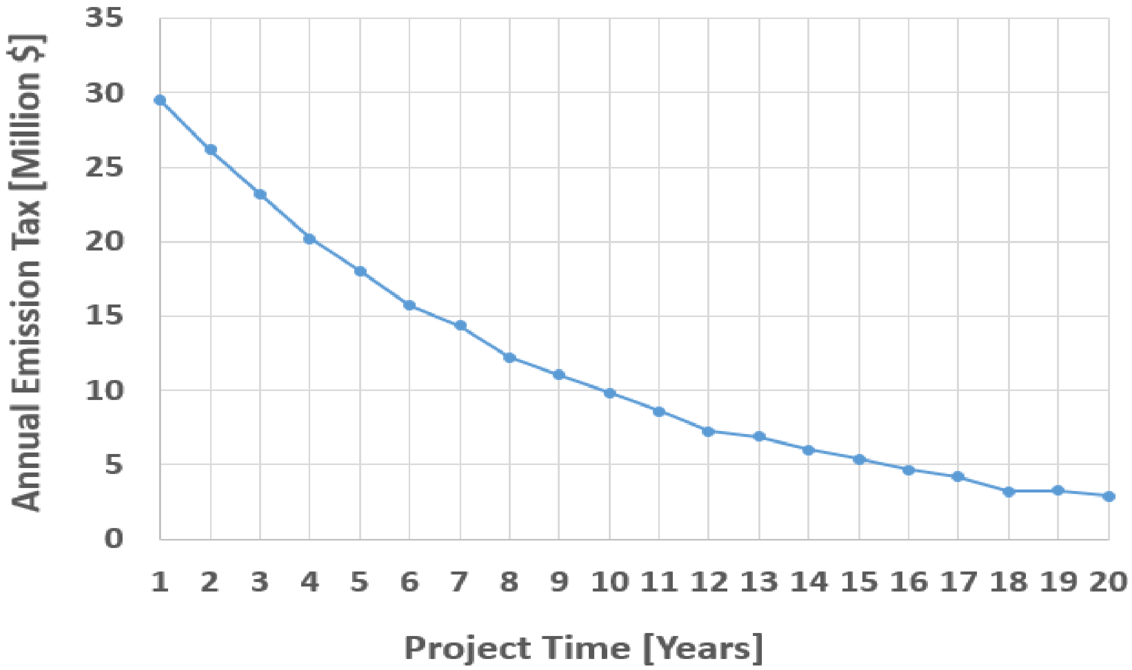


Figure 3-21: Annual CO_2 Emission Tax for the Baseline Fleet

An escalation factor increasing by 2% was introduced yearly, this is to account for future increase in the charged emission tax.

3.5.4.4 Number of staff and salaries for baseline fleet

The number of staff to be involved in this AG utilisation project and their salaries are part of the economic model.

Table 3-8 shows the number of staff involved in the project at the beginning. The table also shows their salaries, this is for all the different fleets of the AD43 gas turbine. The staff strength and the departments in which the staff are divided into are analysed based on information provided by an ex-staff of a Power Generating Company. The salary data are taken from the Bureau of Labor Statistics, US Department of Labor [101] and a few were gotten from reasonable assumptions.

Table 3-8: Number of Staff at the Beginning of the Project & their Salaries (for all AD43 Fleets) [101]

Duty	Number in the Project	Annual Salary Per Staff [$]	Total Salary [$]
Administrative Manager	1	94,840.00	94,840.00
Plants Manager	1	141,650.00	141,650.00
Finance Manager	1	134,330.00	134,330.00
Operators	40	58,490.00	2,339,600.00
Mechanical Department	18	56,390.00	1,015,020.00
Control and Instrumentation Department	15	56,320.00	844,800.00
Electrical Department	15	61,870.00	928,050.00
Performance Department	7	56,390.00	394,730.00
Account/Purchase Dept.	7	75,280.00	526,960.00
Health and Safety Dept.	7	51,270.00	358,890.00
Ware House Dept.	15	25,000.00	375,000.00
Security Department	16	28,460.00	455,360.00
Fire Service	10	48,030.00	480,300.00
Transport	13	38,050.00	494,650.00
Miscellaneous Staff	15	70,000.00	1,050,000.00

Figure 3-22 shows the annual number of staff involved in this project of AG utilisation for the entire project time. The number of staff figures seen below are the sum of the number of staff for both day and night shifts. The gradual reduction of the number of staff involved in the project as seen in Figure 3-22 is as a result of the gradual divestment of redundant units of engines. The number of staff involved in the project is directly proportional to the number of units of engines in the fleet.

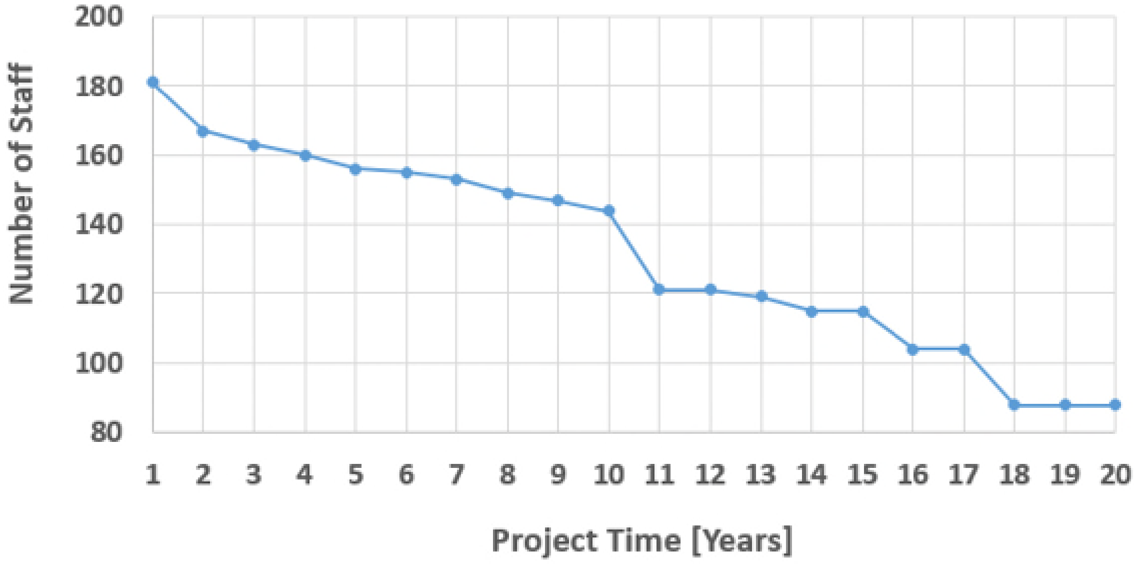


Figure 3-22: Annual Number of Staff in the Project (AD43 Baseline Fleet)

Figure 3-23 shows the influence of engine units' divestment time on the total annual staff salaries. As expected, there is a gradual reduction in the total annual staff salaries due to the gradual reduction in the number of staff involved in the project. As observed in the figure, the total annual staff salaries increased slightly in some years, this is because an increment factor of 1.5% was added to the total annual staff salaries after every 2 years.

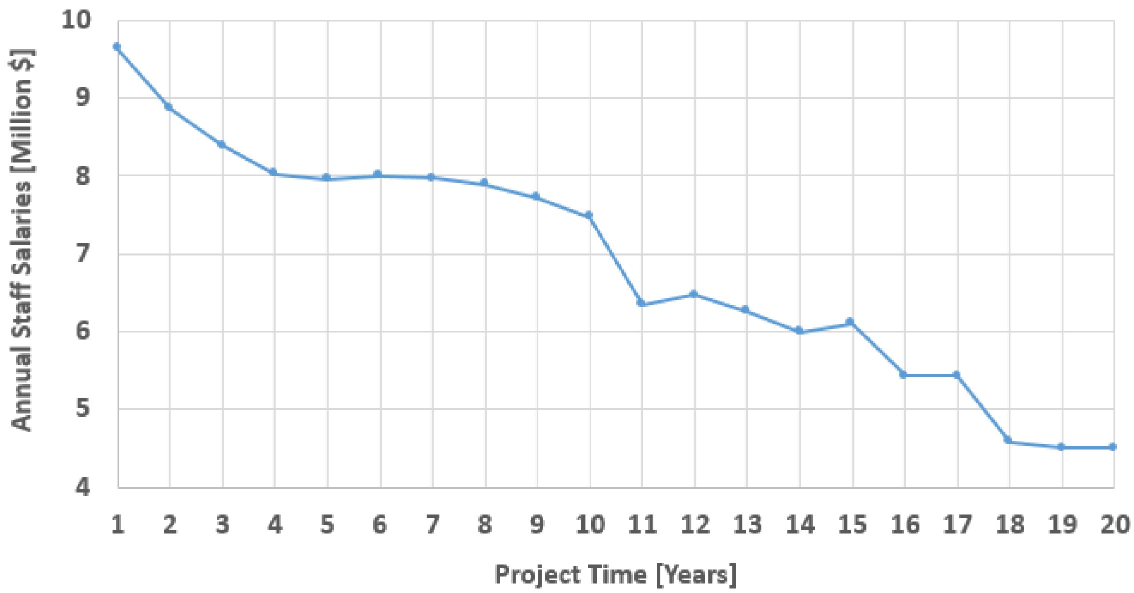


Figure 3-23: The Influence of Engine Divestment Time on the Annual Staff Salaries (AD43 Baseline Fleet)

3.5.4.5 Revenue from sold electricity

The annual revenue from the electricity that is sold to the national grid is the primary source of revenue from this project. It is estimated using the relationship shown in Equation 3-8;

$$Annual\ Revenue_{eg} = Annual_{eg} \times Electricity\ Selling_{tg} \tag{3-8}$$

Where;

$Annual\ Revenue_{eg}$ = annual revenue from electricity sold to grid ($)

$Annual_{eg}$ = annual energy generated by the fleet (kWh)

$Electricity\ Selling_{tg}$ = electricity selling tariff to grid ($/kWh)

The annual energy generated by the baseline fleet and the electricity selling tariff details can be seen in Figure 3-17 and Table 3-7 respectively. Figure 3-24 shows the annual revenue from the electricity that was sold to the national grid.

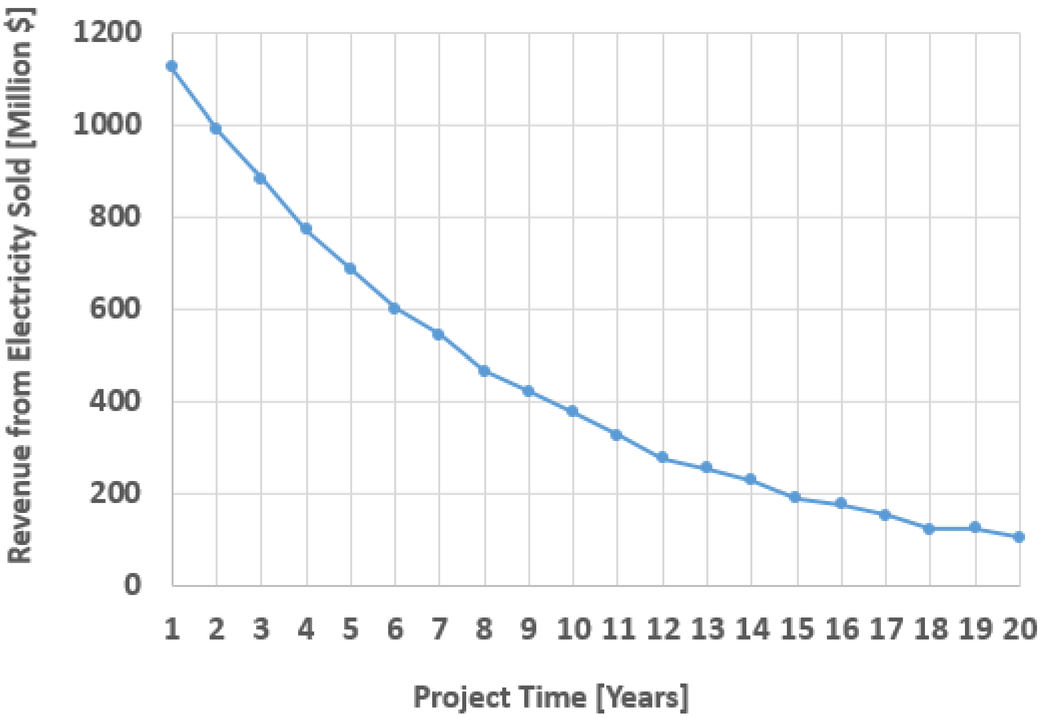


Figure 3-24: Annual Revenue from Electricity Sold to Grid (Baseline Fleet)

An escalation factor increasing annually by 2% was applied to get the annual revenue, this is to account for future rise in the electricity selling tariff.

This revenue is the major source of revenue from this project. As expected, there is a constant fall in annual revenue, as a result of the decline in the fuel available for the project, which affected the power and energy generated.

As seen in Figure 3-24, the revenue generated from the sold electricity declines from $1.1b to $105.7m.

3.5.4.6 Gas turbine divestment sales

The robust model for the economic utilisation of AG has gas turbine divestment sales as one of its source of revenue.

Gas turbine engine salvage value is the estimated resale value of the gas turbine engine at the end of its useful life [102], or its estimated resale value at a time when the owner wants it sold for economic reasons. It is calculated using the relationship in Equations 3-9 and 3-10 below [103];

$$S = P \times (1 - i)^y \qquad \textbf{3-9}$$

Where;

S = salvage value of the gas turbine engine in $/kW

P = original price of the gas turbine engine (engine capital cost) in $/kW

i = gas turbine engine depreciation rate

y = age of gas turbine engine in years

The gas turbine engine divestment sale is calculated using the expression;

$$DS = P \times (1 - i)^y \times GT_{shaft\,power} \qquad \textbf{3-10}$$

Where;

DS = divestment sale of the gas turbine engine in $

$GT_{shaft\,power}$ = shaft power of the gas turbine engine at design point in kW

All other parameters remain the same as explained in Equation 3-9. In estimating the divestment sales, straight line depreciation is assumed, implying that the gas turbine depreciation rate used (i) is constant for all the years of the project as shown in Table 3-7.

Figure 3-25 shows the number of units of engines divested, the divestment sequence/time and the divestment sales made from the baseline fleet. The divestment sale per unit of engine decreases with increase in the age of the engine, this was accounted for by the “gas turbine age”, y, included in the analysis in Equations 3-9 and 3-10. Hence, the reason for the difference in divestment sales for the 2 units of engines sold in the 5th year, 6th year and that sold at the end of the project.

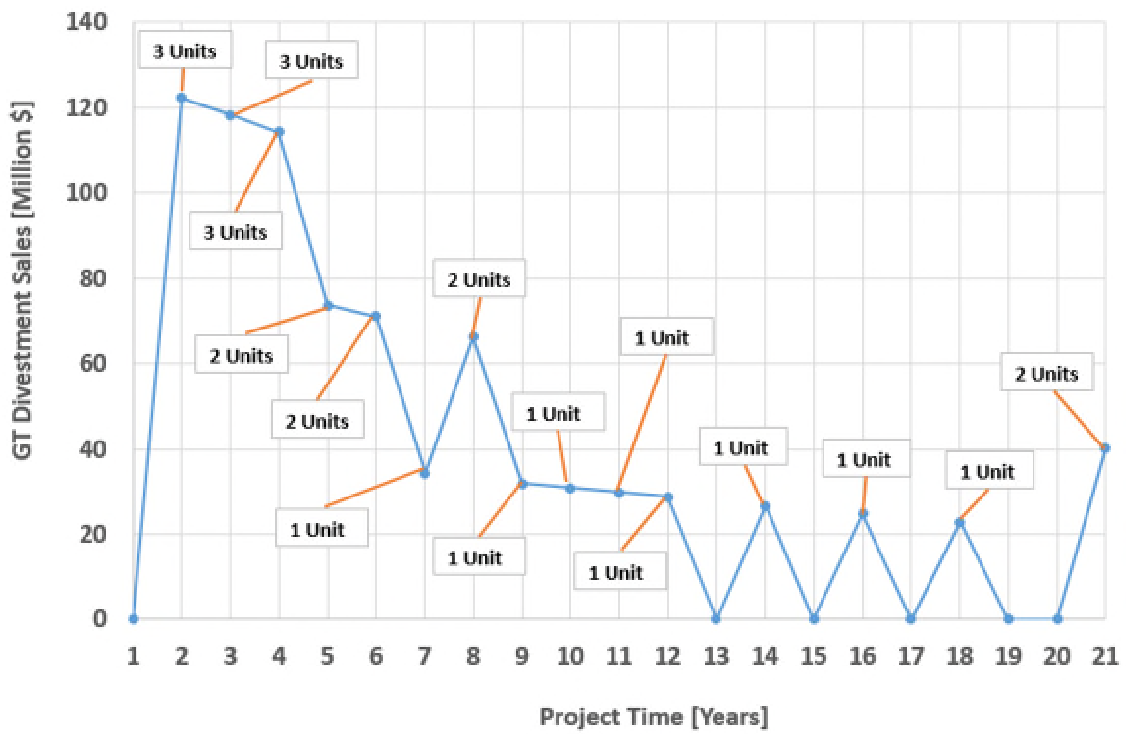


Figure 3-25: The Number of Units of Engines Divested, the Divestment Sequence/Time & the Divestment Sales

3.5.4.7 Loan Repayment

The loan repayments for the various units of engines in the fleet were estimated using the relationship shown in Equation 3-11 [104];

$$L_R = \frac{Engine\ Capital\ Cost\ \times\ Interest\ Rate}{1 - (1 + Interest\ Rate)^{-LD}} \qquad \textbf{3-11}$$

Where;

L_R = Loan repayment ($)

L_D = Loan duration

The loans were assumed to be taken separately for the different units of engines in the fleet, as such, they were also repaid separately. The loan for each unit of engine is paid just before it is divested. The agreed loan duration for the entire fleet is assumed to be 10 years, the loans for the various units of engines are all repaid within this period. Details on the loan interest rates and engine capital cost are in Table 3-7 above.

Figure 3-26 and Figure 3-27 show the estimated loan repayment values for the baseline fleet at varying loan interest rates. The loan repayment increases with increase in the interest rate.

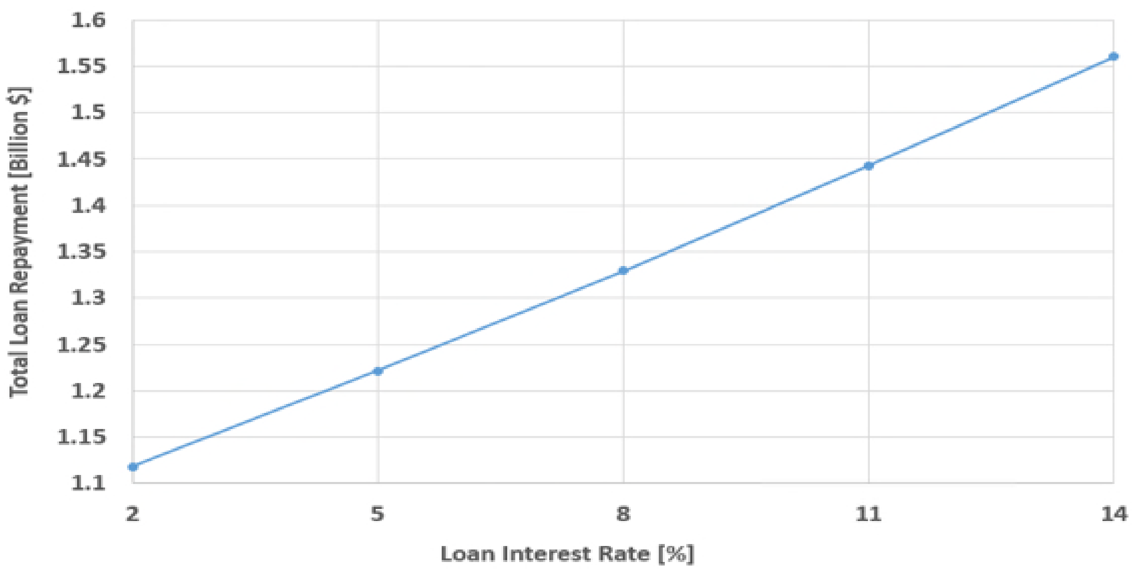


Figure 3-26: Total Loan Repayment for the Baseline Fleet at Varying Loan Interest Rates

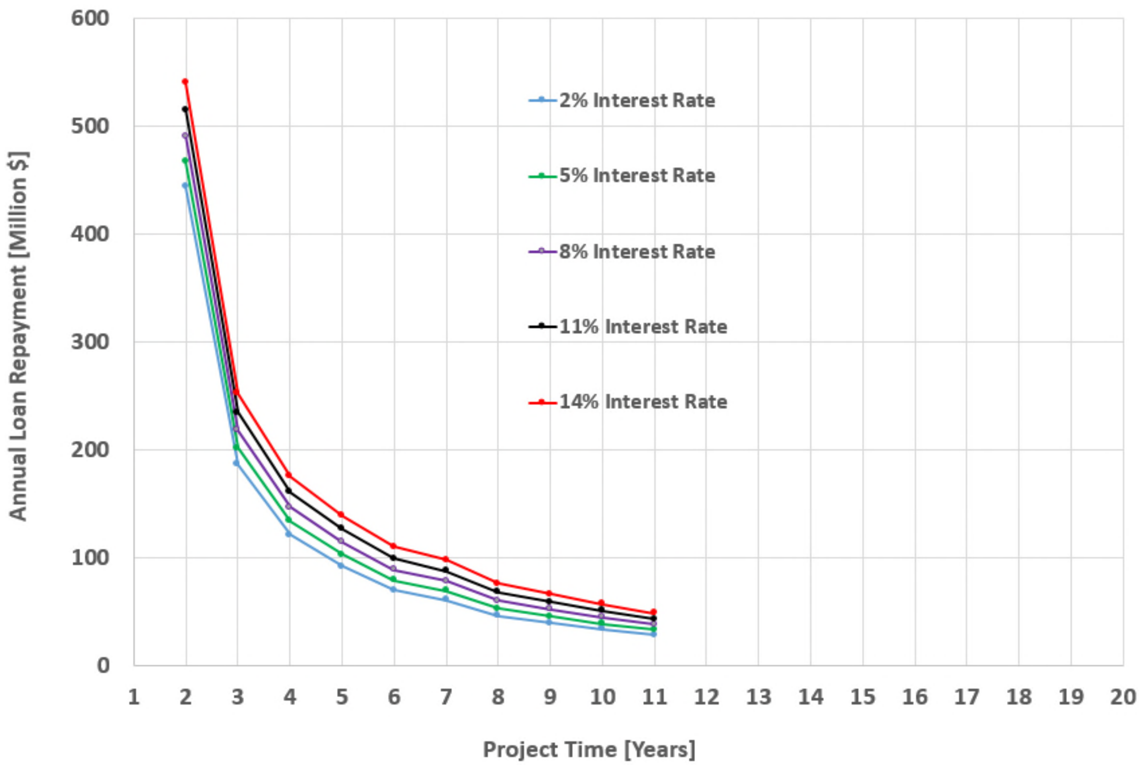


Figure 3-27: Annual Loan Repayment at Varying Loan Interest Rates (AD43 Baseline Fleet)

As seen in Figure 3-27, the loans for all the units of engines in the fleet were all repaid within the 10 years loan duration.

3.5.4.8 Annual Net Cash Flow of the Project

The annual net cash flow of the project were calculated as the sum of all cash inflows and outflows occurring in the project. In this research, the annual sources of cash outflow are the operations and maintenance cost, the salary payment, the emission tax and the loan repayment. Whereas, the sources of cash inflow are the divestment sales and the annual revenue from the electricity sold to the national grid. Figure 3-28 shows the annual net cash flow of the project for the baseline fleet.

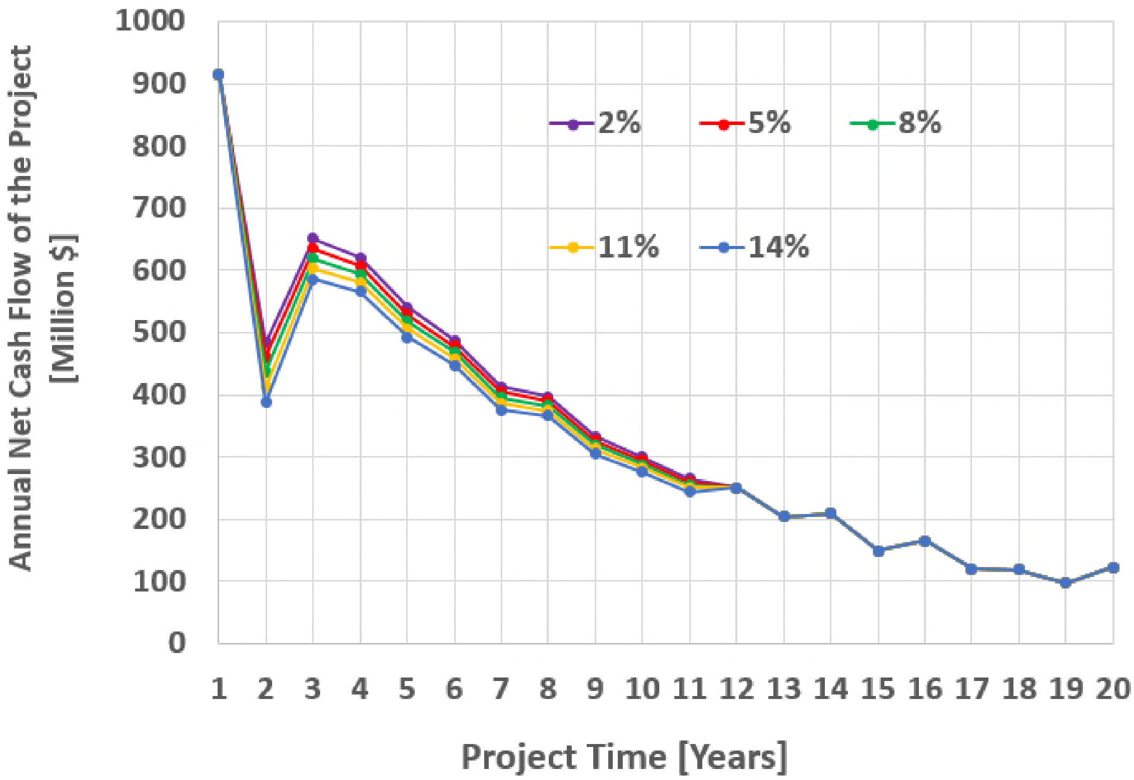


Figure 3-28: Annual Net Cash Flow of the Project at Varying Loan Interest Rates

3.5.4.9 Net Present Value (NPV) Analysis

In this research, the NPV is used as the appraisal method used in ascertaining the economic viability of the project. It was estimated using the relationship in Equation **3-12** below.

$$NPV = \sum_{t=1}^{n} \frac{C_t}{(1+r)^t} - C_o \qquad \textbf{3-12}$$

C_t is the net cash-flow for the year considered in the project, C_o is the initial cost of the project which is also the loan taken, r is the discount rate assumed, and t is the project year under consideration [76]; [85, p.193]; [86]; [87].

Figure 3-29 shows the economic return (NPV) of the project at varying loan interest rates. $2.79b is the economic return (NPV) at 2% loan interest rate. The project is economically viable, implying that the fleet composition for the baseline fleet is good. However, there is the need for an optimiser that will give the fleet composition that will give the maximum power production, a better economic return and the best divestment time for the redundant units of engines in the fleets.

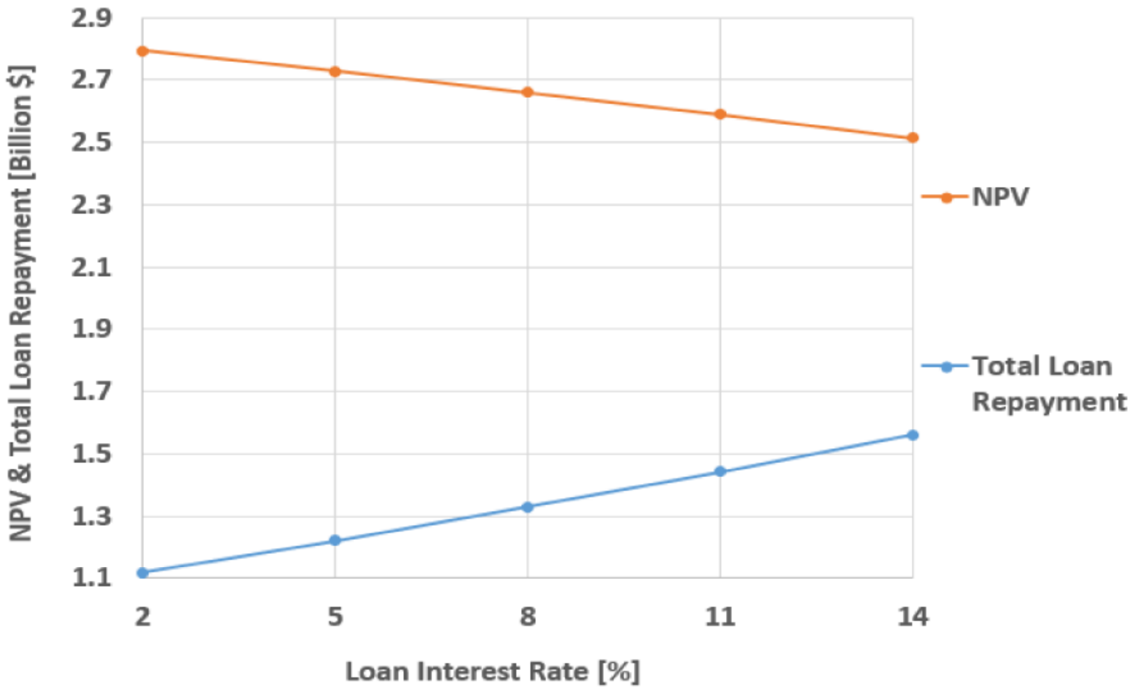


Figure 3-29: NPV & Total Loan Repayment for the Project at Varying Interest Rates (AD43 Baseline Fleet)

3.6 Chapter Summary

Having identified the research aim and objectives in the first chapter of the research, this chapter describes in chronological order the steps and tools used to achieve the aim and objectives.

The associated gas availability data used by the fleets is also shown in this chapter. A brief and introductory explanation as regards the engine degradation aspect of the research was done.

Applying the TERA framework, the performance module was done first. The performance simulations of the different study engines were modelled in TURBOMATCH software; a Cranfield University in-house FORTRAN-based code for simulating both design point and off-design point engine operating conditions.

Engine model specifications at design point were shown for all the study engines together with the specifications for the real engines.

The fleet composition for the baseline fleet is analysed for the entire duration of the project and the divestment sequence/time for the units of engines in the fleet is also illustrated.

As part of the TERA module, the emissions generated by the fleet and the creep life of the individual units of engines in the fleet were all estimated. The emissions were estimated using Hephaestus, a FORTRAN-based code developed in Cranfield University for gas turbine emissions prediction. The creep life were estimated using a simple model based on a relationship between TET and the creep, in Microsoft Excel.

A robust model is developed for the assessment of the economic utilisation of associated gas. The model integrated various technical and economic factors such as capital investment, operations and maintenance cost, emission tax, number of staff and staff salaries, revenue from sold electricity, gas turbine divestment sales and loan repayment. The net present value (NPV) is used as the project appraisal method in this research. The model was used in assessing the economic utilisation of associated gas by the baseline fleet. The energy generated by the baseline fleet for the entire duration of the project is 66.5 billion kWh, whereas, the NPV of the economic return at 2% interest rate is $2.79 billion.

4 GENETIC ALGORITHM, MATLAB AND THE OPTIMISATION PROCESS

4.1 Introduction

Optimisation is the act of making a process or design function as effectively as possible, thereby yielding the optimum benefit. In most occasions, optimisation has to do with minimising or maximising a function known as the fitness function (objective function), subject to some constraints applied on the variables of the function [72, p.145].

4.2 The advantages of GA over other Optimisers

There are many optimisers that can be used for the purpose of minimising or maximising an objective function. Gradient-based method and Particle Swarm optimisation techniques have been used in optimisation. Others include Tabu search, Neural network, Simulated Annealing, Hill-climbing technique, etc [105]. For the purpose of this research, GA is preferred to other optimisers because of its high level of accuracy, its robustness, its flexibility as regards exploring and exploitation of the decision variables space, etc. Although, when using very high population size, the optimisation time could be very lengthy as compared to other optimisers.

4.3 Genetic Algorithms (GAs)

GAs are search algorithms prompted by the natural selection and evolution theory proposed by Charles Darwin [73, p.102]. The GAs can also be said to be a set of search and optimisation methods appropriate in getting the solutions to complex problems. They are specifically suited to getting the optimal solutions to non-deterministic polynomial-time hard problems (complex problems whose solutions cannot usually be attained analytically) [74].

4.4 The GAs method

The GAs use a population of potential solutions in which individuals are usually designated by chromosome strings. Functions are applied to the population which help to mimic the natural evolution principles to evolve the population. In the process of time, the population gets fitter and better adapted to its environment. This generates an array of near optimal solutions [74].

This section explains the key components which are the functional constituents of the GA in seeking the optimal solutions to the optimisation problem in this research. It should be noted that sections 4-4 to 4-6 are linked to section 3.1.2 of this thesis.

4.4.1 GA operators

The GAs have various operators, of which most use the binary string (chromosome) coded form of the design parameters [69]. Below are some of the operators employed by the GAs and their function in an optimisation process.

4.4.1.1 Selection (reproduction) operator

Selection is a process whereby individuals are copied from the supplied data based on their fitness function values. This implies that individuals with higher values have a better chance of contributing one or more child in the next generation [106, p.10-11]. This operator helps the algorithm to achieve more fitted individuals in each succeeding generation. Two popular selection methods are the Roulette Wheel Selection and the Tournament Selection [74].

4.4.1.2 Crossover operator

After selection, crossover could commence in two steps. First, there could be random mating of the newly formed chromosomes (offspring) in the mating pool. Then in the second step, each pair of chromosomes undergoes crossover [106, p.12]. Crossover usually has probability applied, typically 0.7. This implies that it is successfully carried out 70% of the time mating takes place, whereas, 30% of the time the selected individuals move to the next generation unchanged. Crossover operator enables the population of chromosomes to search the available search domain to find likely better solutions. If better solutions are found, this fitness could be carried to the population in the next generation, thus improving the fitness of the new population [74].

4.4.1.3 Mutation operator

As explained earlier, the crossover operator acts as an enabler in the exchange of chromosomes patterns to create new offspring. However, not all permutations of the search domain are attainable with crossover alone, mutation makes it technically realistic to reach the entire search domain [74].

4.4.1.4 Elitism operator

Elitism operator is a genetic algorithm operator that helps in speeding up the performance of the algorithm and also helps in preventing the loss of fitted solutions. In the process of producing a new generation through crossover and mutation, there is the probability that the best chromosome could be lost. The nomenclature given to the method that selectively copies the fittest chromosome (or a number of the best chromosomes) to the new generation is called Elitism [73, p.112]. The most fitted individual is noted as the outcome of the genetic algorithm optimisation.

4.4.2 Handling constraints in optimisation

An optimisation problem could be with a constraint or without a constraint. Constrained optimisation is an optimisation problem having constraint or the reverse, which is unconstrained optimisation, this does not have a constraint. When constrained optimisation is the case, the constraint is identified by a constraint function.

Ideally, genetic algorithms are made to solve unconstrained problems. However, because constrained problems arises naturally and frequently, GAs have been adapted to give solutions to optimisation problems with inequalities and/or equality constraints [73, p.112].

4.5 GA code employed in the study

The optimisation code employed in this study is a GA code written in Matlab programming language. In this code, a function handle was passed into the fitness function and the number of variables, including their upper and lower bounds were specified.

4.5.1 The Aim of the optimisation

The aim of the optimisation is to maximise the fitness function (power produced) by determining the best fleet composition, and also to estimate the best divestment time for each redundant unit of engine in the fleet subject to the constraint of AG availability. From the optimisation results, the effect of various levels of gas turbine degradation on divestment time will be ascertained.

4.5.2 The Optimisation database

The gas turbine performance simulation results obtained from Turbomatch serve as the database and search domain for the optimiser. The database has four columns which are sets of TETs and their corresponding power outputs, efficiencies and fuel flows. For each engine type, the upper bound is the design point TET of the engine, whereas the lower bound varies for the different engines. The step size between data points also varies for the different engines with steps of 5K, 10K or even more.

The optimiser searches the database for the fleet composition which will give the maximum power production. The optimiser interpolates between steps for values that lie between the provided data.

4.5.2.1 Database for the clean fleet optimisation

The database (search domain) for the clean fleet optimisation was derived from performance simulations for the clean engines at design point ambient temperature (288.15K) for the range of TETs as explained above.

4.5.2.2 Gas turbine degradation and the database for the degraded fleets

As part of the risk assessment in this project, the effect of different rates of gas turbine degradation is also considered. This is necessary because gas turbines exhibit the effects of wear and tear over time. The effect of three different rates of degradation is considered; designated as optimistic (OPT) (slow), medium (MED) and pessimistic (PES) (fast) degradation.

This research only considered degradation in the compressor of the gas turbine, because degradation in the compressor accounts for more than half the degradation that takes place in the gas turbine engine. Compressor fouling is assumed to be the cause of the degradation. Degradation in the compressor affects the compressor pressure ratio, flow capacity and efficiency [1, p.25]. Therefore, in the performance simulation model used for the degraded engines, the different rates of degradation were implanted for these parameters; compressor pressure ratio, non-dimensional mass flow and efficiency.

4.5.2.3 Database for the optimistic (OPT) degraded fleets

The Optimistic (OPT) degraded fleet is assumed to be clean originally, that is, at the 1st year of the project. At the 2nd year, degradation is assumed to have commenced and the amount is assumed to be 1.333% degradation. At the 3rd year the degradation escalates to 2.0%. After partial overhauling, the degradation rate reduces to 0.667% at the 4th year of the project. It increases to 1.333% again in the 5th year and then to 2% in the 6th. At the end of the 6th year, partial overhauling takes place again, making the degradation rate at the 7th year to be 0.667%. The cycle continuous with partial overhauling taking place after every 3 years. It implies that for year 1, the units of engines in the OPT degraded fleet are assumed clean. For years 2, 5, 8, 11, 14, 17 and 20, the engines have a degradation rate of 1.333%. Whereas, for years 3, 6, 9, 12, 15, and 18, the engines in the fleet have a degradation rate of 2%. Finally for years 4, 7, 10, 13, 16 and 19, the engines have a degradation rate of 0.667%. So the units of engines in the OPT degraded fleets have degradation rate of a maximum of 2%.

Partial overhauling (not complete overhauling) was assumed because the major aim of this research is to explore the effect of gas turbine degradation on divestment time, as such, it was necessary to leave the engines in degraded mode.

Results of Turbomatch performance simulations of the study engines with the above rates of degradation implanted formed the database (search domain) used by the optimiser for the OPT degraded fleets.

4.5.2.4 Database for the medium (MED) degraded fleets

For the medium (MED) degraded fleets, the rate of degradation is increased, it culminates at 4% degradation. Similarly, at the 1st year, the engines in the fleets are assumed clean. At the 2nd, 5th, 8th, 11th, 14th, 17th and 20th year of the project, the engines have a degradation rate of 2.667%. A degradation rate of 4% is assumed for years 3, 6, 9, 12, 15, and 18. Year 4, 7, 10, 13, 16 and 19 have degradation rate of 1.333%. Partial overhauling also takes place at the end of every 3 years, the degradation gets to its maximum of 4% after every 3 years in this scenario.

Results of Turbomatch performance simulations of the study engines with the above rates of degradation implanted formed the database (search domain) used by the optimiser for the MED degraded fleets.

4.5.2.5 Database for the pessimistic (PES) degraded fleets

The pessimistic (PES) degraded fleets have degradation rates culminating at 6% degradation. As the name implies, it is the worst rate of degradation in this research. As usual, in the 1st year of the project, the engines in the fleets are operated as clean. At the 2nd, 5th, 8th, 11th, 14th, 17th and 20th year of the project, the engines have a degradation rate of 4%. A degradation rate of 6% is assumed for years 3, 6, 9, 12, 15, and 18. Year 4, 7, 10, 13, 16 and 19 have 2% degradation implemented. As in the other scenarios, partial overhauling takes place at the end of every 3 years, the degradation gets to its maximum of 6% after every 3 years.

Similarly, results of Turbomatch performance simulations of the study engines with the above rates of degradation implanted formed the database used by the optimiser for the PES degraded fleets.

These various study scenarios having the clean fleets and the fleets with different rates of degradation were used by the optimiser to show the effect of degradation on gas turbine divestment time.

The various rates of degradation have been chosen to demonstrate that degradation in gas turbines can vary due to the different environmental conditions in which the fleets are exposed to.

Considering these various rates of degradation also account for part of the risk assessment in this project of economic use of AG using gas turbines.

4.5.3 The optimisation settings

4.5.3.1 The objective (fitness) function

The fitness function is the function used by the GA code in the various iterations of the algorithm to evaluate the level of accuracy of all suggested solutions in the search for the optimum value [107]. The fitness functions used in this research varies slightly for the various engines, this is because of the difference in the number of units of engines in the starting fleets for the various study engines. Also, for a particular engine type, the fitness function varies slightly from one year to the other depending on the number of undivested units of engines left in the fleet. As an example, as seen in Appendix E, the fitness function for any of the IC100 fleets at the first year of the project is as shown in Equation 4-1;

Equation 4-1

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

“PO” is the optimised power output for the various units of engines in the fleet (12units of engines), whereas, “y” is the total optimised power.

4.5.3.2 The constraints and constraints equation

The constraints of the optimisation exercise are the annual fuel availability data for the project shown in Figure 3-4. This research seeks to obtain the maximum power possible from the various fleets and to ascertain the best divestment time for the redundant units of engines subject to the constraint of annual fuel availability.

Similarly, the constraint equation varies with engine type. Just as in the case of the fitness function, for fleets of the same engine type, the constraint equation depends on the number of undivested units of engines left in the fleet. It is also very important to note that the constraint equation varies yearly, which is also as a result of the difference in fuel availability for each year of the project. As an example, as seen in Appendix F, the constraint equation for any of the IC100 fleets at the first year of the project is as shown in Equation 4-2;

Equation 4-2

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

The value “59.3519” in Equation 4-2 is the fuel availability for the first year of the project as seen in Figure 3-5. “Fuel C” is the fuel consumption for the different units of engines. “C” is zero for the constraint to be satisfied. Assuming a unit of engine was divested at the end of the first year, the constraint equation for the second year becomes;

Equation 4-3

$$\begin{aligned}\mathrm{C} = \mathrm{Fuel\ C}(1) + \mathrm{Fuel\ C}(2) + \mathrm{Fuel\ C}(3) + \mathrm{Fuel\ }(4) + \mathrm{Fuel\ C}(5) + \mathrm{Fuel\ C}(6) \\ + \mathrm{Fuel\ C}(7) + \mathrm{Fuel\ C}(8) + \mathrm{Fuel\ C}(9) + \mathrm{Fuel\ C}(10) \\ + \mathrm{Fuel\ C}(11) - 51.6361\end{aligned}$$

The value “51.6361” in Equation 4-3 is the fuel availability for the second year of the project.

4.5.3.3 The variables

In the optimisation model used for this research, the variables are the TETs. Just like the fitness function and constraint equation, the number of variables at the beginning of the project differ for the various study engines. The AD43 fleets have 25 variables, the IC100 fleets have 12, and the SS296 and RH296 fleets have 4 variables each. The number of variables at the beginning of the project is the same as the number of units of engines in the starting fleet. Over the years of the project, the number of variables decreases with decrease in the number of units of engines in the fleet due to divestment.

4.5.3.4 The population size

A reliable population size can be gotten by a trial method. In this method, several trials are made using different values for the population size. The value used when the optimal solution is attained is good enough to be used, it is within the range of values to be used as the population size in the optimisation code.

In this research, different values were used for the population size. 10,000 was mostly used, lower values were used when the fleet composition became smaller as a result of gas turbine units divestment. There was need to reduce the population size after the reduction in the number of units of engines in the fleet. This is because the optimal solution was now being attained with lower values of population size within a shorter optimisation time compared to the optimisation time when a higher population size is being used. The optimisation time increases with increase in the population size.

4.5.3.5 Bounds specified

The Upper and Lower Bounds specified vary for the different engine types. The DP TETs of the various engine types were used as the Upper Bounds, thereby restricting the optimiser from exploring TETs higher than the DP for the purpose of avoiding extra maintenance cost as a result of operating at higher TETs. An exception to this was in the 10^{th} year for the clean fleet of the RH296 engine, in which a unit of an engine was allowed for operate at 1558K, as against the DP TET of 1543K. This was allowed for the purpose of maximally utilising the available fuel and optimising the power generated. At the beginning of the optimisation exercise, the Lower Bounds were set as zero. Later on, much higher values were used as Lower Bounds. TETs corresponding to efficiencies of around 0.2 were also used as Lower Bounds.

4.5.3.6 Number of generations

The maximum number of generations for iteration was specified as 200 in the model used. However, because the optimisations were converging at relatively lower number of generations (as an example 13), the maximum number of generations was reduced to 50 so that the changes in the total optimised power in the various generations could be visible in the results interface.

Some GA optimisations converge at much higher number of generations. The optimisation model used is useful for the purpose of this research. The following factors could have resulted to the optimisation converging at the number of generations it did;

- The simplicity of the fitness (objective) function
- It is a single objective optimisation, not multi-objective
- The simplicity of the constraint function
- It is an optimisation with a single constraint
- The size of the database (search domain) is relatively small

Finally, it should be noted that when a population size of 10,000 was used, in some years of the project the optimisation ran for about 9 hours, thereby doing a thorough search of the optimisation domain.

4.5.3.7 Optimisation convergence criteria

The optimisation convergence criteria used are “FunctionTolerance” and “ConstraintTolerance”. GA by default uses 1.0e-06 for both criteria. At the beginning of the optimisation exercise, 1.0e-06 was used for both criteria. However, while exploring the possibility of getting higher accuracy, 1.0e-09 was later used in most cases. These tolerances are limits which determine optimisation convergence.

4.5.4 The effect of the population size used in the optimisation code

The population size affects the length of time the optimiser runs and the accuracy of the optimisation results. It is therefore necessary to ascertain the population size that gives the maximum or minimum of whatever is being optimised. A reliable population size can be gotten by a trial method. In this method, several trials are made using different values for the population size. The value used when the optimal solution is attained is good enough to be used, it is within the range of values to be used as the population size in the optimisation code.

In this research, different values were used for the population size. 10,000 was mostly used, lower values were used when the fleet composition became smaller as a result of gas turbine units divestment. There was need to reduce the population size after the reduction in the number of units of engines in the fleet. This is because the optimal solution was now being attained with lower values of population size. The optimisation time increases with increase in the population size.

4.5.4.1 Sensitivity analysis on the effect of changes in population size on the results of the model

Sensitivity analysis was done to ascertain the effect of changes in population size on the results of the model. This was done using the SS296 fleet and considering the first year, the Upper bound used is the DP TET (1700K), whereas, 1000K was used as the Lower bound. Results show that population size in the range of 900 to 10,000 give higher accuracy than values below this range.

4.5.5 The effect of mutation function used in the optimisation code

The mutation function in the optimisation code provides genetic diversity and helps the algorithm to search a wider space. As a result, it increases the chances of the GA producing individuals with higher fitness values. The mutation function achieves this by either substituting for the genes lost from the population during the process of selection so that they can be tested in a new contest or by bringing the genes that were absent in the initial population [72, p.155-156]; [108].

4.6 Integrating GA in Matlab

Matlab has predefined functions including GA. While the code is written in Matlab, the search for the optimum solution is done by the GA tool. The optimisation code is written with an instruction for Matlab to call the GA. The optimisation was done by developing specific interfaces to connect with the GA in Matlab optimisation code, all within an automated design loop.

4.7 Recommendation

Other optimisation techniques such as Gradient-based method, Particle Swarm, Tabu search, Neural network, Simulated Annealing, Hill-climbing technique, etc could be explored by future researchers.

4.8 Chapter Summary

This chapter describes the GA tool and its operators when used for optimisation purposes. The aim of the optimisation, the objective function to be maximised and the optimisation constraint were also explained in this chapter. This chapter also described the GA in Matlab code developed and employed in this study. The chapter explained how the database (search domain) for the optimiser were generated.

A brief overview was done on gas turbine degradation, the reason for considering degradation of engines in this research was also explained. The effect of different rates of degradation on the project is accounted for in the preparation of the optimisation database for the degraded scenarios. These different rates of degradation are designated as optimistic (slow), medium and pessimistic (fast) degradation. The optimisation settings have been well described in this chapter. The effect of some GA parameters on the optimisation results were also highlighted.

5 OPTIMISATION RESULTS & THEIR INTEGRATION INTO THE TERA MODEL

5.1 Verification of the optimisation model & results

A major concern in this research is to optimise power production, best divestment time for the units of engines in the fleets and the economic return (NPV) from the project. These are major concerns in the mind of governments that want to invest in the economic utilisation of AG.

The baseline fleet is used as the reference fleet because it gives the best fleet composition possible without employing the help of an optimiser. The accuracy of the optimisation model and its result is verified by comparing the optimised power produced and the optimised best divestment time for the optimised AD43 clean fleet to that of the baseline fleet. Both cases are subject to the same constraint of annual fuel availability.

5.1.1 Comparison of the power production by the optimised AD43 clean and baseline fleets

Figures 5-1 and 5-2 show the difference in percentage and megawatt respectively between the optimised power production for the optimised AD43 clean fleet and that of the baseline fleet.

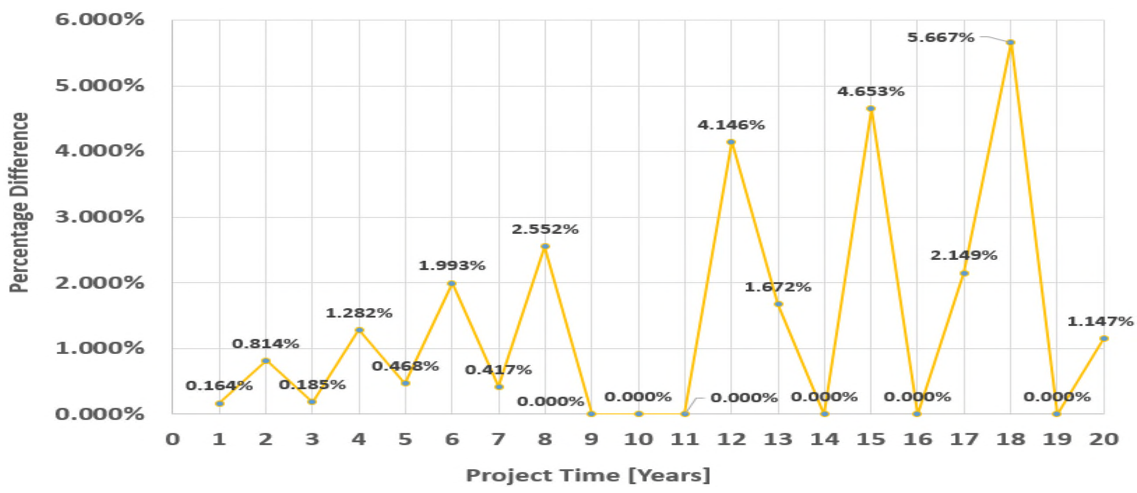


Figure 5-1: Percentage Difference in Power Production by the Optimised (Clean AD43) Fleet & the Baseline Fleet

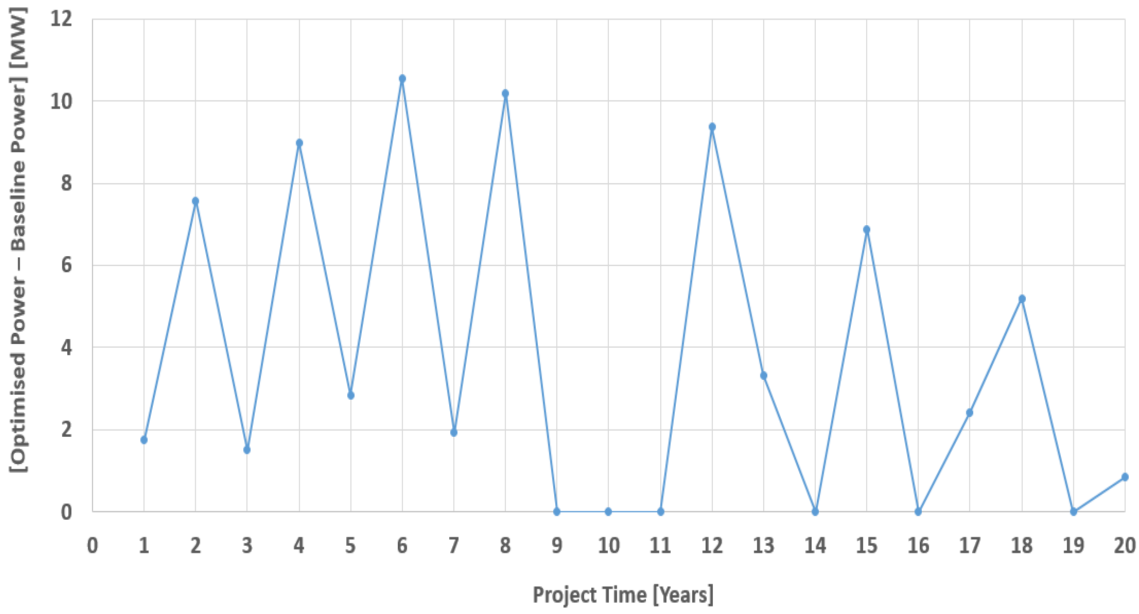


Figure 5-2: Difference in Power Production (MW) Between the Optimised Fleet and the Baseline Fleet

The main reason for the fluctuations observed in Figure 5-1 and 5-2 is the fact that various years of the project have varying fuel availability and varying number of engines in the fleets, hence, the difference in total optimised power for the baseline fleet and the AD43 optimised fleet (clean). Also, in determining the fleet composition, in order not to go beyond the design point TET limit to avoid higher operations and maintenance costs, very little quantity of fuel were unutilised by the baseline fleet in year 4, 5, 6, 8, 12 and 18. This has also contributed to the difference observed for just these years specified. As a recommendation, in achieving the fleet composition, future researchers could keep an upper bound limit greater than the design point TET with about 5K. This would help in full utilisation of all fuel, however, it will also increase the operations and maintenance cost. A future researcher should explore a better economic option.

Figure 5-3 shows the optimised power production for the optimised and baseline fleets on an annual basis. The annual maximum power from the baseline fleet was calculated as the sum of the power values corresponding to the baseline fleet composition shown in Table 3-5. Similarly, that of the optimised fleet is the sum of the optimised power values for the individual units of engines given by the optimiser. These optimised power values for the individual units of engines in the fleet are the power values corresponding to the optimised fleet composition found in section 5.2.1.1, Figure 5-8.

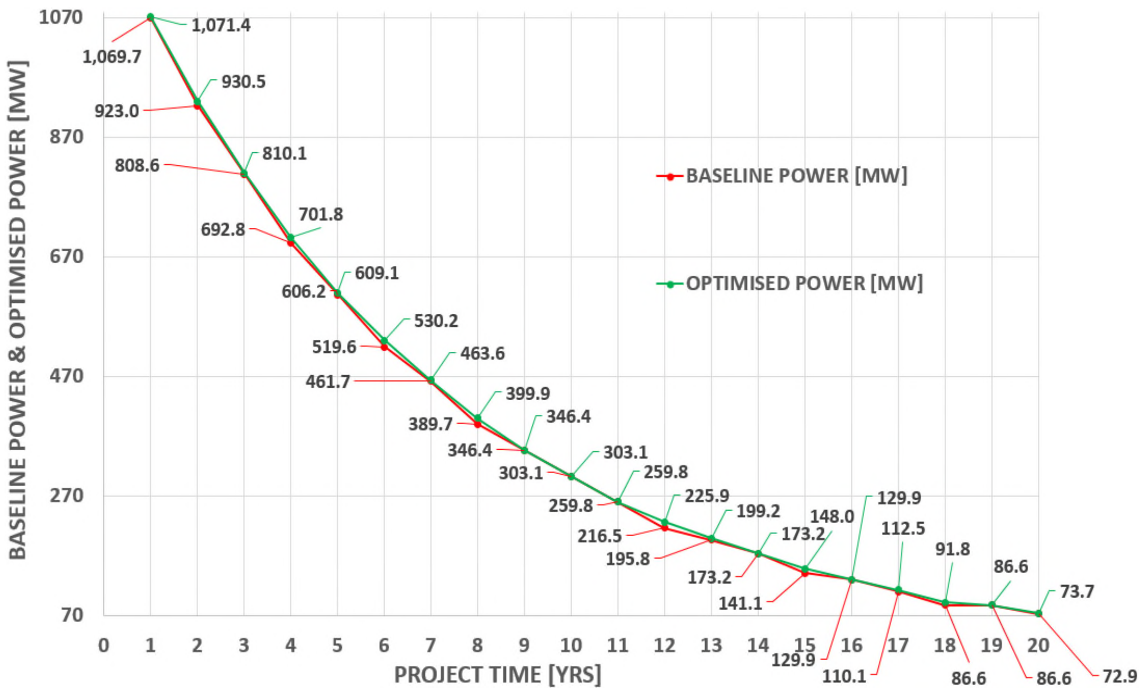


Figure 5-3: Annual Power Production Values for the Baseline and Optimised Fleets

Appendix G.1.8 and G.1.9 show screenshots of the total optimised power values for the clean AD43 optimised fleet for the first and second year of the project respectively.

Figures 5-4 and 5-5 show the sum of optimised power and the energy for the clean AD43 optimised fleet and the baseline fleet.

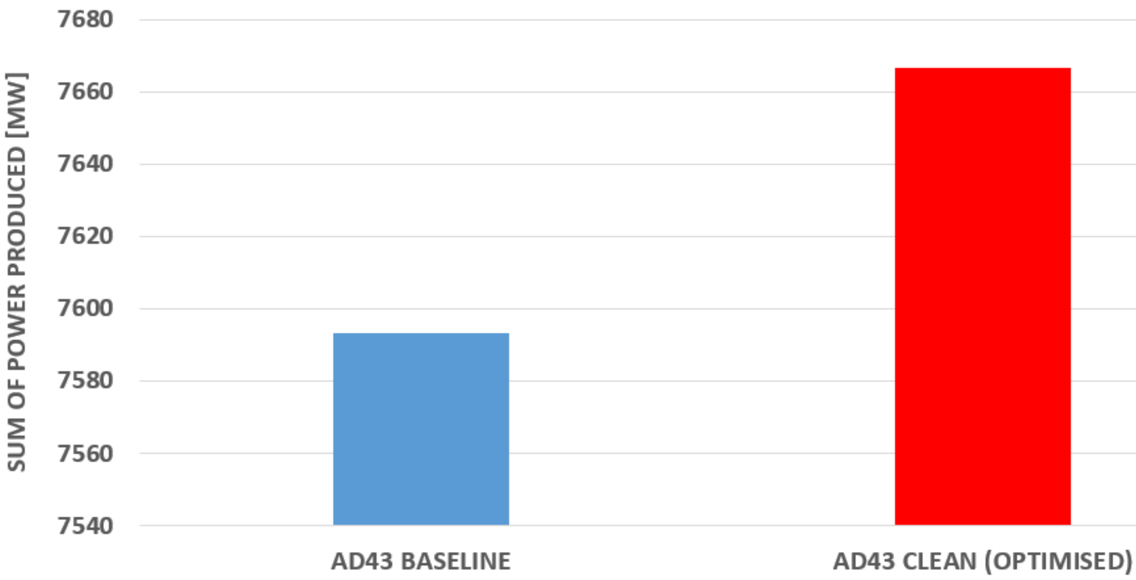


Figure 5-4: Sum of Power Produced (MW) in the Project by the Baseline & Optimised Fleets

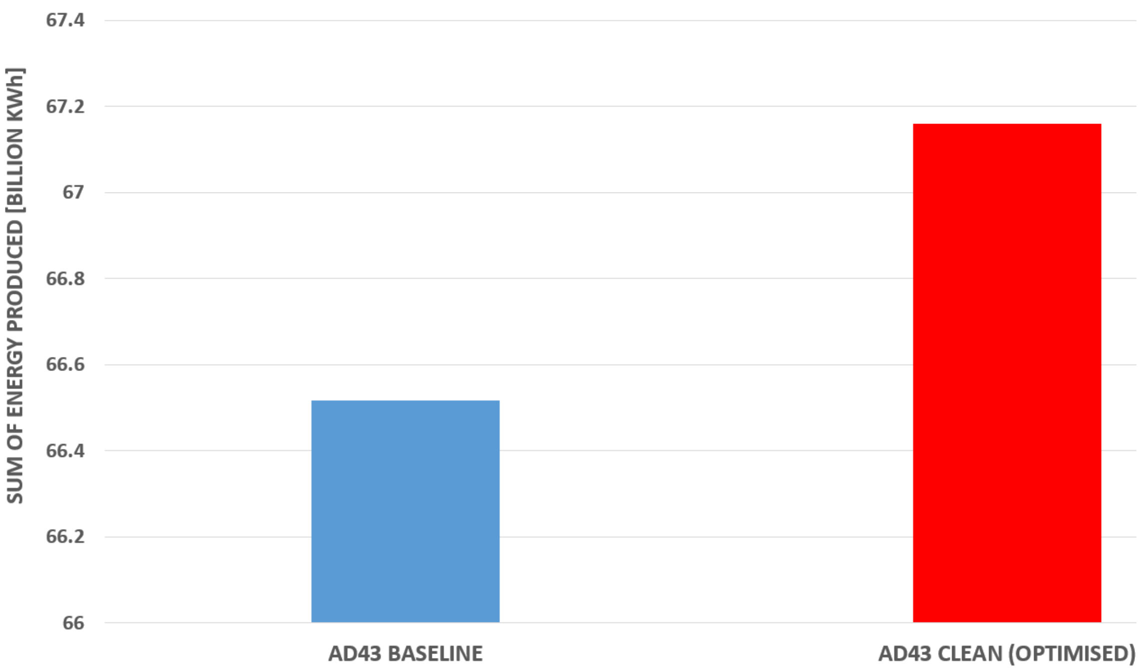


Figure 5-5: Sum of Energy Produced (Billion kWh) in the Project by the Baseline & Optimised Fleets

The big difference between the values of the optimised power and the energy for the clean AD43 optimised fleet and that of the baseline fleet as seen in Figure 5-1 to 5-5 justifies the approach of the optimisation model and its results.

5.1.2 Comparison of the optimised best divestment time for the optimised and baseline fleets

Figure 5-6 shows the optimised best divestment time for the units of engines and the total number of engines divested cumulatively, whereas, Figure 5-7 also shows same but in this case, the number of engines divested per year is shown. As seen from Figure 5-6 and 5-7, the optimiser shifted the divestment time for some of the units of the engines forward (rightward) as compared to the case of the baseline fleet. As an example, in the 4th, 5th, and 6th year of the project, more units of engines were divested in the baseline fleet than in the optimised fleet. This allows the units of engines in the optimised fleet to be maximally utilised before been divested, thereby leading to better economic utilisation of the fleet.

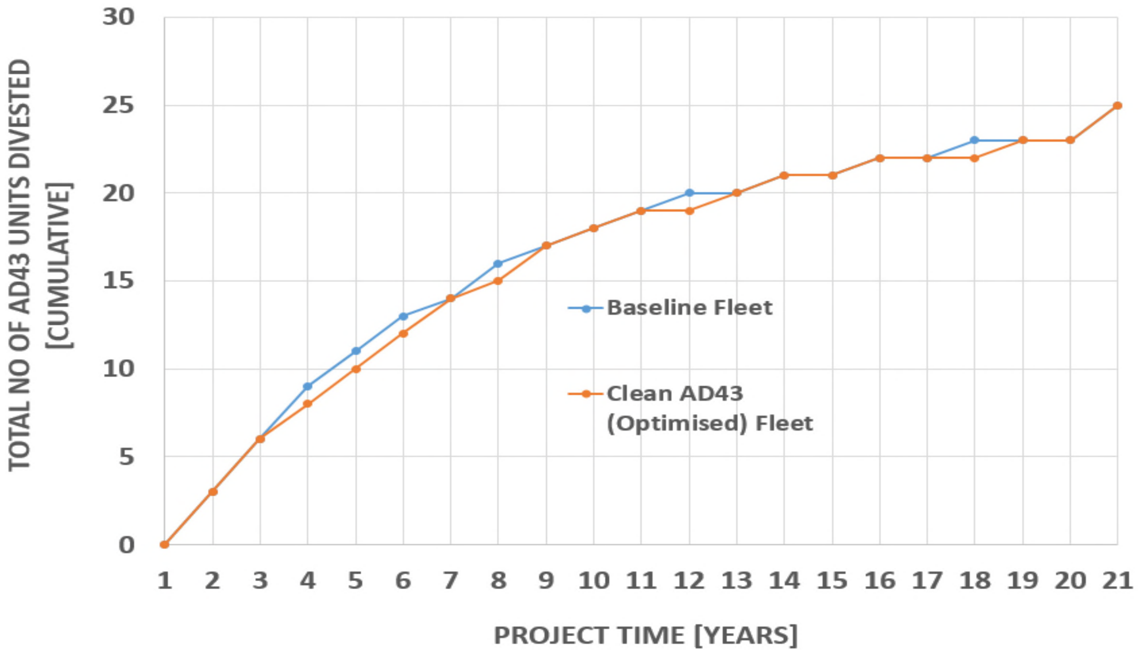


Figure 5-6: Optimised Best Divestment Time & the Number of Units of Engines Divested (Cumulative)

Figure 5-7: Optimised Best Divestment Time & the Number of Units of Engines Divested Yearly

5.2 Optimisation results for all clean & degraded fleets

The results of the optimisation exercise for the clean and degraded fleets (OPT, MED, and PES) for all the study engines – AD43, IC100, SS296 and RH296 gas turbine engines all show very high level of accuracy.

All the results from the optimisation exercise and the baseline scenario were integrated into the TERA framework, which then formed the basis for the economic analysis (NPV) of this project.

5.2.1 Optimised fleet composition for the study engines

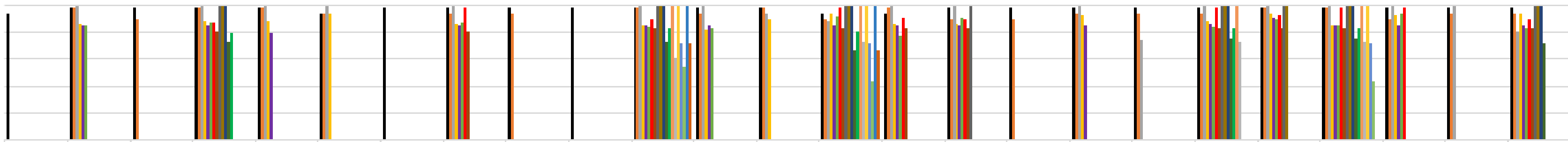
Any government that is investing in the economic utilisation of AG for power generation using gas turbines wants to ensure that their technical team is maximally utilising the units of engines subject to the constraint of depleting fuel availability. Hence the need for optimisation of the fleet composition.

The optimised fleet composition is the fleet with the optimum number of units, operating TET, maximum power and efficiency of each unit in the fleet, thereby yielding a good NPV. Also, the optimised fleet composition shows the optimum time and number of units to be divested from the fleet. When the optimised fleet composition is achieved, the optimiser outputs the performance of the fleet in terms of the TET, power, and efficiency, and it also gives the fuel consumed by the fleet (fuel flow).

5.2.1.1 Optimised fleet composition for the AD43 fleets

Figure 5-8 shows the optimised fleet composition for the AD43 clean fleet for the period of the 20 years. The AD43 fleet has a starting number of 25 units of engines as explained in section 3.5.1.3. Operating the various units of engines in the fleet at the various TETs shown in Figure 5-8, will yield the maximum power and efficiencies for the units of engines in the fleet subject to the optimisation constraint of annual fuel availability. Also, this fleet composition makes the fleet to have an improved economic return, the fleet composition gives the maximum possible power that can be achieved by operating this units of engines subject to the optimisation constraint. As can be seen from the optimised fleet composition (Figure 5-8), divestment of redundant units of engines commenced at the end of the 1st year with 3 units of AD43 engines. Divestment continued at most years of the project as the fuel availability is not enough to meet the fuel requirement of all the engines in the fleet, the final divestment occurred at the end of the project with 2 units of AD43 engine.

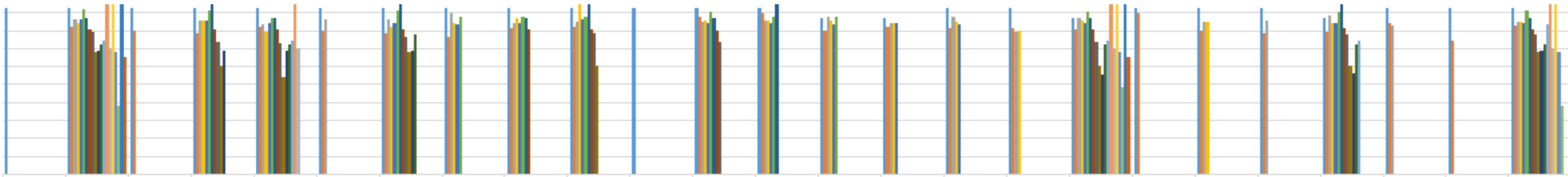
Figure 5-9 to Figure 5-11 show the optimised fleet composition for the OPT, MED and PES degraded AD43 fleets respectively. At the beginning of the project, that is, year 1, all fleets are operated as clean engines, implying that engine degradation is assumed to start from the second year.



	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	1534	1546	1546	1546	1546	1535	1546	1546	1546	1546	1546	1546	1546	1534	1534	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546
YR2		1545	1524	1545	1545	1535		1535	1535		1545	1535	1545	1524	1545	1524	1524	1535	1535	1535	1545	1545	1524	1535	1535
YR3		1549		1550	1550	1549		1549			1550	1550	1536	1522	1550	1549		1549	1486	1549	1549	1550	1550	1549	1501
YR4		1516		1522	1522	1534		1515			1514	1504	1523	1534	1516	1515		1532		1521	1534	1512	1533		1535
YR5		1514		1513	1498			1514			1513	1513		1513	1513	1514		1513		1517	1528	1514	1513		1513
YR6		1514		1517				1520			1510	1509		1528	1495	1528				1510	1525	1513	1536		1506
YR7				1520				1545			1524			1545	1526	1523				1545	1532	1545	1545		1524
YR8				1501				1501			1507			1508	1508	1508				1507	1508	1508			1507
YR9				1550							1550			1550		1550				1550	1550	1550			1550
YR10				1550							1550			1550						1550	1550	1550			1550
YR11				1550							1550			1550						1550		1550			1550
YR12				1484							1483			1466						1488		1489			1480
YR13				1500							1507			1503						1507		1507			
YR14											1550			1550						1550		1550			
YR15											1453			1483						1483		1483			
YR16											1550			1550								1550			
YR17											1480			1480								1480			
YR18											1437			1408								1408			
YR19											1550			1550											
YR20											1481			1467											

ANNUAL NUMBER OF AD43 UNITS IN THE FLEET & THEIR TETs [K]

Figure 5-8: Optimised Fleet Composition for AD43 Clean Fleet

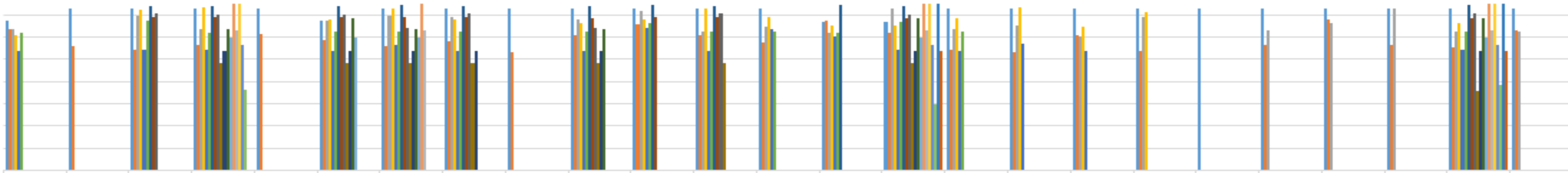


	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546	1534	1534	1546	1546	1534	1546	1546	1546	1535	1546	1546	1546
YR2		1525	1520	1518	1525	1521	1517	1513	1523	1524		1535	1540	1521	1525	1523	1523	1522	1540	1521	1517	1519	1529	1509	1526
YR3		1533		1531	1528	1533	1533	1540	1529	1530		1531	1531	1536	1529	1536	1519	1534		1530	1531	1538	1526		1530
YR4		1529		1531	1518		1524	1529	1534	1550		1531	1531	1531	1529	1530	1520	1531		1529		1529			1531
YR5		1532		1532	1528		1528	1528	1528	1532		1528	1529	1528	1528	1528		1528				1528			1528
YR6		1543		1543	1534		1542	1535	1536	1535		1542	1536	1536				1542				1541			1543
YR7		1534		1550	1534		1550		1534	1550		1534	1550					1534				1550			1534
YR8		1521		1521	1521		1522		1522	1522		1521						1522				1522			1522
YR9		1518		1507	1507		1514			1518		1507						1507				1515			1517
YR10		1496		1482	1468		1496			1482								1482				1482			1496
YR11		1498		1498	1498		1498											1472				1472			1498
YR12		1504			1504		1516											1504				1504			1504
YR13		1509			1509													1509				1509			1527
YR14		1550			1550													1550							1550
YR15		1500			1500													1500							1500
YR16		1550																1550							1550
YR17		1496																1496							1496
YR18		1436																1457							1436
YR19		1550																1550							
YR20		1490																1490							

PROJECT TIME [YRS]

ANNUAL NUMBER OF AD43 UNITS IN THE FLEET & THEIR TETs [K]

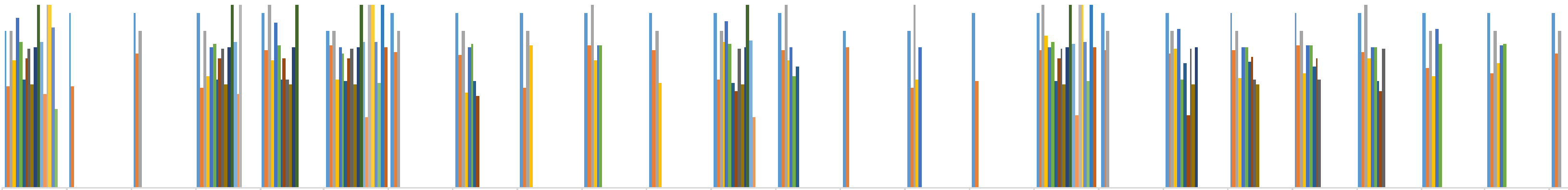
Figure 5-9: Optimised Fleet Composition for AD43 OPT Degraded Fleet



PROJECT TIME [YRS]	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	1534	1546	1546	1546	1546	1535	1546	1546	1546	1546	1546	1546	1546	1534	1534	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546
YR2	1527	1512	1508	1514	1522	1517	1512	1516	1507	1521	1531	1522	1515	1535	1524	1509	1507	1522	1507		1513	1536	1513	1511	1526
YR3	1527		1539	1527		1535	1539	1538		1536	1543	1525	1530	1524	1546	1527	1531	1521	1538		1527	1533	1545	1525	1525
YR4	1522		1544	1547		1536	1546	1536		1533	1536	1546	1539	1530	1531	1538	1547	1530	1543					1533	
YR5	1507		1508	1508		1508	1513	1508		1508	1529	1507	1528	1521	1508	1508	1514	1508						1509	
YR6	1525		1535	1524		1525	1525	1525		1525	1533	1525	1525	1524	1534	1525								1525	
YR7			1548	1548		1548	1549	1548		1548	1549	1548		1549	1548									1549	
YR8			1538	1538		1538	1538	1538		1537	1538	1538			1538									1538	
YR9			1541	1541		1541	1528	1541		1528		1541			1541									1541	
YR10				1497		1497	1497	1497		1497		1497			1497									1472	
YR11				1508		1508	1508	1508		1508					1508									1508	
YR12				1527		1537	1527			1528					1538									1537	
YR13				1520		1520	1520								1520									1520	
YR14				1550			1550								1550									1550	
YR15				1526			1526								1526									1526	
YR16				1550											1550									1550	
YR17				1513											1513									1513	
YR18				1472											1460									1477	
YR19															1550									1550	
YR20															1508									1508	

ANNUAL NUMBER OF AD43 UNITS IN THE FLEET & THEIR TETs [K]

Figure 5-10: Optimised Fleet Composition for AD43 MED Degraded Fleet



	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	1534	1546	1546	1546	1546	1535	1546	1546	1546	1546	1546	1546	1546	1534	1534	1546	1546	1546	1546	1546	1546	1546	1546	1546	1546
YR2	1501	1502	1521	1501	1523	1526	1522	1520	1500	1526	1522	1505	1523	1525	1500	1504	1523	1523	1521	1523	1526	1522	1512	1509	1521
YR3	1535		1534	1534	1550	1534	1535	1534	1534	1550	1534	1534	1550		1550		1550	1534	1534	1534	1534	1550	1534	1534	1534
YR4	1517			1507	1517	1505		1498	1525	1517	1503	1527	1517		1505		1532		1524	1506	1509	1518	1507	1515	
YR5	1542			1525	1539	1525		1525		1526		1540	1525		1525		1525		1536	1525	1525	1525	1535	1526	
YR6	1527			1527	1525	1521		1526		1526		1527	1507				1527		1505	1525	1526	1525	1527	1527	
YR7	1505			1505	1506	1504		1504				1503	1513				1505		1515	1516	1513	1504			
YR8	1518			1518	1518	1518		1495				1498					1518		1484	1518	1518	1498			
YR9	1524			1524	1505	1524						1524					1524		1524	1505	1505	1524			
YR10	1502			1502	1502	1502						1502					1502		1502	1502					
YR11	1525			1525	1525	1525						1525					1525		1525						
YR12	1550			1550	1550	1550						1550					1550								
YR13	1528			1528		1528						1528					1527								
YR14	1497			1497		1483						1483					1483								
YR15	1550			1550		1550											1550								
YR16	1550					1550											1550								
YR17	1537					1528											1528								
YR18	1488					1503											1504								
YR19						1550											1550								
YR20						1525											1525								

PROJECT TIME [YRS]

ANNUAL NUMBER OF AD43 UNITS IN THE FLEET & THEIR TETs [K]

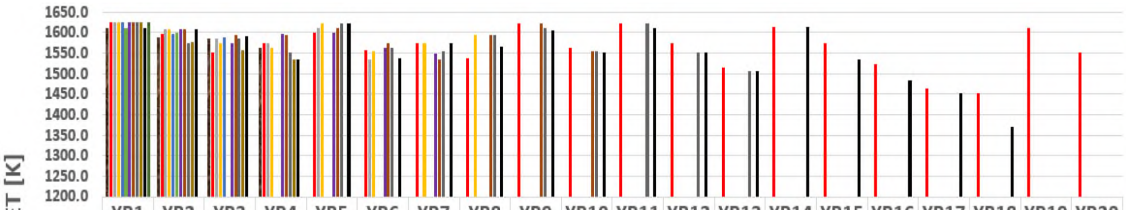
Figure 5-11: Optimised Fleet Composition for AD43 PES Degraded Fleet

The screenshots showing the optimised fleet composition for the 1st and 2nd year of the project for the AD43 clean (optimised) fleet as given by the optimiser are shown in Appendix G.1.8 and G.I.9. They are designated as “Current Best Individuals”, their values were exported to excel for clarity.

5.2.1.2 Optimised Fleet Composition for the IC100 Fleets

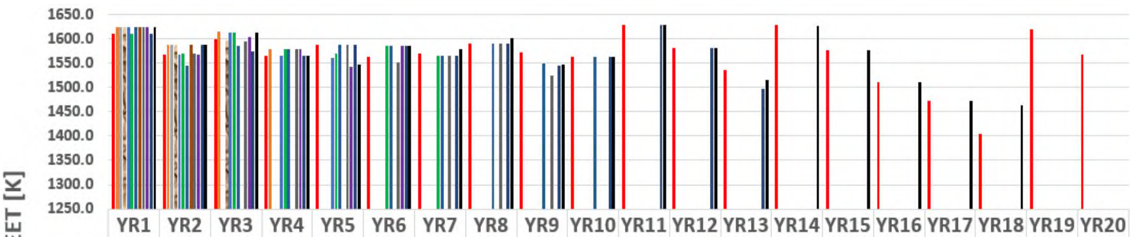
The IC100 fleet has a starting number of 12 units of the engine. This number was chosen by dividing the fuel availability at the 1st year of the project (59.3519Kg/s) by the fuel consumption requirement of the engine at design point (5.0401Kg/s). The fuel available at the 1st year can conveniently serve 11 units of the engine running at design point while the remaining fuel can serve 1 more unit of the engine running at a part-load. This forms the basis why 12 units of IC100 was chosen as the number of units of engine in the starting fleet.

Figure 5-12 to Figure 5-15 show the optimised fleet compositions for the clean, OPT, MED and PES degraded fleets of the IC100 engine respectively. The figures show the number of units of engines in the fleets, their operating TETs and the divestment sequence (number of units of engines divested and the time). In order to maximise the power production subject to the annual fuel availability, the units of engines in the fleets have to be operated at the TETs shown in the figures.



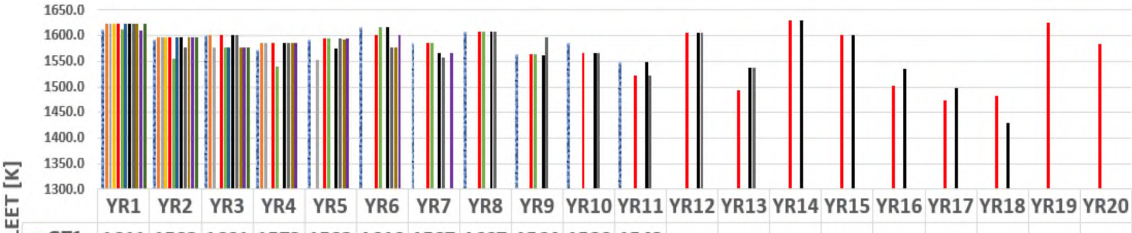
	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1611	1588	1585	1563																
GT2	1624	1596	1552	1575	1599	1557	1574	1538	1621	1562	1622	1574	1515	1612	1574	1524	1462	1451	1611	1552
GT3	1624	1608	1585	1574	1610	1535														
GT4	1624	1608	1575	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 5-12: Optimised Fleet Composition for IC100 Clean Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1611	1568	1600	1565	1588	1562	1570	1590	1572	1562	1630	1581	1534	1630	1577	1511	1471	1403	1619	1568
GT2	1624	1588	1614	1578																
GT3	1624	1588																		
GT4	1624	1588	1597																	
GT5	1624	1568	1613	1565	1559															
GT6	1611	1568	1613	1578	1570	1585	1564													
GT7	1624	1544	1586	1578	1588	1585	1564	1589	1548	1562										
GT8	1624	1588																		
GT9	1624	1568	1595	1578	1589	1552	1564	1589	1525											
GT10	1624	1568	1604	1578	1542	1585														
GT11	1611	1588	1574	1565	1588	1584	1564	1590	1544	1562	1630	1581	1497							
GT12	1624	1588	1613	1565	1548	1585	1578	1600	1546	1562	1630	1581	1516	1626	1577	1511	1471	1463		

Figure 5-13: Optimised Fleet Composition for IC100 OPT Degraded Fleet

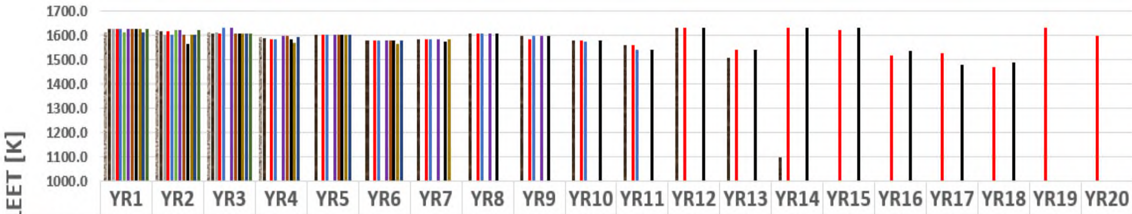


	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1611	1592	1601	1573	1592	1616	1587	1607	1564	1586	1548									
GT2	1624	1597	1601	1586																
GT3	1624	1597	1577	1586	1553															
GT4	1624	1597																		
GT5	1624	1597	1601	1586	1595	1601	1587	1607	1565	1565	1522	1605	1494	1630	1601	1503	1473	1482	1626	1584
GT6	1611	1555	1577	1539	1595	1616	1587	1607	1565											
GT7	1624	1597	1577																	
GT8	1624	1597	1601	1586	1574	1616	1566	1607	1562	1565	1548	1605	1537	1630	1601	1534	1499	1429		
GT9	1624	1578	1601	1586	1595	1577	1557	1607	1597	1565	1522	1605	1537							
GT10	1624	1597	1577	1586	1593	1577														
GT11	1611	1597	1577	1586	1595	1602	1566													
GT12	1624	1596	1577																	

PROJECT TIME [YRS]

GT1 GT2 GT3 GT4 GT5 GT6 GT7 GT8 GT9 GT10 GT11 GT12

Figure 5-14: Optimised Fleet Composition for IC100 MED Degraded Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1611	1619	1610	1591																
GT2	1624	1618	1608	1590	1603	1577	1584	1605	1595	1580	1559	1630	1508	1100						
GT3	1624	1601	1613																	
GT4	1624	1617	1608	1582	1603	1577	1584	1604	1581	1579	1560	1630	1542	1630	1622	1517	1525	1468	1630	1599
GT5	1624	1604	1630	1582	1603	1577	1584	1604	1599	1573	1542									
GT6	1611	1620																		
GT7	1624	1619	1630	1596	1604	1577	1584	1604	1599											
GT8	1624	1602	1608	1599	1602	1577														
GT9	1624	1565	1609	1583	1603	1577	1575	1604	1599	1580	1542	1630	1542	1630	1630	1535	1477	1490		
GT10	1624	1603	1608	1567	1603	1565	1584													
GT11	1611	1603	1608	1594	1602	1577														
GT12	1624	1619	1608																	

PROJECT TIME [YRS]

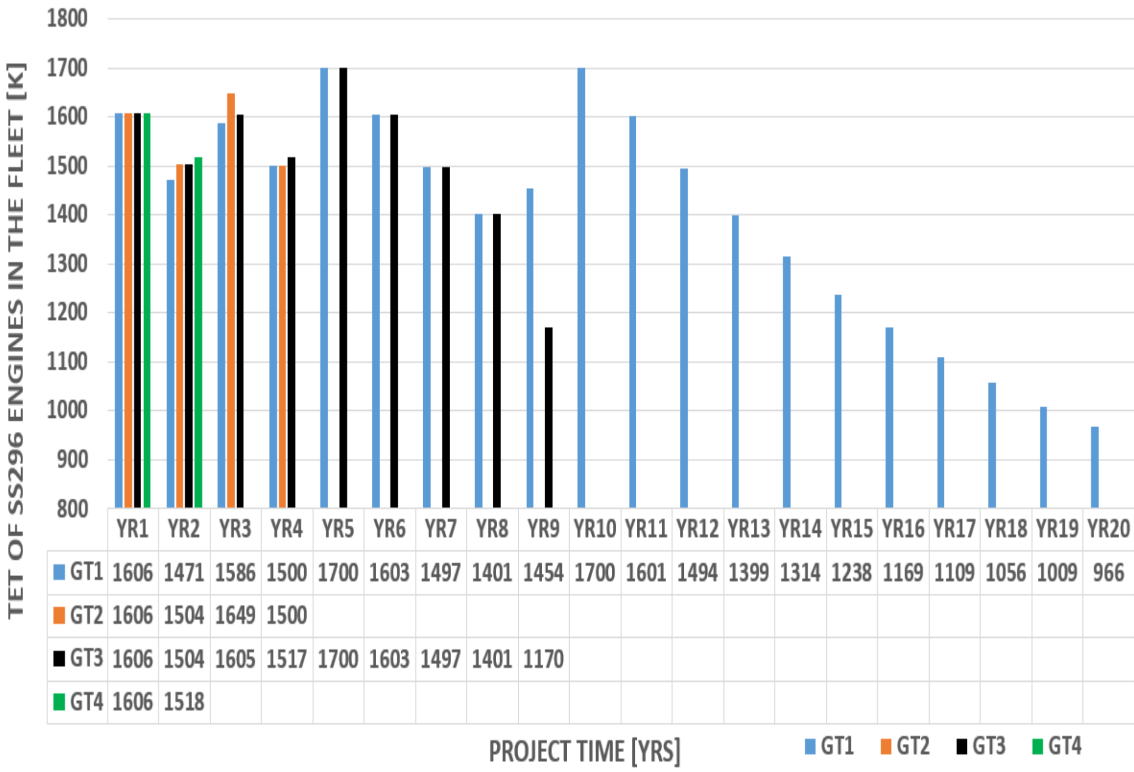
GT1 GT2 GT3 GT4 GT5 GT6 GT7 GT8 GT9 GT10 GT11 GT12

Figure 5-15: Optimised Fleet Composition for IC100 PES Degraded Fleet

5.2.1.3 Optimised Fleet Composition for the SS296 Fleets

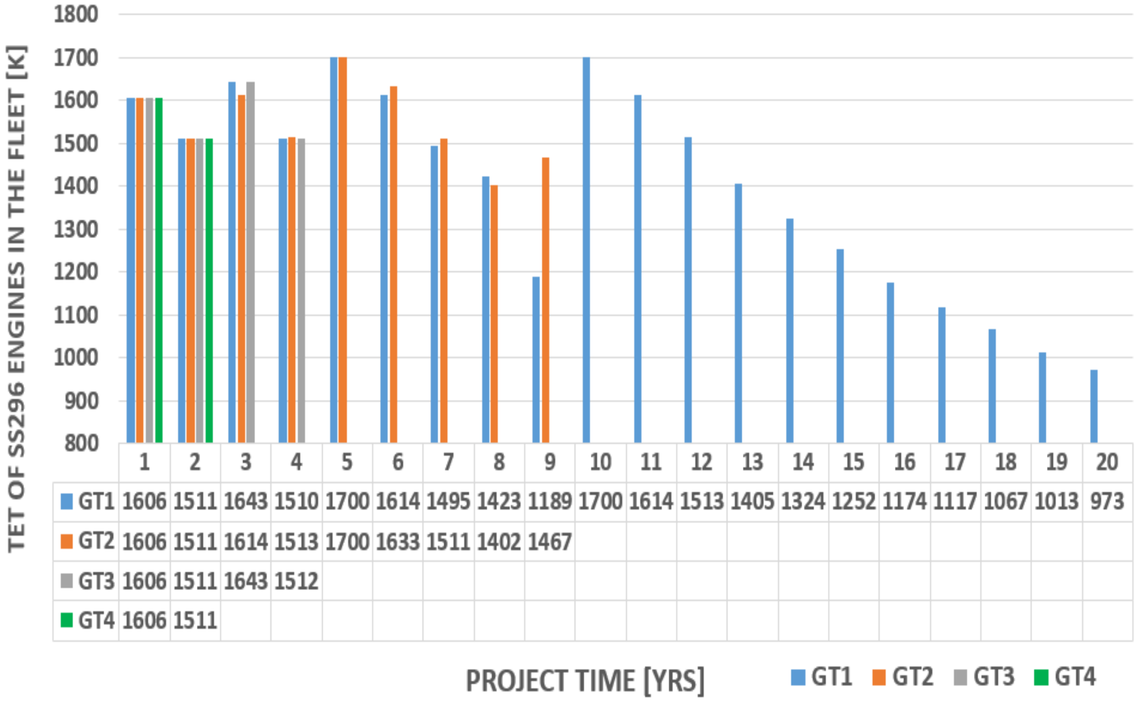
The SS296 fleet has a starting number of 4 units of the engine. This number was gotten by dividing the fuel availability at the 1st year of the project (59.3519Kg/s) by the fuel consumption requirement of the engine at design point (16.5794Kg/s). The fuel available at the 1st year can conveniently serve 3 units of the engine running at design point while the remaining fuel can to serve 1 more unit of the engine running at a part-load. This is the reason why 4 was chosen as the number of units of engines in the starting fleet.

Figure 5-16 to Figure 5-19 show the optimised fleet compositions for the clean, OPT, MED and PES degraded fleets of the SS296 engine respectively.



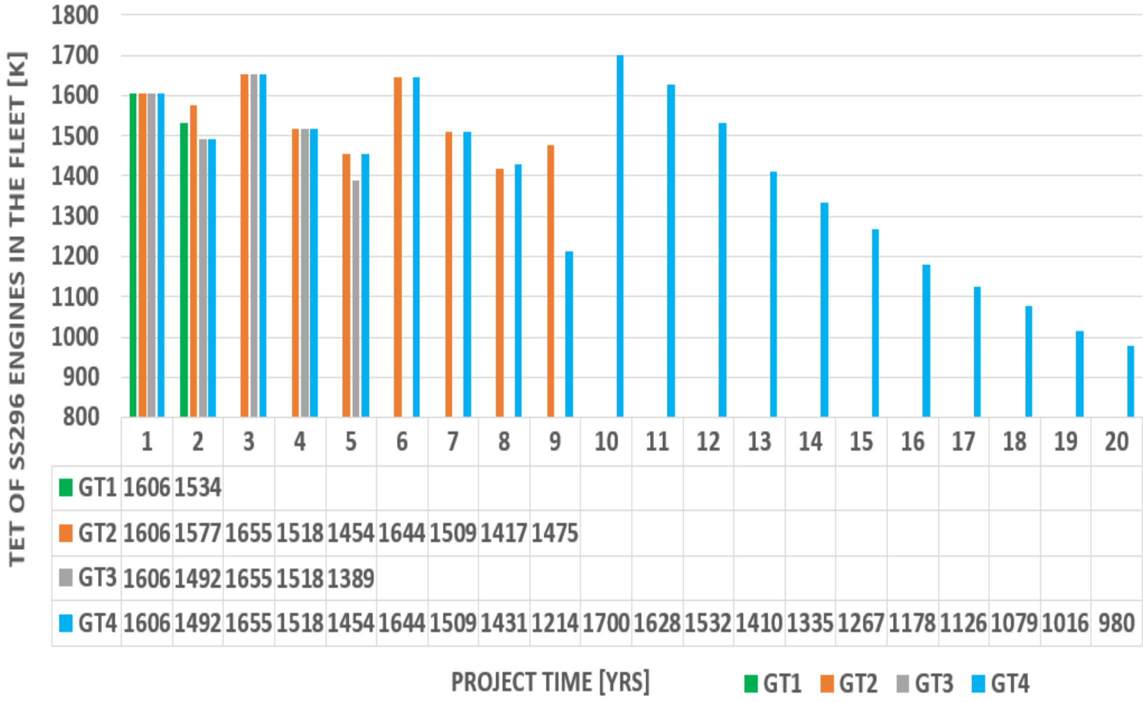
	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	1606	1471	1586	1500	1700	1603	1497	1401	1454	1700	1601	1494	1399	1314	1238	1169	1109	1056	1009	966
GT2	1606	1504	1649	1500																
GT3	1606	1504	1605	1517	1700	1603	1497	1401	1170											
GT4	1606	1518																		

Figure 5-16: Optimised Fleet Composition for SS296 Clean Fleet



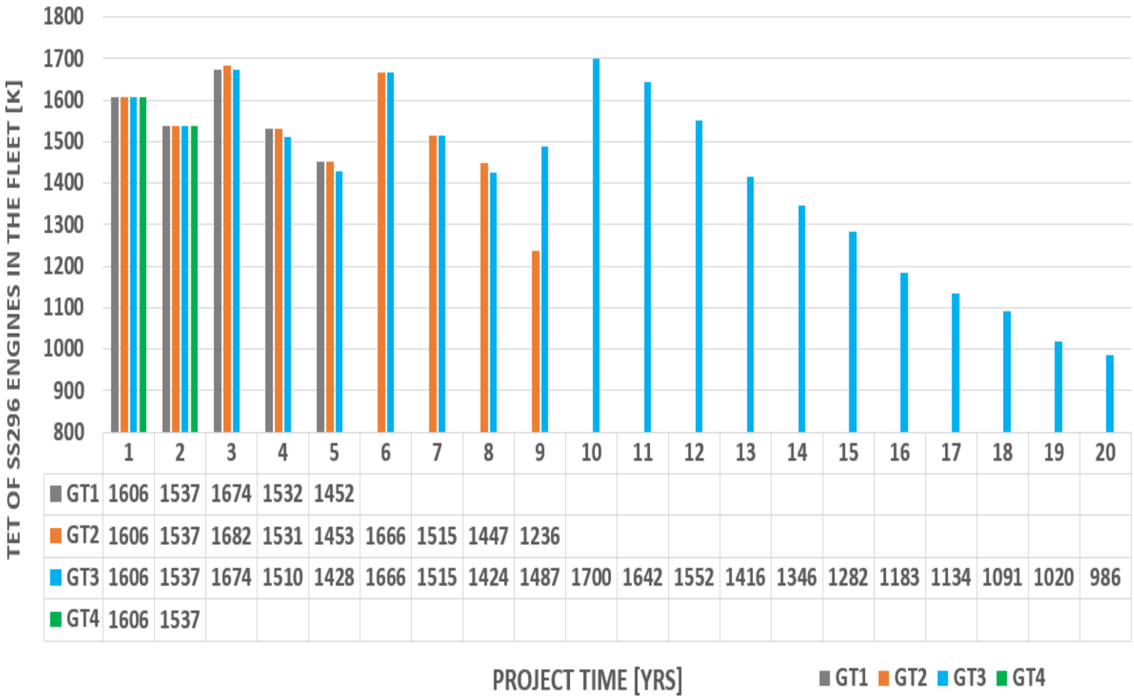
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GT1	1606	1511	1643	1510	1700	1614	1495	1423	1189	1700	1614	1513	1405	1324	1252	1174	1117	1067	1013	973
GT2	1606	1511	1614	1513	1700	1633	1511	1402	1467											
GT3	1606	1511	1643	1512																
GT4	1606	1511																		

Figure 5-17: Optimised Fleet Composition for SS296 OPT Degraded Fleet



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GT1	1606	1534																		
GT2	1606	1577	1655	1518	1454	1644	1509	1417	1475											
GT3	1606	1492	1655	1518	1389															
GT4	1606	1492	1655	1518	1454	1644	1509	1431	1214	1700	1628	1532	1410	1335	1267	1178	1126	1079	1016	980

Figure 5-18: Optimised Fleet Composition for SS296 MED Degraded Fleet



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
GT1	1606	1537	1674	1532	1452															
GT2	1606	1537	1682	1531	1453	1666	1515	1447	1236											
GT3	1606	1537	1674	1510	1428	1666	1515	1424	1487	1700	1642	1552	1416	1346	1282	1183	1134	1091	1020	986
GT4	1606	1537																		

Figure 5-19: Optimised Fleet Composition for SS296 PES Degraded Fleet

5.2.1.4 Optimised Fleet Composition for the RH296 Fleets

The RH296 fleet has a starting number of 4 units of the engine. This number was gotten by dividing the fuel availability at the 1st year of the project (59.3519Kg/s) by the fuel consumption requirement of the engine at design point (16.4153Kg/s). The fuel available at the 1st year can conveniently serve 3 units of the engine running at design point while the remaining fuel can serve 1 more unit of the engine running at a part-load. This is the reason why 4 was chosen as the number of units of engines in the starting fleet.

Figure 5-20 to Figure 5-23 show the optimised fleet compositions for the clean, OPT, MED and PES degraded fleets of the RH296 engine.

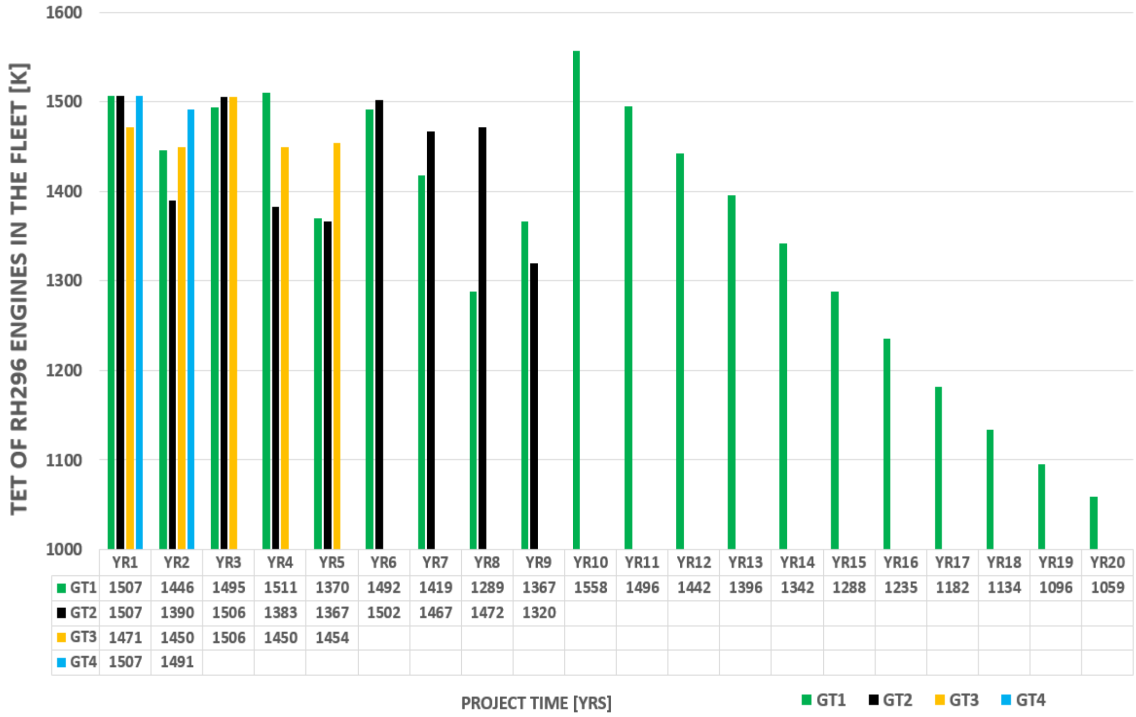


Figure 5-20: Optimised Fleet Composition for RH296 Clean Fleet

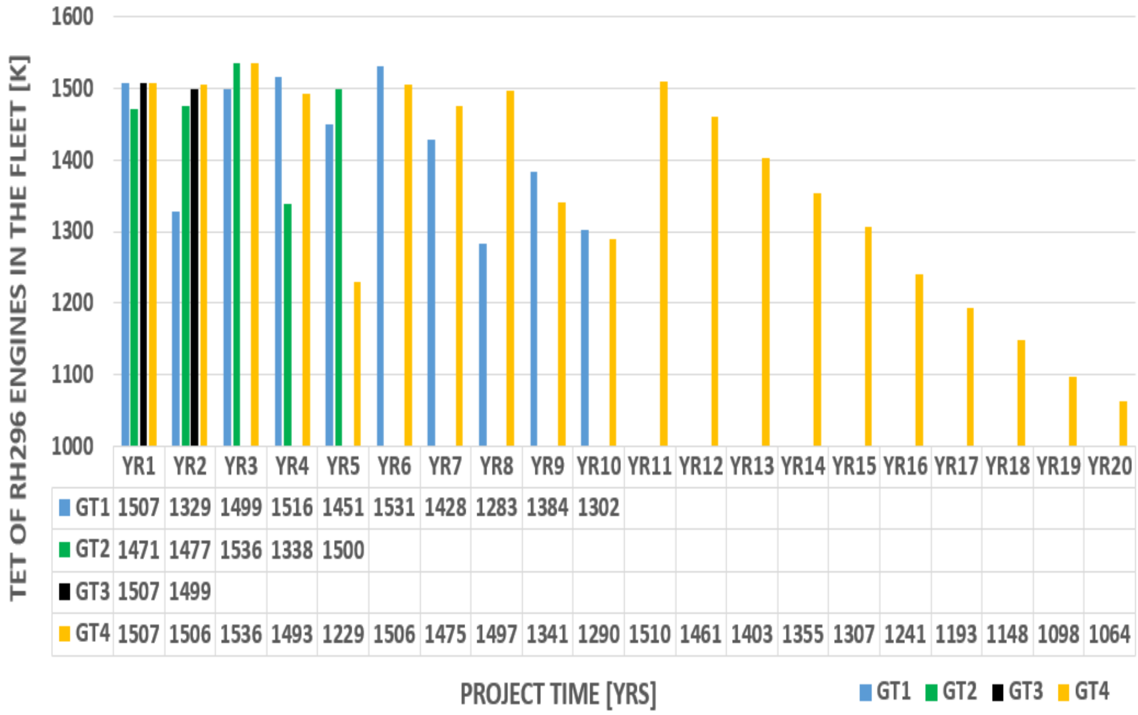


Figure 5-21: Optimised Fleet Composition for RH296 OPT Degraded Fleet

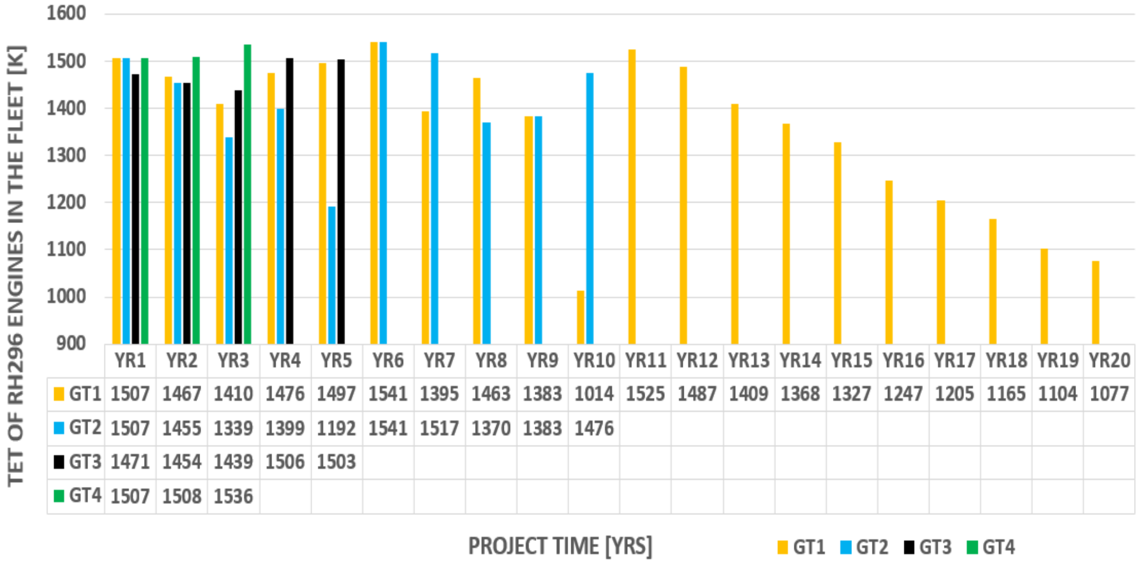


Figure 5-22: Optimised Fleet Composition for RH296 MED Degraded Fleet

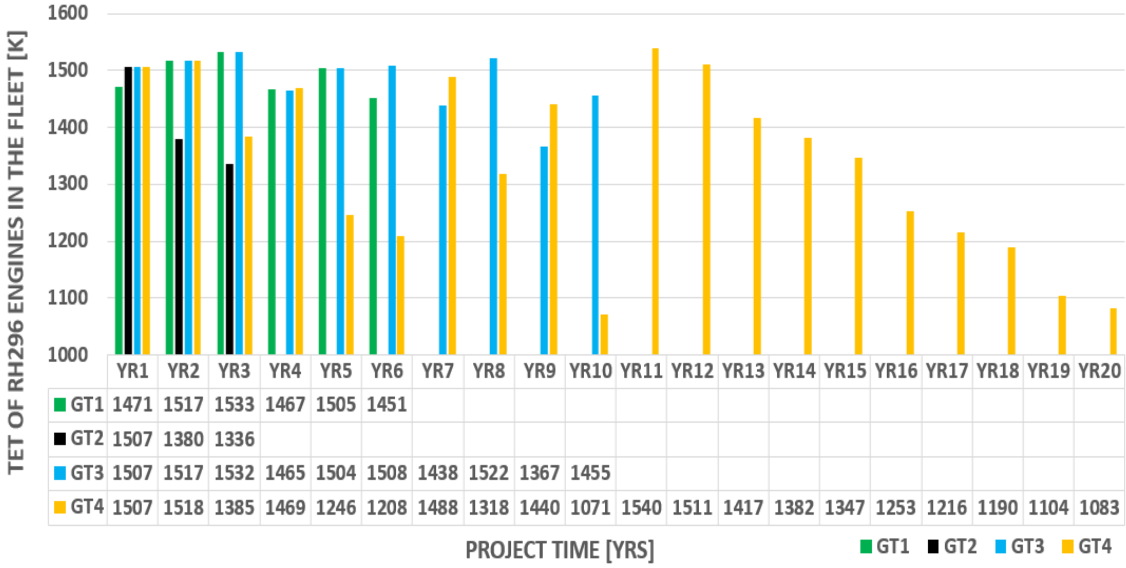


Figure 5-23: Optimised Fleet Composition for RH296 PES Degraded Fleet

On comparing the TETs of the units of engines in the clean fleet and those of the degraded fleets for the same engine type, it is observed that the units of engines in the degraded fleets had to be operated at higher TETs in order to fully utilise the available fuel.

A key observation made is that engine degradation affects the divestment time of the units of engines. This is discussed in the next sub-section.

5.2.2 Optimised engine units' best divestment time for all fleets

Exploring the impact of gas turbine degradation on the divestment time for the redundant units of engines in a fleet is the aim and major contribution to knowledge of this research. Knowledge about the impact of degradation on divestment time helps guide investors. Governments who want to invest in the economic use of AG for power generation using gas turbines would want to know the effect of gas turbine degradation on divestment time and on the economic use of associated gas. Investors will also be interested in knowing the best divestment time for the redundant units of engines, this would help in maximising profit and forward planning.

Figure 5-24 to Figure 5-31 show the optimised best divestment time for the units of engines in the various fleets, together with the effect of gas turbine degradation on the divestment time of the redundant units of engines. As seen from the figures, degradation extends the divestment time, the higher the level of degradation, the later the divestment time. Considering the AD43 fleets (Figure 5-24 and Figure 5-25), it is observed that at the 2nd year of the project, the number of units of engines that were divested are 3, 3, 2, 1, 0 for the baseline, clean (optimised), OPT degraded, MED degraded and PES degraded fleets respectively. At the 3rd year, the total (cumulative) number of units of engines that have been divested are 6, 6, 5, 4, 3 for the baseline, clean (optimised), OPT degraded, MED degraded and PES degraded fleets respectively. The effect of degradation in extending the divestment time for the units of engines continued until the 15th year of the project as seen Figure 5-24 and Figure 5-25. Degradation has similar effect on the divestment time for the units of engines in the IC100, SS296 and RH296 fleets as seen in Figure 5-26 to Figure 5-31.

One of the technical explanation for this occurrence is that, the fuel requirements to operate the degraded units of engines are less, and the divestment was as a result of units of engines being redundant due to shortage of fuel availability. It therefore implies that the more degraded fleets will have their units of engines running for a longer time before being divested. This prolonging of the time of usage of the units of engines in the degraded fleet has a positive impact on the economic utilisation of the fleets. It leads to better economic returns from the units of engines in the fleet, this is in comparison to a case where these same units of engines in these degraded fleets get divested earlier. Divesting a unit of engine at its best divestment time causes that unit of engine to be maximally utilised before being divested, which tends to increase the economic productivity of the fleet.

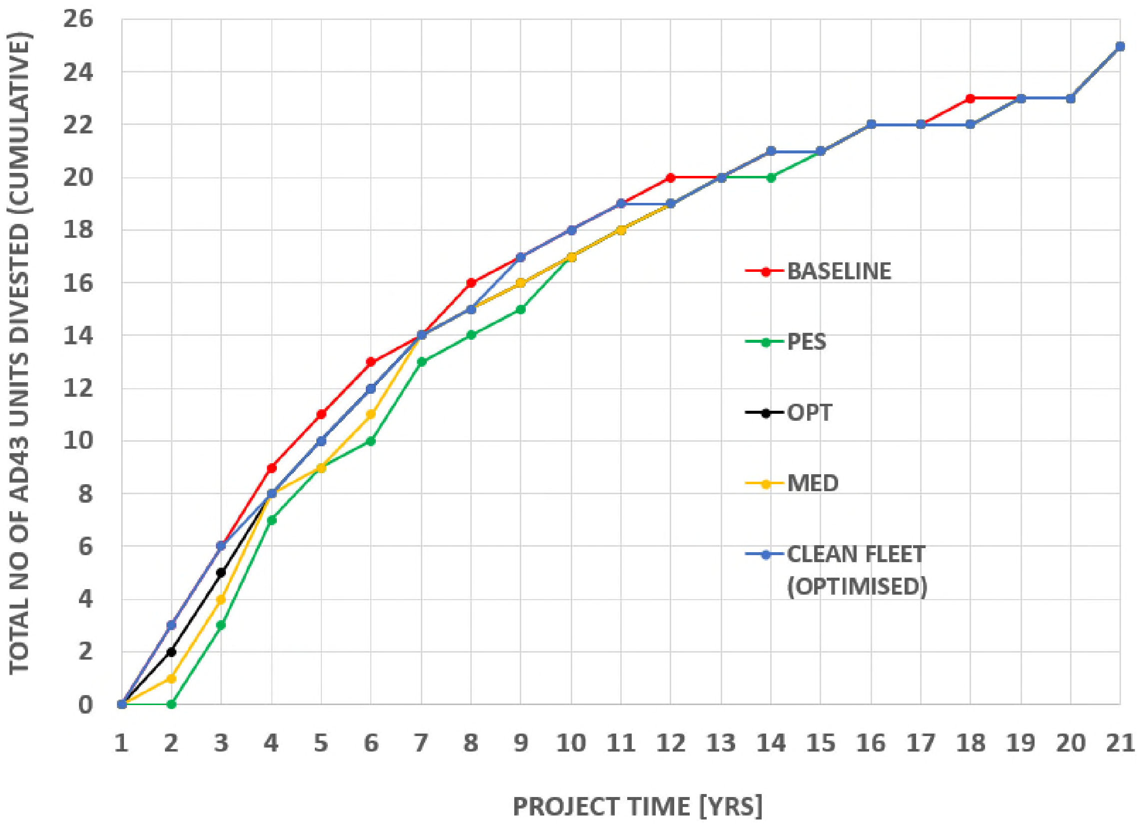


Figure 5-24: Optimised Engine Units' Best Divestment Time & the Effect of Gas Turbine Degradation on Divestment Time [AD43 Fleets]

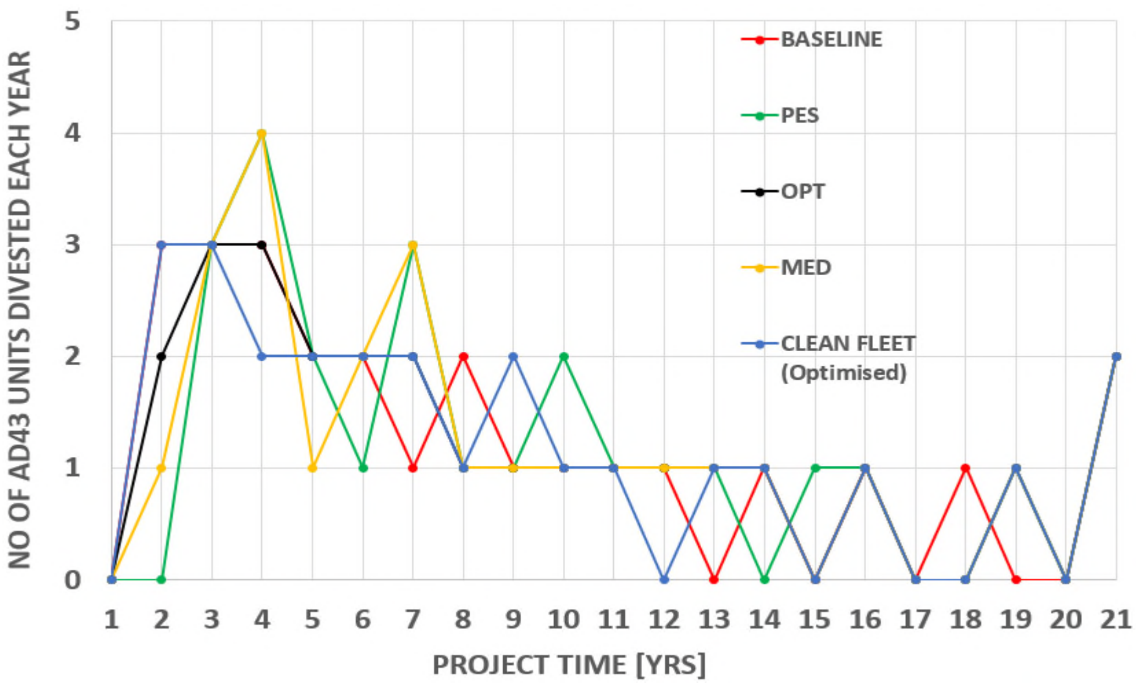


Figure 5-25: Number of AD43 Units Divested Yearly

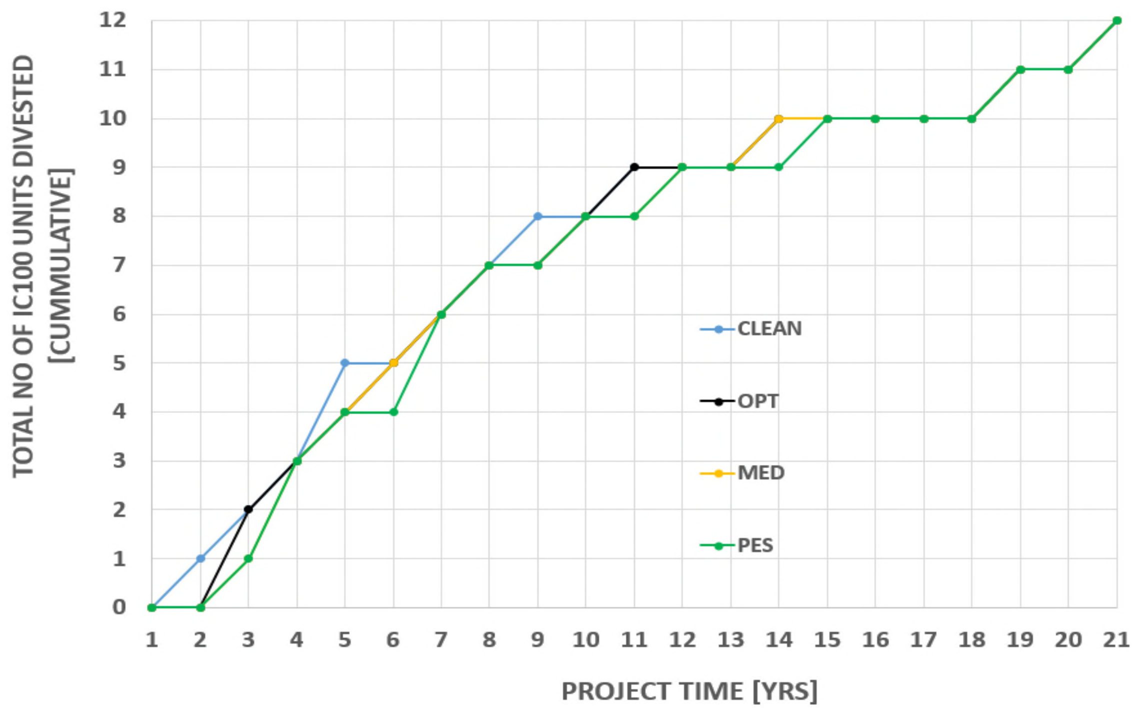


Figure 5-26: Optimised Engine Units' Best Divestment Time & the Effect of Gas Turbine Degradation on Divestment Time [IC100 Fleets]

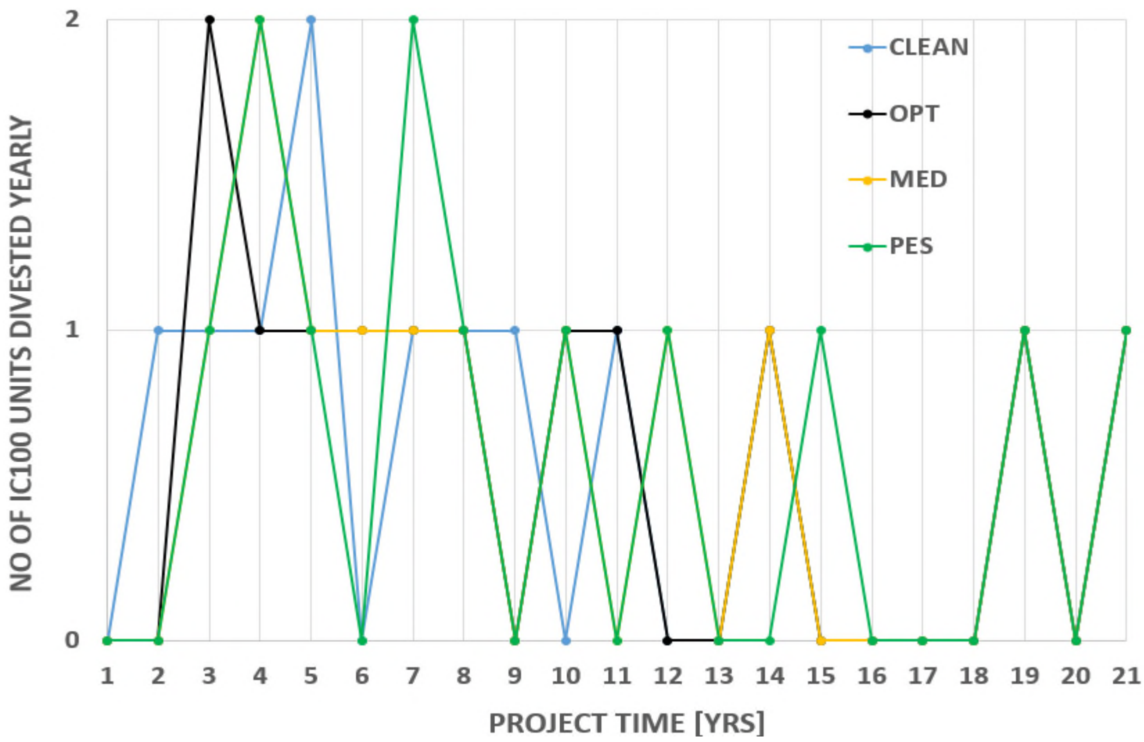


Figure 5-27: Number of IC100 Units Divested Yearly

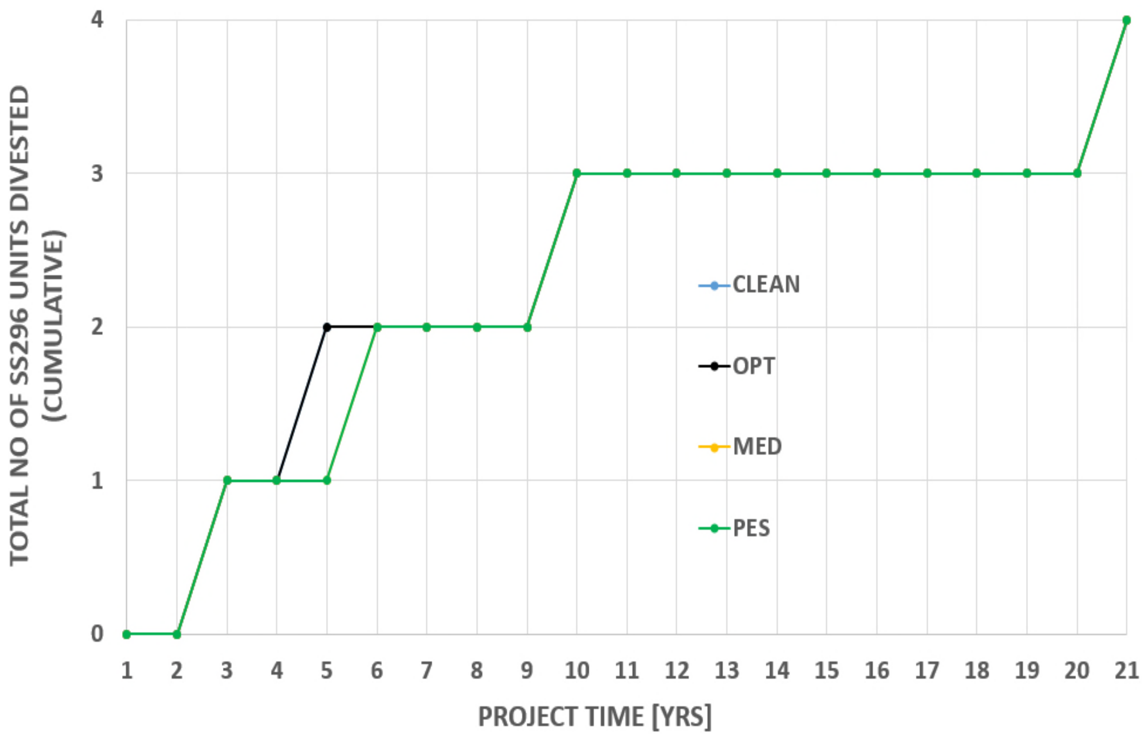


Figure 5-28: Optimised Engine Units' Best Divestment Time & the Effect of Gas Turbine Degradation on Divestment Time [SS296 Fleets]

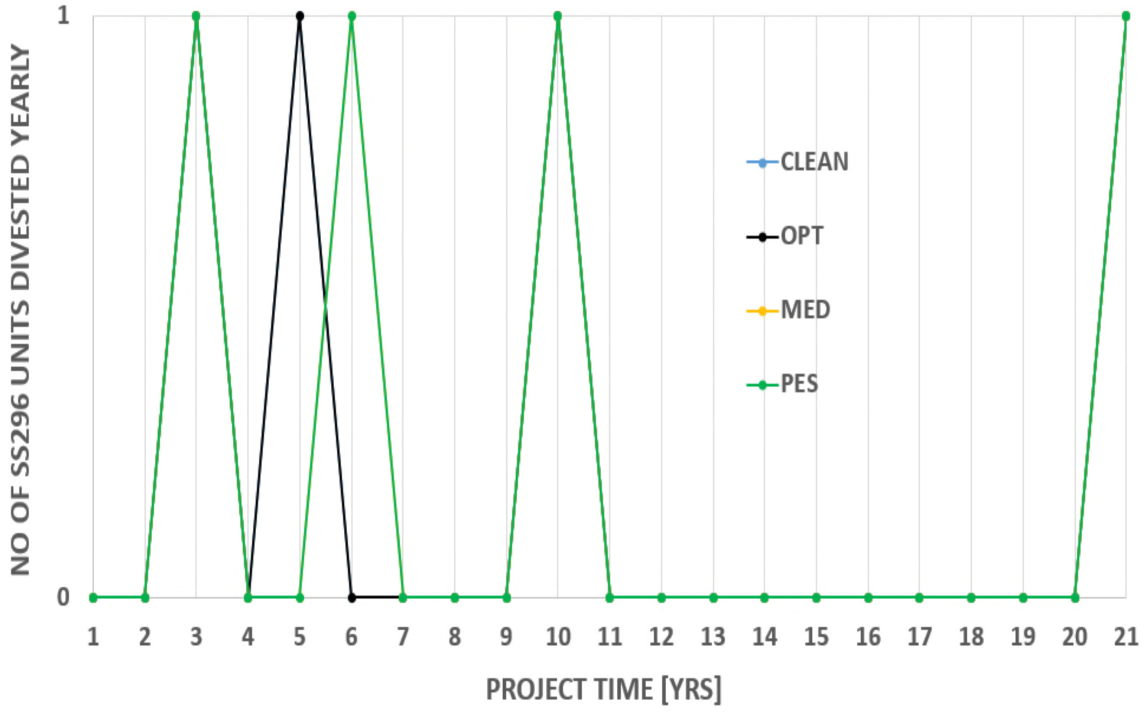


Figure 5-29: Number of SS296 Units Divested Yearly

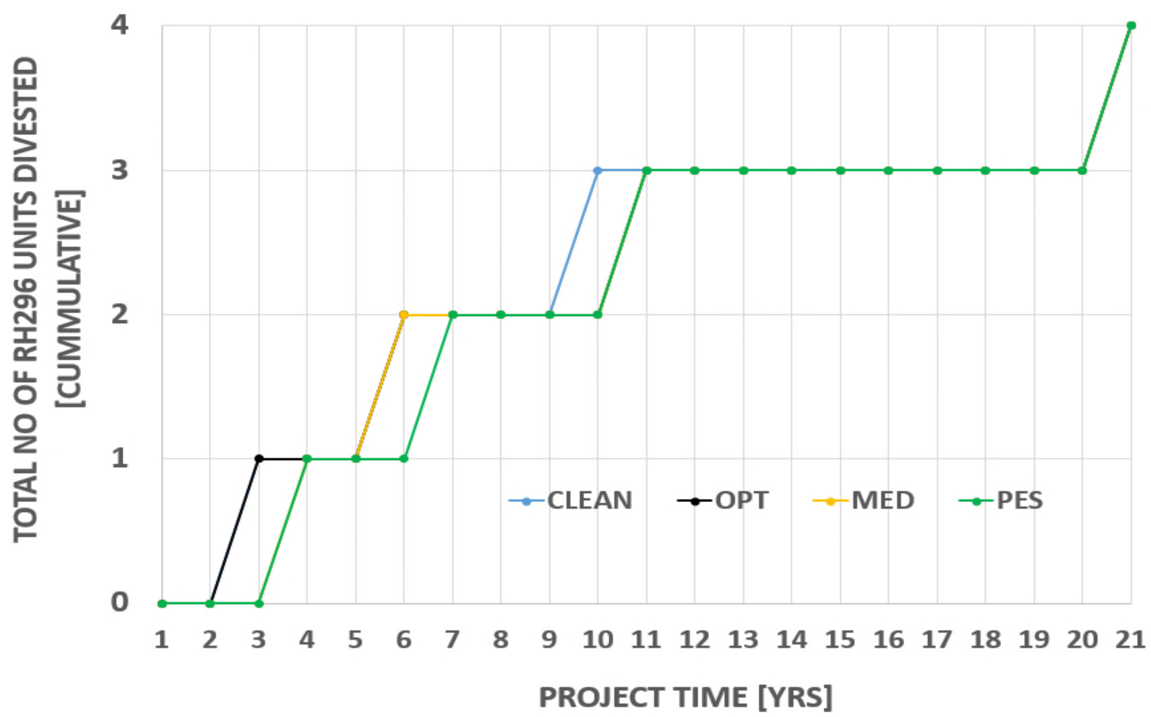


Figure 5-30: Optimised Engine Units Best Divestment Time & the Effect of Gas Turbine Degradation on Divestment Time [RH296 Fleets]

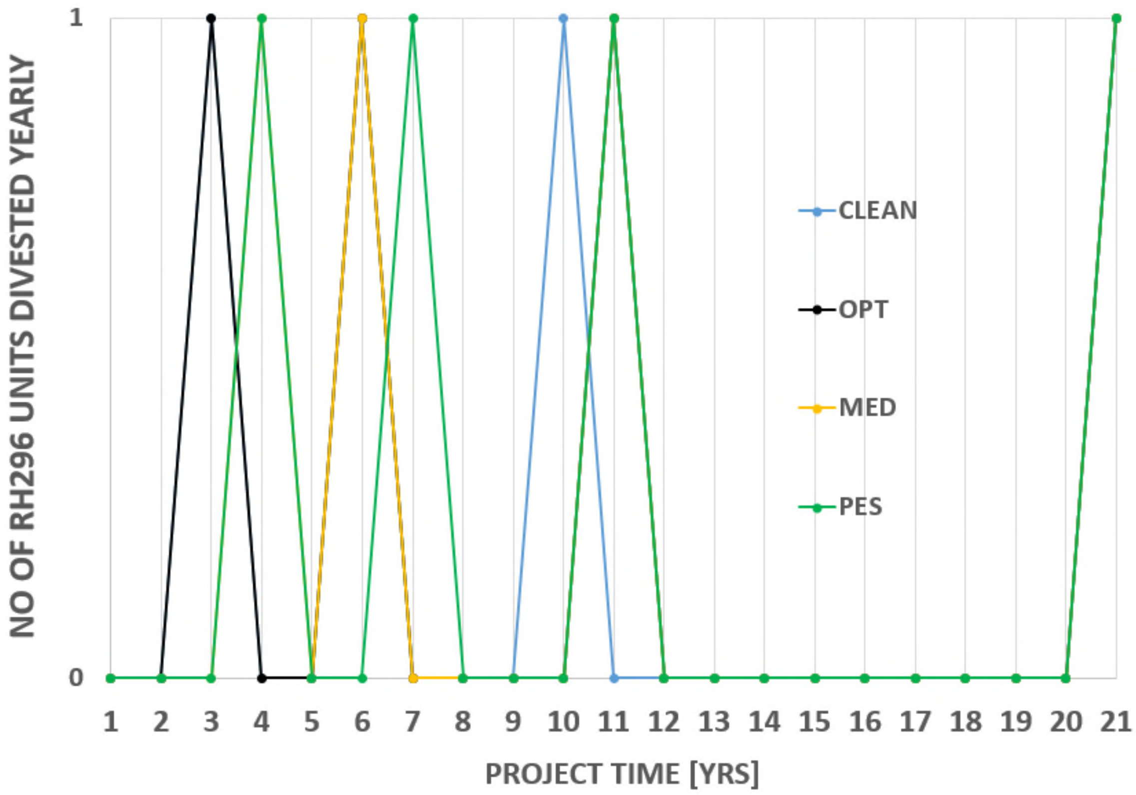


Figure 5-31: Number of RH296 Units Divested Yearly

5.2.3 Optimised power and the energy from the study engines

Generating the optimum power and energy from the fleets subject to the constraint of depleting fuel availability is one of the primary concern of any government that want to invest in the economic utilisation of AG. If the volume of AG was not limited, then getting the maximum possible power and energy from the fleets becomes easy as all the units of engines in all fleets would have been operated at their design point conditions. However, since there is limited fuel availability each year of the project, there is therefore need to use an optimiser to get the optimum power possible from the fleets. The investor (government) would sell the electricity generated to the national grid, this will form a very large source of revenue for the nation.

5.2.3.1 Total optimised power & the energy for all fleets

Figure 5-32 shows the various fleets of engines and their total optimised power in megawatts. This total optimised power is the sum of the optimised power for the individual units of engines in the entire project time. The optimised power for the various units of engines are the power values corresponding to the various optimised fleet compositions explained earlier in sub-section 5.2.1.

From the results of Figure 5-32, the engines with higher simulated efficiencies have higher total optimised power. As an example, considering just the clean fleets of the various study engines, the IC100 fleet has the highest total optimised power, followed by the AD43, then the RH296 and the SS296 having the least. This trend is not a surprise as their simulated efficiency values also have similar trend as seen in Table 3-1 to Table 3-4 and sub-section 5.2.4. The same explanation applies for the degraded fleets, their optimised efficiencies can also be found in sub-section 5.2.4.

The total energy data (Figure 5-33) were gotten by multiplying the corresponding total optimised power by the hours of operation of the engine in a year (8760hrs). The total energy for all the fleets have similar trends as the total optimised power, and the same explanation applies. It therefore implies that the more efficient engines would be given priority in the decision on which engine type is to be recommended to investors of AG utilisation. This recommendation is based on the assumption that all other factors that could have influenced this decision are assumed constant.

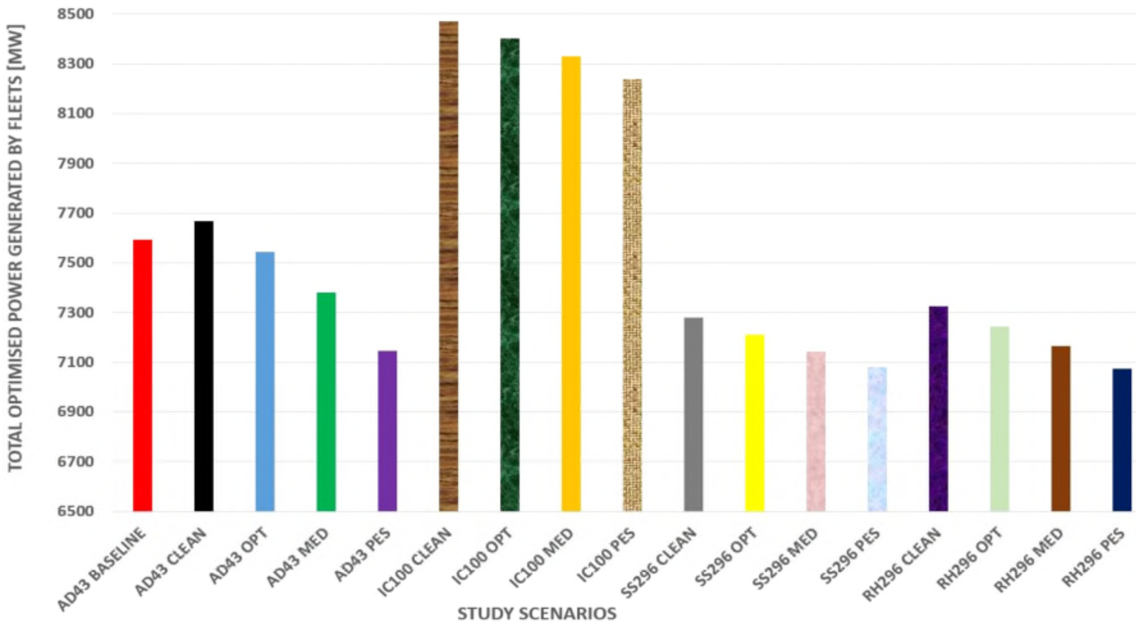


Figure 5-32: Total Optimised Power for all Fleets

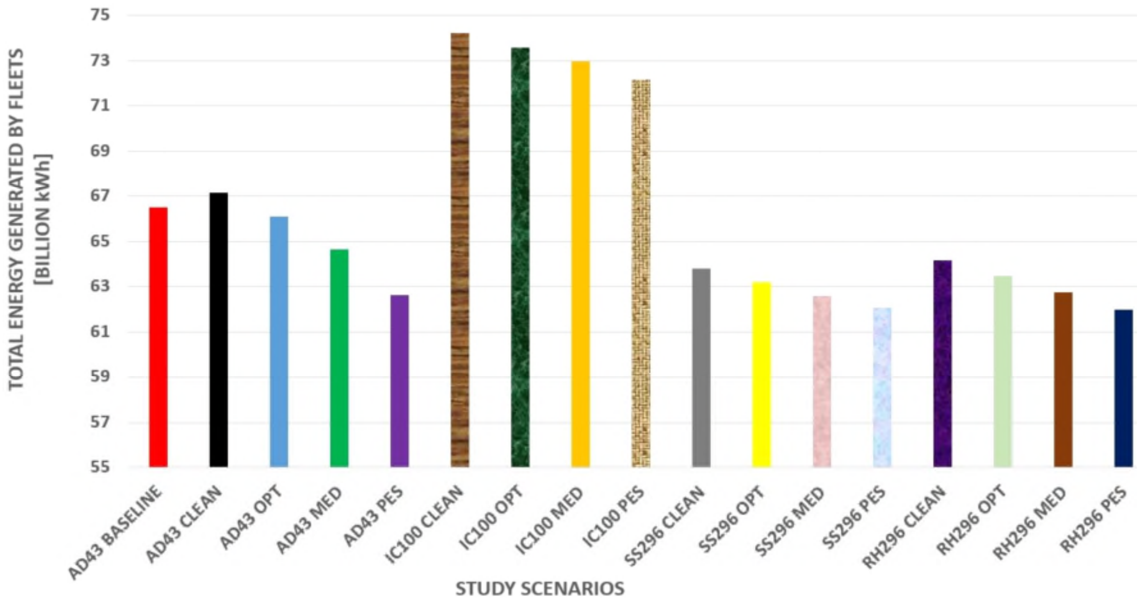


Figure 5-33: Total Energy for all Fleets

5.2.3.2 Annual optimised power & the energy production for the AD43 fleets

Figure 5-34 below shows the annual optimised power from the various fleets of the AD43 engine. These values are the annual sum, that is, the sum of the optimised power for the individual units of engines per year of the project time. These annual optimised power values are the maximum that can be obtained from the various fleets. All fleets are subject to the same optimisation constraint of limited annual fuel availability. At the 1st year of the project, all fleets have the same amount of total optimised power (1071.4MW), this is because all the fleets were operated as clean engines. From Figure 5-34, it is observed that after every 3 years of the project, the total optimised power values of the degraded fleets get closer to that of the clean fleet, this is as a result of the partial overhauling that takes place as explained in sub-sections 4.4.2.3 to 4.4.2.5. Comparing the total optimised power values of the clean (optimised), OPT, MED and PES fleets on an annual basis, with exception of the 1st year, the clean has the highest values, followed by the OPT, then MED and the PES least, although this trend is not so visible in some of the years because the difference in the total optimised power values are very small compared to the scale of the graph.

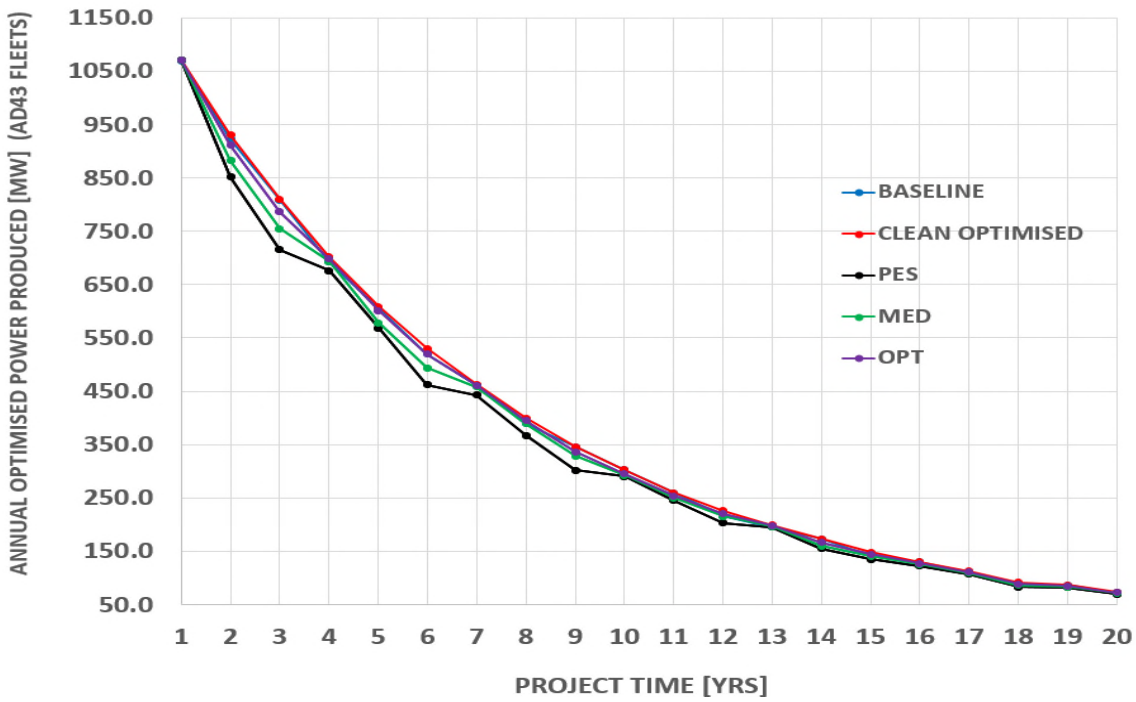


Figure 5-34: Annual Optimised Power Produced by the AD43 Fleets

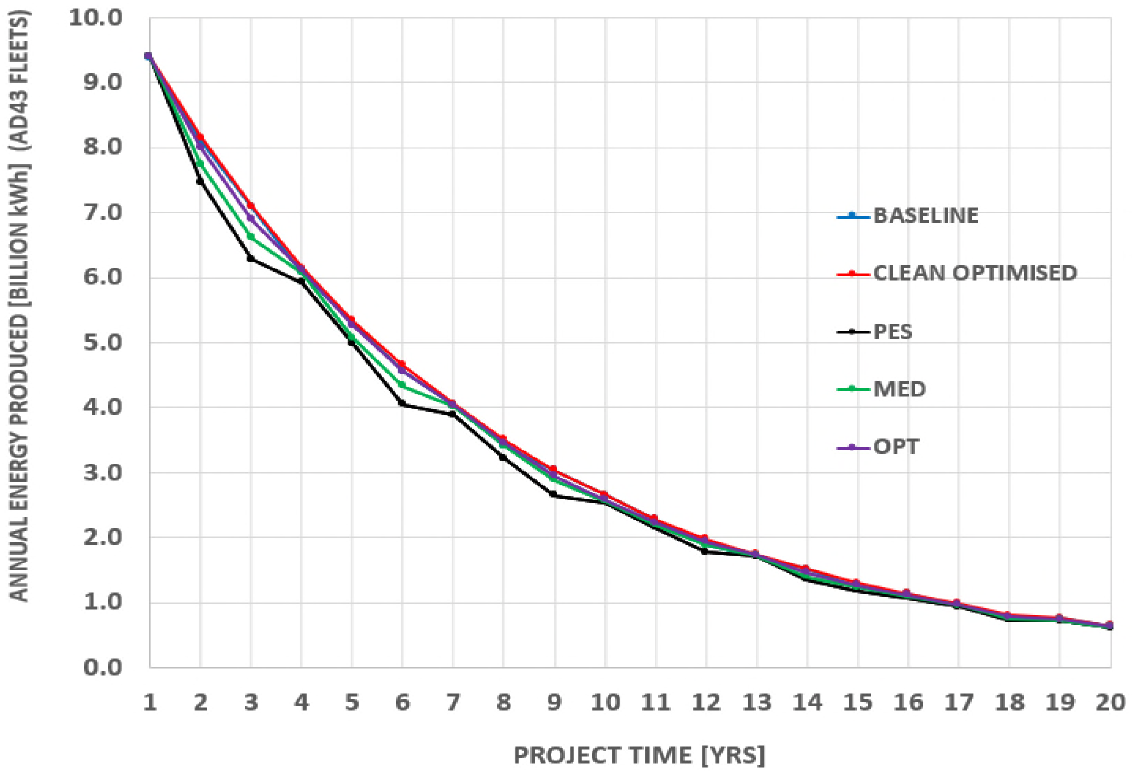


Figure 5-35: Annual Energy Produced by the AD43 Fleets

The annual energy data (Figure 5-35) were calculated by multiplying the corresponding annual optimised power by the hours of operation of the engine in a year (8760hrs). The annual energy for all the fleets have similar trends as the annual optimised power, and the same explanation applies.

Appendix G.1.8 and G.1.9 show screenshots of the total optimised power values for the clean AD43 optimised fleet for the first and second year of the project.

5.2.3.3 Annual optimised power & the energy production for the IC100 fleets

Figure 5-36 shows the annual optimised power for the IC100 fleets. Similarly, at the 1st year of the project, all the fleets have the same amount of total optimised power (1177.9MW). Comparing the total optimised power values of the clean, OPT, MED and PES fleets on an annual basis, the resulting trend is similar to that of the AD43 fleets and the same explanations applies.

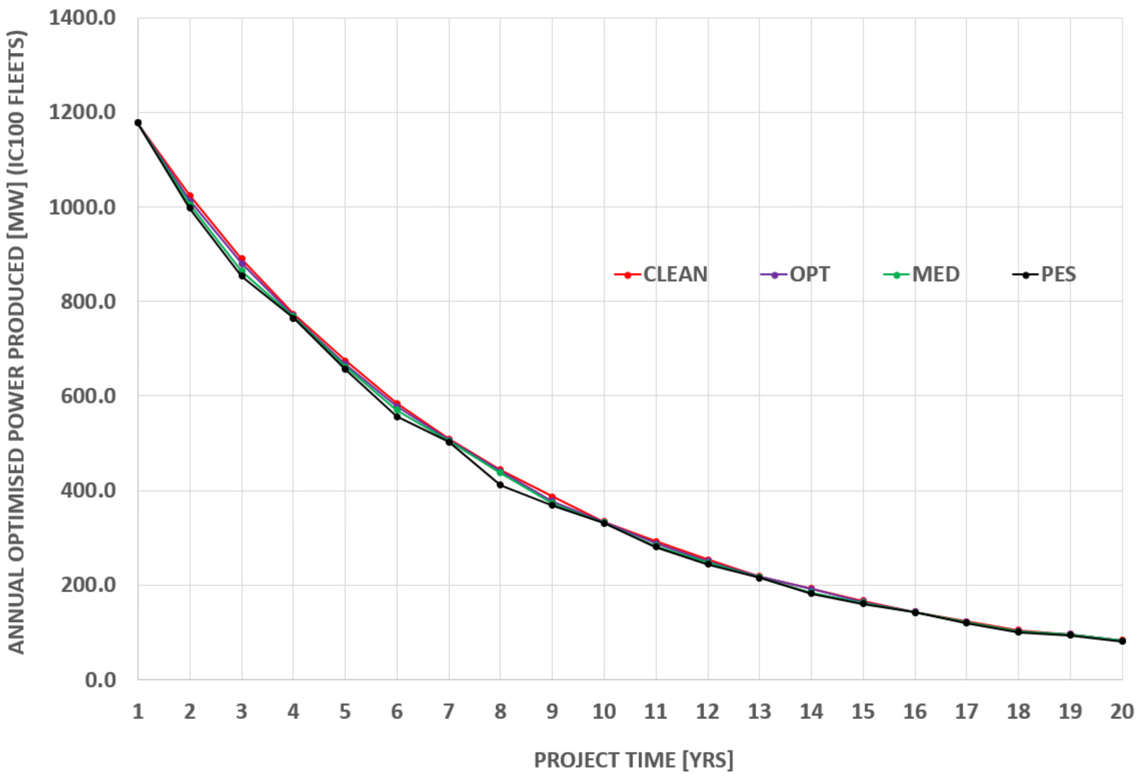


Figure 5-36: Annual Optimised Power Produced by IC100 Fleets

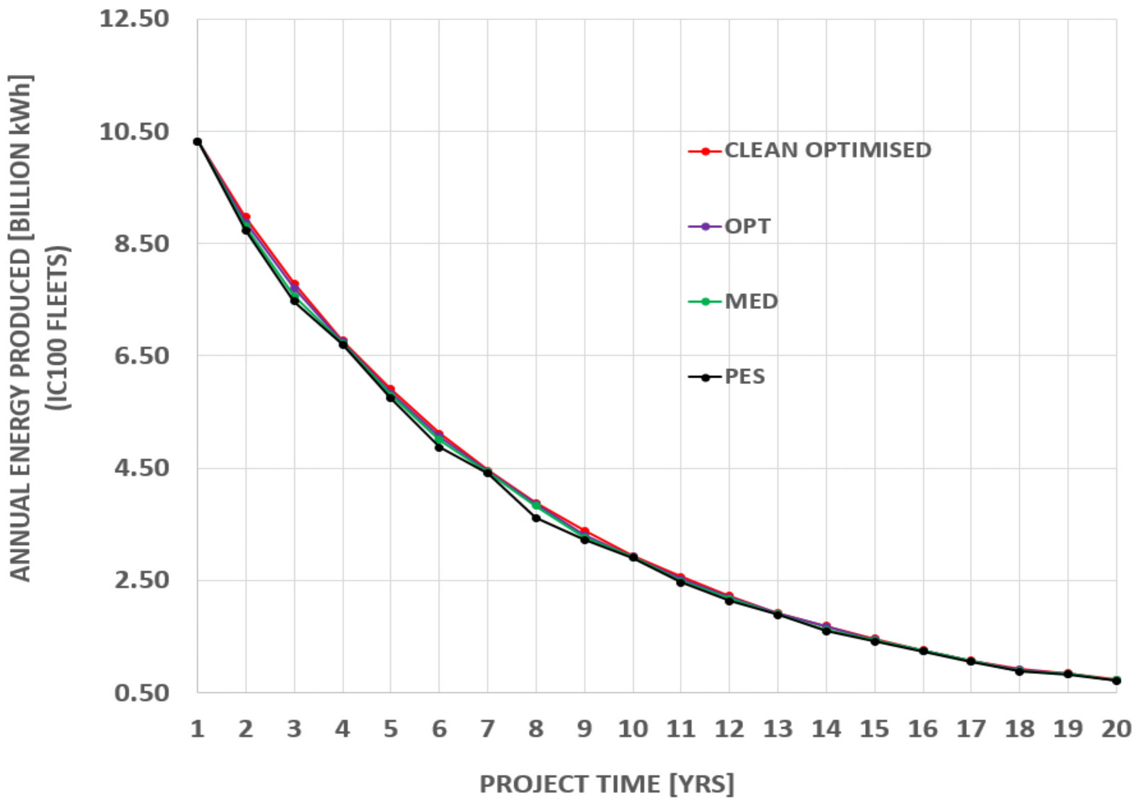


Figure 5-37: Annual Energy Produced by IC100 Fleets

The annual energy data (Figure 5-37) were calculated by using the same approach adopted to get the annual energy for the AD43 fleets. The results seen in Figure 5-37 have similar trends as the annual optimised power, and the same explanation applies.

Screenshots of the total optimised power values of the OPT degraded fleet for the second and tenth year of the project (arbitrarily chosen) are shown in Appendix G.1.10 and G.1.11 respectively.

5.2.3.4 Annual optimised power & the energy production for the SS296 Fleets

Figure 5-38 shows the annual optimised power for the SS296 fleets. As usual, at the 1st year of the project, all the fleets have the same amount of total optimised power (1052.1MW). The results of the clean, OPT, MED and PES fleets of the SS296 engine show similar trends as those of the AD43 and IC100 fleets, and the same explanation applies.

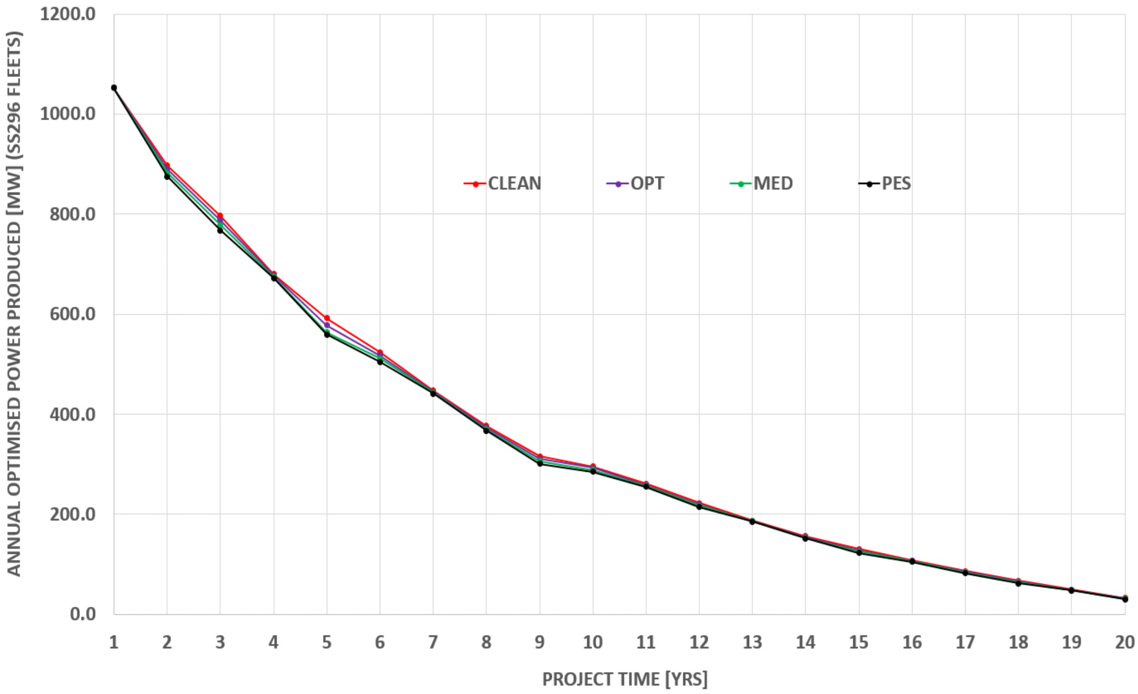


Figure 5-38: Annual Optimised Power Produced by SS296 Fleets

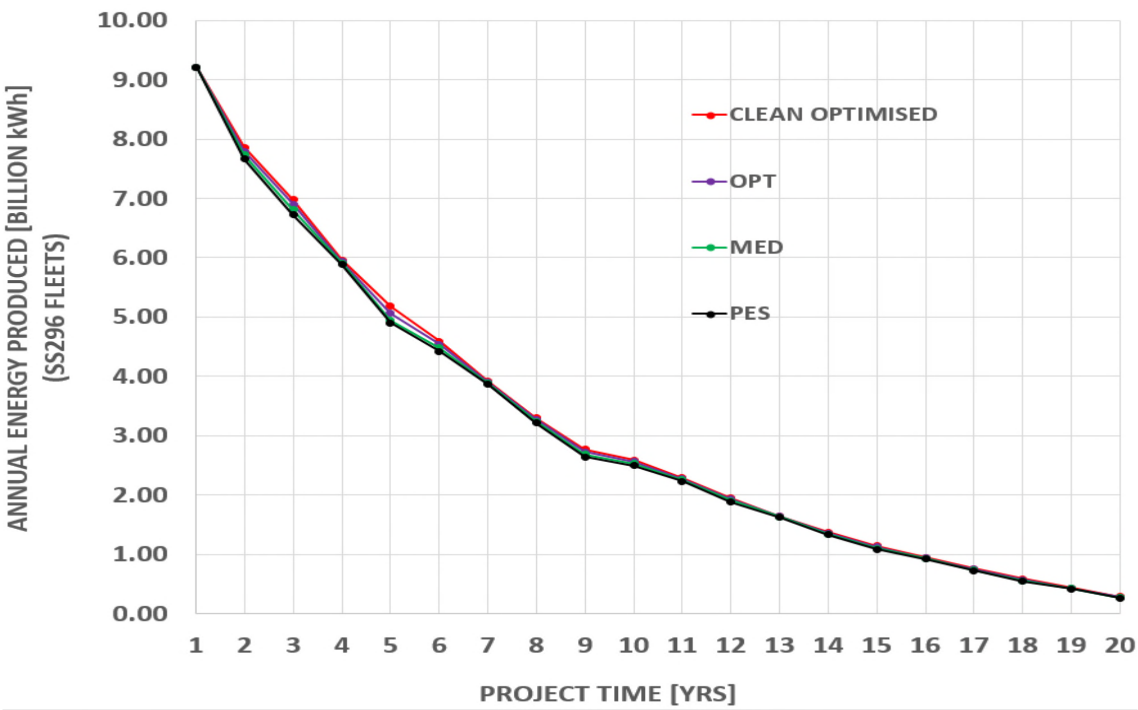


Figure 5-39: Annual Energy Produced by SS296 Fleets

Figure 5-39 shows the annual energy for the SS296 fleets. To avoid repetition, the explanations for the annual energy for the AD43 and IC100 also applies for the SS296 fleets.

The screenshots of the total optimised power values of the OPT and PES degraded fleets for the 7th and 13th year of the project respectively are shown in Appendix G.1.12 and G.1.13 respectively.

5.2.3.5 Annual optimised power & the energy production for the RH296 fleets

Figure 5-40 shows the annual optimised power for the RH296 fleets. As usual, at the 1st year of the project, all the fleets have the same amount of total optimised power (1058.6MW). The trend observed in Figure 5-40 is as expected, at the end of the 2nd year, divestment of a unit of an engine took place in the clean and OPT degraded fleet, making the clean and OPT fleet to have fewer units of engines than the MED and PES fleets. As such, the fewer units of engines in the clean and OPT fleets were operated at much higher TETs than those in the MED and PES fleets, thereby making the optimised power and efficiencies for the units of engines in the clean and OPT fleets much higher than those in the MED and PES fleets. Similar reason resulted to the trend observed in year 6 and 10.

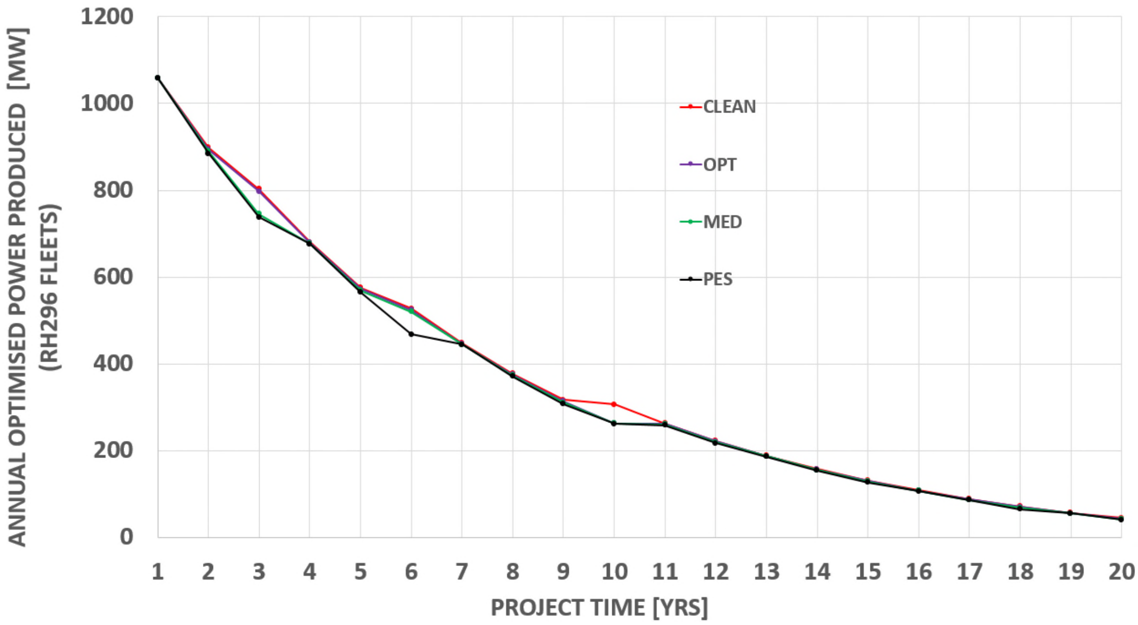


Figure 5-40: Annual Optimised Power Produced by RH296 Fleets

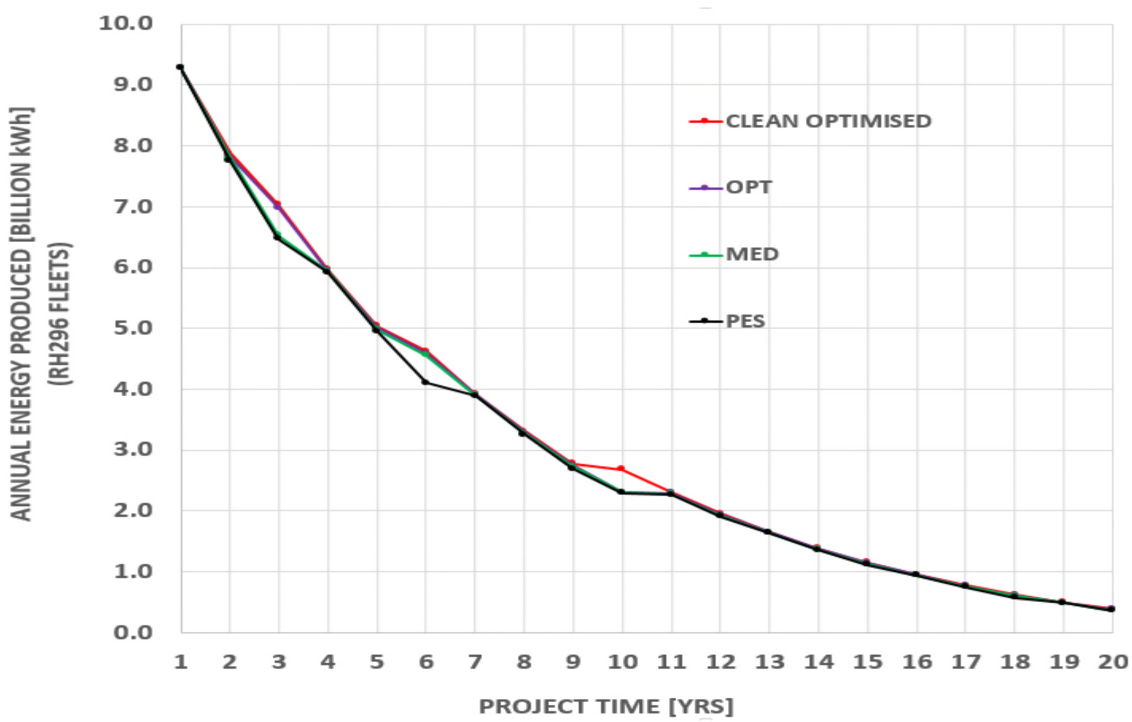


Figure 5-41: Annual Energy Produced by RH296 Fleets

Figure 5-41 shows the annual energy for the RH296 fleets. This graph was generated using the same approach explained earlier. The explanation for the trend is the same as the explanation already done for the annual optimised power.

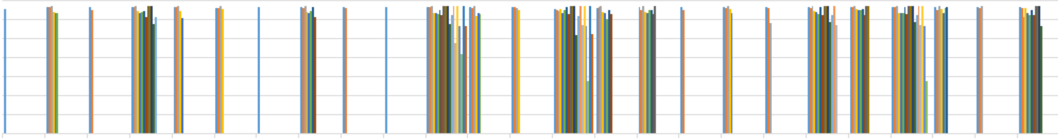
Screenshots showing the total optimised power and the optimised fleet compositions for units of engines in the RH296 fleets can be seen in Appendix G.

5.2.4 Optimised efficiencies of the units of engines in the fleets

In order to maximally utilise the available AG, so as to have a good economic return from the project, the units of engines in the fleets were efficiently utilised. Their efficiencies were optimised. The higher the efficiencies of the units of engines in the fleet, the higher the total optimised power from that fleet.

5.2.4.1 Optimised efficiencies of the units of engines in the AD43 fleets

Figure 5-42 shows the optimised efficiencies of the units of engines in the AD43 clean fleet. Generally, the efficiencies of the units of engines in the fleet decreases down the years of the project, this is as a result of the gradual decline in the optimised power due to the limited fuel availability for the project.

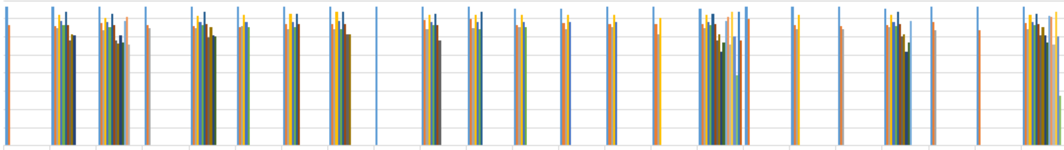


PROJECT TIME [YRS]	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	0.396	0.397	0.397	0.397	0.397	0.396	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.396	0.396	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397	0.397
YR2		0.397	0.395	0.397	0.397	0.396		0.396	0.396		0.397	0.396	0.397	0.395	0.397	0.395	0.395	0.396	0.396	0.396	0.397	0.397	0.395	0.396	0.396
YR3		0.397		0.397	0.397	0.397		0.397			0.397	0.397	0.396	0.394	0.397	0.397		0.397	0.388	0.397	0.397	0.397	0.397	0.397	0.391
YR4		0.394		0.395	0.395	0.396		0.394			0.393	0.392	0.395	0.396	0.394	0.394		0.395		0.394	0.396	0.393	0.396		0.396
YR5		0.393		0.393	0.391			0.393			0.393	0.393		0.393	0.393	0.393		0.393		0.394	0.395	0.393	0.393		0.393
YR6		0.393		0.394				0.394			0.393	0.393		0.395	0.39	0.395				0.393	0.395	0.393	0.396		0.392
YR7				0.394				0.397			0.395			0.397	0.395	0.395				0.397	0.395	0.397	0.397		0.395
YR8				0.391				0.391			0.392			0.393	0.393	0.393				0.392	0.392	0.393			0.392
YR9				0.397							0.397			0.397		0.397				0.397	0.397	0.397			0.397
YR10				0.397							0.397			0.397						0.397	0.397	0.397			0.397
YR11				0.397							0.397			0.397						0.397		0.397			0.397
YR12				0.387							0.387			0.382						0.388		0.389			0.386
YR13				0.391							0.392			0.392						0.392		0.392			
YR14											0.397			0.397						0.397		0.397			
YR15											0.377			0.387						0.387		0.387			
YR16											0.397			0.397								0.397			
YR17											0.386			0.386								0.386			
YR18											0.372			0.358								0.358			
YR19											0.397			0.397											
YR20											0.387			0.382											

OPTIMISED EFFICIENCIES OF THE ENGINES IN THE FLEET

Figure 5-42: Optimised Efficiencies of the Units of Engines in the AD43 Clean Fleet

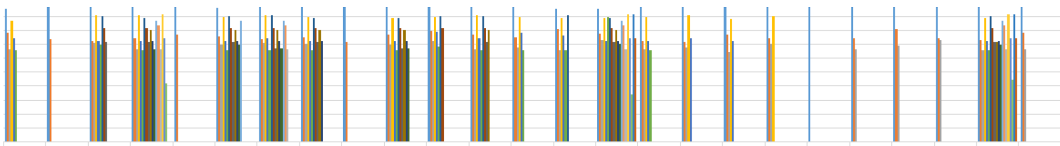
Figure 5-43 to Figure 5-45 show the optimised efficiencies for the units of engines in the OPT, MED and PES degraded fleets of the AD43 engine. As seen from the figures, the efficiencies of the units of engines reduces with degradation. The efficiency of a unit of engine either increases or decreases down the years of the project depending on the TET the engine was operated. However, when only 1 unit of engine is left in the fleet, the efficiency decreases down the years of the project, this is as a result of the fall in power due to shortage of fuel availability.



PROJECT TIME [YRS]	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.395	0.395	0.396	0.396	0.395	0.396	0.396	0.396	0.395	0.396	0.396	0.396
YR2	0.386	0.386	0.387	0.386	0.386	0.385	0.387	0.387		0.389	0.389	0.386	0.387	0.387	0.387	0.386	0.389	0.386	0.386	0.386	0.388	0.384	0.387
YR3		0.384	0.383	0.384	0.384	0.386	0.384	0.384		0.384	0.384	0.385	0.384	0.385	0.381	0.385		0.384	0.384	0.385	0.383		0.384
YR4		0.392	0.390		0.391	0.392	0.392	0.394		0.392	0.392	0.392	0.392	0.392	0.390	0.392		0.392		0.392			0.392
YR5		0.388	0.388		0.388	0.388	0.388	0.388		0.388	0.388	0.388	0.388	0.388		0.388				0.388			0.388
YR6		0.386	0.385		0.386	0.385	0.385	0.384		0.386	0.384	0.385				0.386				0.386			0.386
YR7		0.394	0.392		0.394		0.392	0.394		0.392	0.394					0.392				0.394			0.392
YR8		0.386	0.386		0.386		0.387	0.387		0.386						0.387				0.387			0.387
YR9		0.377	0.377		0.380			0.381		0.377						0.377				0.380			0.380
YR10		0.381	0.376		0.385			0.381								0.381				0.381			0.385
YR11		0.380	0.380		0.380											0.371				0.371			0.380
YR12			0.377		0.380											0.377				0.377			0.377
YR13			0.388													0.388				0.388			0.391
YR14			0.391													0.391							0.391
YR15			0.375													0.375							0.375
YR16																0.394							0.394
YR17																0.380							0.380
YR18																0.358							0.347
YR19																0.394							
YR20																0.378							

OPTIMISED EFFICIENCIES OF THE ENGINES IN THE FLEET

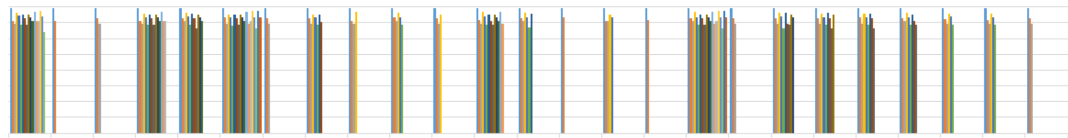
Figure 5-43: Optimised Efficiencies of the Units of Engines in the AD43 OPT Degraded Fleet



PROJECT TIME [YRS]	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	0.395	0.396	0.396	0.396	0.396	0.395	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.395	0.395	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396
YR2	0.378	0.373	0.372	0.374	0.377	0.375	0.373	0.375	0.371	0.376	0.379	0.376	0.374	0.380	0.377	0.372	0.371	0.376	0.374		0.374	0.381	0.373	0.373	0.378
YR3	0.366		0.370	0.366		0.369	0.370	0.370		0.369	0.372	0.366	0.367	0.365	0.372	0.366	0.368	0.364	0.370		0.366	0.368	0.372	0.365	0.366
YR4	0.387		0.390	0.390		0.389	0.390	0.389		0.388	0.389	0.390	0.389	0.388	0.388	0.389	0.390	0.388	0.390					0.388	
YR5	0.374		0.372	0.372		0.372	0.373	0.372		0.372	0.378	0.374	0.378	0.376	0.372	0.372	0.374	0.372						0.372	
YR6	0.365		0.369	0.365		0.365	0.365	0.365		0.365	0.368	0.365	0.365	0.365	0.389	0.365								0.365	
YR7			0.390	0.389		0.390	0.391	0.389		0.389	0.390	0.390		0.391	0.389									0.390	
YR8			0.381	0.381		0.381	0.381	0.381		0.381	0.381	0.381			0.381									0.381	
YR9			0.371	0.371		0.371	0.367	0.371		0.367		0.371			0.371									0.371	
YR10				0.380		0.380	0.380	0.380		0.380		0.380			0.380									0.371	
YR11				0.372		0.372	0.372	0.372		0.372					0.372									0.372	
YR12				0.366		0.369	0.366			0.366					0.370									0.369	
YR13				0.386		0.386	0.386								0.386									0.386	
YR14				0.383			0.383								0.383									0.383	
YR15				0.366			0.366								0.366									0.366	
YR16				0.391											0.391									0.391	
YR17				0.374											0.374									0.374	
YR18				0.341											0.334									0.344	
YR19															0.391									0.391	
YR20															0.374									0.374	

OPTIMISED EFFICIENCIES OF THE ENGINES IN THE FLEET

Figure 5-44: Optimised Efficiencies of the Units of Engines in the AD43 MED Degraded Fleet



PROJECT TIME [YRS]

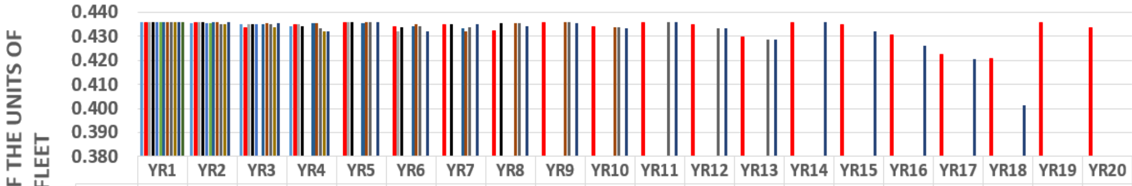
	GT1	GT2	GT3	GT4	GT5	GT6	GT7	GT8	GT9	GT10	GT11	GT12	GT13	GT14	GT15	GT16	GT17	GT18	GT19	GT20	GT21	GT22	GT23	GT24	GT25
YR1	0.395	0.396	0.396	0.396	0.396	0.395	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.395	0.395	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396	0.396
YR2	0.356	0.356	0.364	0.356	0.365	0.366	0.364	0.364	0.355	0.366	0.364	0.358	0.365	0.365	0.356	0.357	0.364	0.365	0.364	0.365	0.366	0.364	0.360	0.359	0.364
YR3	0.348		0.348	0.348	0.354	0.348	0.348	0.348	0.348	0.354	0.348	0.348	0.354		0.354		0.354	0.348	0.348	0.348	0.348	0.354	0.348	0.348	0.348
YR4	0.380			0.378	0.380	0.377		0.374	0.383	0.380	0.376	0.383	0.380		0.377		0.384		0.382	0.377	0.378	0.381	0.378	0.380	
YR5	0.371			0.365	0.370	0.365		0.365		0.366		0.371	0.365		0.365		0.365		0.369	0.365	0.365	0.365	0.369	0.366	
YR6	0.345			0.344	0.344	0.341		0.344		0.344		0.344	0.334				0.345		0.333	0.343	0.344	0.343	0.344	0.344	
YR7	0.377			0.377	0.377	0.376		0.377				0.376	0.379				0.377		0.380	0.380	0.379	0.377			
YR8	0.363			0.363	0.363	0.363		0.353				0.355					0.363		0.348	0.363	0.363	0.355			
YR9	0.343			0.343	0.333	0.343						0.343					0.343		0.343	0.332	0.332	0.343			
YR10	0.376			0.376	0.376	0.376						0.376					0.376		0.376	0.376					
YR11	0.365			0.365	0.365	0.365						0.365					0.365		0.365						
YR12	0.354			0.354	0.354	0.354						0.354					0.354								
YR13	0.383			0.383		0.383						0.383					0.383								
YR14	0.354			0.354		0.347						0.347					0.347								
YR15	0.354			0.354		0.354											0.354								
YR16	0.387					0.387											0.387								
YR17	0.369					0.366											0.366								
YR18	0.321					0.332											0.332								
YR19						0.387											0.387								
YR20						0.365											0.365								

OPTIMISED EFFICIENCIES OF THE ENGINES IN THE FLEET

Figure 5-45: Optimised Efficiencies of the Units of Engines in the AD43 PES Degraded Fleet

5.2.4.2 Optimised efficiencies of the units of engines in the IC100 fleets

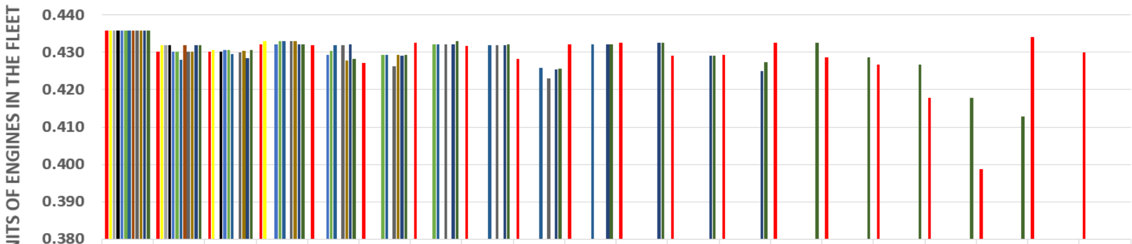
Figure 5-46 to Figure 5-49 show the optimised efficiencies for the units of engines in the clean, OPT, MED and PES degraded fleets of the IC100 engine respectively. The trend for the optimised efficiencies of these fleets are similar to that of the AD43 fleets, and the same explanation applies.



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.436	0.435	0.435	0.434																
GT2	0.436	0.436	0.434	0.435	0.436	0.434	0.435	0.432	0.436	0.434	0.436	0.435	0.430	0.436	0.435	0.431	0.423	0.421	0.436	0.434
GT3	0.436	0.436	0.435	0.435	0.436	0.432														
GT4	0.436	0.436	0.435	0.434	0.436	0.434	0.435	0.436												
GT5	0.436	0.436	0.435																	
GT6	0.436	0.436																		
GT7	0.436	0.436	0.435	0.436	0.436	0.434	0.433													
GT8	0.436	0.436	0.436	0.435	0.436	0.435	0.432	0.436	0.436	0.434										
GT9	0.436	0.435	0.435	0.433	0.436	0.434	0.434	0.436	0.436	0.434	0.436	0.434	0.429							
GT10	0.436	0.435	0.434	0.432																
GT11	0.436	0.436	0.435	0.432	0.436	0.432	0.435	0.434	0.436	0.433	0.436	0.434	0.429	0.436	0.432	0.426	0.421	0.401		
GT12	0.436																			

PROJECT TIME [YRS]

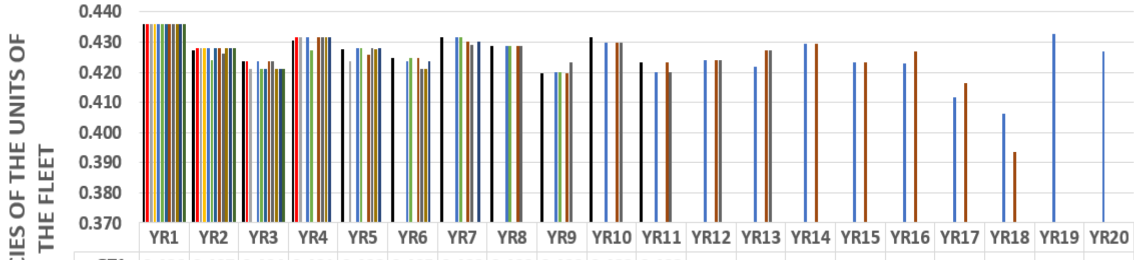
Figure 5-46: Optimised Efficiencies of the Units of Engines in the IC100 Clean Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.436	0.430	0.430	0.432	0.432	0.427	0.433	0.432	0.428	0.432	0.433	0.429	0.429	0.433	0.429	0.427	0.418	0.399	0.434	0.430
GT2	0.436	0.432	0.431	0.433																
GT3	0.436	0.432																		
GT4	0.436	0.432	0.430																	
GT5	0.436	0.430	0.431	0.432	0.429															
GT6	0.436	0.430	0.431	0.433	0.430	0.429	0.432													
GT7	0.436	0.428	0.429	0.433	0.432	0.429	0.432	0.432	0.426	0.432										
GT8	0.436	0.432																		
GT9	0.436	0.430	0.430	0.433	0.432	0.426	0.432	0.432	0.423											
GT10	0.436	0.430	0.430	0.433	0.428	0.429														
GT11	0.436	0.432	0.428	0.432	0.432	0.429	0.432	0.432	0.425	0.432	0.433	0.429	0.425							
GT12	0.436	0.432	0.431	0.432	0.428	0.429	0.433	0.432	0.426	0.432	0.433	0.429	0.427	0.433	0.429	0.427	0.418	0.413		

PROJECT TIME [YRS]

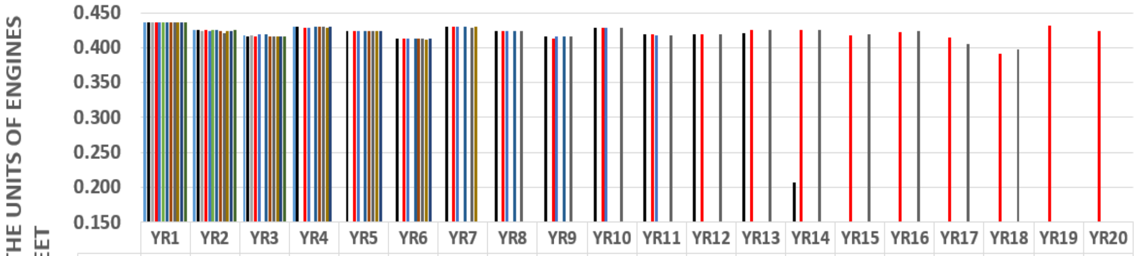
Figure 5-47: Optimised Efficiencies of the Units of Engines in the IC100 OPT Degraded Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.436	0.427	0.424	0.431	0.428	0.425	0.432	0.429	0.420	0.432	0.423									
GT2	0.436	0.428	0.424	0.432																
GT3	0.436	0.428	0.421	0.432	0.424															
GT4	0.436	0.428																		
GT5	0.436	0.428	0.424	0.432	0.428	0.424	0.432	0.429	0.420	0.430	0.420	0.424	0.422	0.429	0.423	0.423	0.412	0.406	0.433	0.427
GT6	0.436	0.424	0.421	0.427	0.428	0.425	0.432	0.429	0.420											
GT7	0.436	0.428	0.421																	
GT8	0.436	0.428	0.424	0.432	0.426	0.425	0.430	0.429	0.420	0.430	0.423	0.424	0.427	0.429	0.423	0.427	0.416	0.394		
GT9	0.436	0.426	0.424	0.432	0.428	0.421	0.429	0.429	0.423	0.430	0.420	0.424	0.427							
GT10	0.436	0.428	0.421	0.432	0.428	0.421														
GT11	0.436	0.428	0.421	0.432	0.428	0.424	0.430													
GT12	0.436	0.428	0.421																	

PROJECT TIME [YRS]

Figure 5-48: Optimised Efficiencies of the Units of Engines in the IC100 MED Degraded Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.436	0.425	0.417	0.430																
GT2	0.436	0.425	0.417	0.430	0.424	0.413	0.429	0.424	0.415	0.429	0.419	0.419	0.421	0.207						
GT3	0.436	0.424	0.417																	
GT4	0.436	0.425	0.417	0.429	0.424	0.413	0.429	0.424	0.414	0.429	0.419	0.419	0.425	0.426	0.418	0.422	0.415	0.392	0.431	0.423
GT5	0.436	0.424	0.419	0.429	0.424	0.413	0.429	0.424	0.416	0.429	0.417									
GT6	0.436	0.425																		
GT7	0.436	0.425	0.419	0.430	0.424	0.413	0.429	0.424	0.416											
GT8	0.436	0.424	0.417	0.430	0.424	0.413														
GT9	0.436	0.420	0.417	0.429	0.424	0.413	0.428	0.424	0.416	0.429	0.417	0.419	0.425	0.426	0.419	0.424	0.405	0.397		
GT10	0.436	0.424	0.417	0.428	0.424	0.411	0.429													
GT11	0.436	0.424	0.417	0.430	0.424	0.413														
GT12	0.436	0.425	0.417																	

PROJECT TIME [YRS]

Figure 5-49: Optimised Efficiencies of the Units of Engines in the IC100 PES Degraded Fleet

5.2.4.3 Optimised efficiencies of the units of engines in the SS296 fleets

Figure 5-50 to Figure 5-53 show the optimised efficiencies for the units of engines in the clean, OPT, MED and PES degraded fleets of the SS296 engine respectively. The trend for the optimised efficiencies of these fleets are similar to those of the AD43 and IC100 fleets, and the same explanation applies.

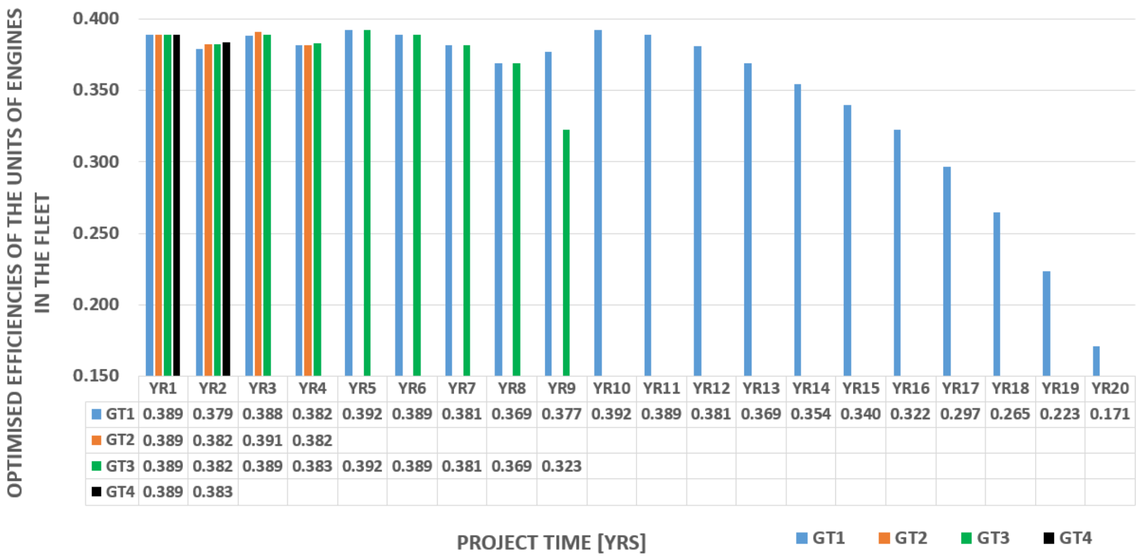


Figure 5-50: Optimised Efficiencies of the Units of Engines in the SS296 Clean Fleet

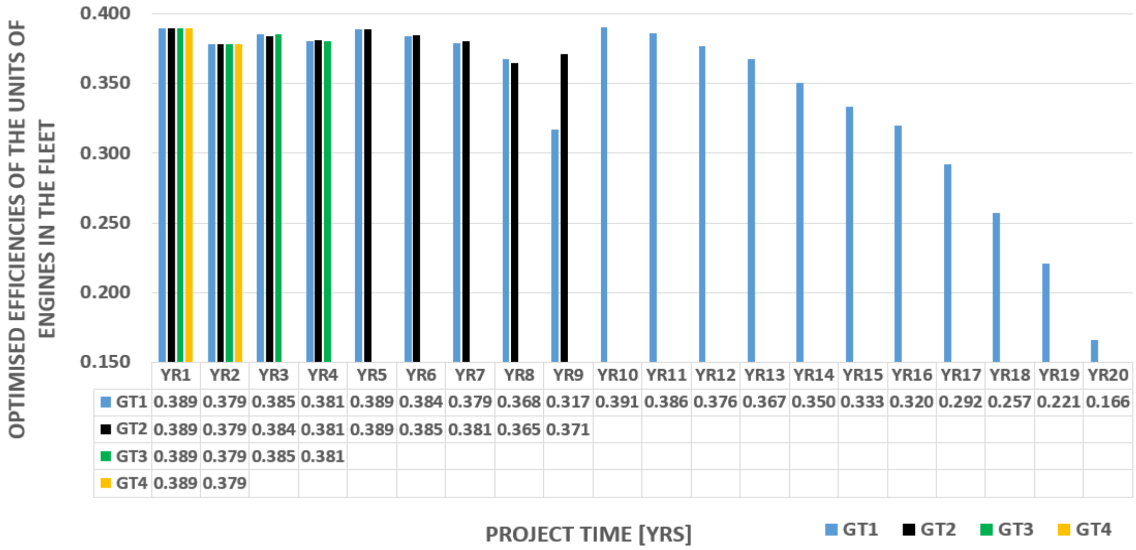
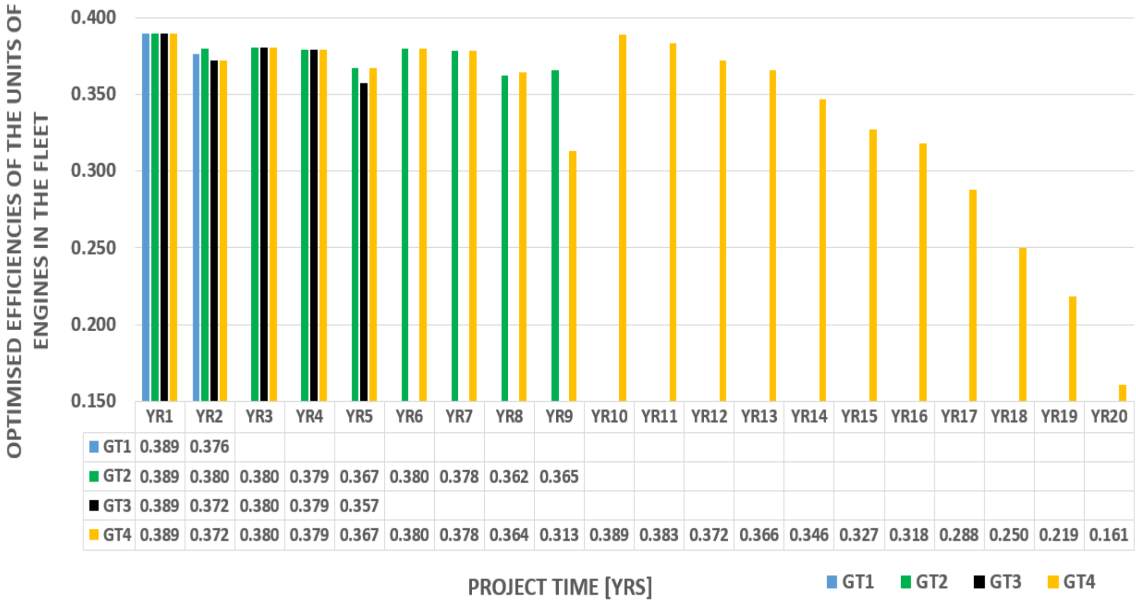
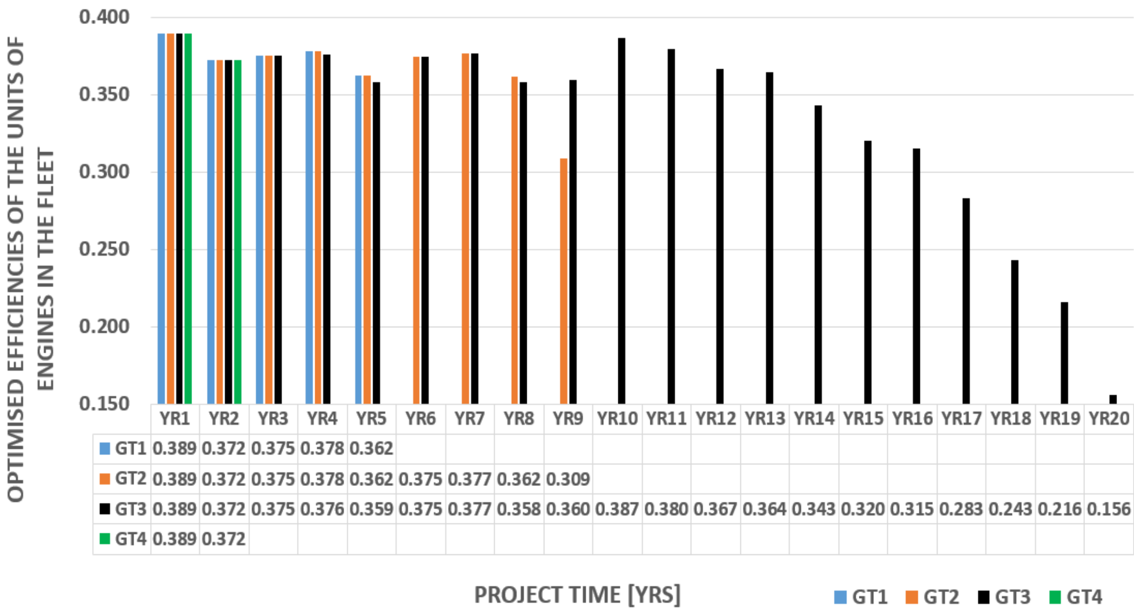


Figure 5-51: Optimised Efficiencies of the Units of Engines in the SS296 OPT Degraded Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.389	0.376																		
GT2	0.389	0.380	0.380	0.379	0.367	0.380	0.378	0.362	0.365											
GT3	0.389	0.372	0.380	0.379	0.357															
GT4	0.389	0.372	0.380	0.379	0.367	0.380	0.378	0.364	0.313	0.389	0.383	0.372	0.366	0.346	0.327	0.318	0.288	0.250	0.219	0.161

Figure 5-52: Optimised Efficiencies of the Units of Engines in the SS296 MED Degraded Fleet

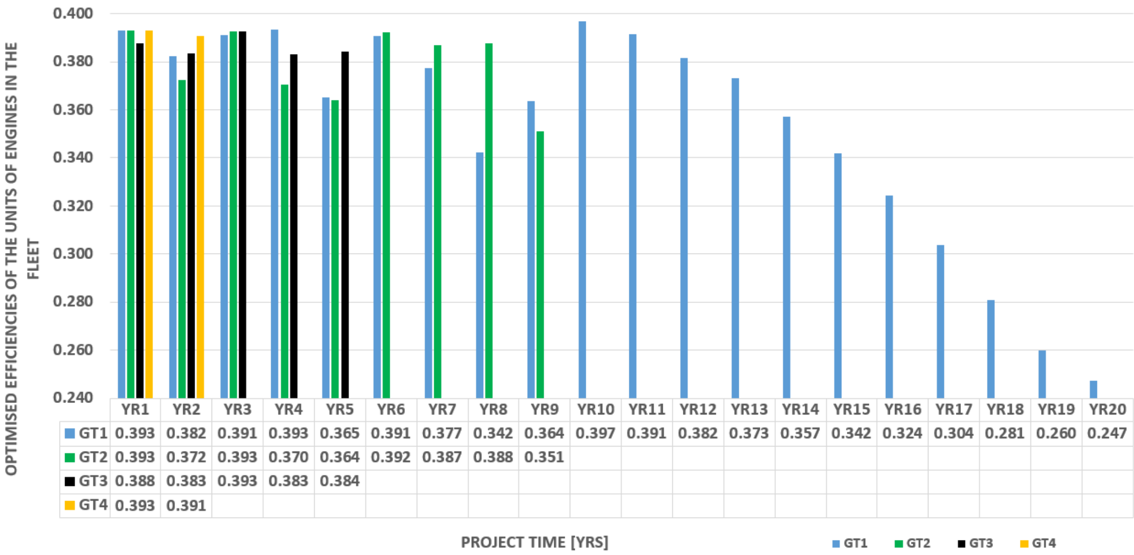


	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.389	0.372	0.375	0.378	0.362															
GT2	0.389	0.372	0.375	0.378	0.362	0.375	0.377	0.362	0.309											
GT3	0.389	0.372	0.375	0.376	0.359	0.375	0.377	0.358	0.360	0.387	0.380	0.367	0.364	0.343	0.320	0.315	0.283	0.243	0.216	0.156
GT4	0.389	0.372																		

Figure 5-53: Optimised Efficiencies of the Units of Engines in the SS296 PES Degraded Fleet

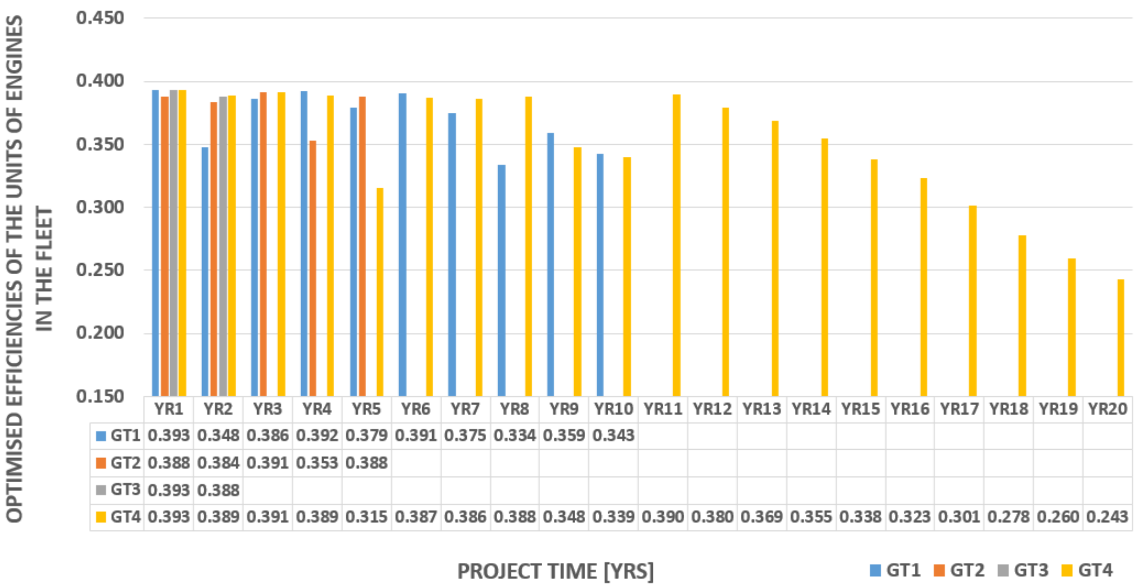
5.2.4.4 Optimised efficiencies of the units of engines in the RH296 fleets

Figure 5-54 and Figure 5-55 show the optimised efficiencies for the units of engines in the clean and OPT degraded fleets of the RH296 engine respectively.



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.393	0.382	0.391	0.393	0.365	0.391	0.377	0.342	0.364	0.397	0.391	0.382	0.373	0.357	0.342	0.324	0.304	0.281	0.260	0.247
GT2	0.393	0.372	0.393	0.370	0.364	0.392	0.387	0.388	0.351											
GT3	0.388	0.383	0.393	0.383	0.384															
GT4	0.393	0.391																		

Figure 5-54: Optimised Efficiencies of the Units of Engines in the RH296 Clean Fleet



	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.393	0.348	0.386	0.392	0.379	0.391	0.375	0.334	0.359	0.343										
GT2	0.388	0.384	0.391	0.353	0.388															
GT3	0.393	0.388																		
GT4	0.393	0.389	0.391	0.389	0.315	0.387	0.386	0.388	0.348	0.339	0.390	0.380	0.369	0.355	0.338	0.323	0.301	0.278	0.260	0.243

Figure 5-55: Optimised Efficiencies of the Units of Engines in the RH296 OPT Degraded Fleet

Appendix G.1.6 and G.1.7 show the optimised efficiencies for the units of engines in the MED and PES degraded fleets of the RH296 engine.

5.2.5 Optimised Fuel Utilisation by the Fleets

Figure 5-56 shows the optimised fuel utilisation by the units of engines in the RH296 clean fleet. The fuel available for the project was well economically utilised by the fleet to get the maximum power and a good economic return.

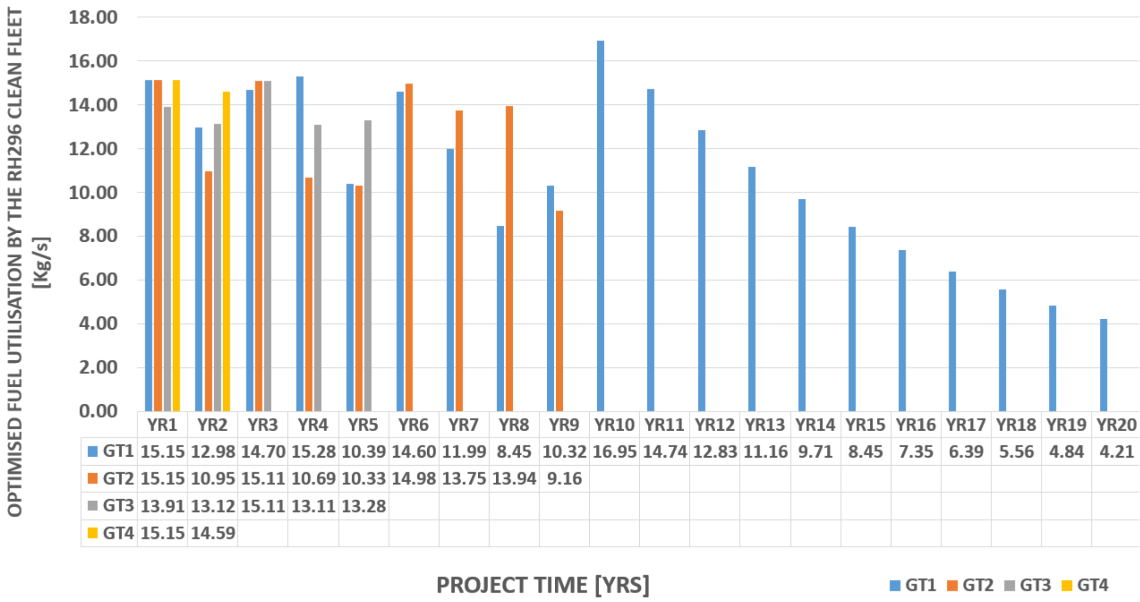


Figure 5-56: Optimised Fuel Utilisation by the RH296 Clean Fleet

5.3 Creep life/maintenance module for optimised fleets

The creep life of the units of engines in the optimised fleets were analysed using the same simple creep life model used in sub-section 3.5.3.

5.3.1 Creep life assessment for the optimised fleets

In evaluating the creep life of the various engines in the degraded fleets, the same creep life model was applied, in this case, 6000hrs was taken as the minimum. For the following levels of degradation - 0.667%, 1.333%, 2%, 2.667%, 4% and 6%, it was assumed that the creep life of the degraded engine would be 80%, 68%, 56%, 49%, 40% and 24% of the creep life of the clean engine respectively, for the same TET. This degraded engines' creep life assumptions is based on the creep life analysis seen in Naeem's work [109] as seen in Figure 5-57.

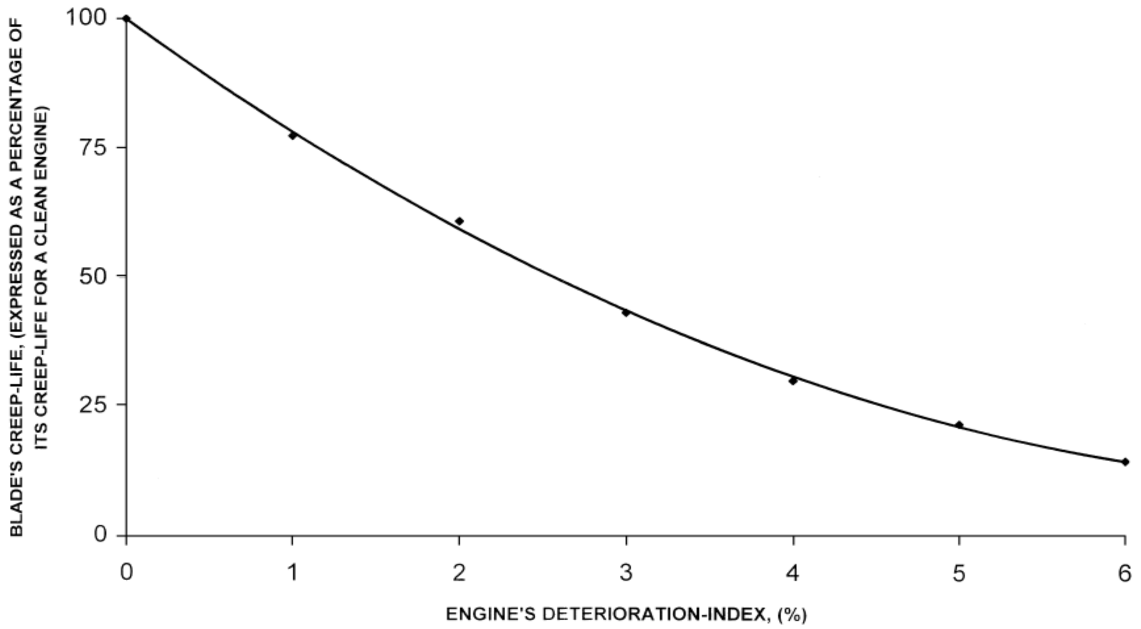


Figure 5-57: Blade's predicted creep-life for the stipulated engine's-deterioration-index [109, p.208]

Figure 5-58 and Figure 5-59 show graphs of TET against creep life for the 3rd units of engines in the clean and OPT degraded fleets of the SS296 engine.

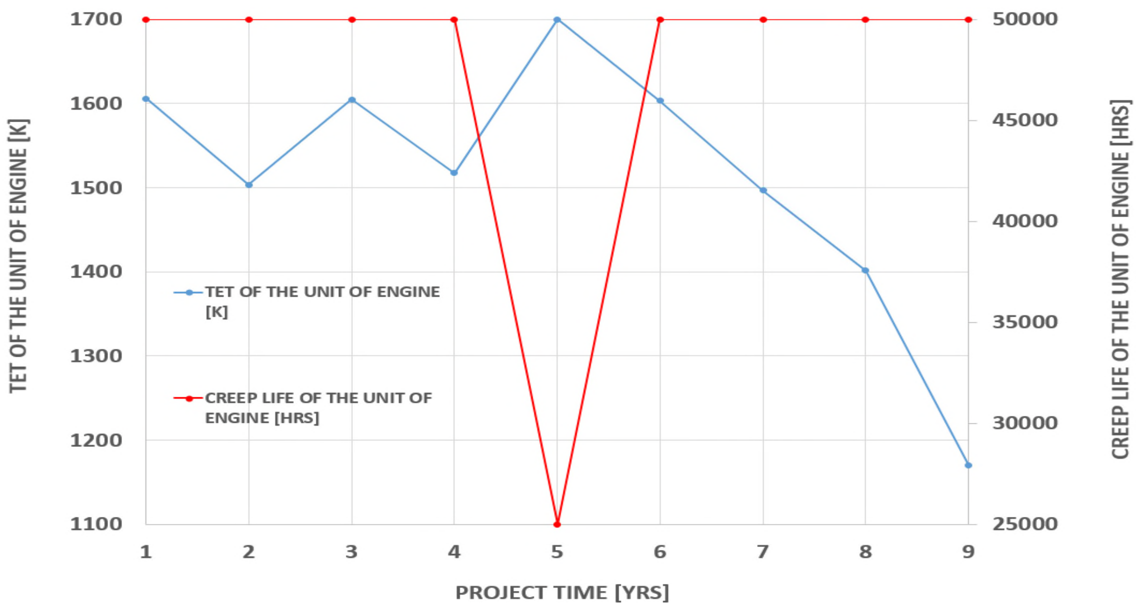


Figure 5-58: TET against Creep Life of the 3rd Unit of Engine in the SS296 Clean Fleet [Divested after the 9th year]

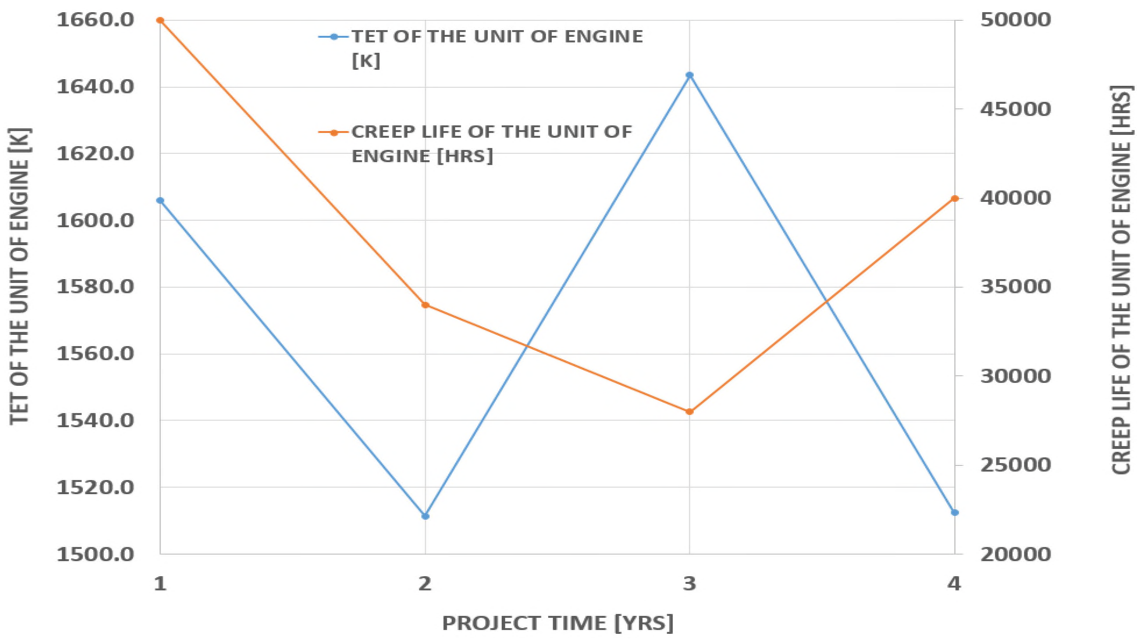


Figure 5-59: TET against Creep Life of the 3rd Unit of Engine in the SS296 OPT Degraded Fleet [Divested after the 4th year]

5.4 Emission prediction for the optimised fleets

Figure 5-60 and Figure 5-61 show the predicted emissions generated by the AD43 clean (optimised) fleet for the entire duration of the project.

The gradual fall in the emission generated as seen in Figure 5-60 and Figure 5-61 is basically as a result of the divestments of units of engines in the fleet.

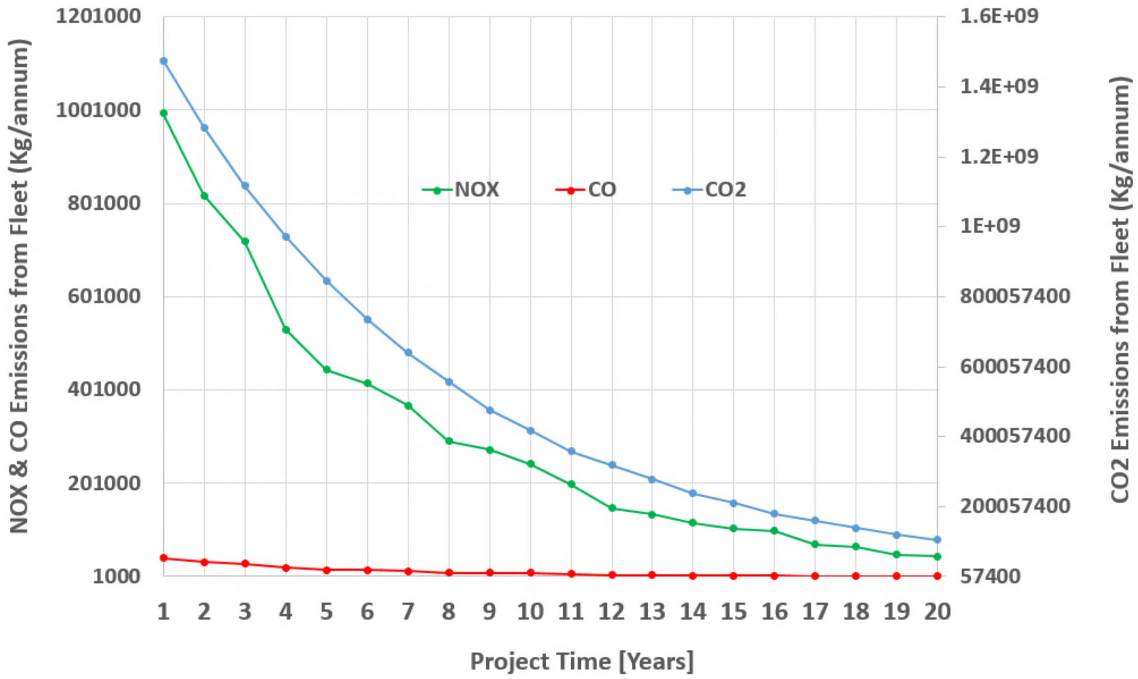


Figure 5-60: Emissions Generated by the AD43 Clean (Optimised) Fleet

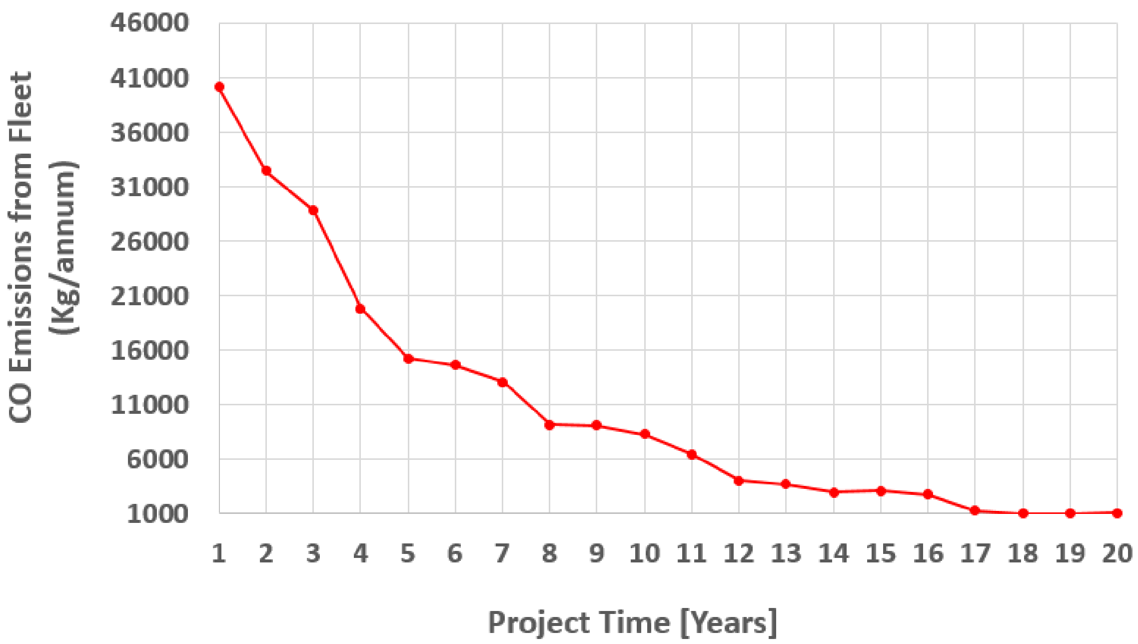


Figure 5-61: CO Emissions Generated by the AD43 Clean (Optimised Fleet)

5.5 Chapter Summary

This chapter shows the results of the optimisation for the various fleets.

The fleet composition, power and efficiencies for the various study scenarios were optimised. The energy generated by the fleets were also calculated.

The optimisation model and its results were verified by comparing with the results of the baseline fleet. An increase of 1.0% was achieved for the optimised power of the clean (43.3MW) aero-derivative fleet as against the baseline fleet.

Using the results of the optimised power for the clean fleets as an example, the (100MW) aero-derivative intercool fleet has the highest total optimised power, followed by the (43.3MW) aero-derivative fleet, then the (296MW) reheat fleet and the (296MW) single shaft fleet having the least.

The GA in MATLAB code was used in optimising the divestment time of the redundant units of engines in the various fleets. Results of the optimisation show that engine degradation extends the divestment time of the redundant units of engines in the various fleets. For example, at the 2nd year of the project; 0, 1, 2, 3, 3 are the respective number of units of engines divested in the PES degraded, MED degraded, OPT degraded, clean (optimised) and baseline fleets of the (43.3MW) aero-derivative engine.

As part of the TERA module, the emissions generated by the fleet and the creep life of the individual units of engines in the fleet were all estimated.

6 ECONOMIC EVALUATION OF THE OPTIMISED FLEETS

This chapter assesses the impact of the various optimised fleets on the economic use of AG. It also analyses the influence of engine degradation on the economic utilisation of AG. The model and methodology used will serve as a guide to investors who would want to invest in the economic utilisation of AG for power generation using gas turbines.

The approaches adopted in the various sub-sections of this chapter are similar to those used in the economic analysis in chapter 3 of this research. The only difference is that while chapter 3 dealt with the economics of the baseline fleet, this chapter deals with the economics of the optimised fleets of the various engines. Therefore, to avoid repetitions, reference will be regularly made to the explanations, equations and tables in chapter 3.

The input data and the assumptions for the economic assessment of the optimised fleets are contained in Table 3-7.

6.1 Capital investment on the fleets

As noted in sub-section 3.5.4.1, the starting capital for the AD43 fleets was obtained by taking business loan. The starting capital for the RH296, IC100 and SS296 fleets were also gotten by taking business loan. Using the same approach (Equation 3-1) adopted in estimating the starting capital for the AD43 fleets, it implies that the starting capital for the RH296, IC100 and SS296 fleets are \$815,776,000, \$1,143,600,000 and \$815,776,000 respectively. Fleets of the same engine type all have the same starting capital, this is because all fleets started as clean at the beginning (1st year) of the project.

A range of 2 to 8% are used as the loan interest rate, the loan repayment holiday is taken as 1 year, whereas, the loan duration is 10 years.

6.2 Operation & maintenance cost of the optimised fleets

6.2.1 Annual fleet operations & maintenance cost

The annual operations and maintenance costs for the optimised fleets were estimated using the relationships in Equations 3-2 to 3-6 and the factors outlined in Table 3-7. To account for the effect of inflation on the cost of engine spare parts, chemicals, consumables, etc., an annual escalation of 2% increase was applied to the annual operations and maintenance cost.

The annual operations and maintenance costs of the fleets depend on many factors, among which are the power produced, the creep life of the individual units of engines in the fleet and how frequent engine overhauling takes place for the degraded fleets. Figure 6-1 shows the annual operations and maintenance costs for the AD43 fleets. The combined effect of power produced, creep life and engine overhauling gives rise to the trend seen in Figure 6-1. For the degraded fleets, the creep life gets worse every 3 years and engine overhauling also takes place at the same period, hence, the rise observed in the annual operations and maintenance cost of the PES and MED fleets as seen in some of the years of the project.

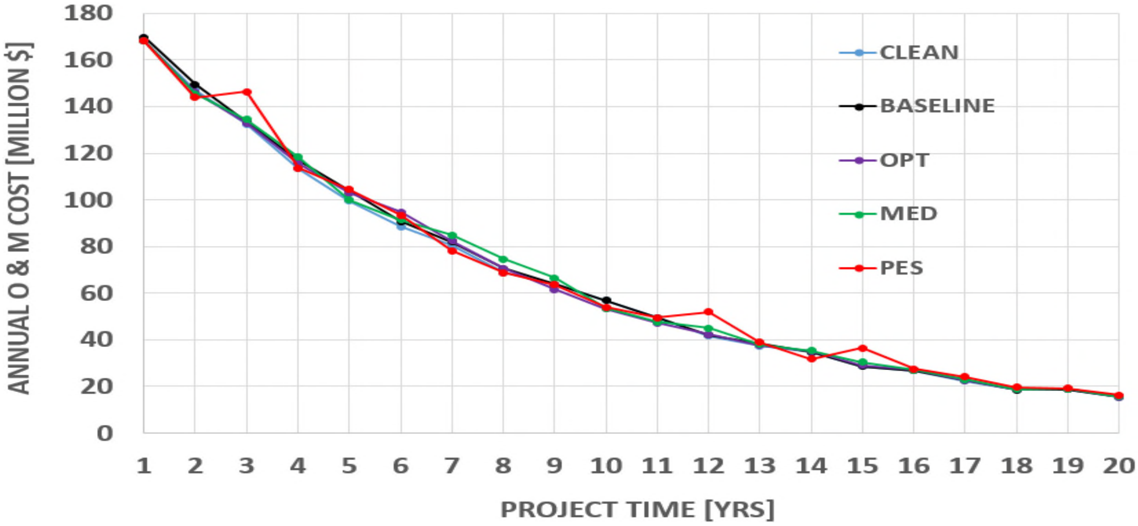


Figure 6-1: Annual Operations & Maintenance Costs for the AD43 Fleets

6.2.2 Total operations & maintenance cost of all fleets

Figure 6-2 shows the total operations and maintenance costs for all the fleets in this research. The data used in plotting this figure are obtained by summing up the annual operations and maintenance costs of all the fleets for the entire project time. The combined effect of the power produced, creep life and engine overhauling of the units of engines in the various fleets resulted in the trend observed in Figure 6-2. The more power a fleet produces, the higher its operations and maintenance cost. However, with the influence of the lower creep life and the overhauling that takes place for the degraded fleets, the PES degraded fleet of the IC100 engine has the highest total operations and maintenance cost, followed by the MED and OPT degraded fleets of the same engine type.

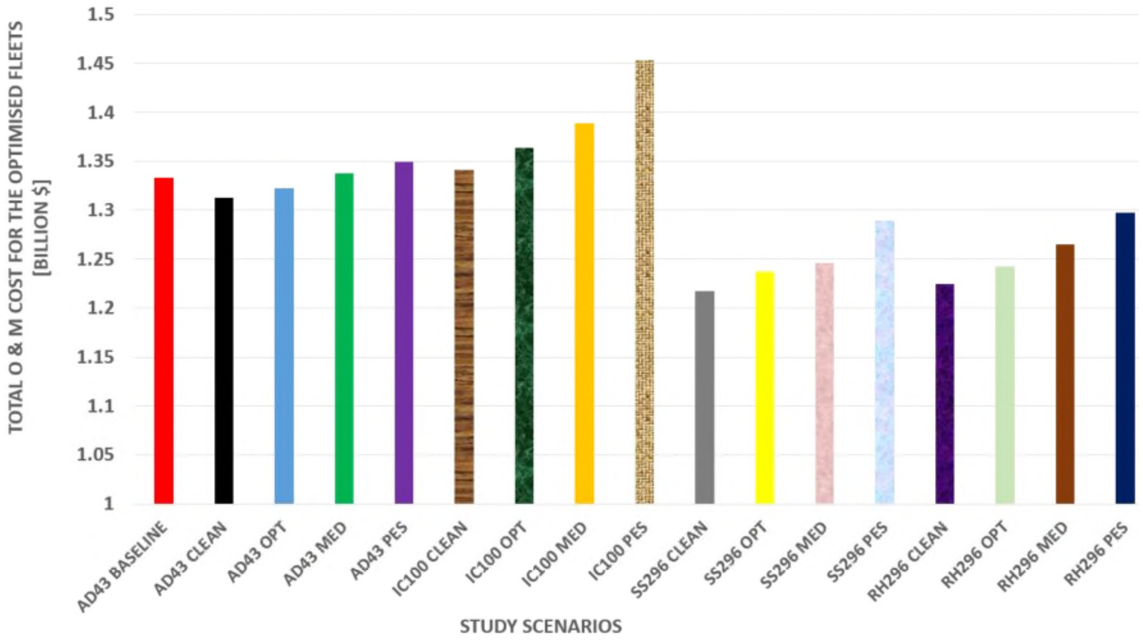


Figure 6-2: Total Operations & Maintenance Costs for all Fleets

6.3 Emission tax from the optimised fleets

The model for the economic use of AG would not be robust enough without considering the effect of emission tax. As explained in sub-section 3.5.4.3, only CO_2 emission is taxed. 0.02$/kg is the assumed emission tax.

To account for the effect of future increase in the assumed emission tax, an annual escalation of 2% increase was applied to the annual emission tax. Using the relationship shown in Equation 3-7 and the CO_2 emission data shown in Figure 5-60, the annual emission tax for the optimised fleet of the clean AD43 engine are estimated as shown in Figure 6-3, both figures (5-60 and 6-3) have the same reason for the trend observed.

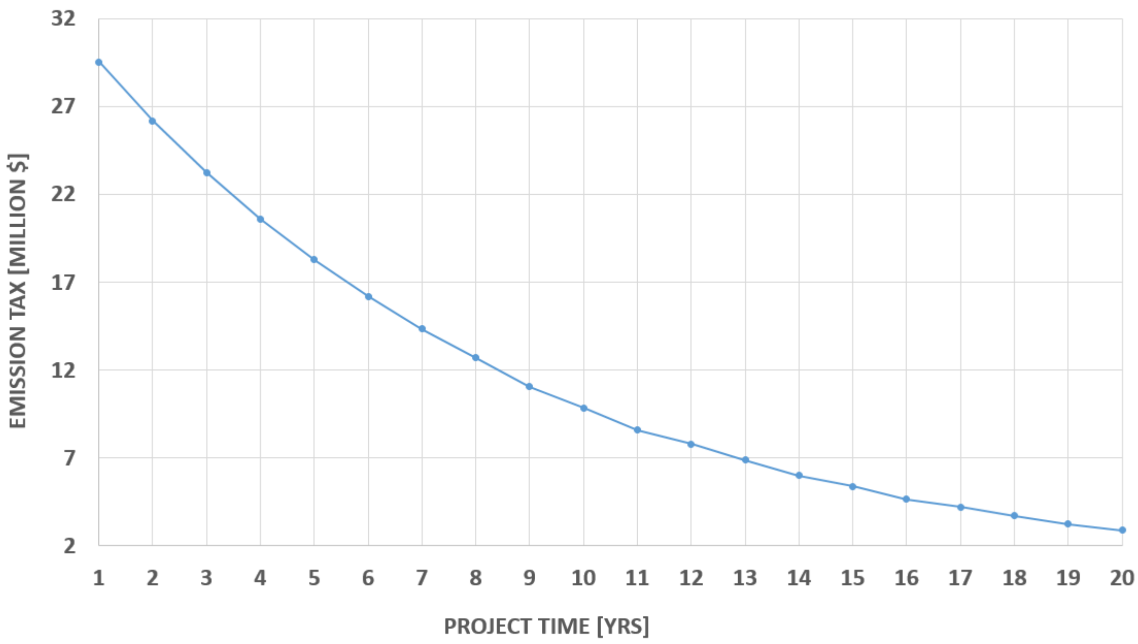


Figure 6-3: Annual CO_2 Emission Tax for the Clean AD43 (Optimised) Fleet

6.4 Number of staff in the project and staff salaries

Another two essential parts of the economic model for the profitable utilisation of associated gas are the annual number of staff to be involved in the project and their annual salaries.

6.4.1 Number of staff for the various fleets

The number of staff varies for the different fleets. Fleets with more units of engines have more staff than fleets with less units. All fleets of the same engine type have the same number of staff at the beginning of the project, this is because they all have the same number of units of engines at the beginning of the project. However, over the years of the project, due to engine unit's divestment, the staff strength of the various fleets would differ because the annual staff strength is dependent on the number of units of engines in the fleet.

Table 3-8 shows the initial number of staff involved in the project and their salaries for all AD43 fleets. Table 6-1 shows the initial number of staff involved in the project and their salaries for all SS296 and RH296 fleets.

Table 6-1: Number of Staff at the Beginning of the Project & their Salaries (for all SS296 & RH296 Fleets) [92]

Duty	Number in the Project	Annual Salary per Staff [$]	Total Salary [$]
Administrative Manager	1	94,840.00	94,840.00
Plants Manager	1	141,650.00	141,650.00
Finance Manager	1	134,330.00	134,330.00
Operators	10	58,490.00	584,900.00
Mechanical Department	10	56,390.00	563,900.00
Control and Instrumentation Department	10	56,320.00	563,200.00
Electrical Department	10	61,870.00	618,700.00
Performance Department	10	56,390.00	563,900.00
Account/Purchase Department	2	75,280.00	150,560.00
Health and Safety Department	4	51,270.00	205,080.00
Ware House Department	4	25,000.00	100,000.00
Security Department	4	28,460.00	113,840.00
Fire Service	4	48,030.00	192,120.00
Transport Department	4	38,050.00	152,200.00
Miscellaneous Staff	4	70,000.00	280,000.00

6.4.1.1 Number of staff at the beginning of the project

Figure 6-4 shows the number of staff at the beginning of the project for all the different engine types used in the research. The fleets with more units of engines have a higher number of staff.

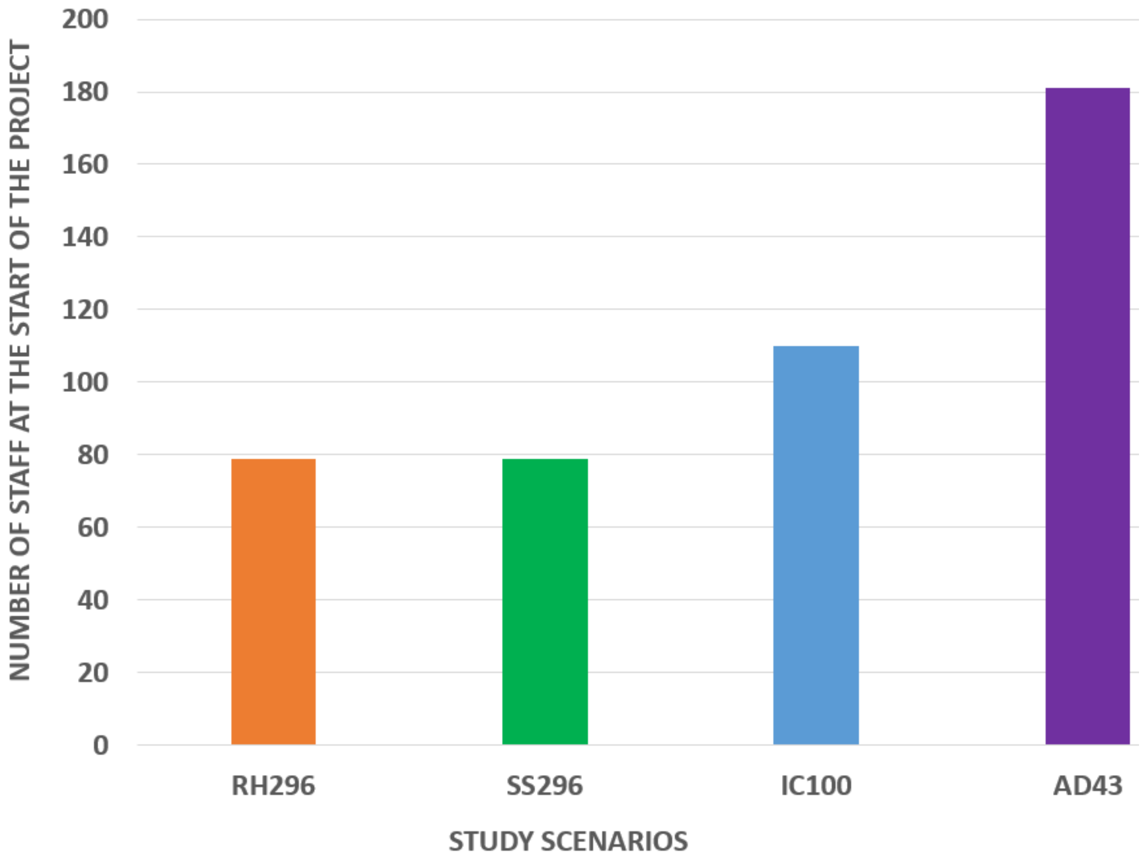


Figure 6-4: Number of Staff at the Beginning of the Project for all the Engine Types

6.4.1.2 Annual number of staff for the fleets

Figure 6-5 shows the effect of engine units' divestment time on the annual number of staff in the project for all RH296 fleets. The number of staff in each fleet reduces with engine units' divestment. The PES degraded fleet has more staff at the 2nd and 5th years of the project, because it has one more unit of engine at these years compared with the clean, OPT and MED degraded fleets (see Figure 5-30).

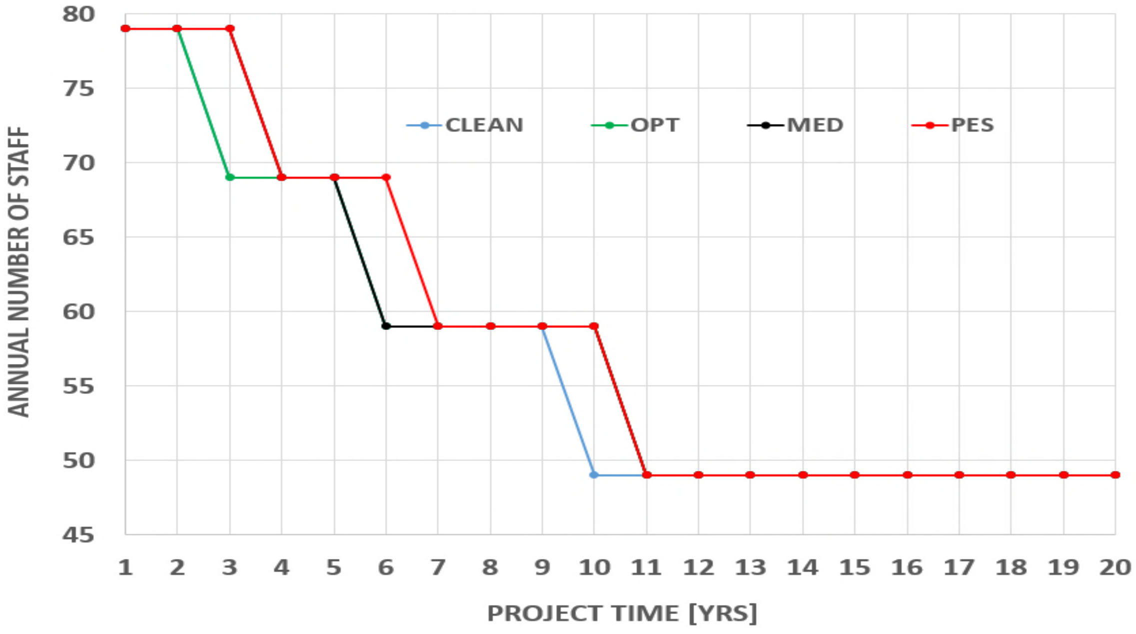


Figure 6-5: The Effect of Engine Units' Divestment Time on the Annual Number of Staff in the Project (RH296 Fleets)

6.4.2 Staff salaries for the various fleets

6.4.2.1 Annual staff salaries

The annual staff salaries are estimated based on the number of staff involved in each year of the project and the staff salaries data seen in Table 6-1. An incremental factor of 1.5% was added to the total annual staff salaries after every 2 years of the project.

Figure 6-6 shows the influence of engine units' divestment time on the annual staff salaries for the RH296 fleets. The explanation for the trend observed in Figure 6-5 also applies for Figure 6-6, while the increase observed in the annual staff salaries for some years of the project is as a result of the 1.5% incremental factor applied.

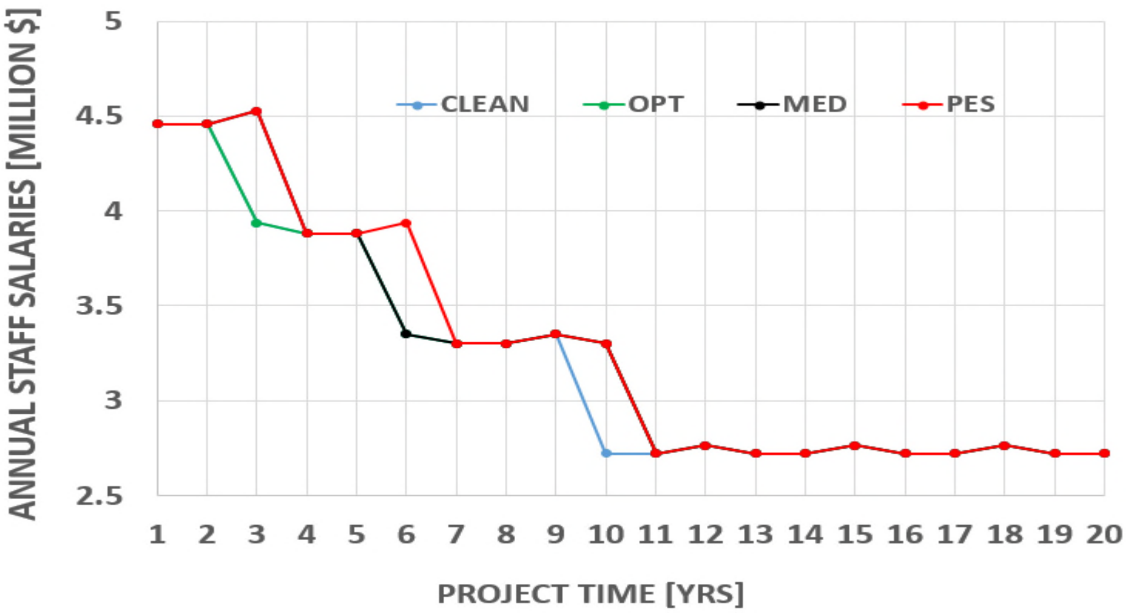


Figure 6-6: The Influence of Engine Units' Divestment Time on the Annual Staff Salaries (RH296 Fleets)

6.4.2.2 Total staff salaries for the entire project time (all fleets)

Figure 6-7 shows the total staff salaries for all the fleets in this research. The fleets with more staff have higher staff salaries. Considering the total staff salaries for the fleets of the same engine type, it is observed that the higher degraded fleets have higher total staff salaries. The reason for this trend is because the units of engines in the higher degraded fleets lasts longer before being divested, and the number of staff in each year of the project is dependent on the number of units of engines in the fleet. Therefore, the PES degraded fleet will have higher total staff salaries than other fleets of the same engine type as observed in the Figure 6-7.

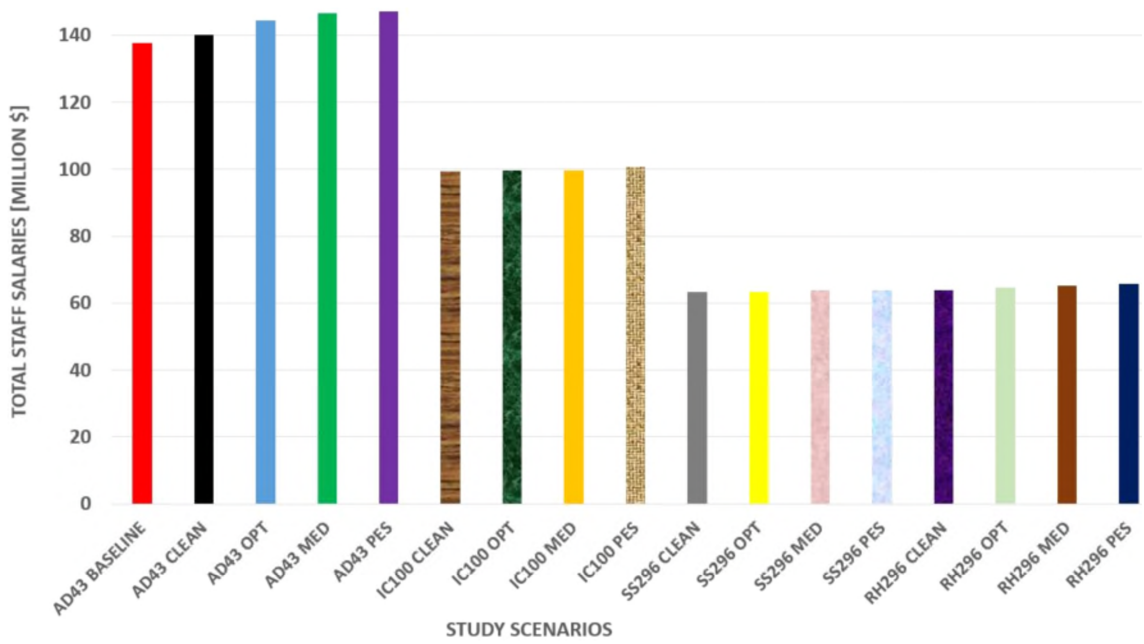


Figure 6-7: Total Staff Salaries for all Fleets

6.5 Gas turbine engines divestment sales and loan repayment analysis

As a result of the need to have a robust model for the economic utilisation of AG using gas turbines, gas turbine divestment sales and loan repayment are also included in the economic model.

6.5.1 Gas turbine divestment sales

Gas turbine divestment sales is one of the sources of revenue in this proposed economic model for AG utilisation. The divested units of engines are sold and the money is added up as part of the revenue made from the project.

The divestment time of a unit of an engine influences its divestment sale. Therefore, a unit of an engine in a fleet will have different divestment sales depending on the time of its divestment. The same explanations, assumptions and equations used in estimating the divestment sales for the units of engines in the baseline fleet are also applied for all the other fleets in this study (see sub-section 3.5.4.6). The gas turbine engine depreciation rate was taken to be 0.0516/annum for the clean fleets [86] as seen in Table 3-7. The assumed gas turbine depreciation rates for the OPT, MED and PES degraded units of engines are 0.0616, 0.0716 and 0.0816/annum respectively. Figure 3-25 shows the annual divestment sales for the baseline fleet, Figure 6-8 shows the total divestment sales for all the fleets in the study. As seen in Equation 3-10, the combined effect of the original price, depreciation rate, age and the shaft power of the engine at design point resulted in Figure 6-8.

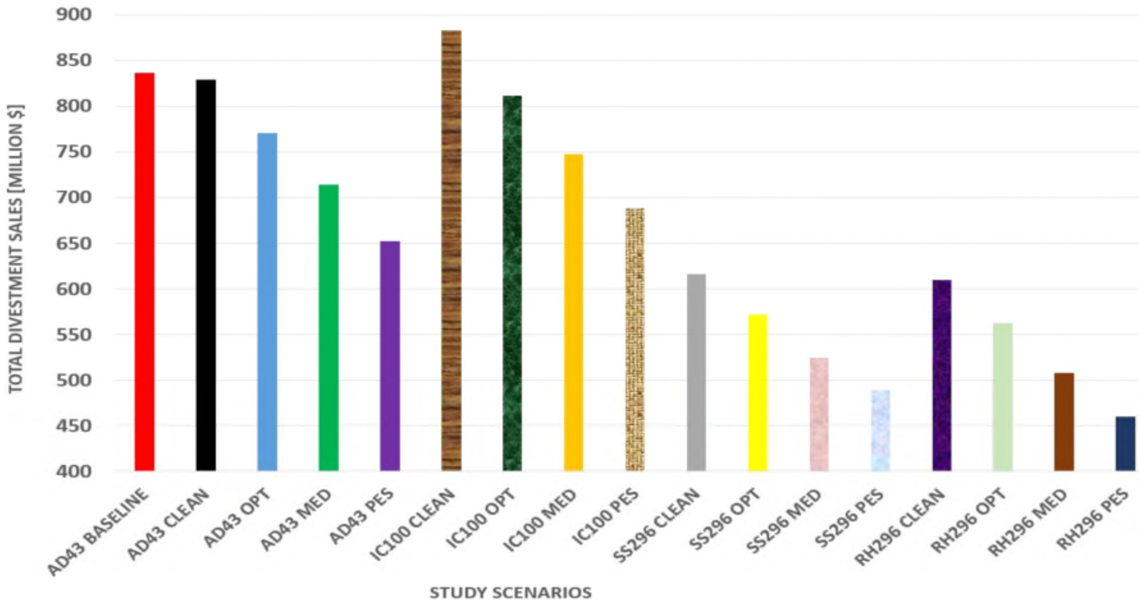


Figure 6-8: Total Divestment Sales for the Various Fleets

6.5.2 Loan repayment for all fleets

The loan repayments for the various units of engines in the different fleets were estimated using Equation 3-11. To avoid repetition, all explanations and assumptions made in estimating the loan repayment for the baseline fleet also applies to all other fleets in the study (see sub-section 3.5.4.7).

6.5.2.1 Annual loan repayment for the fleets

Figure 6-9 shows the annual loan repayments for the AD43 fleets at a loan interest rate of 2%. The loans were assumed to be taken separately for the different units of engines in the fleet, as such, they were also repaid separately. The loan for each unit of engine is paid just before the engine is divested and the different units of engines in the AD43 fleets have their different divestment times. This is the reason for the slight difference observed in the annual loan repayment values for the different AD43 fleets as seen in Figure 6-9.

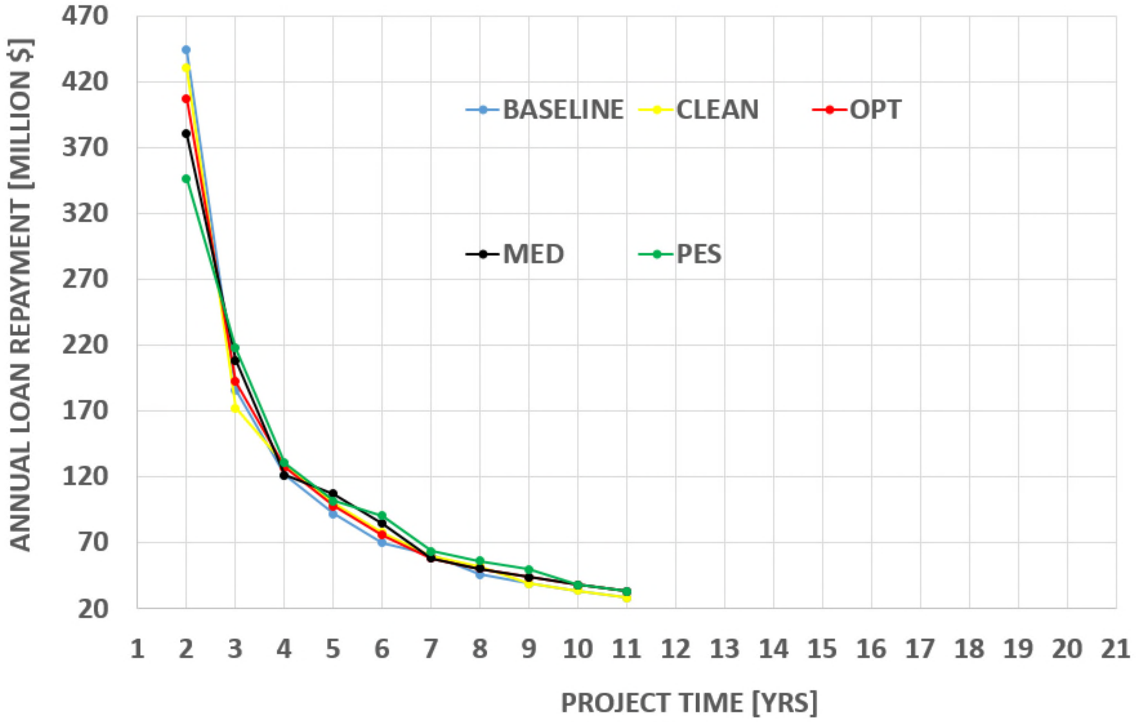


Figure 6-9: Annual Loan Repayment for the AD43 Fleets (2% Interest Rate)

6.5.2.2 Total loan repayment for all fleets

Figure 6-10 shows the total loan repayment for all the fleets at 2% interest rate. As seen from Equation 3-11, apart from the interest rate used which is the same for all fleets, the two variables that determine the loan repayment are the engine capital cost and the loan duration. The loan duration for each unit of engine is dependent on the divestment time, as the loan is paid just before the unit of engine is divested. The loan repayment values seen in Figure 6-10 are as a result of the combined effect of the engine capital costs, the loan durations and the total number of units of engines in the fleets. From Figure 6-10, considering fleets of the same engine type, the pessimistic degraded fleets have the highest total loan repayment values, followed by the medium, then optimistic, and the clean is least. The reason for this trend is because the units of engines in the higher degraded fleets have longer divestment time, as a result, their loan duration is longer, which impacts on the loan repayment. The longer the loan duration, the higher the loan repayment.

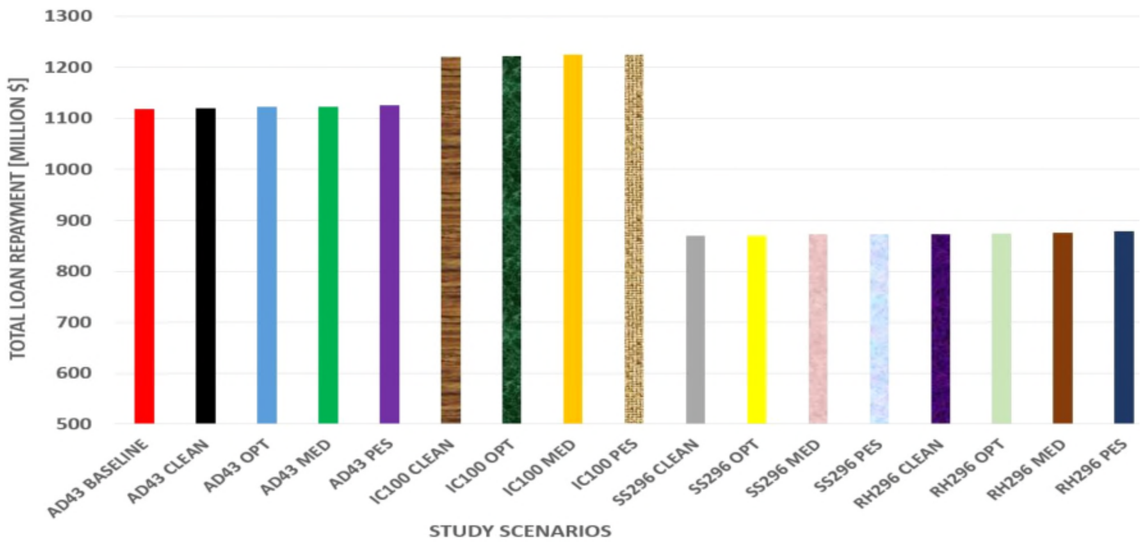


Figure 6-10: Total Loan Repayment for all Fleets (2% Interest Rate)

6.6 Revenue from sold electricity

The major revenue from this project of AG utilisation comes from selling of the electricity that is generated by the various fleets. The electricity obtained from the various optimised fleets is sold to the national grid of which ever country the project is applied to. For the purpose of this research, the assumed electricity selling tariff to the national grid is 0.12$/kWh.

6.6.1 Annual revenue from sold electricity

As seen in Equation 3-8, the revenue from the sold electricity ($) is obtained by multiplying the energy generated in kWh by the electricity selling tariff to grid in $/kWh.

Figure 6-11 to Figure 6-14 show the annual revenue from the electricity sold to the national grid for the different fleets. The same assumptions made in estimating the annual revenue from the sold electricity for the baseline fleet also applies for all the other fleets (see sub-section 3.5.4.5).

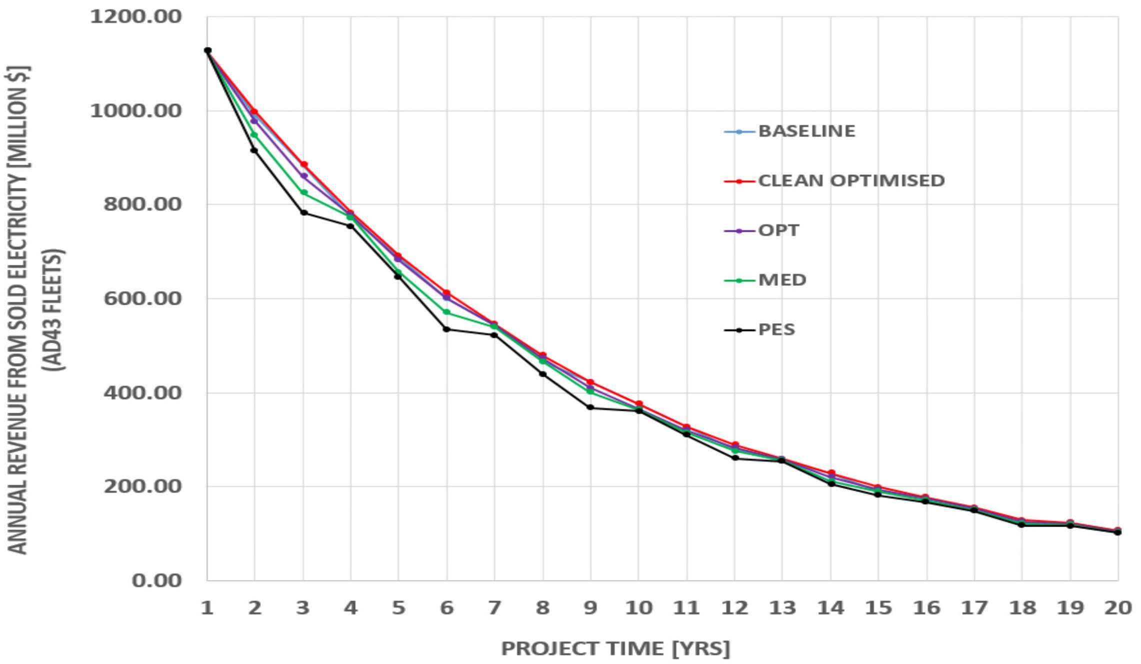


Figure 6-11: Annual Revenue from Electricity Sold to Grid (AD43 Fleets)

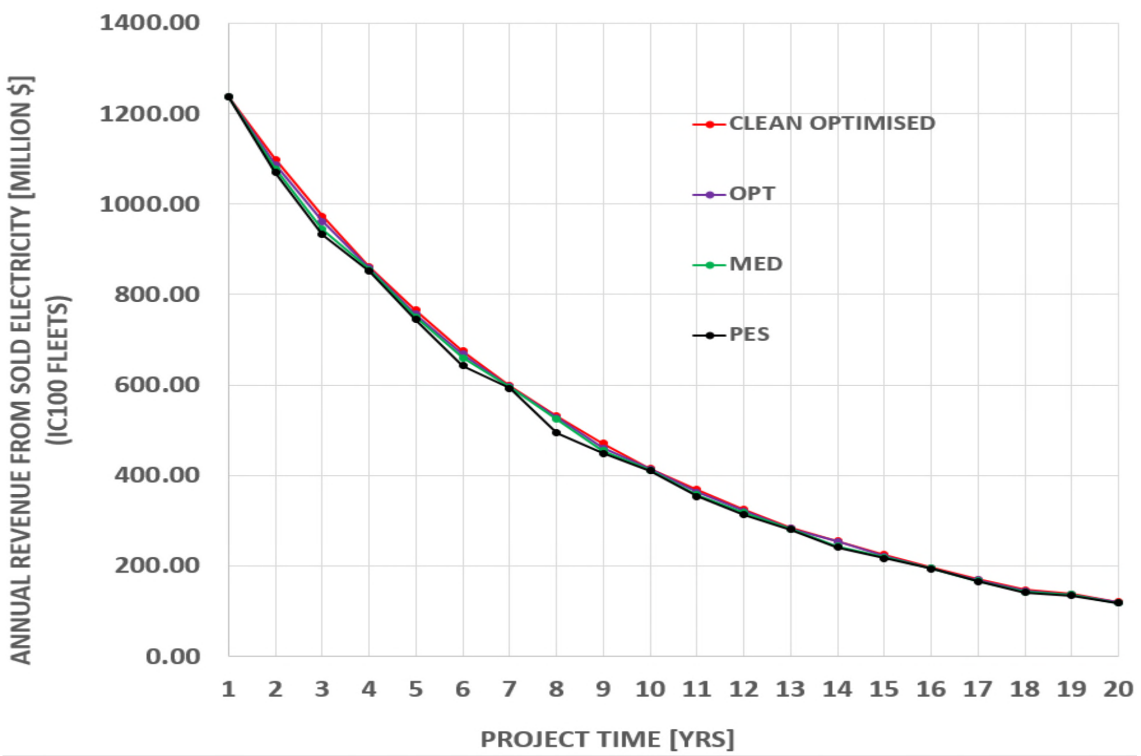


Figure 6-12: Annual Revenue from Electricity Sold to Grid (IC100 Fleets)

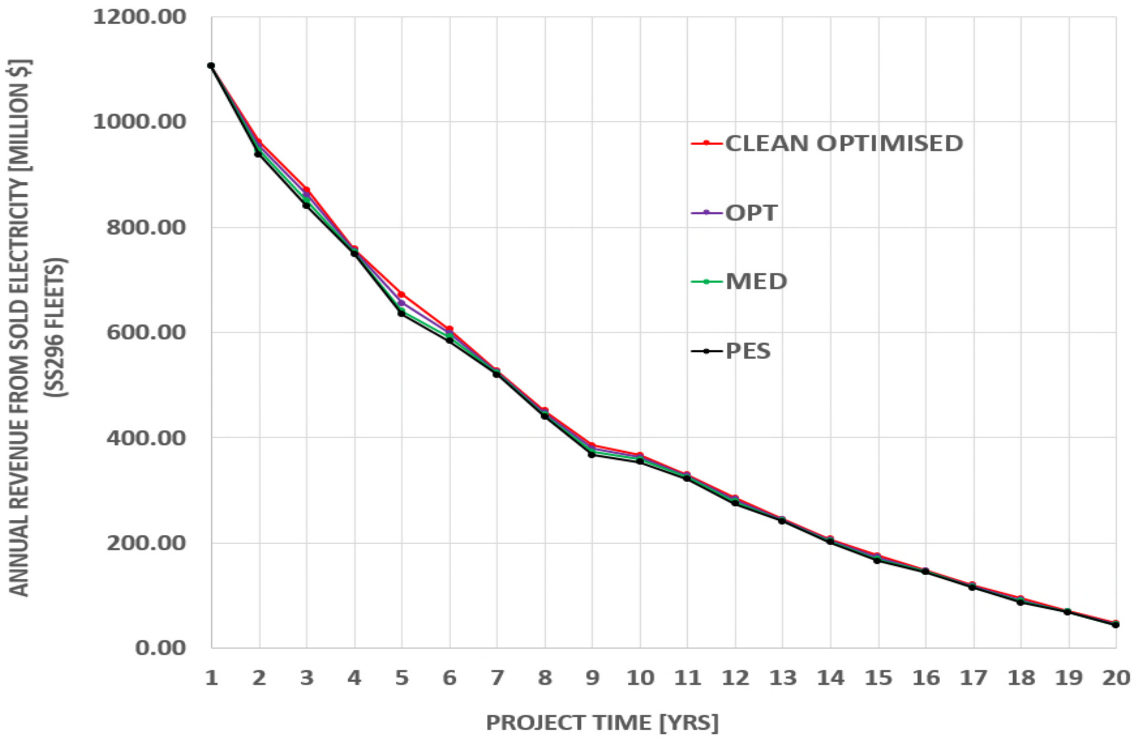


Figure 6-13: Annual Revenue from Electricity Sold to Grid (SS296 Fleets)

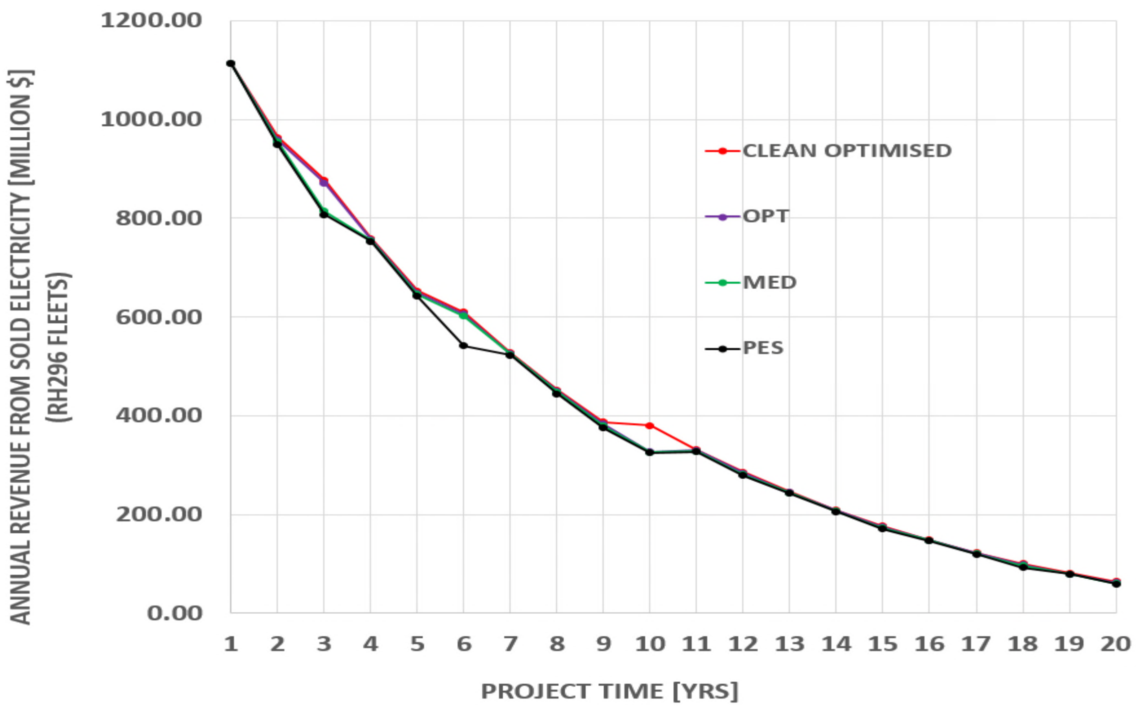


Figure 6-14: Annual Revenue from Electricity Sold to Grid (RH296 Fleets)

Comparing the annual revenue from the sold electricity for the different fleets as seen in Figure 6-11 to Figure 6-14 with their corresponding annual optimised power and annual energy as seen in sub-section 5.2.3. From the comparison, it is seen that the same trends also applies for the annual revenue from the sold electricity, and the reason for the trends remain the same as explained for the annual optimised power and the annual energy.

As seen in Figure 6-11 to Figure 6-14, at the first year of the project, the revenue generated from each of the AD43, IC100, SS296 and RH296 fleets are $1.13b, $1.24b, $1.11b and $1.11b respectively, with exception of the baseline fleet (AD43 baseline) which is $1.12b.

6.6.2 Total revenue from sold electricity

Figure 6-15 shows the total revenue generated from the sold electricity for all the fleets in this research. From the results of Figure 6-15, the engines with higher simulated efficiencies generated higher revenue. As an example, considering just the clean fleets of the various study engines, the IC100 fleet generated the highest revenue, followed by the AD43, then the RH296 and the SS296 fleet has the least. This trend is not a surprise as their simulated efficiency values also have similar trend as seen in Table 3-1 to Table 3-4 and sub-section 5.2.4. The same explanation applies for the degraded fleets, their optimised efficiencies can also be found in sub-section 5.2.4.

It therefore implies that the engines with higher efficiencies would be given priority in the decision on which engine type is to be recommended to AG usage investors. This recommendation is based on the assumption that all other factors that could have influenced this decision are assumed constant.

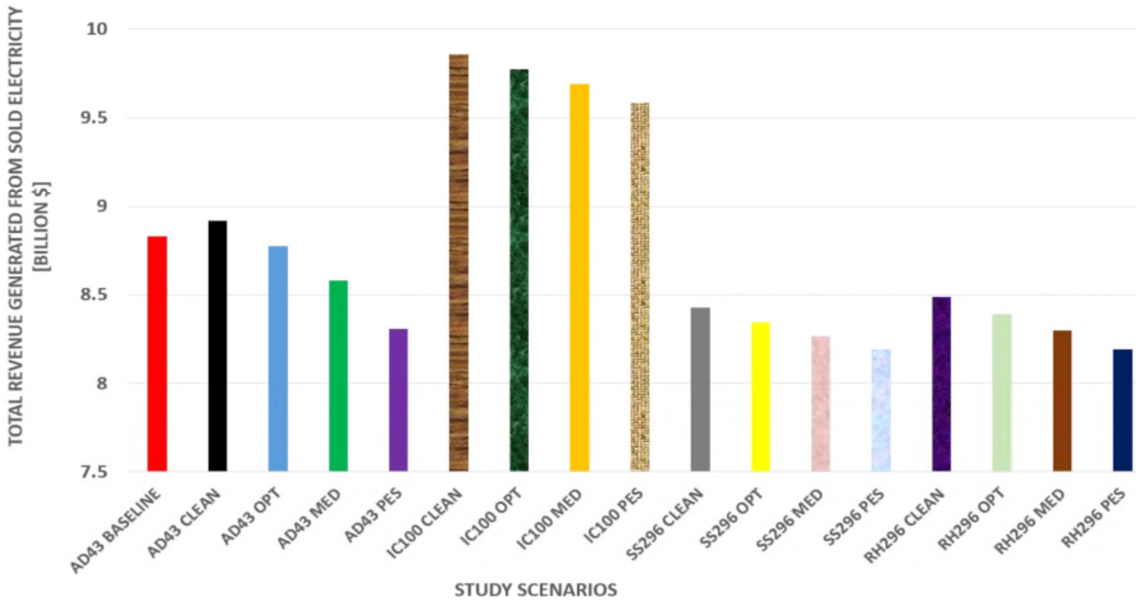


Figure 6-15: Total Revenue Generated from Sold Electricity

6.7 Net present value (NPV) analysis

The robust model developed for the economic use of AG integrated several technical and economic factors as seen in this chapter of the research. Figure 6-16 shows the economic return (NPV) from the project for the various fleets considered. Figure 6-16 shows the combined effects of the various technical and economic factors considered such as capital investment, operations and maintenance cost, emission tax, staff salaries, gas turbine divestment sales, loan repayment and revenue from sold electricity.

Considering only the clean fleets of Figure 6-16, IC100 fleet whose unit of engine at design point has the highest efficiency, this fleet also emerged with the highest NPV of \$3.24b. This is because of the domineering effect of the revenue from the sold electricity. This was not the case for the AD43 optimised fleet, although its unit engine has efficiency that is slightly higher than that of the RH296 and SS296 engines at design point, and consequently, its fleet generated more energy and electricity revenue than the RH296 and SS296 fleets. However, the combined effect of the operations and maintenance costs, loan repayments and staff salaries of the AD43 fleet reduced the effect of its generated revenue. These negative cash flows were higher in the AD43 fleet as compared with those of the

RH296 and SS296 fleets, this is because of the higher cost of running of the 25units of engines in the AD43 fleet as compared with the 4units in the RH296 and SS296 fleets.

It is worth noting that the gas turbine divestment sales were also a good source of revenue as seen in Figure 6-8.

While the various factors had effect on the economic return (NPV) of this project, the revenue from the sold electricity had domineering effect, hence, the reason for the very high NPV of the various fleets. It therefore implies, that investing in the economic use of AG for power generation using gas turbines would be a very promising business for any country currently flaring this huge source of energy.

As a recommendation to governments who want to invest in the economic utilisation of AG using gas turbines, a good blend of high efficiency and power output should be key factors in the choice of the fleet of engines to purchase.

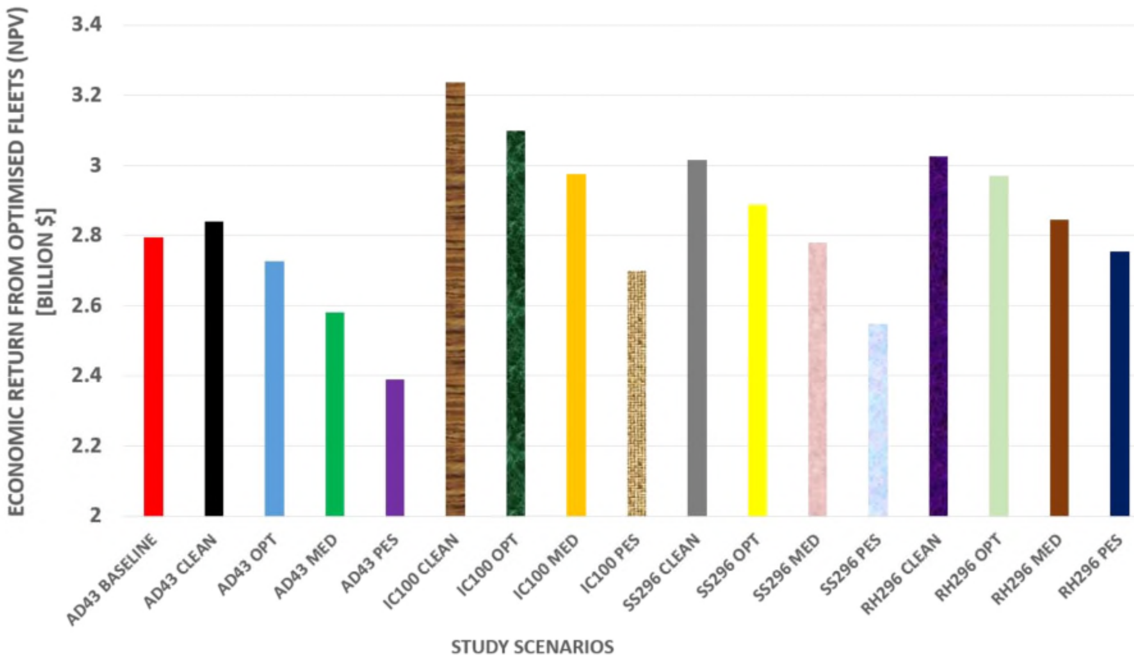


Figure 6-16: Economic Return from the Optimised Fleets (NPV) at 2% Loan Interest Rate

6.7.1 The effect of the various levels of gas turbine degradation on the NPV of the project

Figure 6-17 shows the results of the assessment of the impact of gas turbine degradation on the economic use of AG. For the AD43 fleets, the baseline, clean (optimised), the OPT, the MED and the PES degraded fleets generated $2.79b, $2.84b, $2.73b, $2.58b and $2.39b respectively as seen in Figure 6-16. It implies that compressor degradation as a result of fouling reduced the NPV of the project by 4.0%, 9.1% and 15.8% for the OPT, MED and PES degraded fleets of the AD43 engine respectively as seen in Figure 6-17, this is in comparison with the NPV for the clean fleet. Comparing the NPV for the baseline fleet and the optimised (clean) fleet of the AD43 engine, the improvement of the economic performance of the clean fleet resulted in a 1.6% increase in the NPV.

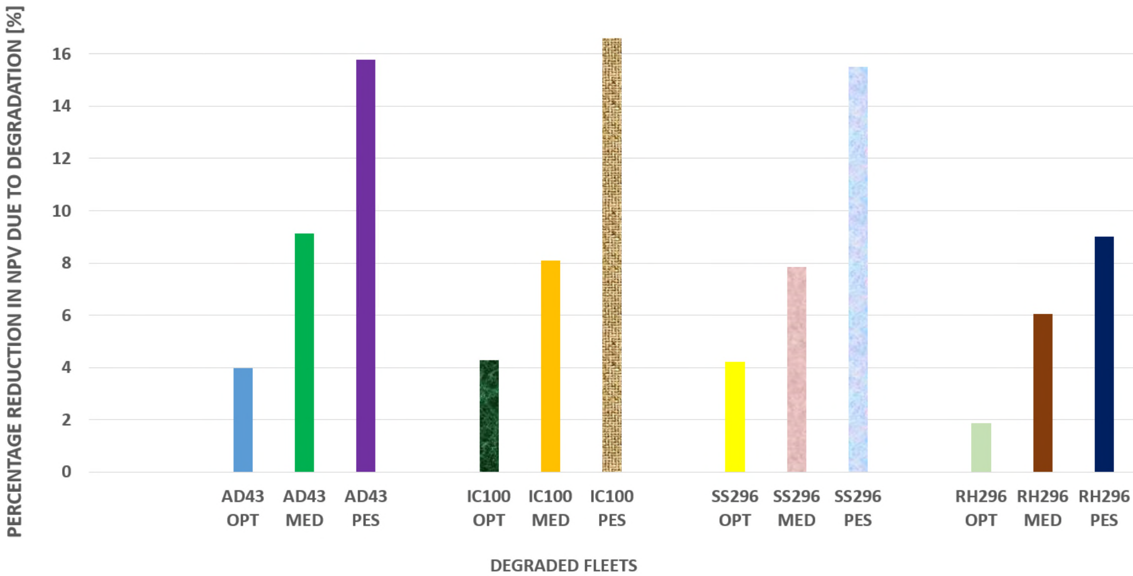


Figure 6-17: Assessment on the Impact of Gas Turbine Degradation on the Economic Use of AG

6.7.2 The effect of the optimised best divestment time on the NPV of the project

Optimisation of the best divestment time for the units of engines in all the fleets used in the research resulted to increased economic return (NPV) from the fleets. Comparing the NPV for the baseline fleet and the optimised (clean) fleet of the

AD43 engine (Figure 6-16), optimisation of the best divestment time for the units of engines in the optimised (clean) fleet resulted to a 1.6% increase in the NPV.

As seen from Figure 6-15, the revenue from the sold electricity is the domineering source of revenue from this AG use project. Optimising the best divestment time for the units of engines in the fleets obviously led to maximal use of the engines before been divested, thereby generating more energy and more revenue from the electricity sold to the national grid. The impact of the optimised best divestment time are the economic return (NPV) results shown in Figure 6-16.

6.7.3 Sensitivity analysis on the effects of various variables on the NPV of the project

Sensitivity analysis is the study of the influence of various input factors on the model output [110, p.6]. The effect of various factors on the economic utilisation of AG is examined, this together with the effect of the various levels of gas turbine degradation account for the risk assessment analysis done for the project.

6.7.3.1 The effect of varying loan interest rate on the NPV

The loan interest rate used in the economic model is 2% as seen in Figure 6-16. There could be the possibility of the loan interest rate being higher, to account for this, the effect of increase in the loan interest rate is examined.

6.7.3.1.1 The effect of 5% loan interest rate

Figure 6-18 shows the economic return (NPV) from the optimised fleets when the loan was taken at an interest rate of 5%. From Figure 6-18, the IC100 clean fleet has the highest NPV whereas the AD43 PES fleet has the least, and the values are $3.16b and $2.32b respectively. When compared with their corresponding values for 2% interest rate, the decrease was 2.3% and 3.0% respectively (Figure 6-19). Figure 6-19 shows the percentage decrease in the NPV for the various fleets when a 5% loan interest rate is applied as against the 2% applied in the economic model. As seen in Figure 6-10, the total loan repayment for the more degraded fleets are higher, it implies that the increase in the loan interest rate would have more negative impact on the NPV of the more degraded fleets as seen in Figure 6-19.

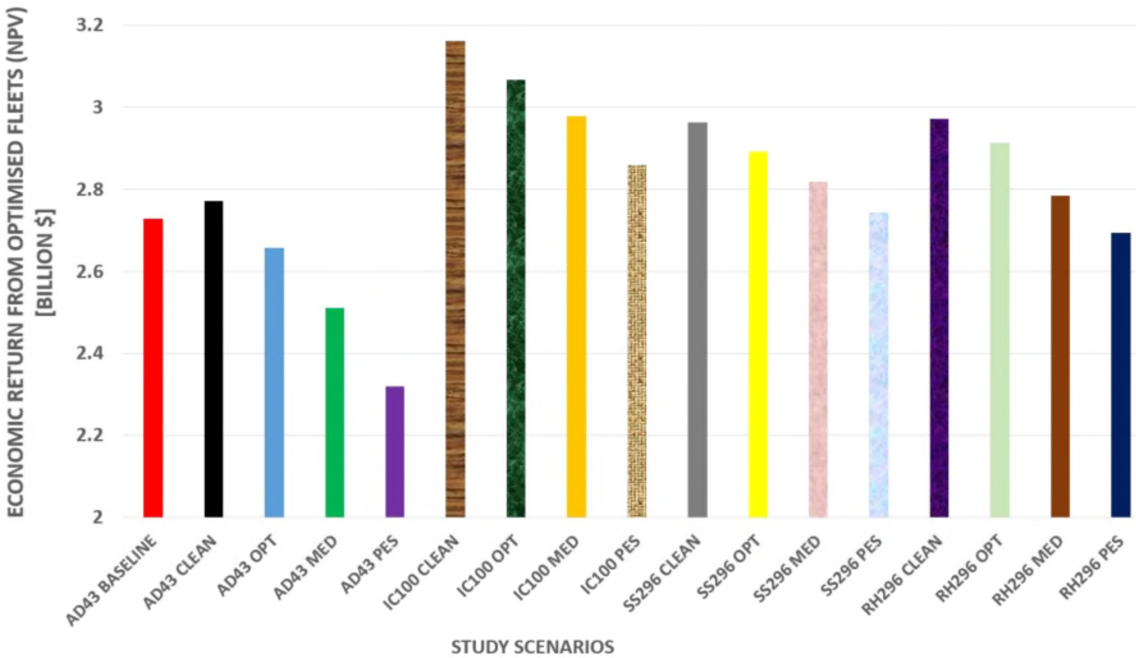


Figure 6-18: Economic Return from the Optimised Fleets (NPV) with 5% Loan Interest Rate Applied

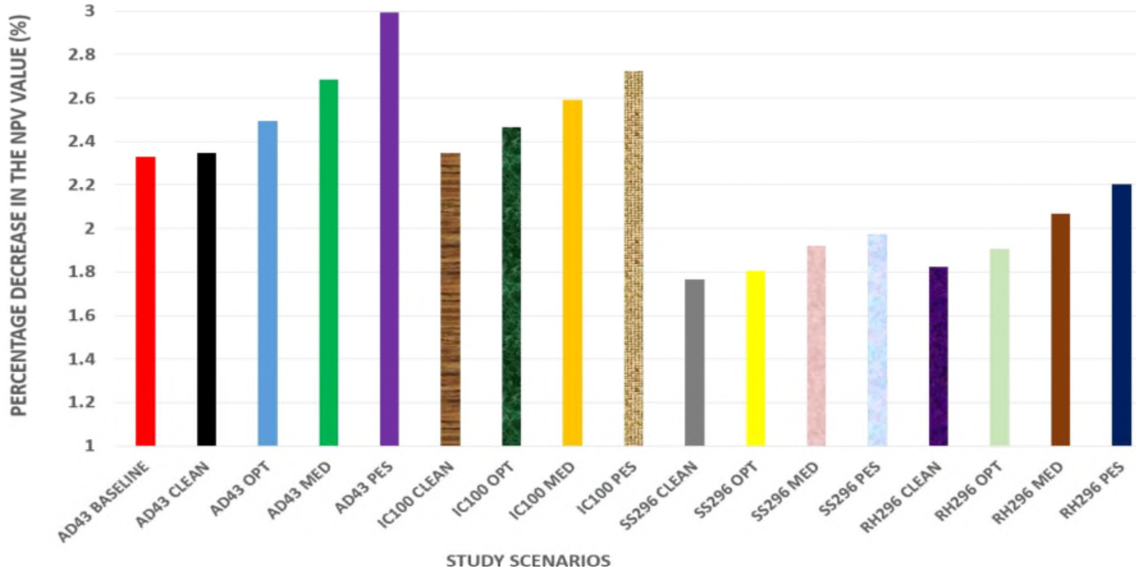


Figure 6-19: Percentage Decrease in the NPV with 5% Loan Interest Rate Applied

6.7.3.1.2 The effect of 8% loan interest rate

Figure 6-20 shows the economic return from the optimised fleets when an 8% loan interest rate was applied. Figure 6-21 shows the percentage decrease in the NPV when an 8% loan interest rate is applied as against the 2% applied in the economic model. The same explanations for the trend observed in Figure 6-19 also applies for Figure 6-21.

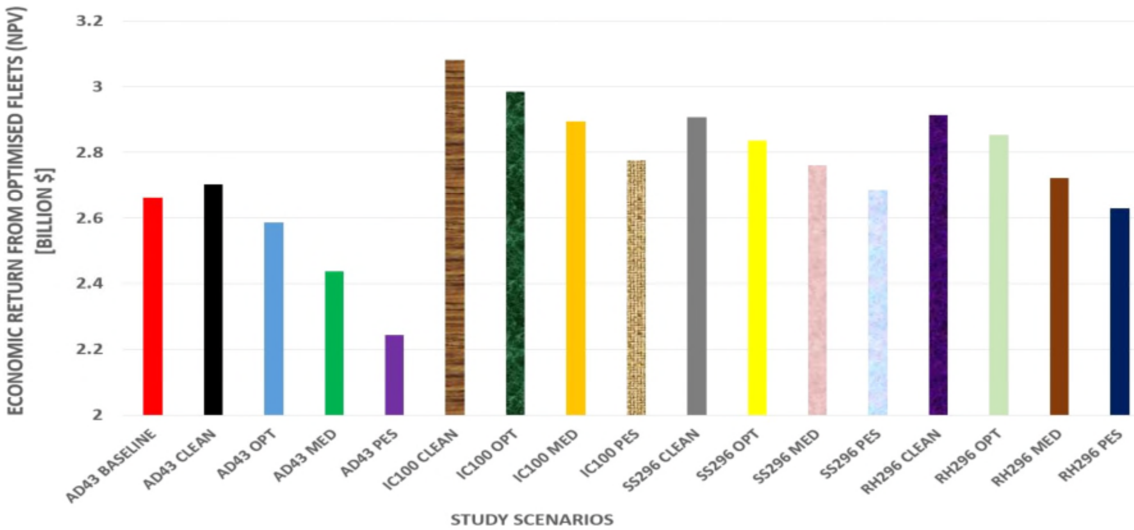


Figure 6-20: Economic Return from the Optimised Fleets (NPV) with 8% Loan Interest Rate Applied

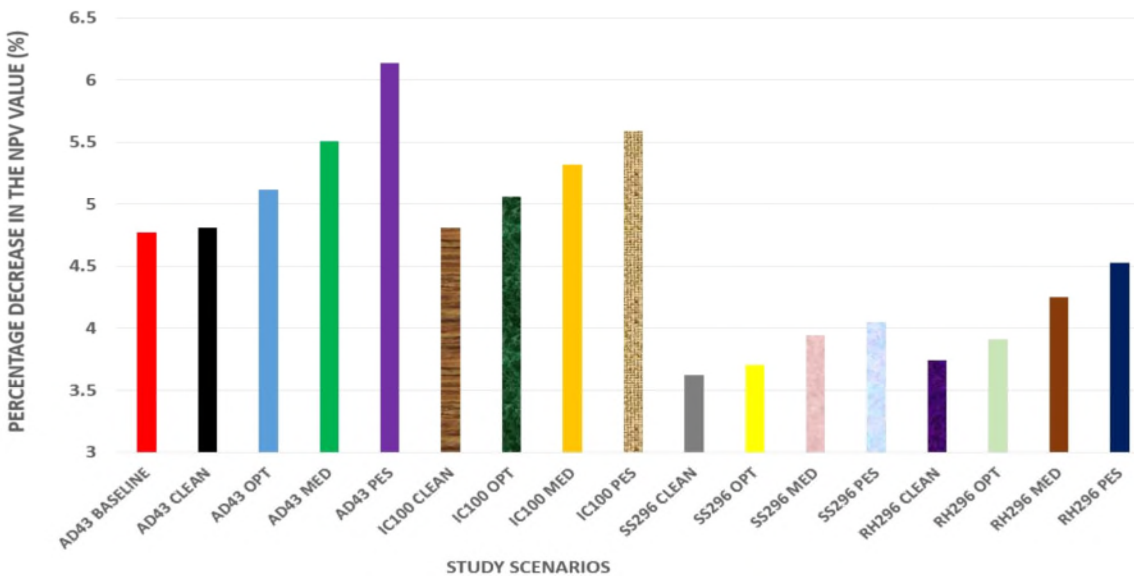


Figure 6-21: Percentage Decrease in the NPV with 8% Loan Interest Rate Applied

6.7.3.2 The effect of varying emission tax on the NPV of the project

Emission tax of 0.02 was used in the economic model. As explained earlier, due to legislative concerns, this research only considered emission tax as a result of CO_2 emissions from the fleets. But CO_2 emission is not currently being taxed. Therefore, the effect of applying zero emission tax on the economic return from the fleet is assessed.

6.7.3.2.1 The effect of zero emission tax

Figure 6-22 and Figure 6-23 show the economic return from the optimised fleets (NPV) and the percentage increase in the NPV when zero emission tax is applied. The IC100 clean fleet has the highest NPV and AD43 PES fleet has the least, and the values are \$3.37b and \$2.53b respectively as seen in Figure 6-22.

As seen in Figure 6-23, the decrease in emission tax from 0.02 used in the economic model to zero resulted in increased NPV. Comparing the percentage increase in NPV for the fleets of any of the study engines, it is observed that the higher degraded fleets have higher percentage increase as seen in Figure 6-23. This is because the less degraded fleets have NPV values much higher than the additional amount as compared to the higher degraded fleets, therefore the effect of this additional amount is better appreciated in the higher degraded fleets.

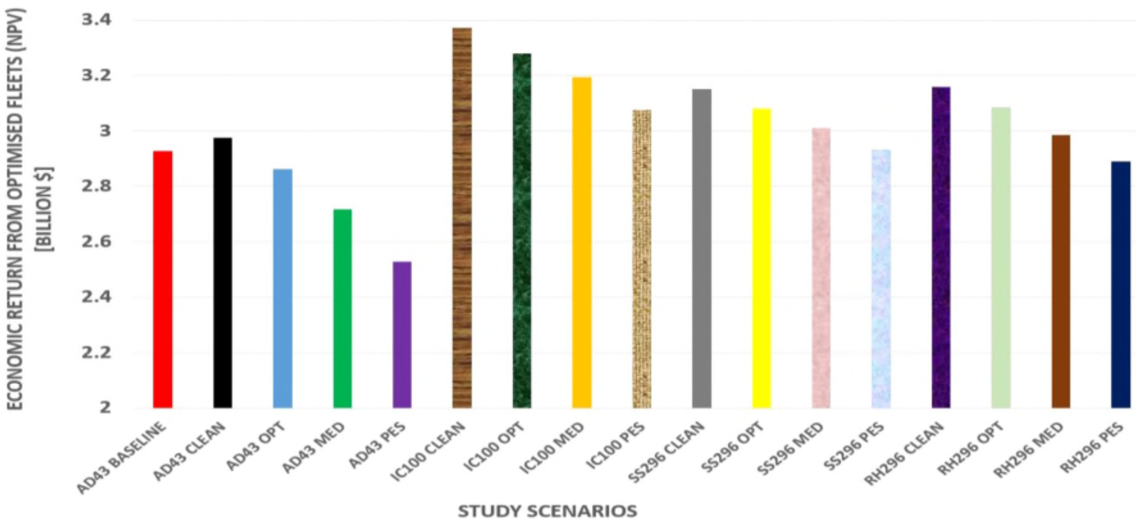


Figure 6-22: Economic Return from the Optimised Fleets (NPV) (Zero Emission Tax Assumed)

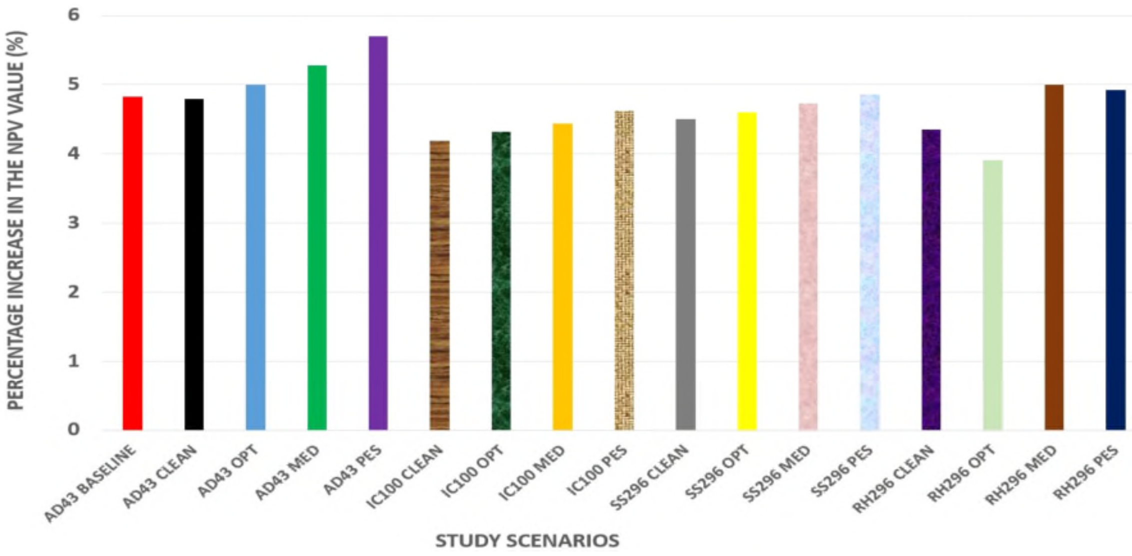


Figure 6-23: Percentage Increase in the NPV with Zero Emission Tax Applied

6.7.3.3 The effect of varying engine capital cost on the NPV

The engine capital cost greatly affects the economic return of the fleet. Table 3-7 shows the assumed engine capital costs data for the various engines used in the study. Let “Y” be the engine capital cost used for a particular engine in the study. The effect of varying each of the engine capital costs by using (Y±20) is assessed.

6.7.3.3.1 Effect of reduced engine capital cost

Figure 6-24 and Figure 6-25 show the economic return from the optimised fleets (NPV) and the percentage increase in the NPV when (Y-20) is used as the engine capital cost. The IC100 clean fleet has the highest NPV and AD43 PES fleet has the least, and the values are $3.27b and $2.42b respectively as seen in Figure 6-24.

From Figure 6-25, comparing the percentage increase in the NPV for a particular engine type, it is observed that the higher the level of degradation, the higher the percentage increase in the NPV. In order to understand the reason for this trend, it should be noted that the engine capital cost directly affects the loan repayment and the divestment sales. The loan repayment and divestment sales reduce with reduction in the engine capital cost (see Equations 3-10 and 3-11). Loan repayment and divestment sales also affect the NPV. From Figure 6-8 and Figure 6-10, the divestment sales generated decreases with increasing level of degradation while the loan repayment increases with increasing level of degradation. The combined effect of loan repayment and divestment sales gives a decreasing NPV as the level of degradation increases. It therefore implies that a reduction in engine capital cost will have a higher positive impact on the NPV for the fleet with higher level of degradation as seen in Figure 6-25.

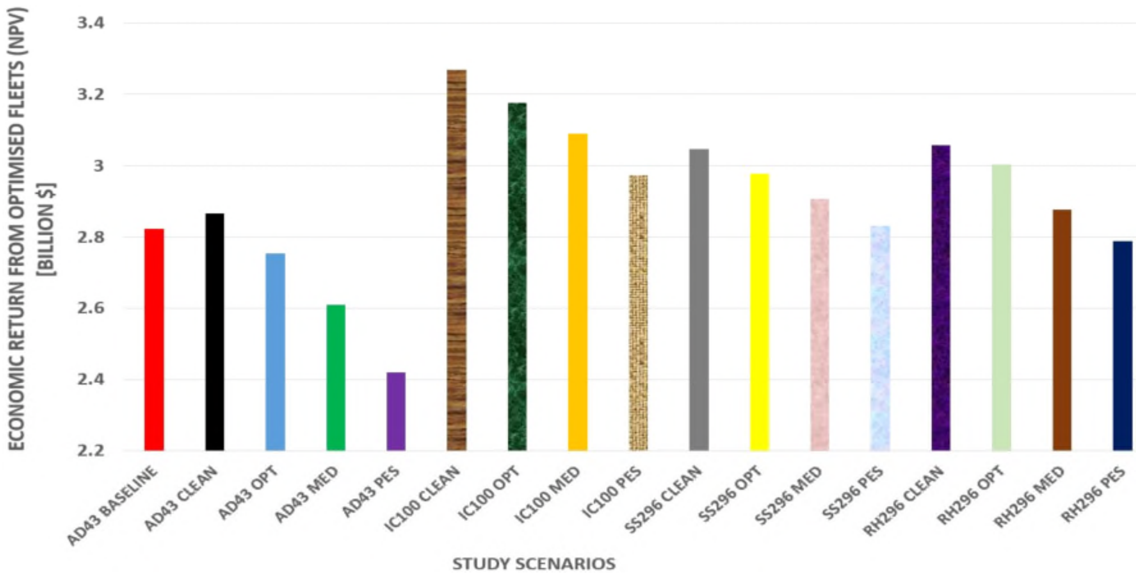


Figure 6-24: Economic Return from the Optimised Fleets (NPV) using (Y-20) as Engine Capital Cost

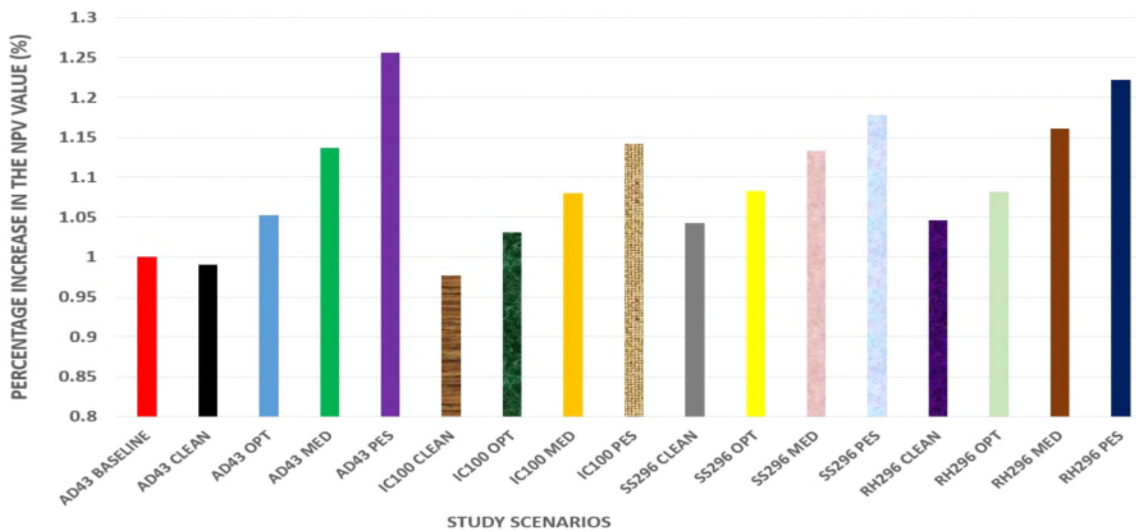


Figure 6-25: Percentage Increase in the NPV when (Y-20) is applied as the Engine Capital Cost

6.7.3.3.2 Effect of increased engine capital cost

Figure 6-26 and Figure 6-27 show the economic return from the optimised fleets (NPV) and the percentage decrease in the NPV when (Y+20) is used as the engine capital cost. The IC100 clean fleet has the highest NPV and AD43 PES fleet has the least, and the values are $3.21b and $2.36b respectively as seen in Figure 6-26. For the same reason as explained in sub-section 6.7.3.3.1, an increase in engine capital cost will have a higher negative impact on the NPV for the fleet with higher level of degradation as seen in Figure 6-27.

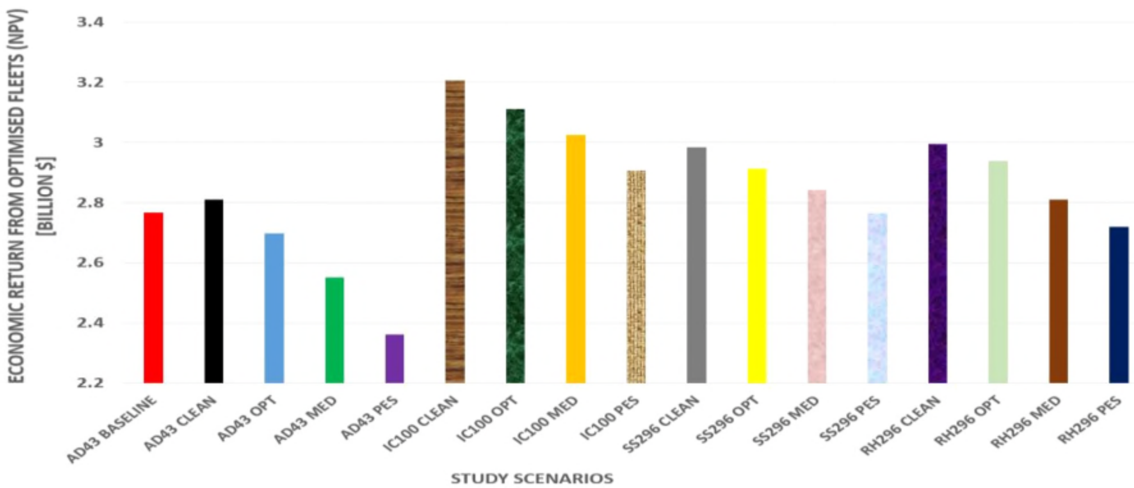


Figure 6-26: Economic Return from the Optimised Fleets (NPV) using (Y+20) as Engine Capital Cost

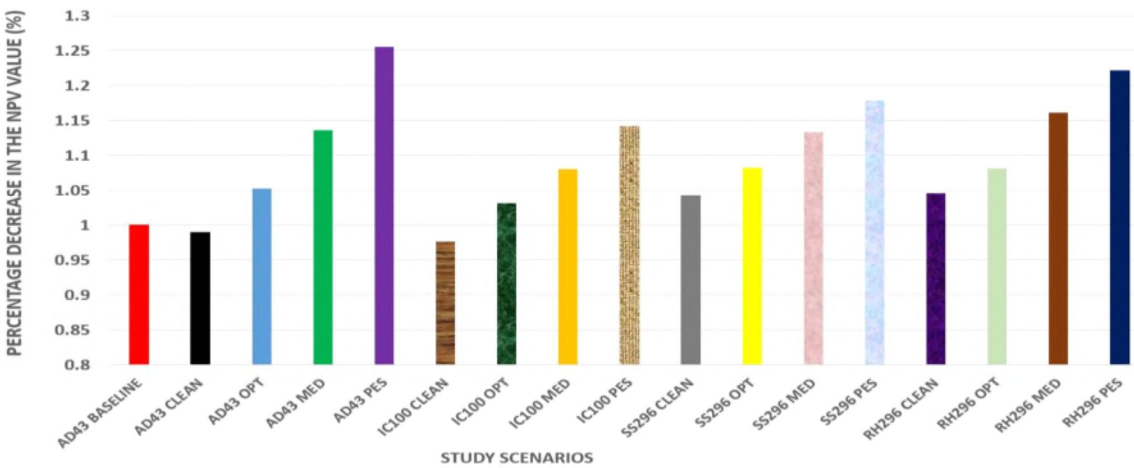


Figure 6-27: Percentage Decrease in the NPV when (Y+20) is Applied as the Engine Capital Cost

6.8 Chapter Summary

This chapter contains the economic evaluation of the various optimised fleets. In this chapter, the robust model developed for the economic use of AG was used in the evaluation of the profitable economic performance of the various fleets of gas turbines. An increase of 1.6% in the NPV of the optimised clean (43.3MW) aero-derivative fleet as against the baseline was achieved.

Comparing all the fleets, the optimised fleet (clean) of the (100MW) aero-derivative intercooled engine has the highest NPV of $3.24b and the PES degraded fleet of the (43.3MW) aero-derivative engine has the least NPV of $2.39b.

The robust economic model was also used in the assessment of the impact of gas turbine degradation on the economic use of AG. Gas turbine degradation had a significant impact on the economic utilisation of AG. For example, for the (43.3MW) aero-derivative fleets, compressor degradation reduced the NPV of the project by 4.0%, 9.1% and 15.8% for the OPT, MED and PES degraded fleets respectively.

Results of sensitivity analysis showing the effect of some technical and economic factors on the economic return (NPV) of the project are also highlighted in this chapter.

7 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

7.1 Conclusions

AG is being wasted to flaring in Nigeria and some other countries. This wastage has led to great economic loss and life-threatening environmental impact. AG are hydrocarbon rich and as such can be harnessed as fuel for combustion in gas turbines. Using this fuel for power generation has been attracting an increasing interest due to the energy, economic and environmental benefits. At some point in the life span of an AG utilisation project, some units of engines in the fleet will become redundant due to the decline in AG availability. Investing in the economic use of AG for power generation using gas turbines would require a model for evaluating the effect of gas turbine degradation on the divestment time of the redundant units of engines. Therefore, the aim of this research is to explore the effect of gas turbine degradation on the divestment time for redundant units of engines in a fleet.

The conclusions drawn from this research are hinged on the research aim and objectives. They are outlined as shown below;

7.1.1 Development of gas turbine engine performance model

By employing TURBOMATCH software; a Cranfield University in-house FORTRAN-based code, gas turbine performance simulation models were successfully generated for the different study engines. These models were used in simulating both design point and off-design point engine operating conditions.

The results of the engine performance simulation for the various engines were verified by comparing the design point simulated data with the performance data of the real engines as given in the public domain.

The simulated engine performance results were the database (search domain) used by the optimiser in evaluating the optimised fleet composition and power. The simulated engine performance results were also the basis for the Techno-

Economic and Environmental Risk Assessment (TERA) of this AG utilisation project.

7.1.2 Evaluation of the baseline fleet composition

The baseline fleet composition was successfully achieved. In order to get the maximum power possible from the fleet, all the units of engines in the fleet were operated at design point condition using the annual associated gas available. When the fuel availability cannot serve all the units of engines when they are all operated at design point, the last unit of engine in the fleet is operated at a part-load. If the fuel available is too small for the last unit of engine to be operated at a part-load, then this unit of engine becomes redundant and is divested. This was done for the entire time of the project.

7.1.3 Optimising the fleet composition, power and efficiencies for the various study scenarios

The fleet composition, power and efficiencies for the various study scenarios were optimised. The search domain (database) used by the optimiser are data obtained from TURBOMATCH performance simulation of the various study engines at both clean and degraded modes. The optimisation was done by developing specific interfaces to connect with a GA in MATLAB optimisation code, all within an automated design loop. This process was done annually, till the project duration was completed.

The optimisation model and its results were verified by comparing with the results of the baseline fleet. An increase of 1.0% was achieved for the optimised power of the clean (43.3MW) aero-derivative fleet as against the baseline fleet.

7.1.4 Fleet emission and creep life estimation

Emission formation estimation was done for the entire duration of the project and for each of the various study scenarios, this was done using Hephaestus, a FORTRAN-based emission prediction code developed in Cranfield University.

The creep life estimation for the various fleets were done using a simple creep life model developed in Microsoft Excel.

7.1.5 Assessment on the impact of gas turbine degradation on the divestment time and on the economic utilisation of AG

A GA in MATLAB code has been successfully developed which was used in optimising the best divestment time of the redundant units of engines in the various fleets. Results of the optimisation show that engine degradation extends the divestment time of the redundant units of engines in the various fleets. For example, at the 2nd year of the project; 0, 1, 2, 3, 3 are the respective number of units of engines divested in the PES degraded, MED degraded, OPT degraded, clean (optimised) and baseline fleets of the (43.3MW) aero-derivative engine.

Gas turbine degradation had a significant impact on the economic utilisation of AG. For example, for the (43.3MW) aero-derivative fleets, compressor degradation reduced the NPV of the project by 4.0%, 9.1% and 15.8% for the OPT, MED and PES degraded fleets respectively.

7.1.6 Improving the economic performance of the various fleets of gas turbines for power generation

The robust model developed for the economic utilisation of AG integrated several technical and economic factors. The economic performance show an increase of 1.6% in the NPV of the optimised clean (43.3MW) aero-derivative fleet as against the baseline fleet.

Comparing all the fleets, the clean fleet of the (100MW) aero-derivative intercooled engine has the highest NPV of \$3.24b and the PES degraded fleet of the (43.3MW) aero-derivative engine having the least NPV of \$2.39b.

This research shows that investing in the economic use of AG for power generation as against the current practice of flaring will be of high economic and environmental benefit. The research has proposed a model that can be used for the profitable economic utilisation of AG.

7.2 Significant Contributions to Knowledge

7.2.1 Development of a model for evaluating the effect of engine degradation on the divestment time for redundant units of engine

After doing a detailed literature review on the economic utilisation of AG using gas turbines, the research gap as evident in public domain is the lack of literature that show the effect of gas turbine degradation on the divestment time for redundant units of engines in a fleet.

This research has successfully developed a model for evaluating the effect of gas turbine degradation on the divestment time for redundant units of engines. This model serves as a guide for investors who would want to invest in the economic utilisation of AG using gas turbines.

7.2.2 Development of a model and methodology for investing in AG utilisation

AG is being wasted to flaring in many countries. A robust model and methodology has been developed in this research which would serve as a guide for investing in AG utilisation.

7.2.2.1 Development of a model for the assessment of the impact of engine degradation on the economic use of AG

As seen in the public domain, the models already provided for the economic utilisation of AG lack robustness due to the absence of the effect of degradation on the divestment time for redundant units of engines, which is a key element. The effect of engine degradation on divestment time and cost have been integrated into the model presented in this research. The robustness of the economic model proposed by this research makes it useful as a guide for investing in AG utilisation.

7.2.2.2 Development of a model for the improvement of the economic performance of a fleet of gas turbines for power generation

As a result of the depletion of natural gas, AG which is a form of natural gas is also gradually depleting. Investing in the economic utilisation of AG will require a model for optimising the fleet composition, the power and economic return (NPV) from the fleets subject to the constraint of depleting AG availability.

This research has successfully produced a GA model for the optimisation of gas turbine fleet composition, power and improvement of the economic return from the fleet (NPV) given the constraint of limited AG availability.

7.2.3 Reliable results for AG investment planning

The results of the optimised divestment times for the degraded fleets are a novel contribution to knowledge. The optimised divestment times, fleet compositions, power and the improved economic returns from the project are also a big contribution to knowledge. These results can be used as estimates of expected returns on investing in AG utilisation.

7.3 Recommendations for Future Work

7.3.1 Mixed fleet composition

It will be great to see the outcome of the optimisation of a fleet comprising of the four engine types studied. Future researchers will have to give diligent attention to the fact that an engine may have higher power output than another engine, and their efficiencies may be the reverse. Therefore, the optimisation of both power output and efficiency at the same time becomes more complicated.

7.3.2 Effect of degradation of more engine components

This research considered the effect of compressor degradation on the divestment time and on the economic utilisation of AG. The effect of degradation of more engine components should also be explored.

7.3.3 Impact of changes in the ambient temperature on the optimisation results

In this research, the performance simulations were done at design point ambient temperature (288.15K). Future researchers could investigate the impact of changes in the ambient temperature on the optimisation results and on the economic returns.

7.3.4 The effect of operating the engines at temperatures higher than the design point TET

In this research, because of the need to improve the economic returns, the TETs in the search domain were restricted to temperatures not higher than the design point TET. This was done to avoid incurring huge cost of maintenance of the engines. However, research can be done to see the economic returns when the engines in the fleet are operated beyond the design point TET, the trade-off between getting more power and incurring much higher maintenance cost should be analysed.

7.3.5 The impact of a detailed creep life analysis

A detailed creep life analysis should be done for the various units of engines in the various fleets, after which operations and maintenance cost analysis should be estimated using the creep life results.

7.3.6 Emission comparison

The emissions generated when AG is used as gas turbine fuel is worth comparing with the emissions generated when the AG is just flared. This will show in detail the environmental benefit of harnessing AG as gas turbine fuel instead of flaring it.

7.3.7 Industrial gas turbine emission prediction tool

The tool utilised in this research is limited in the sense that it was used on the assumption of a generic combustor. A better tool could be used for a detailed gas turbine emission prediction when using AG.

7.3.8 More detailed gas turbine simulation models

The gas turbine performance models used in this research are simple models, more detailed models could be used.

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APPENDICES

Appendix A : AG (Fuel) Availability for the Project

A.1 AG availability

The data underneath is the AG available for the different years of the project. It also served as the optimisation constraint.

Year	Fuel availability (m^3/day)	Fuel availability (kg/s)
1	**40,000**	**59.3519**
2	**34,800**	**51.6361**
3	**30,276**	**44.9234**
4	**26,340**	**39.0832**
5	**22,916**	**34.0027**
6	**19,937**	**29.5824**
7	**17,345**	**25.7364**
8	**15,090**	**22.3905**
9	**13,128**	**19.4793**
10	**11,421**	**16.9464**
11	**9936**	**14.743**
12	**8645**	**12.8274**
13	**7521**	**11.1596**
14	**6543**	**9.70848**
15	**5692**	**8.44577**
16	**4952**	**7.34776**
17	**4309**	**6.39368**
18	**3749**	**5.56275**
19	**3261**	**4.83866**
20	**2837**	**4.20953**

Source of AG availability data (m^3/day) : [1, p.94-95]

A.2 Conversion of AG data from m^3/day to kg/s

Assuming that the AG is compressed natural gas, this assumption was made because it is the closest fuel to AG in the Aqua-calc conversion tool [105, 106, 107]. Using this tool, 40,000m^3 equals 5128000kg of the fuel. Therefore, 40,000m^3/day of AG would be equivalent to 59.3519kg/s of the same fuel. This is for the 1st year, this conversion process is applied to get the fuel availability in kg/s as seen in Appendix A.1.

Appendix B : TURBOMATCH Input and Output Files

Below are some of the input files for the FORTRAN programmed instructions for TURBOMATCH which were used in simulating the design and off-design performance of the clean and degraded study engines.

B.1 Input and output file for RH296

B.1.1 One of the input file used for simulating clean RH296 engine

```
RH296 Engine
Author: Obhuo Mafel

------------------
////
OD SI GM VA FP
 -1
 -1
INTAKE S1-2          D1-6                 R300
COMPRE S2-3          D7-18                R301      V7 V8
BURNER S3-4          D19-26               R304
TURBIN S4-5          D27-40,150,41                          V28
BURNER S5-6          D42-49               R303
TURBIN S6-7          D50-63,151,64                          V51
NOZCON S7-8,1        D65-66               R305
PERFOR S1,0,0        D27,68-70,305,300,303,0,0,304
CODEND

BRICK DATA ITEMS////
! INTAKE
1 0.0               ! ALTITUDE
2 0.0               ! ISA DEVIATION:Tamb=288.15 K, Pamb=1.01325 bar
3 0.0               ! MACH NUMBER
4 0.99              ! PRESSURE RECOVERY
5 0.0               ! DEVIATION FROM ISA PRESSURE
6 0.0               ! RELATIVE HUMIDITY

! COMPRESSOR
7 -1.0              ! SURGE MARGIN
8 -1.0              ! DESIGN SPEED
9 33.3              ! DESIGN PRESSURE RATIO
10 0.85             ! ISENTROPIC EFFICIENCY
11 0.0              ! ERROR SELECTION
12 3.0              ! COMPRESSOR MAP NUMBER
13   1.0            ! SHAFT NUMBER
14   1.0            ! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
15   1.0            ! SCALING FACTOR OF NON-D MASS FLOW - DEGRADATION FACTOR
16   1.0            ! SCALING FACTOR OF ETAC (ISENTROPIC EFFICIENCY) - DEGRADATION F
17   0.5            ! EFFECTIVE COMPONENT VOLUME (M^3)
18   0.0            ! STATOR ANGLE (VSV) RELATIVE TO DP


!BURNER 1
19 0.05             ! PRESSURE LOSS 0%
20 1.0              ! EFFICIENCY
21 -1.0             ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
22 0.0              ! WATER FLOW (Kg s-1 or lb s-1) or (<0) water to air ratio
23 288.             ! TEMPERATURE OF WATER STREAM (K)
24 0.0              ! PHASE OF VAPOUR (0=liq, 1=vapour)
25 1.0              ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION FA
26 0.08             ! EFFECTIVE COMPONENT VOLUME (m^3)

! TURBINE 1
27 296000000.0      ! AUXILIARY POWER REQUIRED
28 -1.              ! NON DIMENTIONAL MASS FLOW
29 -1.              ! NON DIMENTIONAL SPEED
30 0.9              ! ISENTROPIC EFFICIENCY
31 -1.0             ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
32 1.0              ! SHAFT NUMBER
33 3.0              ! TURBINE MAP NUMBER
34 4.0              ! POWER INDEX N
35 1.0              ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FAC
36 1.0              ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
37 1.0              ! SCALING FACTOR OF ETAC IS (ISENTROPIC EFFICIENCY) - DEGRADATIO
38 10000            ! ROTOR ROTATIONAL SPEED(RPS)
39 -1.0             ! ROTOR MOMENT OF INERTIA (Kg M2)
40 -1.0             ! EFFECTIVE COMPONENT VOLUME
150 0.230605
41 0.0              ! NGV ANGLE, RELATIVE TO DP

!BURNER 2
42 0.05             ! PRESSURE LOSS 0%
43 1.0              ! EFFICIENCY
44 -1.0             ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
45 0.0              ! WATER FLOW (Kg s-1 or lb s-1) or (<0) water to air ratio
46 288.             ! TEMPERATURE OF WATER STREAM (K)
47 0.0              ! PHASE OF VAPOUR (0=liq, 1=vapour)
48 1.0              ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION FA
49 0.08             ! EFFECTIVE COMPONENT VOLUME (m^3)
```

```
! TURBINE 2
50 0.0          ! AUXILIARY POWER REQUIRED
51 -1.          ! NON DIMENTIONAL MASS FLOW
52 -1.          ! NON DIMENTIONAL SPEED
53 0.9          ! ISENTROPIC EFFICIENCY
54 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
55 1.0          ! SHAFT NUMBER
56 4.0          ! TURBINE MAP NUMBER
57 4.0        ! POWER INDEX N
58 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FAC
59 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
60 1.0          ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATIO
61 10000        ! ROTOR ROTATIONAL SPEED(RPS)
62 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
63 -1.0         ! EFFECTIVE COMPONENT VOLUME
151 2.0
64 0.0          ! NGV ANGLE, RELATIVE TO DP


! NOZCON
65 -1.0         ! AREA FIXED
66 -1.0         ! SCALING FACTOR

! PERFORMANCE
!67 -1.0         ! REQUIRED OUTPUT (HERE TAKEN BY THE ARITHY)
68 -1.0         ! PROPELLER EFFICIENCY
69 0.0          ! SCALLING INDEX
70 0.0          ! REQUIRED DP NET THRUST OR POWER OUTPUT FOR PT


-1
1 2 644.00      ! MASS FLOW
4 6 1543.0      ! TURBINE ENTRY TEMPERATURE 1
6 6 1543.0      ! TURBINE ENTRY TEMPERATURE 2
-1
-1
4 6 1523.0      ! TURBINE ENTRY TEMPERATURE 1
6 6 1523.0      ! TURBINE ENTRY TEMPERATURE 2
-1
-1
4 6 1503.0      ! TURBINE ENTRY TEMPERATURE 1
6 6 1503.0      ! TURBINE ENTRY TEMPERATURE 2
-1
-3
```

B.1.2 One of the output file for the simulated clean RH296 engine

```
 TURBOMATCH SCHEME - VERSION 2.1d - Windows version

****************  Version 2.1d  (20171201))***************

******  Licensed to be used for studies at Cranfield University *****

LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
15 BD Items printable by any call of:-
OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV

 Input "Program" follows

RH296

Author: Obhuo Mafel


 ------------------

 ////
 OD SI GM VA FP
 -1
 -1
INTAKE S1-2         D1-6                  R300
COMPRE S2-3         D7-18                 R301      V7 V8
BURNER S3-4         D19-26                R304
TURBIN S4-5         D27-40,150,41                          V28
BURNER S5-6         D42-49                R303
TURBIN S6-7         D50-63,151,64                          V51
NOZCON S7-8,1       D65-66                R305
PERFOR S1,0,0       D27,68-70,305,300,303,0,0,304
CODEND

BRICK DATA ITEMS////
! INTAKE
1 0.0              ! ALTITUDE
2 0.0              ! ISA DEVIATION:Tamb=288.15 K, Pamb=1.01325 bar
3 0.0              ! MACH NUMBER
4 0.99             ! PRESSURE RECOVERY
5 0.0              ! DEVIATION FROM ISA PRESSURE
6 0.0              ! RELATIVE HUMIDITY

! COMPRESSOR
7 -1.0             ! SURGE MARGIN
8 -1.0             ! DESIGN SPEED
9 33.3             ! DESIGN PRESSURE RATIO
10 0.85            ! ISENTROPIC EFFICIENCY
11 0.0             ! ERROR SELECTION
12 3.0             ! COMPRESSOR MAP NUMBER
13  1.0            ! SHAFT NUMBER
14  1.0            ! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
15  1.0            ! SCALING FACTOR OF NON-D MASS FLOW - DEGRADATION FACTOR
16  1.0            ! SCALING FACTOR OF ETAc (ISENTROPIC EFFICIENCY) - DEGRADATION
17  0.5            ! EFFECTIVE COMPONENT VOLUME (M^3)
18  0.0            ! STATOR ANGLE (VSV) RELATIVE TO DP


!BURNER 1
19 0.05            ! PRESSURE LOSS 0%
20 1.0             ! EFFICIENCY
21 -1.0            ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
22 0.0             ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
23 288.            ! TEMPERATURE OF WATER STREAM (K)
24 0.0             ! PHASE OF VAPOUR (0=liq, 1=vapour)
25 1.0             ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION F
26 0.08            ! EFFECTIVE COMPONENT VOLUME (m^3)
```

```
! TURBINE 1
27 296000000.0  ! AUXILIARY POWER REQUIRED
28 -1.          ! NON DIMENTIONAL MASS FLOW
29 -1.          ! NON DIMENTIONAL SPEED
30 0.9          ! ISENTROPIC EFFICIENCY
31 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
32 1.0          ! SHAFT NUMBER
33 3.0          ! TURBINE MAP NUMBER
34 4.0          ! POWER INDEX N
35 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FA
36 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
37 1.0          ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATI
38 10000        ! ROTOR ROTATIONAL SPEED(RPS)
39 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
40 -1.0         ! EFFECTIVE COMPONENT VOLUME
150 0.230605
41 0.0          ! NGV ANGLE, RELATIVE TO DP

!BURNER 2
42 0.05         ! PRESSURE LOSS 0%
43 1.0          ! EFFICIENCY
44 -1.0         ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
45 0.0          ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
46 288.         ! TEMPERATURE OF WATER STREAM (K)
47 0.0          ! PHASE OF VAPOUR (0=liq, 1=vapour)
48 1.0          ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION F
49 0.08         ! EFFECTIVE COMPONENT VOLUME (m^3)


! TURBINE 2
50 0.0          ! AUXILIARY POWER REQUIRED
51 -1.          ! NON DIMENTIONAL MASS FLOW
52 -1.          ! NON DIMENTIONAL SPEED
53 0.9          ! ISENTROPIC EFFICIENCY
54 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
55 1.0          ! SHAFT NUMBER
56 4.0          ! TURBINE MAP NUMBER
57 4.0          ! POWER INDEX N
58 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FA
59 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
60 1.0          ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATI
61 10000        ! ROTOR ROTATIONAL SPEED(RPS)
62 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
63 -1.0         ! EFFECTIVE COMPONENT VOLUME
151 2.0
64 0.0          ! NGV ANGLE, RELATIVE TO DP


! NOZCON
65 -1.0         ! AREA FIXED
66 -1.0         ! SCALING FACTOR

! PERFORMANCE
!67 -1.0         ! REQUIRED OUTPUT (HERE TAKEN BY THE ARITHY)
68 -1.0         ! PROPELLER EFFICIENCY
69 0.0          ! SCALLING INDEX
70 0.0          ! REQUIRED DP NET THRUST OR POWER OUTPUT FOR PT
-1
1 2 644.00      ! MASS FLOW
4 6 1543.0      ! TURBINE ENTRY TEMPERATURE 1
6 6 1543.0      ! TURBINE ENTRY TEMPERATURE 2
-1

Number of Variables calculated by Appendix 4 Procedure
(excluding any Splitters and/or Compressors on same Shaft)    =  5
Number of obligatory Errors calculated by Appendix 4 Procedure =  4

                                            Processor time 03:13:06
```

```
                    The Units for this Run are as follows:-
Temperature = K    Pressure = Atmospheres    Length = metres
Area = sq metres   Mass Flow = kg/sec        Velocity = metres/sec
Force = Newtons    s.f.c.(Thrust) =  g/kN sec   s.f.c.(Power) = g/MJ
Sp. Thrust =     N/kg/sec      Power =    Watts
1
      ***** DESIGN POINT ENGINE CALCULATIONS *****

***** AMBIENT AND INLET parameters *****
Alt. =        0.0      I.S.A. Dev. =     0.000        PDev. =     0.000
Mach No. =  0.00       Etar = 0.9900        Momentum Drag =      0.00
Rel.Humidity =   0.00

***** COMPRESSOR  1 parameters *****
PRSF =  0.43901E+01       ETASF =  0.10138E+01      WASF =  0.64733E+01
DGPRSF =  0.10000E+01     DGETASF =  0.10000E+01    DGWASF =  0.10000E+01
Z = 0.85000               PR =  33.300              ETA = 0.85000
PCN =   1.0000            CN = 1.00000              COMWK =  0.38016E+09
STATOR ANGLE =   0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10000E+01   DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 1.6484       WFB =  12.6175        WWB = 0.00000

***** TURBINE  1 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10210E+01      TFSF =  0.18780E+01
DHSF =  0.35058E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01    DGDHSF =  0.10000E+01
TF =  438.521              ETA = 0.90000              CN =  3.100
AUXWK =  0.68259E+08       NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.15593E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10686E+01   DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 0.8333       WFB =   3.7978        WWB = 0.00000

***** TURBINE  2 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10342E+01      TFSF =  0.40001E+01
DHSF =  0.91658E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01    DGDHSF =  0.10000E+01
TF =  409.640              ETA = 0.90000              CN =  3.100
AUXWK =  0.22774E+09       NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.52023E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =  0.10000E+01   DGNCOSF =  0.10000E+01
Area =  5.4610            Exit Velocity =  303.14   Gross Thrust = 200403.98
Nozzle Coeff. =  0.10000E+01

Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area	W.A.R.	X
1	0.00000	644.000	1.00000	1.00000	288.15	288.15	0.0	******	0.00000	0.000
2	0.00000	644.000	******	0.99000	******	288.15	******	******	0.00000	0.000
3	0.00000	644.000	******	32.96700	******	848.07	******	******	0.00000	0.000
4	0.01959	656.618	******	31.31865	******	1543.00	******	******	0.00000	0.000
5	0.01959	656.618	******	16.66510	******	1354.81	******	******	0.00000	0.000
6	0.02549	660.415	******	15.83185	******	1543.00	******	******	0.00000	0.000
7	0.02549	660.415	******	1.19305	******	908.81	******	******	0.00000	0.000
8	0.02549	660.415	1.00037	1.19305	869.69	908.81	303.1	5.4610	0.00000	0.000

```
  Shaft Power = 296000000.00
   Net Thrust =     200403.98
 Equiv. Power = 308921438.60
    Fuel Flow =  16.4153
       S.F.C. =  0.0555
     E.S.F.C. =  0.0531
Sp. Sh. Power =    459627.33
Sp. Eq. Power =    479691.67
Sh. Th. Effy. =  0.3959971
    Sim. time =  0.0000
          Time Now 03:13:06

**************************************************
 -1
 4 6 1523.0        ! TURBINE ENTRY TEMPERATURE 1
 6 6 1523.0        ! TURBINE ENTRY TEMPERATURE 2
 -1
                                              Processor time 03:13:06
```

```
**************************************************
BERR_ep( 1) =     0.61099E-02
BERR_ep( 2) =     0.89962E-03
BERR_ep( 3) =     0.16821E-01
BERR_ep( 4) =     0.67958E-02
1

      ***** OFF DESIGN ENGINE CALCULATIONS. Converged after    0 Loops *****

***** AMBIENT AND INLET parameters *****
Alt. =        0.0        I.S.A. Dev. =     0.000        PDev. =     0.000
Mach No. =    0.00       Etar = 0.9900          Momentum Drag =      0.00
Rel.Humidity =   0.00

***** COMPRESSOR  1 parameters *****
PRSF =   0.43901E+01       ETASF =   0.10138E+01      WASF =   0.64733E+01
DGPRSF =   0.10000E+01     DGETASF =   0.10000E+01    DGWASF =   0.10000E+01
Z = 0.84568                PR =   32.318              ETA = 0.84955
PCN =     0.9883           CN = 0.98830               COMWK =   0.36695E+09
STATOR ANGLE =     0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =   0.10000E+01   DGETASF =   0.10000E+01
ETA = 1.00000              DLP = 1.6107        WFB =   12.0543        WWB = 0.00000

***** TURBINE  1 parameters *****
CNSF =   0.12177E+03       ETASF =   0.10210E+01      TFSF =   0.18780E+01
DHSF =   0.35058E+04
DGETASF =   0.10000E+01     DGTFSF =   0.10000E+01    DGDHSF =   0.10000E+01
TF =  438.841               ETA = 0.89963               CN =   3.084
AUXWK =   0.28239E+09       NGV ANGLE = 0.00       TOTWK (COMWK+AUXWK) = 0.15012E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =   0.10686E+01   DGETASF =   0.10000E+01
ETA = 0.99756              DLP = 0.8090        WFB =    3.6580        WWB = 0.00000

***** TURBINE  2 parameters *****
CNSF =   0.12177E+03       ETASF =   0.10342E+01      TFSF =   0.40001E+01
DHSF =   0.91658E+04
DGETASF =   0.10000E+01     DGTFSF =   0.10000E+01    DGDHSF =   0.10000E+01
TF =  409.593               ETA = 0.90115               CN =   3.084
AUXWK =   0.00000E+00       NGV ANGLE = 0.00       TOTWK (COMWK+AUXWK) = 0.49908E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =   0.10000E+01   DGNCOSF =   0.10000E+01
Area =   5.4610            Exit Velocity =   293.49   Gross Thrust = 189408.26
Nozzle Coeff. =   0.10000E+01

Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000


Station  F.A.R. Mass Flow  Pstatic   Ptotal Tstatic  Ttotal    Vel    Area    W.A.R.    X
    1   0.00000  629.648  1.00000  1.00000  288.15  288.15    0.0  ******  0.00000  0.000
    2   0.00000  629.648   ******  0.99000  ******  288.15 ******  ******  0.00000  0.000
    3   0.00000  629.648   ****** 31.99481  ******  841.34 ******  ******  0.00000  0.000
    4   0.01914  641.702   ****** 30.38412  ****** 1523.00 ******  ******  0.00000  0.000
    5   0.01914  641.702   ****** 16.17983  ****** 1337.05 ******  ******  0.00000  0.000
    6   0.02495  645.360   ****** 15.37087  ****** 1523.00 ******  ******  0.00000  0.000
    7   0.02495  645.360   ******  1.18149  ******  898.37 ******  ******  0.00000  0.000
    8   0.02495  645.360  1.00000  1.18149  861.58  898.37  293.5  5.4610  0.00000  0.000


  Shaft Power = 282385252.37
   Net Thrust =     189408.26
 Equiv. Power = 294597721.00
    Fuel Flow =  15.7123
       S.F.C. =   0.0556
     E.S.F.C. =   0.0533
Sp. Sh. Power =    448480.99
Sp. Eq. Power =    467876.69
Sh. Th. Effy. =  0.3946857
    Sim. time =   0.0000
        Time Now 03:13:06

**************************************************
 -1
 4 6 1503.0      ! TURBINE ENTRY TEMPERATURE 1
 6 6 1503.0      ! TURBINE ENTRY TEMPERATURE 2
 -1
                                   Processor time 03:13:06
```

```
*************************************************
BERR_ep( 1) =     0.61101E-02
BERR_ep( 2) =     0.82659E-03
BERR_ep( 3) =     0.17157E-01
BERR_ep( 4) =     0.60005E-02

Loop    1
BERR_ep( 1) =     0.48606E-04
BERR_ep( 2) =     0.36426E-04
BERR_ep( 3) =     0.85272E-03
BERR_ep( 4) =     0.94758E-03
1

     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after    1 Loops *****


***** AMBIENT AND INLET parameters *****
Alt. =         0.0       I.S.A. Dev. =     0.000       PDev. =     0.000
Mach No. =    0.00       Etar = 0.9900        Momentum Drag =      0.00
Rel.Humidity =  0.00

***** COMPRESSOR   1 parameters *****
PRSF =  0.43901E+01        ETASF =  0.10138E+01      WASF =  0.64733E+01
DGPRSF =  0.10000E+01      DGETASF =  0.10000E+01    DGWASF =  0.10000E+01
Z = 0.84141                PR =   31.317             ETA = 0.84785
PCN =    0.9755            CN = 0.97555              COMWK =  0.35398E+09
STATOR ANGLE =   0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10000E+01  DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 1.5727        WFB =  11.4884        WWB = 0.00000

***** TURBINE   1 parameters *****
CNSF =  0.12177E+03        ETASF =  0.10210E+01      TFSF =  0.18780E+01
DHSF =  0.35058E+04
DGETASF =  0.10000E+01      DGTFSF =  0.10000E+01    DGDHSF =  0.10000E+01
TF =  439.268               ETA = 0.89914              CN =  3.064
AUXWK =  0.26810E+09        NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.14424E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10686E+01  DGETASF =  0.10000E+01
ETA = 0.99504             DLP = 0.7842        WFB =   3.5168        WWB = 0.00000

***** TURBINE   2 parameters *****
CNSF =  0.12177E+03        ETASF =  0.10342E+01      TFSF =  0.40001E+01
DHSF =  0.91658E+04
DGETASF =  0.10000E+01      DGTFSF =  0.10000E+01    DGDHSF =  0.10000E+01
TF =  409.581               ETA = 0.90251              CN =  3.064
AUXWK =  0.00000E+00        NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.47783E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =  0.10000E+01  DGNCOSF =  0.10000E+01
Area =  5.4610             Exit Velocity =  283.68   Gross Thrust = 178653.66
Nozzle Coeff. =  0.10000E+01


Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area	W.A.R.	X
1	0.00000	614.771	1.00000	1.00000	288.15	288.15	0.0	******	0.00000	0.000
2	0.00000	614.771	******	0.99000	******	288.15	******	******	0.00000	0.000
3	0.00000	614.771	******	31.00349	******	835.04	******	******	0.00000	0.000
4	0.01869	626.259	******	29.43077	******	1503.00	******	******	0.00000	0.000
5	0.01869	626.259	******	15.68670	******	1319.37	******	******	0.00000	0.000
6	0.02441	629.776	******	14.90251	******	1503.00	******	******	0.00000	0.000
7	0.02441	629.776	******	1.17084	******	888.12	******	******	0.00000	0.000
8	0.02441	629.776	1.00000	1.17084	853.64	888.12	283.7	5.4610	0.00000	0.000

```
  Shaft Power = 268095343.36
   Net Thrust =    178653.66
 Equiv. Power = 279614387.54
    Fuel Flow =  15.0052
       S.F.C. =   0.0560
     E.S.F.C. =   0.0537
Sp. Sh. Power =    436089.99
Sp. Eq. Power =    454827.13
Sh. Th. Effy. =  0.3923693
    Sim. time =  0.0000
        Time Now 03:13:06
```

B.2 Input file for AD43 engine

B.2.1 One of the input file used for simulating clean AD43 engine

```
AD43 Engine
Author: Obhuo Mafel
________________________________________
////
OD SI GM VA FP
-1
-1
INTAKE  S1,2       D1-6          R200
COMPRE  S2,3       D7-18         R205     V7
COMPRE  S3,4       D19-30        R205     V19   V20
PREMAS  S4,25,5    D31-34
PREMAS  S5,25,6    D35-38
BURNER  S6,7       D39-46        R215
MIXEES  S7,25,8
TURBIN  S8,9       D47-61                 V48
MIXEES  S9,25,10
TURBIN  S10,11     D62-76                 V62   V63
NOZCON  S11,12,1   D77,78         R220
PERFOR  S1,0,0     D62,79-81,220,200,215,0,0,0,0,0,0
CODEND

DATA ITEMS ////
1 0.0               ! INTAKE: Altitude [m]
2 0.0               ! Deviation from ISA temperature [K]
3 0.0               ! Mach number
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: Z = (R-R[choke])/(R[surge]-R[choke]) (if =-1. the default value 0.85 is invoked)
8 1.0               ! Relative rotational speed PCN
9 2.3225            ! DP Pressure ratio
10 0.85             ! isentropic efficiency
11 0.0              ! Error selection
12 3.0              ! Compressor Map Number
13 1.0              ! Shaft number
14 1.0              ! Scaling factor of Pressure Ratio - Degradation factor
15 1.0              ! Scaling factor of Non-D Mass Flow - Degradation factor
16 1.0              ! Scaling factor of ETAc is (Compressor isentropic efficiency) - Degradation factor
17 0.02             ! Effective component volume [m^3]
18 -1.0             ! Stator angle (VSV) relative to DP


19 -1.0             ! COMPRESSOR HP: Z = (R-R[choke])/(R[surge]-R[choke]) (if =-1. the default value 0.85 is invoked)
20 1.0              ! Relative rotational speed PCN
21 12.5286          ! DP Pressure ratio
22 0.85             ! isentropic efficiency
23 1.0              ! Error selection
24 4.0              ! Compressor Map Number
25 2.0              ! Shaft number
26 1.0              ! Scaling factor of Pressure Ratio - Degradation factor
27 1.0              ! Scaling factor of Non-D Mass Flow - Degradation factor
28 1.0              ! Scaling factor of ETAc is (Compressor isentropic efficiency) - Degradation factor
29 -1.0             ! Effective component volume [m^3]
30 0.0              ! Stator angle (VSV) relative to DP

31 0.05             ! BYPASS:  (Wout/Win) BPR = 6.4 CRUISE!
32 0.0              ! DELTA W
33 1.0              ! LAMBDA P
34 0.0              ! DELTA P

35 0.05             ! PREMAS: LAMDA W Cooling bypass (Wout/Win)
36 0.0              ! DELTA W
37 1.0              ! LAMBDA P
38 0.0              ! DELTA P

39 0.05             ! COMBUSTOR: Pressure loss (=Total pressure loss/Inlet total pressure)
40 0.999            ! Combustion efficiency
41 -1.0             ! Fuel flow (If -1. is given the TET must be determined in the station vector
42 0.0              ! (>0) Water flow [kg s-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 non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
49 -1                    ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
50 0.9                   ! Design isentropic efficiency
51 -1.0                  ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
52 2.0                   ! Shaft Number (for power turbine, the value "0." is used)
53 5.0                   ! Turbine map umber
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 ETAc 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 D.P.

62 43300000.0            ! POWER TURBINE: Auxiliary or power output [W]
63 0.8                   ! Relative non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
64 0.6                   ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
65 0.9                   ! Design isentropic efficiency
66 -1.0                  ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
67 1.0                   ! Shaft Number (for power turbine, the value "0." is used)
68 5.0                   ! Turbine map umber
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 ETAc is (Turbine isentropic efficiency) - Degradation factor
73 200                   ! Rotor rotational speed [RPS]
74 20.0                  ! Rotor moment of inertia [kg.m^2]
75 -1.0                  ! Effective component volume [m^3]
76 0.0                   ! NGV angle, relative to D.P.

77 -1.0                  ! CONVERGENT NOZZLE: = "-1" exit area is fixed
78 1.0                   ! Scaling factor


79 0.9                   ! ENGINE RESULTS: Propeller efficiency (= -1 for turbojet/turbofan)
80 0.0                   ! Scaling index ("1" = scalling needed, "0" = no scaling)
81 0.0                   ! Required DP net thrust(Turbojet,turbofan) or shaft power (Turboprop.turboshaft)
                         ! = 0 if Scaling index = 0
-1
1 2 129.80               ! item 2 at station 1 = Mass flow(kg/s)
7 6 1550.0               ! item 6 at station 7 = Total temperature (K)
-1
-1
7 6 1545.0
-1
-1
7 6 1540.0
-1
-1
7 6 1535.0
-1
-1
7 6 1530.0
-1
-1
7 6 1525.0
-1
-1
7 6 1520.0
-1
-1
7 6 1515.0
-1
-1
7 6 1510.0
-1
-1
7 6 1505.0
-1
-3
```

B.3 Design point input file for clean SS296 engine

```
SS296 Engine
AUTHOR: OBHUO MAFEL

////
OD SI GM VA FP
-1
-1
INTAKE S1,2     D1-6        R200
COMPRE S2,3     D7-18       R205    V7 V8
PREMAS S3,25,4  D19-22
BURNER S4,5     D23-30      R215
MIXEES S5,25,6
TURBIN S6,7     D31-45              V32
DUCTER S7,8     D46-50      R220
NOZCON S8,9,1   D51-52      R225
PERFOR S1,0,0   D31,53-55,225,200,215,0,0,220,0,0,0
CODEND

DATA ITEMS ////

1 0.0                 ! INTAKE: ALTITUDE [m]
2 0.0                 ! Deviation from ISA temperature [K]
3 0.0                 ! MACH NUMBER
4 -1                  ! Pressure recovery, according to USAF
5 0.                  ! Deviation from ISA pressure [atm]
6 0.                  ! Relative humidity [%]

7 -1                  ! COMPRESSOR - FAN: Z = (R-R[choke])/(R[surge]-R[choke])
8 1.                  ! Relative rotational speed PCN
9 19.5                ! DP PRESSURE RATIO
10 0.88               ! ISENTROPIC EFFICIENCY
11 0                  ! ERROR SELECTION
12 3                  ! COMPRESSOR MAP NUMBER
13 1.                 ! Shaft number
14 1.                 ! Scaling factor of Pressure Ratio – Degradation factor
15 1.                 ! Scaling factor of Non-D Mass Flow – Degradation factor
16 1.                 ! Scaling factor of ETAc is (Compressor isentropic efficiency) – Degradation factor
17 0.03               ! Effective component volume [m^3]
18 0.                 ! Stator angle (VSV) relative to DP


19 0.1                ! PREMAS: LAMDA W Cooling bypass (Wout/Win)
20 0.                 ! DELTA W
21 1.                 ! LAMBDA P
22 0.                 ! DELTA P

23 0.05               ! COMBUSTOR: Pressure loss (=Total pressure loss/Inlet total pressure)
24 0.999              ! Combustion efficiency
25 -1                 ! Fuel flow (If -1. is given the TET must be determined in the station vector
26 0.                 ! (>0) Water flow [kg s-1 or lb s-1] or (<0) Water to air ratio
27 288.               ! Temperature of water stream [K]
28 0.                 ! Phase of water (0=liquid, 1=vapour)
29 1.                 ! Scaling factor of ETAb (combustion efficiency) – Degradation factor
30 0.05               ! Effective component volume [m^3]

31 296000000.         ! TURBINE: Auxiliary or power output [W]
32 -1                 ! Relative non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
33 -1                 ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
34 0.90               ! Design isentropic efficiency
35 -1.                ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
36 1.                 ! Shaft Number (for power turbine, the value "0." is used)
37 3.                 ! Turbine map umber
38 1000.              ! Power law index "n" (POWER = PCN^n) If = -1, power is assumed to be a constant
39 1.                 ! Scaling factor of TF (non-D inlet mass flow) – Degradation factor
40 1.                 ! Scaling factor of DH (enthalpy change) – Degradation factor
41 1.                 ! Scaling factor of ETAc is (Turbine isentropic efficiency) – Degradation factor
42 3000.              ! Rotor rotational speed [RPS]
43 15.                ! Rotor moment of inertia [kg.m^2]
44 0.05               ! Effective component volume [m^3]
45 0.                 ! NGV angle, relative to D.P.

46 0.0                ! SWITCH (NO REHEATING AT ALL)
47 0.0                ! TOTAL PRESSURE LOSS/INLET TOTAL PRESSURE
48 0.0                ! COMBUSTION EFFICIENCY
49 1000000.0          ! LIMITING VALUE OF FUEL FLOW
50 -1                 ! Effective component volume [m^3]

51 -1.                ! CONVERGENT NOZZLE: Swich set (= "-1" if exit area is fixed)
52 1.                 ! Scaling factor
```

```
53  1.00            ! SHAFT EFFICIENCY
54  0.0             ! SCALE INDEX
55  0.0             ! DESIGN NET THRUST
-1
1 2 650.0           ! INLET MASS FLOW
5 6 1700.0          ! TURBINE ENTRY TEMPERATURE (TET)
-1
-3
```

B.4 Design point input file for clean IC100 engine

```
IC100 Engine
Author: Obhuo Mafel
_____________________________________________________
////
OD  SI  GM  VA  FP
-1
-1
INTAKE  S1,2        D1-6            R300
COMPRE  S2,3        D7-18           R301        V7  V8
PREMAS  S3,16,4     D19-22
DUCTER  S4,5        D23-27          R302
COMPRE  S5,6        D28-39          R303        V28 V29
PREMAS  S6,17,7     D40-43
BURNER  S7,8        D44-51          R304
MIXEES  S8,17,9
TURBIN  S9,10       D52-66                      V53
MIXEES  S10,16,11
TURBIN  S11,12      D67-81                      V68

TURBIN  S12,13      D82-96                      V82 V83
DUCTER  S13,14      D97-101            R305
NOZCON  S14,15,1    D102-103           R306
PERFOR  S1,0,0      D82,104-106,306,300,304,0,0,0,0,0,0
CODEND

DATA ITEMS ////
1 0.0               ! INTAKE: Altitude [m]
2 0.0               ! Deviation from ISA temperature [K]
3 0.0               ! Mach 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 - FAN: Z = (R-R[choke])/(R[surge]-R[choke])
8 1.0               ! Relative rotational speed PCN
9 3.5               ! DP Pressure ratio
10 0.86             ! isentropic efficiency
11 0.0              ! Error selection
12 4.0              ! Compressor Map Number
13 1.0              ! Shaft number
14 1.0              ! Scaling factor of Pressure Ratio – Degradation factor
15 1.0              ! Scaling factor of Non-D Mass Flow – Degradation factor
16 1.0              ! Scaling factor of ETAC is (Compressor isentropic efficiency) – Degradation factor
17 -1.0             ! Effective component volume [m^3]
18 -1.0             ! Stator angle (VSV) relative to DP

19 0.1              ! BYPASS:  (Wout/Win) BPR = 6.4 CRUISE!
20 0.0              ! DELTA W
21 1.0              ! LAMBDA P
22 0.0              ! DELTA P

23 2.0              ! BYPASS DUCT - DUCTER: Air duct
24 0.01             ! Total pressure loss: DELTA(P)/Pin (Pressure loss = 1%)
25 0.90             ! Combustion efficiency
26 100000           ! Limiting value of Fuel Flow (=100000 if not needed)
27 -1               ! Effective component volume [m^3]

28 -1.0             ! COMPRESSOR HP: Z = (R-R[choke])/(R[surge]-R[choke]) |
29 1.0              ! Relative rotational speed PCN
30 12.0             ! DP Pressure ratio
31 0.86             ! isentropic efficiency
32 0.0              ! Error selection
33 5.0              ! Compressor Map Number
34 2.0              ! Shaft number
35 1.0              ! Scaling factor of Pressure Ratio – Degradation factor
36 1.0              ! Scaling factor of Non-D Mass Flow – Degradation factor
37 1.0              ! Scaling factor of ETAC is (Compressor isentropic efficiency) – Degradation factor
38 -1.0             ! Effective component volume [m^3]
39 0.0              ! Stator angle (VSV) relative to DP
```

```
40 0.05            ! PREMAS: LAMDA W Cooling bypass (Wout/Win)
41 0.0             ! DELTA W
42 1.0             ! LAMBDA P
43 0.0             ! DELTA P

44 0.05            ! COMBUSTOR: Pressure loss (=Total pressure loss/Inlet total pressure)
45 0.999           ! Combustion efficiency
46 -1.0            ! Fuel flow (If -1. is given the TET must be determined in the station vector
47 0.0             ! (>0) Water flow [kg s-1 or lb s-1] or (<0) Water to air ratio
48 288.0           ! Temperature of water stream [K]
49 0.0             ! Phase of water (0=liquid, 1=vapour)
50 1.0             ! Scaling factor of ETAb (combustion efficiency) - Degradation factor
51 -1.0            ! Effective component volume [m^3]

52 0.0             ! HP TURBINE: Auxiliary or power output [W]
53 -1              ! Relative non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
54 -1              ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
55 0.9             ! Design isentropic efficiency
56 -1.0            ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
57 2.0             ! Shaft Number (for power turbine, the value "0." is used)
58 5.0             ! Turbine map umber
59 -1.0            ! Power law index "n" (POWER = PCN^n) If = -1, power is assumed to be a constant
60 1.0             ! Scaling factor of TF (non-D inlet mass flow) - Degradation factor
61 1.0             ! Scaling factor of DH (enthalpy change) - Degradation factor
62 1.0             ! Scaling factor of ETAc is (Turbine isentropic efficiency) - Degradation factor
63 200             ! Rotor rotational speed [RPS]
64 15.0            ! Rotor moment of inertia [kg.m^2]
65 -1.0            ! Effective component volume [m^3]
66 0.0             ! NGV angle, relative to D.P.


67 0.0             ! IP TURBINE: Auxiliary or power output [W]
68 -1.0            ! Relative non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
69 -1.0            ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
70 0.9             ! Design isentropic efficiency
71 -1.0            ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
72 1.0             ! Shaft Number (for power turbine, the value "0." is used)
73 5.0             ! Turbine map umber
74 -1.0            ! Power law index "n" (POWER = PCN^n) If = -1, power is assumed to be a constant
75 1.0             ! Scaling factor of TF (non-D inlet mass flow) - Degradation factor
76 1.0             ! Scaling factor of DH (enthalpy change) - Degradation factor
77 1.0             ! Scaling factor of ETAc is (Turbine isentropic efficiency) - Degradation factor
78 200.0           ! Rotor rotational speed [RPS]
79 20.0            ! Rotor moment of inertia [kg.m^2]
80 -1              ! Effective component volume [m^3]
81 0.0             ! NGV angle, relative to D.P.

82 100000000.0     ! FPT TURBINE: Auxiliary or power output [W]
83 -1.0            ! Relative non-dimensional massflow W/Wmax (if = -1, value 0.8 is invoked)
84 -1.0            ! Relative non-rimensional speed CN (if = -1, value 0.6 is invoked)
85 0.9             ! Design isentropic efficiency
86 1.0             ! Relative non-dimensional speed PCN (= -1 for compressor turbine)
87 0.0             ! Shaft Number (for power turbine, the value "0." is used)
88 5.0             ! Turbine map umber
89 -1.0            ! Power law index "n" (POWER = PCN^n) If = -1, power is assumed to be a constant
90 1.0             ! Scaling factor of TF (non-D inlet mass flow) - Degradation factor
91 1.0             ! Scaling factor of DH (enthalpy change) - Degradation factor
92 1.0             ! Scaling factor of ETAc is (Turbine isentropic efficiency) - Degradation factor
93 200.0           ! Rotor rotational speed [RPS]
94 20.0            ! Rotor moment of inertia [kg.m^2]
95 -1.0            ! Effective component volume [m^3]
96 0.0             ! NGV angle, relative to D.P.

97 0.0             ! BYPASS DUCT - DUCTER: Air duct
98 0.01            ! Total pressure loss: DELTA(P)/Pin (Pressure loss = 1%)
99 0.0             ! Combustion efficiency
100 100000         ! Limiting value of Fuel Flow (=100000 if not needed)
101 -1             ! Effective component volume [m^3]

102 -1.0           ! CONVERGENT NOZZLE: = "-1" exit area is fixed
103 1.0            ! Scaling factor


104 0.9            ! ENGINE RESULTS: Propeller efficiency (= -1 for turbojet/turbofan)
105 0.             ! Scaling index ("1" = scalling needed, "0" = no scaling)
106 0.             ! Required DP net thrust(Turbojet,turbofan) or shaft power (Turboprop.turboshaft)
                   ! = 0 if Scaling index = 0
-1
1 2 216.0          ! item 2 at station 1 = Mass flow(kg/s)
5 6 310.0          ! Intercooler outlet temperature
8 6 1630.0         ! item 6 at station 5 = Total temperature (K)
-1                 ! End of DP data
-3
```

Appendix C : Levels of Degradation Implemented in the Study and their Turbomatch Input / Output Files

C.1 Levels of degradation implemented for the study scenarios

Year	OPT (%)	MED (%)	PES (%)	Description
1	**0**	**0**	**0**	**All engines are clean at the 1st year of the project, therefore level of degradation is 0**
2	**1.333**	**2.666**	**4.0**	**Degradation has commenced**
3	**2.0**	**4.0**	**6.0**	**Partial overhauling takes place at the end of every 3 years**
4	**0.667**	**1.333**	**2.0**	**Reduced level of degradation as a result of the partial overhauling**
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**	

C.2 Turbomatch input and output files for the degraded engines

C.2.1 One of the input file for the PES degraded RH296 engine, 3rd year of the project

```
RH296 Engine
Author: OBHUO MAFEL

------------------
////
OD SI GM VA FP
 -1
 -1
INTAKE S1-2          D1-6                  R300
COMPRE S2-3          D7-18                 R301      V7 V8
BURNER S3-4          D19-26                R304
TURBIN S4-5          D27-40,150,41                           V28
BURNER S5-6          D42-49                R303
TURBIN S6-7          D50-63,151,64                           V51
NOZCON S7-8,1        D65-66                R305
PERFOR S1,0,0        D27,68-70,305,300,303,0,0,304
CODEND

BRICK DATA ITEMS////
! INTAKE
1 0.0               ! ALTITUDE
2 0.0               ! ISA DEVIATION:Tamb=288.15 K, Pamb=1.01325 bar
3 0.0               ! MACH NUMBER
4 0.99              ! PRESSURE RECOVERY
5 0.0               ! DEVIATION FROM ISA PRESSURE
6 0.0               ! RELATIVE HUMIDITY

! COMPRESSOR
7 -1.0              ! SURGE MARGIN
8 -1.0              ! DESIGN SPEED
9 33.3              ! DESIGN PRESSURE RATIO
10 0.85             ! ISENTROPIC EFFICIENCY
11 0.0              ! ERROR SELECTION
12 3.0              ! COMPRESSOR MAP NUMBER
13   1.0            ! SHAFT NUMBER
14   1.0            ! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
15   1.0            ! SCALING FACTOR OF NON-D MASS FLOW - DEGRADATION FACTOR
16   1.0            ! SCALING FACTOR OF ETAC (ISENTROPIC EFFICIENCY) - DEGRADATION F
17   0.5            ! EFFECTIVE COMPONENT VOLUME (M^3)
18   0.0            ! STATOR ANGLE (VSV) RELATIVE TO DP


!BURNER 1
19 0.05            ! PRESSURE LOSS 0%
20 1.0             ! EFFICIENCY
21 -1.0            ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
22 0.0             ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
23 288.            ! TEMPERATURE OF WATER STREAM (K)
24 0.0             ! PHASE OF VAPOUR (0=liq, 1=vapour)
25 1.0             ! Sacling Factor of ETAC (Combustion Efficiency) - DEGRADATION FA
26 0.08            ! EFFECTIVE COMPONENT VOLUME (m^3)

! TURBINE 1
27 296000000.0  ! AUXILIARY POWER REQUIRED
28 -1.          ! NON DIMENTIONAL MASS FLOW
29 -1.          ! NON DIMENTIONAL SPEED
30 0.9          ! ISENTROPIC EFFICIENCY
31 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
32 1.0          ! SHAFT NUMBER
33 3.0          ! TURBINE MAP NUMBER
34 4.0          ! POWER INDEX N
35 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FAC
36 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
37 1.0          ! SCALING FACTOR OF ETAC IS (ISENTROPIC EFFICIENCY) - DEGRADATIO
38 10000        ! ROTOR ROTATIONAL SPEED(RPS)
39 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
40 -1.0         ! EFFECTIVE COMPONENT VOLUME
150 0.230605
41 0.0          ! NGV ANGLE, RELATIVE TO DP

!BURNER 2
42 0.05            ! PRESSURE LOSS 0%
43 1.0             ! EFFICIENCY
44 -1.0            ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
45 0.0             ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
46 288.            ! TEMPERATURE OF WATER STREAM (K)
47 0.0             ! PHASE OF VAPOUR (0=liq, 1=vapour)
48 1.0             ! Sacling Factor of ETAC (Combustion Efficiency) - DEGRADATION FA
49 0.08            ! EFFECTIVE COMPONENT VOLUME (m^3)
```

```
! TURBINE 2
50 0.0          ! AUXILIARY POWER REQUIRED
51 -1.           ! NON DIMENTIONAL MASS FLOW
52 -1.           ! NON DIMENTIONAL SPEED
53 0.9          ! ISENTROPIC EFFICIENCY
54 -1.0          ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
55 1.0           ! SHAFT NUMBER
56 4.0           ! TURBINE MAP NUMBER
57 4.0        ! POWER INDEX N
58 1.0           ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FAC
59 1.0           ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
60 1.0           ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATIO
61 10000         ! ROTOR ROTATIONAL SPEED(RPS)
62 -1.0          ! ROTOR MOMENT OF INERTIA (Kg M2)
63 -1.0          ! EFFECTIVE COMPONENT VOLUME
151 2.0
64 0.0           ! NGV ANGLE, RELATIVE TO DP


! NOZCON
65 -1.0          ! AREA FIXED
66 -1.0          ! SCALING FACTOR

! PERFORMANCE
!67 -1.0          ! REQUIRED OUTPUT (HERE TAKEN BY THE ARITHY)
68 -1.0          ! PROPELLER EFFICIENCY
69 0.0           ! SCALLING INDEX
70 0.0           ! REQUIRED DP NET THRUST OR POWER OUTPUT FOR PT

-1
1 2 644.00       ! MASS FLOW
4 6 1543.0       ! TURBINE ENTRY TEMPERATURE 1
6 6 1543.0       ! TURBINE ENTRY TEMPERATURE 2
-1

                  ! Introducing deterioration
14 0.94           ! COMPRE#1 DETERIORATION OF 6.0% IN PRESSURE RATIO
15 0.94           ! COMPRE#1 DETERIORATION OF 6.0% IN NON-DIMENSIONAL MASS FLOW
16 0.94           ! COMPRE#1 DETERIORATION OF 6.0% IN EFFICIENCY
-1
-1
-1                ! SCALING FACTORS ARE NOT CHANGED -- DETERIORATION CONSTANT
4 6 1533.0        ! TURBINE ENTRY TEMPERATURE 1
6 6 1533.0        ! TURBINE ENTRY TEMPERATURE 2
-1
-1
4 6 1523.0        ! TURBINE ENTRY TEMPERATURE 1
6 6 1523.0        ! TURBINE ENTRY TEMPERATURE 2
-1
-3
```

C.3 One of the of the output file for the PES degraded RH296 engine, 3rd year of the project

```
 TURBOMATCH SCHEME - VERSION 2.1d - Windows version

****************  Version 2.1d  (20171201))***************

******  Licensed to be used for studies at Cranfield University *****

LIMITS:100 Codewords, 800 Brick Data Items, 50 Station Vector
15 BD Items printable by any call of:-
OUTPUT, OUTPBD, OUTPSV, PLOTIT, PLOTBD or PLOTSV

 Input "Program" follows

RH296 Engine

Author: OBHUO MAFEL


 ------------------

 ////
 OD SI GM VA FP
 -1
 -1
INTAKE S1-2         D1-6                R300
COMPRE S2-3         D7-18               R301      V7 V8
BURNER S3-4         D19-26              R304
TURBIN S4-5         D27-40,150,41                           V28
BURNER S5-6         D42-49              R303
TURBIN S6-7         D50-63,151,64                           V51
NOZCON S7-8,1       D65-66              R305
PERFOR S1,0,0       D27,68-70,305,300,303,0,0,304
CODEND

BRICK DATA ITEMS////
! INTAKE
1 0.0            ! ALTITUDE
2 0.0            ! ISA DEVIATION:Tamb=288.15 K, Pamb=1.01325 bar
3 0.0            ! MACH NUMBER
4 0.99           ! PRESSURE RECOVERY
5 0.0            ! DEVIATION FROM ISA PRESSURE
6 0.0            ! RELATIVE HUMIDITY

! COMPRESSOR
7 -1.0           ! SURGE MARGIN
8 -1.0           ! DESIGN SPEED
9 33.3           ! DESIGN PRESSURE RATIO
10 0.85          ! ISENTROPIC EFFICIENCY
11 0.0           ! ERROR SELECTION
12 3.0           ! COMPRESSOR MAP NUMBER
13  1.0          ! SHAFT NUMBER
14  1.0          ! SCALING FACTOR OF PRESSURE RATIO - DEGRADATION FACTOR
15  1.0          ! SCALING FACTOR OF NON-D MASS FLOW - DEGRADATION FACTOR
16  1.0          ! SCALING FACTOR OF ETAc (ISENTROPIC EFFICIENCY) - DEGRADATION
17  0.5          ! EFFECTIVE COMPONENT VOLUME (M^3)
18  0.0          ! STATOR ANGLE (VSV) RELATIVE TO DP


!BURNER 1
19 0.05         ! PRESSURE LOSS 0%
20 1.0          ! EFFICIENCY
21 -1.0         ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
22 0.0          ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
23 288.         ! TEMPERATURE OF WATER STREAM (K)
24 0.0          ! PHASE OF VAPOUR (0=liq, 1=vapour)
25 1.0          ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION F
26 0.08         ! EFFECTIVE COMPONENT VOLUME (m^3)
```

```
! TURBINE 1
27 296000000.0  ! AUXILIARY POWER REQUIRED
28 -1.          ! NON DIMENTIONAL MASS FLOW
29 -1.          ! NON DIMENTIONAL SPEED
30 0.9          ! ISENTROPIC EFFICIENCY
31 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
32 1.0          ! SHAFT NUMBER
33 3.0          ! TURBINE MAP NUMBER
34 4.0          ! POWER INDEX N
35 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FA
36 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
37 1.0          ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATI
38 10000        ! ROTOR ROTATIONAL SPEED(RPS)
39 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
40 -1.0         ! EFFECTIVE COMPONENT VOLUME
150 0.230605
41 0.0          ! NGV ANGLE, RELATIVE TO DP

!BURNER 2
42 0.05        ! PRESSURE LOSS 0%
43 1.0         ! EFFICIENCY
44 -1.0        ! FUEL FLOW (-1 = TET SPECIFIED. SEE SV DATA)
45 0.0         ! WATER FLOW (Kg s-1 or lb s-1) or (<0) Water to air ratio
46 288.        ! TEMPERATURE OF WATER STREAM (K)
47 0.0         ! PHASE OF VAPOUR (0=liq, 1=vapour)
48 1.0         ! Sacling Factor of ETAc (Combustion Efficiency) - DEGRADATION F
49 0.08        ! EFFECTIVE COMPONENT VOLUME (m^3)


! TURBINE 2
50 0.0         ! AUXILIARY POWER REQUIRED
51 -1.          ! NON DIMENTIONAL MASS FLOW
52 -1.          ! NON DIMENTIONAL SPEED
53 0.9         ! ISENTROPIC EFFICIENCY
54 -1.0         ! RELATIV ROTATIONAL SPEED (COMP TURB=-1)
55 1.0          ! SHAFT NUMBER
56 4.0          ! TURBINE MAP NUMBER
57 4.0        ! POWER INDEX N
58 1.0          ! SCALING FACTOR OF TF (NON-D INLET MASS FLOW) - DEGRADATION FA
59 1.0          ! SCALING FACTOR OF DH (ENTHALPY CHANGE) - DEGRADATION FACTOR
60 1.0          ! SCALING FACTOR OF ETAc IS (ISENTROPIC EFFICIENCY) - DEGRADATI
61 10000        ! ROTOR ROTATIONAL SPEED(RPS)
62 -1.0         ! ROTOR MOMENT OF INERTIA (Kg M2)
63 -1.0         ! EFFECTIVE COMPONENT VOLUME
151 2.0
64 0.0          ! NGV ANGLE, RELATIVE TO DP


! NOZCON
65 -1.0         ! AREA FIXED
66 -1.0         ! SCALING FACTOR

! PERFORMANCE
!67 -1.0         ! REQUIRED OUTPUT (HERE TAKEN BY THE ARITHY)
68 -1.0         ! PROPELLER EFFICIENCY
69 0.0          ! SCALLING INDEX
70 0.0          ! REQUIRED DP NET THRUST OR POWER OUTPUT FOR PT
-1
1 2 644.00      ! MASS FLOW
4 6 1543.0      ! TURBINE ENTRY TEMPERATURE 1
6 6 1543.0      ! TURBINE ENTRY TEMPERATURE 2
-1

Number of Variables calculated by Appendix 4 Procedure
(excluding any Splitters and/or Compressors on same Shaft)     =  5
Number of obligatory Errors calculated by Appendix 4 Procedure =  4

                                             Processor time 00:42:00
```

```
                    The Units for this Run are as follows:-

Temperature = K    Pressure = Atmospheres    Length = metres

Area = sq metres   Mass Flow = kg/sec        Velocity = metres/sec

Force = Newtons    s.f.c.(Thrust) =  g/kN sec    s.f.c.(Power) = g/MJ

Sp. Thrust =     N/kg/sec      Power =    Watts
1

      ***** DESIGN POINT ENGINE CALCULATIONS *****


***** AMBIENT AND INLET parameters *****
Alt. =       0.0      I.S.A. Dev. =     0.000       PDev. =     0.000
Mach No. =  0.00      Etar = 0.9900        Momentum Drag =      0.00
Rel.Humidity =  0.00

***** COMPRESSOR  1 parameters *****
PRSF =  0.43901E+01       ETASF =  0.10138E+01     WASF =  0.64733E+01
DGPRSF =  0.10000E+01     DGETASF =  0.10000E+01   DGWASF =  0.10000E+01
Z = 0.85000               PR =  33.300             ETA = 0.85000
PCN =    1.0000           CN = 1.00000             COMWK =  0.38016E+09
STATOR ANGLE =   0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10000E+01  DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 1.6484       WFB =  12.6175       WWB = 0.00000

***** TURBINE  1 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10210E+01     TFSF =  0.18780E+01
DHSF =  0.35058E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01   DGDHSF =  0.10000E+01
TF =  438.521              ETA = 0.90000             CN =  3.100
AUXWK =  0.68259E+08       NGV ANGLE = 0.00     TOTWK (COMWK+AUXWK) = 0.15593E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10686E+01  DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 0.8333       WFB =   3.7978       WWB = 0.00000

***** TURBINE  2 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10342E+01     TFSF =  0.40001E+01
DHSF =  0.91658E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01   DGDHSF =  0.10000E+01
TF =  409.640              ETA = 0.90000             CN =  3.100
AUXWK =  0.22774E+09       NGV ANGLE = 0.00     TOTWK (COMWK+AUXWK) = 0.52023E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =  0.10000E+01  DGNCOSF =  0.10000E+01
Area =  5.4610            Exit Velocity =  303.14  Gross Thrust = 200403.98
Nozzle Coeff. =  0.10000E+01


Scale Factor on above Mass Flows, Areas, Thrusts & Powers =     1.0000
```

```
Station  F.A.R. Mass Flow   Pstatic    Ptotal Tstatic  Ttotal     Vel    Area     W.A.R.     X
    1   0.00000  644.000   1.00000   1.00000  288.15  288.15     0.0  ******  0.00000  0.000
    2   0.00000  644.000    ******   0.99000  ******  288.15  ******  ******  0.00000  0.000
    3   0.00000  644.000    ******  32.96700  ******  848.07  ******  ******  0.00000  0.000
    4   0.01959  656.618    ******  31.31865  ****** 1543.00  ******  ******  0.00000  0.000
    5   0.01959  656.618    ******  16.66510  ****** 1354.81  ******  ******  0.00000  0.000
    6   0.02549  660.415    ******  15.83185  ****** 1543.00  ******  ******  0.00000  0.000
    7   0.02549  660.415    ******   1.19305  ******  908.81  ******  ******  0.00000  0.000
    8   0.02549  660.415   1.00037   1.19305  869.69  908.81   303.1  5.4610  0.00000  0.000

  Shaft Power = 296000000.00
   Net Thrust =     200403.98
 Equiv. Power = 308921438.60
    Fuel Flow =  16.4153
       S.F.C. =  0.0555
     E.S.F.C. =  0.0531
Sp. Sh. Power =    459627.33
Sp. Eq. Power =    479691.67
Sh. Th. Effy. =  0.3959971
    Sim. time =  0.0000
          Time Now 00:42:00

************************************************

               |! Introducing deterioration
 14 0.94        ! COMPRE#1 DETERIORATION OF 6.0% IN PRESSURE RATIO
 15 0.94        ! COMPRE#1 DETERIORATION OF 6.0% IN NON-DIMENSIONAL MASS FLOW
 16 0.94        ! COMPRE#1 DETERIORATION OF 6.0% IN EFFICIENCY
 -1
 -1
                                                  Processor time 00:42:00

************************************************
BERR_ep( 1) =    0.11686E-02
BERR_ep( 2) =    0.10747E-02
BERR_ep( 3) =    0.48543E-01
BERR_ep( 4) =   -0.42167E-01

Loop   1
BERR_ep( 1) =    0.17749E-03
BERR_ep( 2) =   -0.51001E-02
BERR_ep( 3) =    0.16854E-01


Loop    2
BERR_ep( 1)  =    -0.82312E-05
BERR_ep( 2)  =     0.17705E-04
BERR_ep( 3)  =     0.27265E-03
BERR_ep( 4)  =     0.11157E-02
1
     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   2 Loops *****


***** AMBIENT AND INLET parameters *****
Alt. =       0.0       I.S.A. Dev. =     0.000       PDev. =     0.000
Mach No. =   0.00      Etar = 0.9900       Momentum Drag =       0.00
Rel.Humidity =   0.00

***** COMPRESSOR   1 parameters *****
PRSF =   0.41267E+01      ETASF =   0.95295E+00      WASF =   0.60849E+01
DGPRSF =   0.94000E+00    DGETASF =   0.94000E+00    DGWASF =   0.94000E+00
Z = 0.84792               PR =  28.361               ETA = 0.78985
PCN =    0.9516           CN = 0.95160               COMWK =   0.32677E+09
STATOR ANGLE =    0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =   0.10000E+01   DGETASF =   0.10000E+01
ETA = 1.00000             DLP = 1.4281        WFB =   10.8274        WWB = 0.00000

***** TURBINE   1 parameters *****
CNSF =   0.12177E+03      ETASF =   0.10210E+01      TFSF =   0.18780E+01
DHSF =   0.35058E+04
DGETASF =   0.10000E+01    DGTFSF =   0.10000E+01    DGDHSF =   0.10000E+01
TF =   442.546             ETA = 0.89491              CN =   2.950
AUXWK =   0.24272E+09      NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.13175E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =   0.10686E+01   DGETASF =   0.10000E+01
ETA = 0.99581             DLP = 0.7186        WFB =    3.2235        WWB = 0.00000

***** TURBINE   2 parameters *****
CNSF =   0.12177E+03      ETASF =   0.10342E+01      TFSF =   0.40001E+01
DHSF =   0.91658E+04
DGETASF =   0.10000E+01    DGTFSF =   0.10000E+01    DGDHSF =   0.10000E+01
TF =   410.597             ETA = 0.91091              CN =   2.950
```

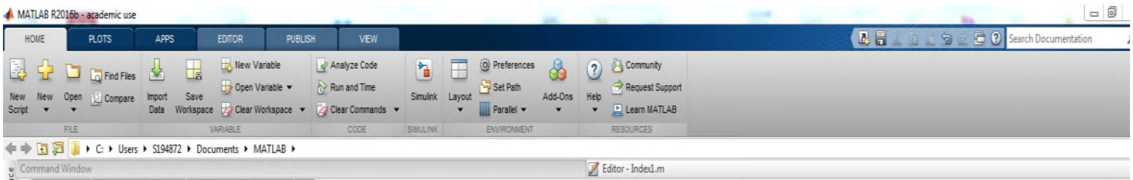
```
AUXWK =  0.00000E+00     NGV ANGLE = 0.00     TOTWK (COMWK+AUXWK) = 0.43774E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =  0.10000E+01  DGNCOSF =  0.10000E+01
Area =  5.4610          Exit Velocity =  267.01  Gross Thrust = 151415.80
Nozzle Coeff. =  0.10000E+01


Scale Factor on above Mass Flows, Areas, Thrusts & Powers =    1.0000


Station  F.A.R. Mass Flow   Pstatic    Ptotal  Tstatic  Ttotal     Vel    Area     W.A.R.    X
    1   0.00000   553.027  1.00000   1.00000  288.15   288.15     0.0  ******   0.00000  0.000
    2   0.00000   553.027   ******   0.99000  ******   288.15  ******  ******   0.00000  0.000
    3   0.00000   553.027   ******  28.07760  ******   848.59  ******  ******   0.00000  0.000
    4   0.01958   563.855   ******  26.64952  ****** 1543.00  ******  ******   0.00000  0.000
    5   0.01958   563.855   ******  14.28121  ****** 1357.85  ******  ******   0.00000  0.000
    6   0.02541   567.078   ******  13.56258  ****** 1543.00  ******  ******   0.00000  0.000
    7   0.02541   567.078   ******   1.14357  ******   922.08  ******  ******   0.00000  0.000
    8   0.02541   567.078  1.00000   1.14357  891.83   922.08   267.0  5.4610   0.00000  0.000

  Shaft Power = 242722177.34
   Net Thrust =     151415.80
 Equiv. Power = 252485007.17
    Fuel Flow =   14.0509
       S.F.C. =    0.0579
     E.S.F.C. =    0.0557
Sp. Sh. Power =     438897.43
Sp. Eq. Power =     456550.87
Sh. Th. Effy. =    0.3793619
    Sim. time =    0.0000
         Time Now 00:42:00


**********************************************************
 -1              ! SCALING FACTORS ARE NOT CHANGED -- DETERIORATION CONSTANT
 4 6 1533.0      ! TURBINE ENTRY TEMPERATURE 1
 6 6 1533.0      ! TURBINE ENTRY TEMPERATURE 2
 -1
                                        Processor time 00:42:00

**********************************************************
BERR_ep( 1) =    0.28590E-02
BERR_ep( 2) =    0.35094E-02
BERR_ep( 3) =    0.41002E-02
BERR_ep( 4) =   -0.13875E-01
1

     ***** OFF DESIGN ENGINE CALCULATIONS. Converged after   0 Loops *****


***** AMBIENT AND INLET parameters *****
Alt. =        0.0       I.S.A. Dev. =     0.000        PDev. =     0.000
Mach No. =  0.00        Etar = 0.9900         Momentum Drag =      0.00
Rel.Humidity =   0.00

***** COMPRESSOR  1 parameters *****
PRSF =  0.41267E+01       ETASF =  0.95295E+00     WASF =  0.60849E+01
DGPRSF =  0.94000E+00     DGETASF =  0.94000E+00   DGWASF =  0.94000E+00
Z = 0.84589               PR =  27.912             ETA = 0.78786
PCN =   0.9448            CN = 0.94481             COMWK =  0.32123E+09
STATOR ANGLE =   0.00

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10000E+01  DGETASF =  0.10000E+01
ETA = 1.00000             DLP = 1.4116       WFB =  10.5603       WWB = 0.00000

***** TURBINE  1 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10210E+01     TFSF =  0.18780E+01
DHSF =  0.35058E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01   DGDHSF =  0.10000E+01
TF =  442.726              ETA = 0.89429             CN =  2.938
AUXWK =  0.23587E+09       NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.12905E+09

***** COMBUSTION CHAMBER parameters *****
ETASF =  0.10686E+01  DGETASF =  0.10000E+01
ETA = 0.99448             DLP = 0.7073       WFB =   3.1584       WWB = 0.00000

***** TURBINE  2 parameters *****
CNSF =  0.12177E+03       ETASF =  0.10342E+01     TFSF =  0.40001E+01
DHSF =  0.91658E+04
DGETASF =  0.10000E+01     DGTFSF =  0.10000E+01   DGDHSF =  0.10000E+01
TF =  410.530              ETA = 0.91157             CN =  2.938
AUXWK =  0.00000E+00       NGV ANGLE = 0.00      TOTWK (COMWK+AUXWK) = 0.42804E+09

***** CONVERGENT NOZZLE  1 parameters *****
NCOSF =  0.10000E+01  DGNCOSF =  0.10000E+01
Area =  5.4610            Exit Velocity =  262.45  Gross Thrust = 146970.71
Nozzle Coeff. =  0.10000E+01
```

Scale Factor on above Mass Flows, Areas, Thrusts & Powers = 1.0000

Station	F.A.R.	Mass Flow	Pstatic	Ptotal	Tstatic	Ttotal	Vel	Area	W.A.R.	X
1	0.00000	546.266	1.00000	1.00000	288.15	288.15	0.0	******	0.00000	0.000
2	0.00000	546.266	******	0.99000	******	288.15	******	******	0.00000	0.000
3	0.00000	546.266	******	27.63245	******	846.04	******	******	0.00000	0.000
4	0.01933	556.827	******	26.22087	******	1533.00	******	******	0.00000	0.000
5	0.01933	556.827	******	14.05882	******	1349.08	******	******	0.00000	0.000
6	0.02511	559.985	******	13.35151	******	1533.00	******	******	0.00000	0.000
7	0.02511	559.985	******	1.13905	******	917.13	******	******	0.00000	0.000
8	0.02511	559.985	1.00000	1.13905	887.86	917.13	262.5	5.4610	0.00000	0.000

Shaft Power = 235865409.41
Net Thrust = 146970.71
Equiv. Power = 245341633.75
Fuel Flow = 13.7187
S.F.C. = 0.0582
E.S.F.C. = 0.0559
Sp. Sh. Power = 431777.38
Sp. Eq. Power = 449124.64
Sh. Th. Effy. = 0.3775727
Sim. time = 0.0000
Time Now 00:42:00

Appendix D : MATLAB and GA Script used in Optimising Best Divestment Time, Fleet Composition and Economic Returns




```
% Modelled by MAFEL OBHUO, 2017


% MATLAB and GA Script for Optimising Best Divestment Time
% MATLAB and GA Script for Optimising Fleet Composition
% MATLAB and GA Script for Optimising Power and Energy Generation
% MATLAB and GA Script for Optimising Economic Returns

clear
close all

% Optimise power and energy generation
% Engine Type: IC100

%options = optimoptions(@ga,'MutationFcn',@mutationadaptfeasible);

options = optimoptions(@ga,'PlotFcn',{@gaplotbestf,@gaplotbestindiv,@gaplotmaxconstr,@gaplotscores,@gaplotpareto}, ...
    'Display','iter', 'PopulationSize',10000, 'MaxGenerations',50, 'FunctionTolerance', 1e-9,'ConstraintTolerance', 1.000000000000000e-09);

ObjectiveFunction = @fitness_function;
nvars = 12;    % Number of variables
LB = [0 0 0 0 0 0 0 0 0 0 0 0];   % Lower bound
UB = [1630 1630 1630 1630 1630 1630 1630 1630 1630 1630 1630 1630];  % Upper bound
ConstraintFunction = @constraint_function;
[x,fval] = ga(ObjectiveFunction,nvars,[],[],[],[],LB,UB, ...
    ConstraintFunction,options);

filename = 'AD43.csv';
AD43 = csvread(filename);
```

```

filename = 'AD43_2.csv';
AD43_2 = csvread(filename);

filename = 'AD43_3.csv';
AD43_3 = csvread(filename);

filename = 'AD43_4.csv';
AD43_4 = csvread(filename);

filename = 'AD43_5.csv';
AD43_5 = csvread(filename);

filename = 'AD43_6.csv';
AD43_6 = csvread(filename);

filename = 'AD43_7.csv';
AD43_7 = csvread(filename);

filename = 'AD43_8.csv';
AD43_8 = csvread(filename);

filename = 'AD43_9.csv';
AD43_9 = csvread(filename);

filename = 'AD43_10.csv';
AD43_10 = csvread(filename);
```

```
filename = 'AD43_11.csv';
AD43_11 = csvread(filename);

filename = 'AD43_12.csv';
AD43_12 = csvread(filename);

for i=1:length(AD43)
    AD43_TET(i) = AD43(i,1);
    AD43_fuel_c(i) = AD43(i,2);
    AD43_power(i) = AD43(i,3);
    AD43_ETA(i) = AD43(i,4);
end

for i=1:length(AD43_2)
    AD43_2_TET(i) = AD43_2(i,1);
    AD43_2_fuel_c(i) = AD43_2(i,2);
    AD43_2_power(i) = AD43_2(i,3);
    AD43_2_ETA(i) = AD43_2(i,4);
end

for i=1:length(AD43_3)
    AD43_3_TET(i) = AD43_3(i,1);
    AD43_3_fuel_c(i) = AD43_3(i,2);
    AD43_3_power(i) = AD43_3(i,3);
    AD43_3_ETA(i) = AD43_3(i,4);
end
```

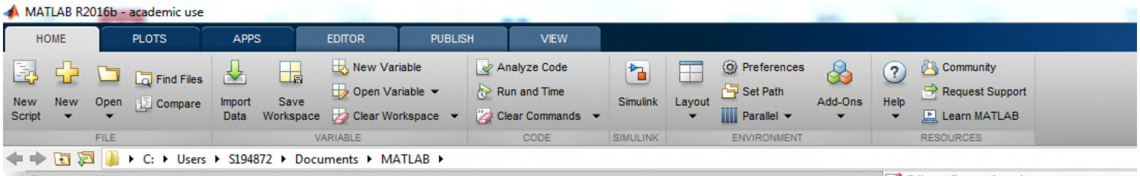
```
for i=1:length(AD43_4)
    AD43_4_TET(i) = AD43_4(i,1);
    AD43_4_fuel_c(i) = AD43_4(i,2);
    AD43_4_power(i) = AD43_4(i,3);
    AD43_4_ETA(i) = AD43_4(i,4);
end

for i=1:length(AD43_5)
    AD43_5_TET(i) = AD43_5(i,1);
    AD43_5_fuel_c(i) = AD43_5(i,2);
    AD43_5_power(i) = AD43_5(i,3);
    AD43_5_ETA(i) = AD43_5(i,4);
end

for i=1:length(AD43_6)
    AD43_6_TET(i) = AD43_6(i,1);
    AD43_6_fuel_c(i) = AD43_6(i,2);
    AD43_6_power(i) = AD43_6(i,3);
    AD43_6_ETA(i) = AD43_6(i,4);
end

for i=1:length(AD43_7)
    AD43_7_TET(i) = AD43_7(i,1);
    AD43_7_fuel_c(i) = AD43_7(i,2);
    AD43_7_power(i) = AD43_7(i,3);
    AD43_7_ETA(i) = AD43_7(i,4);
end
```

```
for i=1:length(AD43_8)
    AD43_8_TET(i) = AD43_8(i,1);
    AD43_8_fuel_c(i) = AD43_8(i,2);
    AD43_8_power(i) = AD43_8(i,3);
    AD43_8_ETA(i) = AD43_8(i,4);
end

for i=1:length(AD43_9)
    AD43_9_TET(i) = AD43_9(i,1);
    AD43_9_fuel_c(i) = AD43_9(i,2);
    AD43_9_power(i) = AD43_9(i,3);
    AD43_9_ETA(i) = AD43_9(i,4);
end

for i=1:length(AD43_10)
    AD43_10_TET(i) = AD43_10(i,1);
    AD43_10_fuel_c(i) = AD43_10(i,2);
    AD43_10_power(i) = AD43_10(i,3);
    AD43_10_ETA(i) = AD43_10(i,4);
end

for i=1:length(AD43_11)
    AD43_11_TET(i) = AD43_11(i,1);
    AD43_11_fuel_c(i) = AD43_11(i,2);
    AD43_11_power(i) = AD43_11(i,3);
    AD43_11_ETA(i) = AD43_11(i,4);
end
```

```
for i=1:length(AD43_12)
    AD43_12_TET(i) = AD43_12(i,1);
    AD43_12_fuel_c(i) = AD43_12(i,2);
    AD43_12_power(i) = AD43_12(i,3);
    AD43_12_ETA(i) = AD43_12(i,4);
end

%interpolate
    PO(1) = interp1(AD43_TET, AD43_power, x(1), 'spline');
    PO(2) = interp1(AD43_2_TET, AD43_2_power, x(2), 'spline');
    PO(3) = interp1(AD43_3_TET, AD43_3_power, x(3), 'spline');
    PO(4) = interp1(AD43_4_TET, AD43_4_power, x(4), 'spline');
    PO(5) = interp1(AD43_5_TET, AD43_5_power, x(5), 'spline');
    PO(6) = interp1(AD43_6_TET, AD43_6_power, x(6), 'spline');
    PO(7) = interp1(AD43_7_TET, AD43_7_power, x(7), 'spline');
    PO(8) = interp1(AD43_8_TET, AD43_8_power, x(8), 'spline');
    PO(9) = interp1(AD43_9_TET, AD43_9_power, x(9), 'spline');
    PO(10) = interp1(AD43_10_TET, AD43_10_power, x(10), 'spline');
    PO(11) = interp1(AD43_11_TET, AD43_11_power, x(11), 'spline');
    PO(12) = interp1(AD43_12_TET, AD43_12_power, x(12), 'spline');
```

```
    FF(1) = interp1(AD43_TET, AD43_fuel_c, x(1), 'spline');
    FF(2) = interp1(AD43_2_TET, AD43_2_fuel_c, x(2), 'spline');
    FF(3) = interp1(AD43_3_TET, AD43_3_fuel_c, x(3), 'spline');
    FF(4) = interp1(AD43_4_TET, AD43_4_fuel_c, x(4), 'spline');
    FF(5) = interp1(AD43_5_TET, AD43_5_fuel_c, x(5), 'spline');
    FF(6) = interp1(AD43_6_TET, AD43_6_fuel_c, x(6), 'spline');
    FF(7) = interp1(AD43_7_TET, AD43_7_fuel_c, x(7), 'spline');
    FF(8) = interp1(AD43_8_TET, AD43_8_fuel_c, x(8), 'spline');
    FF(9) = interp1(AD43_9_TET, AD43_9_fuel_c, x(9), 'spline');
    FF(10) = interp1(AD43_10_TET, AD43_10_fuel_c, x(10), 'spline');
    FF(11) = interp1(AD43_11_TET, AD43_11_fuel_c, x(11), 'spline');
    FF(12) = interp1(AD43_12_TET, AD43_12_fuel_c, x(12), 'spline');

    ET(1) = interp1(AD43_TET, AD43_ETA, x(1), 'spline');
    ET(2) = interp1(AD43_2_TET, AD43_2_ETA, x(2), 'spline');
    ET(3) = interp1(AD43_3_TET, AD43_3_ETA, x(3), 'spline');
    ET(4) = interp1(AD43_4_TET, AD43_4_ETA, x(4), 'spline');
    ET(5) = interp1(AD43_5_TET, AD43_5_ETA, x(5), 'spline');
    ET(6) = interp1(AD43_6_TET, AD43_6_ETA, x(6), 'spline');
    ET(7) = interp1(AD43_7_TET, AD43_7_ETA, x(7), 'spline');
    ET(8) = interp1(AD43_8_TET, AD43_8_ETA, x(8), 'spline');
    ET(9) = interp1(AD43_9_TET, AD43_9_ETA, x(9), 'spline');
    ET(10) = interp1(AD43_10_TET, AD43_10_ETA, x(10), 'spline');
    ET(11) = interp1(AD43_11_TET, AD43_11_ETA, x(11), 'spline');
    ET(12) = interp1(AD43_12_TET, AD43_12_ETA, x(12), 'spline');
```

Appendix E : MATLAB and Genetic Algorithms Script for Optimisation Fitness (Objective) Function




```
% Modelled by MAFEL OBHUO, 2017


% FITNESS (OBJECTIVE) FUNCTION
function y = fitness_function(x)
%SIMPLE_FITNESS fitness function for GA

filename = 'AD43.csv';
AD43 = csvread(filename);

filename = 'AD43_2.csv';
AD43_2 = csvread(filename);

filename = 'AD43_3.csv';
AD43_3 = csvread(filename);

filename = 'AD43_4.csv';
AD43_4 = csvread(filename);

filename = 'AD43_5.csv';
AD43_5 = csvread(filename);

filename = 'AD43_6.csv';
AD43_6 = csvread(filename);

filename = 'AD43_7.csv';
AD43_7 = csvread(filename);
```

```
filename = 'AD43_8.csv';
AD43_8 = csvread(filename);

filename = 'AD43_9.csv';
AD43_9 = csvread(filename);

filename = 'AD43_10.csv';
AD43_10 = csvread(filename);

filename = 'AD43_11.csv';
AD43_11 = csvread(filename);

filename = 'AD43_12.csv';
AD43_12 = csvread(filename);

for i=1:length(AD43)
    AD43_TET(i) = AD43(i,1);
    AD43_fuel_c(i) = AD43(i,2);
    AD43_power(i) = AD43(i,3);
    AD43_ETA(i) = AD43(i,4);
end

for i=1:length(AD43_2)
    AD43_2_TET(i) = AD43_2(i,1);
    AD43_2_fuel_c(i) = AD43_2(i,2);
    AD43_2_power(i) = AD43_2(i,3);
    AD43_2_ETA(i) = AD43_2(i,4);
end
```

```
for i=1:length(AD43_3)
    AD43_3_TET(i) = AD43_3(i,1);
    AD43_3_fuel_c(i) = AD43_3(i,2);
    AD43_3_power(i) = AD43_3(i,3);
    AD43_3_ETA(i) = AD43_3(i,4);
end

for i=1:length(AD43_4)
    AD43_4_TET(i) = AD43_4(i,1);
    AD43_4_fuel_c(i) = AD43_4(i,2);
    AD43_4_power(i) = AD43_4(i,3);
    AD43_4_ETA(i) = AD43_4(i,4);
end

for i=1:length(AD43_5)
    AD43_5_TET(i) = AD43_5(i,1);
    AD43_5_fuel_c(i) = AD43_5(i,2);
    AD43_5_power(i) = AD43_5(i,3);
    AD43_5_ETA(i) = AD43_5(i,4);
end

for i=1:length(AD43_6)
    AD43_6_TET(i) = AD43_6(i,1);
    AD43_6_fuel_c(i) = AD43_6(i,2);
    AD43_6_power(i) = AD43_6(i,3);
    AD43_6_ETA(i) = AD43_6(i,4);
end
```

```
for i=1:length(AD43_7)
    AD43_7_TET(i) = AD43_7(i,1);
    AD43_7_fuel_c(i) = AD43_7(i,2);
    AD43_7_power(i) = AD43_7(i,3);
    AD43_7_ETA(i) = AD43_7(i,4);
end

for i=1:length(AD43_8)
    AD43_8_TET(i) = AD43_8(i,1);
    AD43_8_fuel_c(i) = AD43_8(i,2);
    AD43_8_power(i) = AD43_8(i,3);
    AD43_8_ETA(i) = AD43_8(i,4);
end

for i=1:length(AD43_9)
    AD43_9_TET(i) = AD43_9(i,1);
    AD43_9_fuel_c(i) = AD43_9(i,2);
    AD43_9_power(i) = AD43_9(i,3);
    AD43_9_ETA(i) = AD43_9(i,4);
end

for i=1:length(AD43_10)
    AD43_10_TET(i) = AD43_10(i,1);
    AD43_10_fuel_c(i) = AD43_10(i,2);
    AD43_10_power(i) = AD43_10(i,3);
    AD43_10_ETA(i) = AD43_10(i,4);
end
```

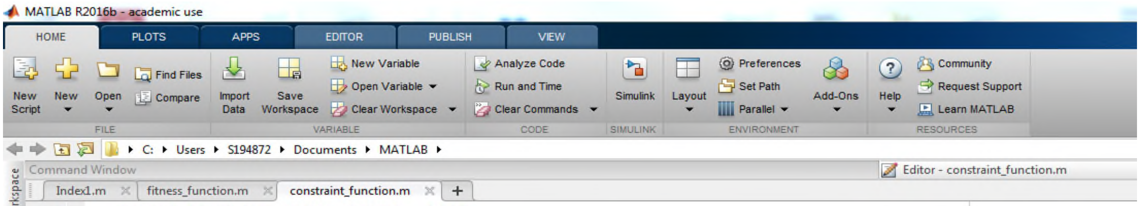
```
for i=1:length(AD43_11)
    AD43_11_TET(i) = AD43_11(i,1);
    AD43_11_fuel_c(i) = AD43_11(i,2);
    AD43_11_power(i) = AD43_11(i,3);
    AD43_11_ETA(i) = AD43_11(i,4);
end

for i=1:length(AD43_12)
    AD43_12_TET(i) = AD43_12(i,1);
    AD43_12_fuel_c(i) = AD43_12(i,2);
    AD43_12_power(i) = AD43_12(i,3);
    AD43_12_ETA(i) = AD43_12(i,4);
end

%interpolate
    PO(1) = interp1(AD43_TET, AD43_power, x(1), 'spline');
    PO(2) = interp1(AD43_2_TET, AD43_2_power, x(2), 'spline');
    PO(3) = interp1(AD43_3_TET, AD43_3_power, x(3), 'spline');
    PO(4) = interp1(AD43_4_TET, AD43_4_power, x(4), 'spline');
    PO(5) = interp1(AD43_5_TET, AD43_5_power, x(5), 'spline');
    PO(6) = interp1(AD43_6_TET, AD43_6_power, x(6), 'spline');
    PO(7) = interp1(AD43_7_TET, AD43_7_power, x(7), 'spline');
    PO(8) = interp1(AD43_8_TET, AD43_8_power, x(8), 'spline');
    PO(9) = interp1(AD43_9_TET, AD43_9_power, x(9), 'spline');
    PO(10) = interp1(AD43_10_TET, AD43_10_power, x(10), 'spline');
    PO(11) = interp1(AD43_11_TET, AD43_11_power, x(11), 'spline');
    PO(12) = interp1(AD43_12_TET, AD43_12_power, x(12), 'spline');
```

```
    FF(1) = interp1(AD43_TET, AD43_fuel_c, x(1), 'spline');
    FF(2) = interp1(AD43_2_TET, AD43_2_fuel_c, x(2), 'spline');
    FF(3) = interp1(AD43_3_TET, AD43_3_fuel_c, x(3), 'spline');
    FF(4) = interp1(AD43_4_TET, AD43_4_fuel_c, x(4), 'spline');
    FF(5) = interp1(AD43_5_TET, AD43_5_fuel_c, x(5), 'spline');
    FF(6) = interp1(AD43_6_TET, AD43_6_fuel_c, x(6), 'spline');
    FF(7) = interp1(AD43_7_TET, AD43_7_fuel_c, x(7), 'spline');
    FF(8) = interp1(AD43_8_TET, AD43_8_fuel_c, x(8), 'spline');
    FF(9) = interp1(AD43_9_TET, AD43_9_fuel_c, x(9), 'spline');
    FF(10) = interp1(AD43_10_TET, AD43_10_fuel_c, x(10), 'spline');
    FF(11) = interp1(AD43_11_TET, AD43_11_fuel_c, x(11), 'spline');
    FF(12) = interp1(AD43_12_TET, AD43_12_fuel_c, x(12), 'spline');

    ET(1) = interp1(AD43_TET, AD43_ETA, x(1), 'spline');
    ET(2) = interp1(AD43_2_TET, AD43_2_ETA, x(2), 'spline');
    ET(3) = interp1(AD43_3_TET, AD43_3_ETA, x(3), 'spline');
    ET(4) = interp1(AD43_4_TET, AD43_4_ETA, x(4), 'spline');
    ET(5) = interp1(AD43_5_TET, AD43_5_ETA, x(5), 'spline');
    ET(6) = interp1(AD43_6_TET, AD43_6_ETA, x(6), 'spline');
    ET(7) = interp1(AD43_7_TET, AD43_7_ETA, x(7), 'spline');
    ET(8) = interp1(AD43_8_TET, AD43_8_ETA, x(8), 'spline');
    ET(9) = interp1(AD43_9_TET, AD43_9_ETA, x(9), 'spline');
    ET(10) = interp1(AD43_10_TET, AD43_10_ETA, x(10), 'spline');
    ET(11) = interp1(AD43_11_TET, AD43_11_ETA, x(11), 'spline');
    ET(12) = interp1(AD43_12_TET, AD43_12_ETA, x(12), 'spline');
```

```
if  x(1) < 1070
    PO(1) = 0;
end
if  x(2) < 1070
    PO(2) = 0;
end
if  x(3) < 1070
    PO(3) = 0;
end
if  x(4) < 1070
    PO(4) = 0;
end
if  x(5) < 1070
    PO(5) = 0;
end

if  x(6) < 1070
    PO(6) = 0;
end
if  x(7) < 1070
    PO(7) = 0;
end
if  x(8) < 1070
    PO(8) = 0;
end
if  x(9) < 1070
    PO(9) = 0;
end
```

```
if  x(10) < 1070
    PO(10) = 0;
end

if  x(11) < 1070
    PO(11) = 0;
end
if  x(12) < 1070
    PO(12) = 0;
end

  y = -1*(PO(1) + PO(2) + PO(3) + PO(4) +  PO(5) + PO(6) + PO(7) + PO(8) + PO(9) +  PO(10) + PO(11) + PO(12) );
```

Appendix F : MATLAB and Genetic Algorithms Script for Optimisation Constraint Function




```
% Modelled by MAFEL OBHUO, 2017


% CONSTRAINT FUNCTION
% OPTIMISATION CONSTRAINT = YEARLY ASSOCIATED GAS AVAILABILITY

function [c, ceq] = constraint_function(x)
%SIMPLE_CONSTRAINT Nonlinear inequality constraints.

filename = 'AD43.csv';
AD43 = csvread(filename);

filename = 'AD43_2.csv';
AD43_2 = csvread(filename);

filename = 'AD43_3.csv';
AD43_3 = csvread(filename);

filename = 'AD43_4.csv';
AD43_4 = csvread(filename);

filename = 'AD43_5.csv';
AD43_5 = csvread(filename);

filename = 'AD43_6.csv';
AD43_6 = csvread(filename);

filename = 'AD43_7.csv';
AD43_7 = csvread(filename);
```

```
filename = 'AD43_8.csv';
AD43_8 = csvread(filename);

filename = 'AD43_9.csv';
AD43_9 = csvread(filename);

filename = 'AD43_10.csv';
AD43_10 = csvread(filename);

filename = 'AD43_11.csv';
AD43_11 = csvread(filename);

filename = 'AD43_12.csv';
AD43_12 = csvread(filename);

for i=1:length(AD43)
    AD43_TET(i) = AD43(i,1);
    AD43_fuel_c(i) = AD43(i,2);
    AD43_power(i) = AD43(i,3);
    AD43_ETA(i) = AD43(i,4);
end

for i=1:length(AD43_2)
    AD43_2_TET(i) = AD43_2(i,1);
    AD43_2_fuel_c(i) = AD43_2(i,2);
    AD43_2_power(i) = AD43_2(i,3);
    AD43_2_ETA(i) = AD43_2(i,4);
end
```

```
for i=1:length(AD43_3)
    AD43_3_TET(i) = AD43_3(i,1);
    AD43_3_fuel_c(i) = AD43_3(i,2);
    AD43_3_power(i) = AD43_3(i,3);
    AD43_3_ETA(i) = AD43_3(i,4);
end

for i=1:length(AD43_4)
    AD43_4_TET(i) = AD43_4(i,1);
    AD43_4_fuel_c(i) = AD43_4(i,2);
    AD43_4_power(i) = AD43_4(i,3);
    AD43_4_ETA(i) = AD43_4(i,4);
end

for i=1:length(AD43_5)
    AD43_5_TET(i) = AD43_5(i,1);
    AD43_5_fuel_c(i) = AD43_5(i,2);
    AD43_5_power(i) = AD43_5(i,3);
    AD43_5_ETA(i) = AD43_5(i,4);
end

for i=1:length(AD43_6)
    AD43_6_TET(i) = AD43_6(i,1);
    AD43_6_fuel_c(i) = AD43_6(i,2);
    AD43_6_power(i) = AD43_6(i,3);
    AD43_6_ETA(i) = AD43_6(i,4);
end
```

```
for i=1:length(AD43_7)
    AD43_7_TET(i) = AD43_7(i,1);
    AD43_7_fuel_c(i) = AD43_7(i,2);
    AD43_7_power(i) = AD43_7(i,3);
    AD43_7_ETA(i) = AD43_7(i,4);
end

for i=1:length(AD43_8)
    AD43_8_TET(i) = AD43_8(i,1);
    AD43_8_fuel_c(i) = AD43_8(i,2);
    AD43_8_power(i) = AD43_8(i,3);
    AD43_8_ETA(i) = AD43_8(i,4);
end

for i=1:length(AD43_9)
    AD43_9_TET(i) = AD43_9(i,1);
    AD43_9_fuel_c(i) = AD43_9(i,2);
    AD43_9_power(i) = AD43_9(i,3);
    AD43_9_ETA(i) = AD43_9(i,4);
end

for i=1:length(AD43_10)
    AD43_10_TET(i) = AD43_10(i,1);
    AD43_10_fuel_c(i) = AD43_10(i,2);
    AD43_10_power(i) = AD43_10(i,3);
    AD43_10_ETA(i) = AD43_10(i,4);
end
```

```
for i=1:length(AD43_11)
    AD43_11_TET(i) = AD43_11(i,1);
    AD43_11_fuel_c(i) = AD43_11(i,2);
    AD43_11_power(i) = AD43_11(i,3);
    AD43_11_ETA(i) = AD43_11(i,4);
end

for i=1:length(AD43_12)
    AD43_12_TET(i) = AD43_12(i,1);
    AD43_12_fuel_c(i) = AD43_12(i,2);
    AD43_12_power(i) = AD43_12(i,3);
    AD43_12_ETA(i) = AD43_12(i,4);
end

%interpolate
    fuel_c(1) = interp1(AD43_TET, AD43_fuel_c, x(1), 'spline');
    fuel_c(2) = interp1(AD43_2_TET, AD43_2_fuel_c, x(2), 'spline');
    fuel_c(3) = interp1(AD43_3_TET, AD43_3_fuel_c, x(3), 'spline');
    fuel_c(4) = interp1(AD43_4_TET, AD43_4_fuel_c, x(4), 'spline');
    fuel_c(5) = interp1(AD43_5_TET, AD43_5_fuel_c, x(5), 'spline');
    fuel_c(6) = interp1(AD43_6_TET, AD43_6_fuel_c, x(6), 'spline');
    fuel_c(7) = interp1(AD43_7_TET, AD43_7_fuel_c, x(7), 'spline');
    fuel_c(8) = interp1(AD43_8_TET, AD43_8_fuel_c, x(8), 'spline');
    fuel_c(9) = interp1(AD43_9_TET, AD43_9_fuel_c, x(9), 'spline');
    fuel_c(10) = interp1(AD43_10_TET, AD43_10_fuel_c, x(10), 'spline');
    fuel_c(11) = interp1(AD43_11_TET, AD43_11_fuel_c, x(11), 'spline');
    fuel_c(12) = interp1(AD43_12_TET, AD43_12_fuel_c, x(12), 'spline');
```

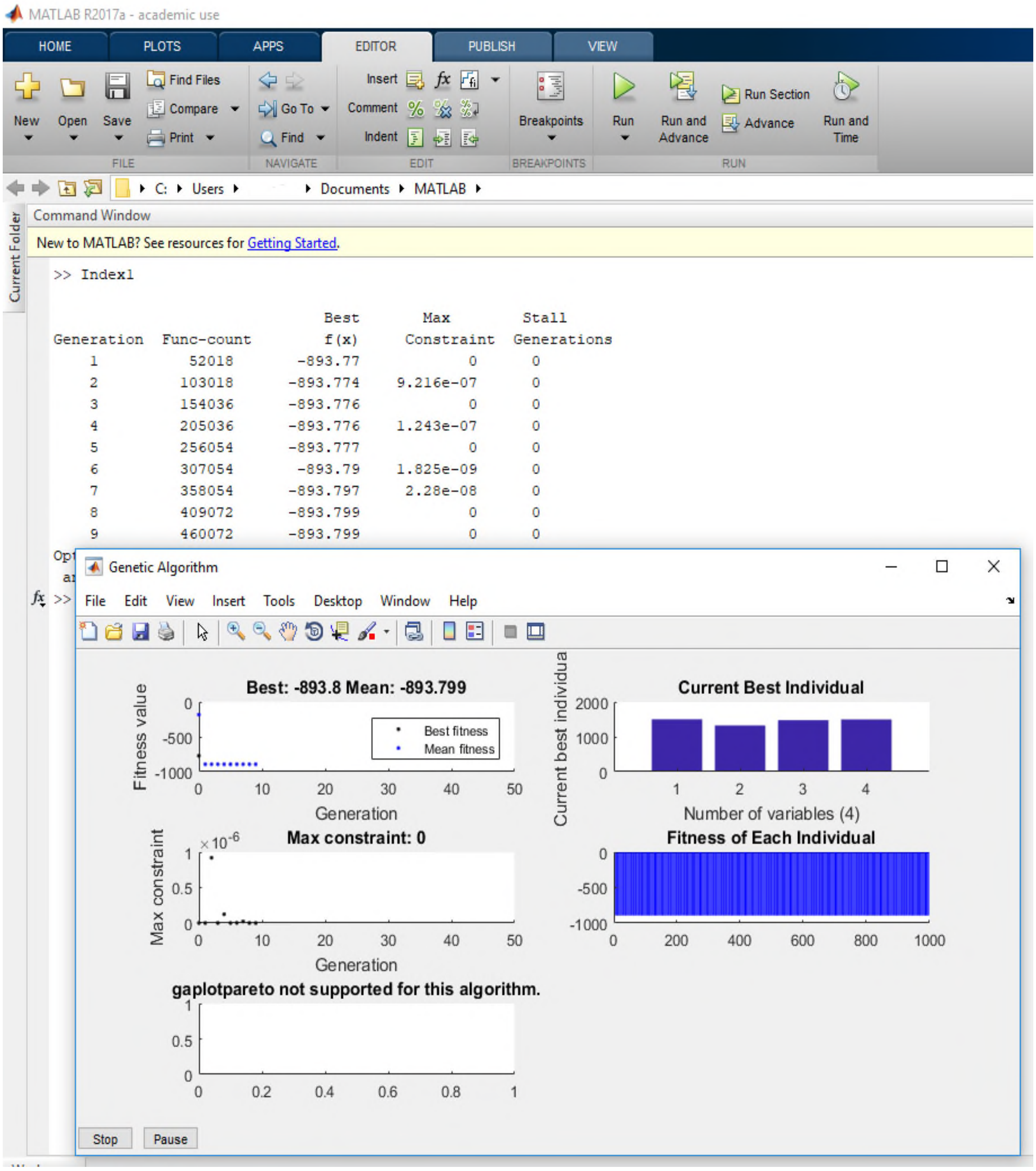
```
if  x(1) < 1070
    fuel_c(1) = 0;
end
if  x(2) < 1070
    fuel_c(2) = 0;
end

if  x(3) < 1070
    fuel_c(3) = 0;
end
if  x(4) < 1070
    fuel_c(4) = 0;
end

if  x(5) < 1070
    fuel_c(5) = 0;
end
if  x(6) < 1070
    fuel_c(6) = 0;
end

if  x(7) < 1070
    fuel_c(7) = 0;
end
if  x(8) < 1070
    fuel_c(8) = 0;
end
```

```
if  x(9) < 1070
    fuel_c(9) = 0;
end
if  x(10) < 1070
    fuel_c(10) = 0;
end

if  x(11) < 1070
    fuel_c(11) = 0;
end
if  x(12) < 1070
    fuel_c(12) = 0;
end

c = fuel_c(1) + fuel_c(2) + fuel_c(3) + fuel_c(4) + fuel_c(5) + fuel_c(6) + fuel_c(7) + fuel_c(8) + fuel_c(9) + fuel_c(10) + fuel_c(11) + fuel_c(12) - 59.3519;

% No nonlinear equality constraints:
ceq = [];
```

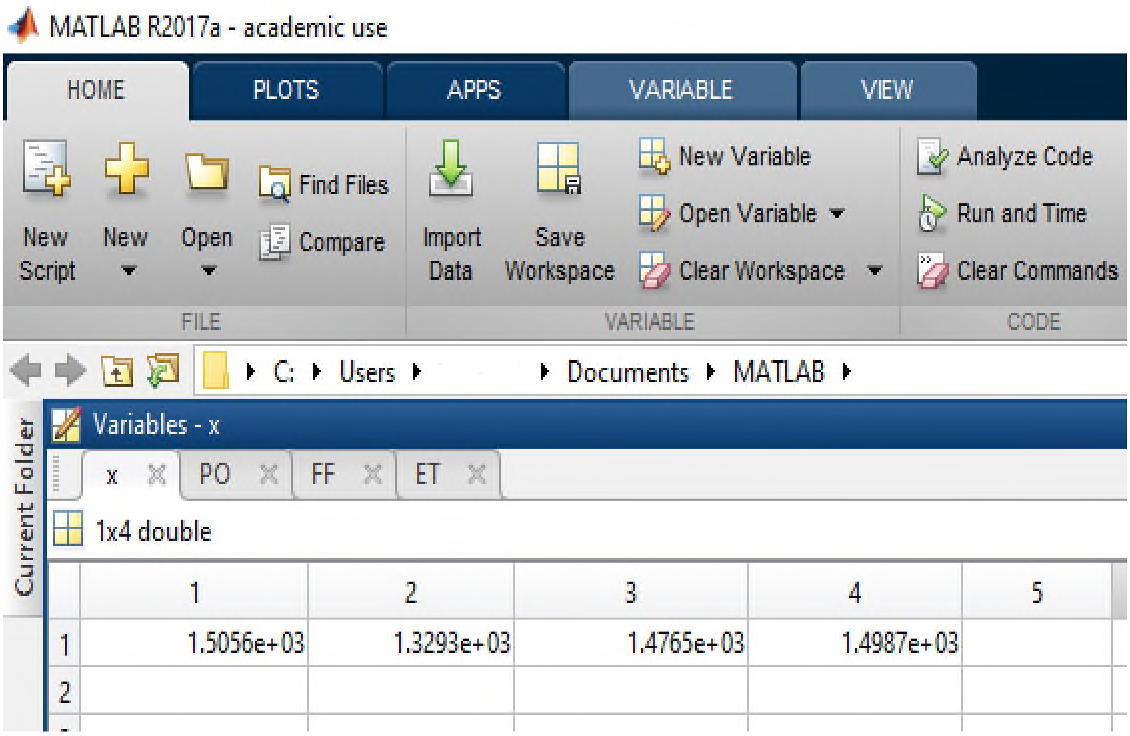
Appendix G : Screenshots of the Optimised Fleet Composition, Power Production, Efficiency and Fuel Usage

G.1 Optimised fleet composition, power production, efficiency and fuel utilisation of the optimistic degraded RH296 fleet, year 2

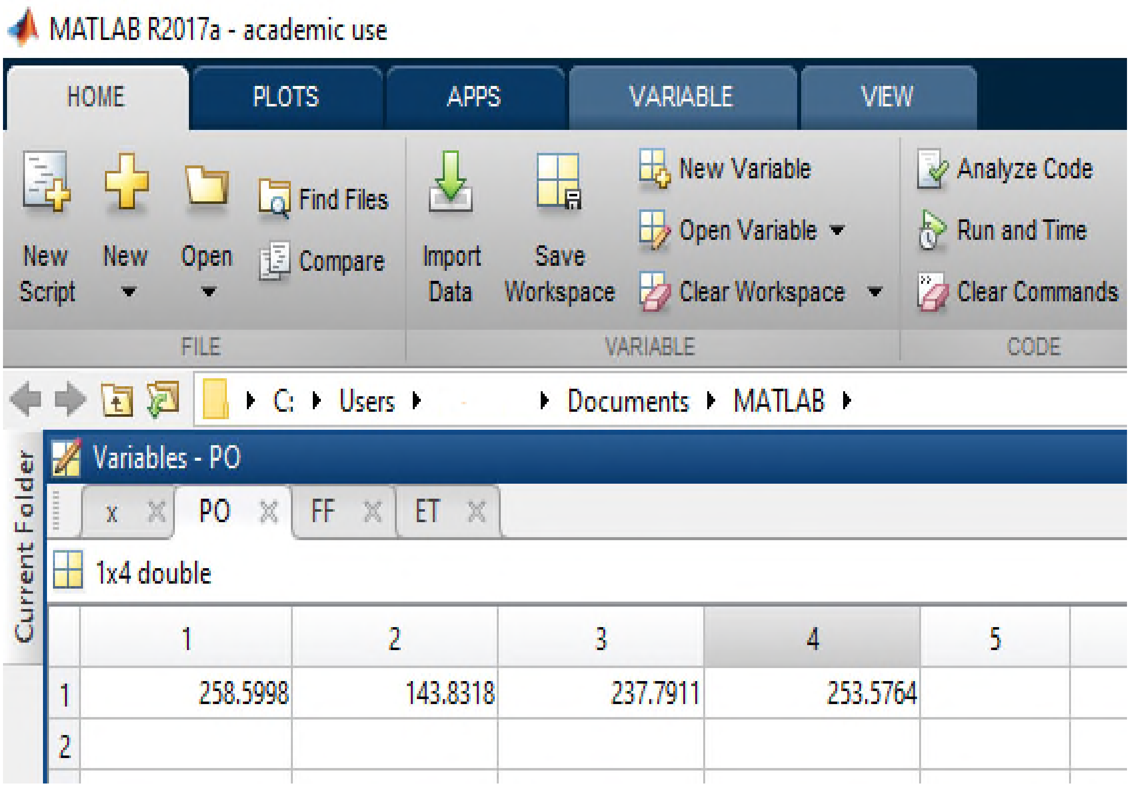
G.1.1 Screenshot of optimised fleet composition and power production



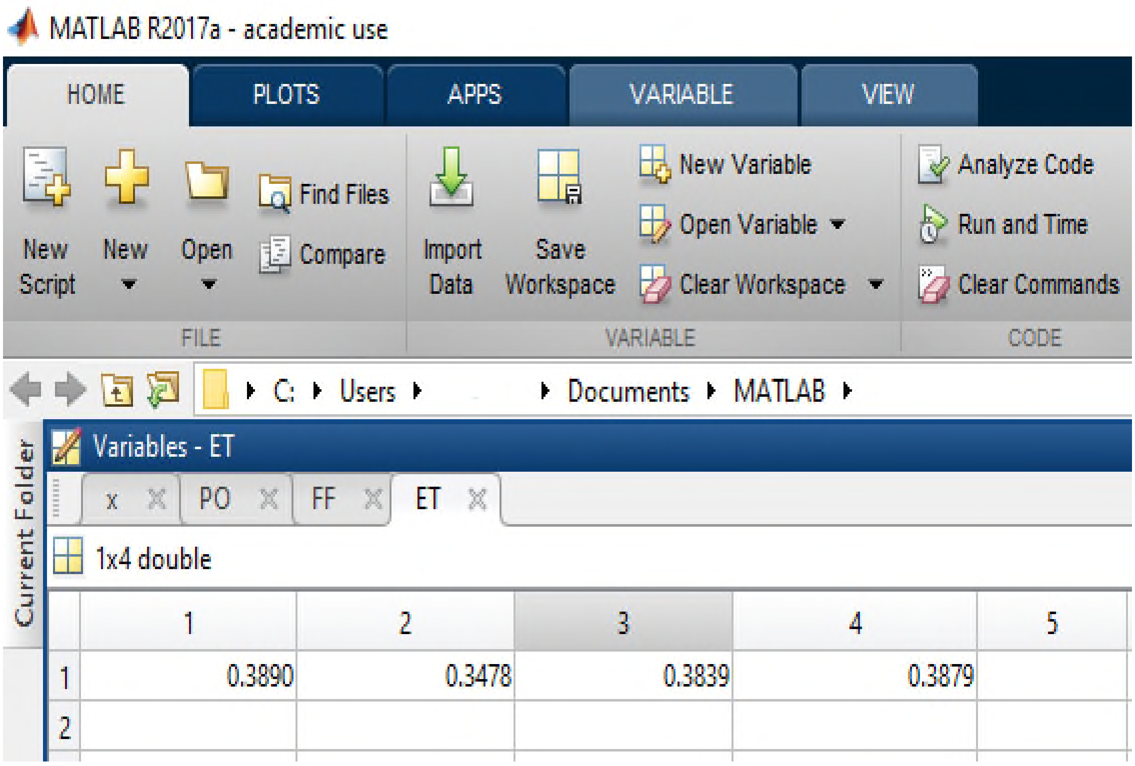
G.1.2 Screenshot of optimised fleet composition in MATLAB Excel



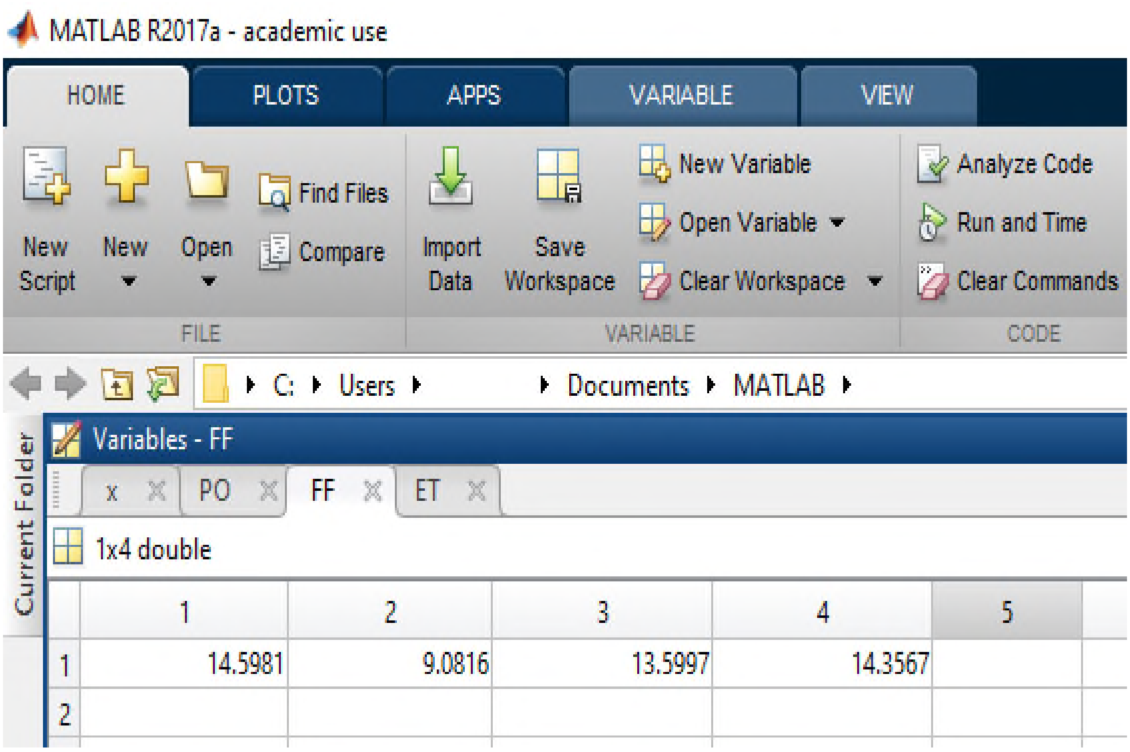
G.1.3 Screenshot of the optimised power in MATLAB Excel



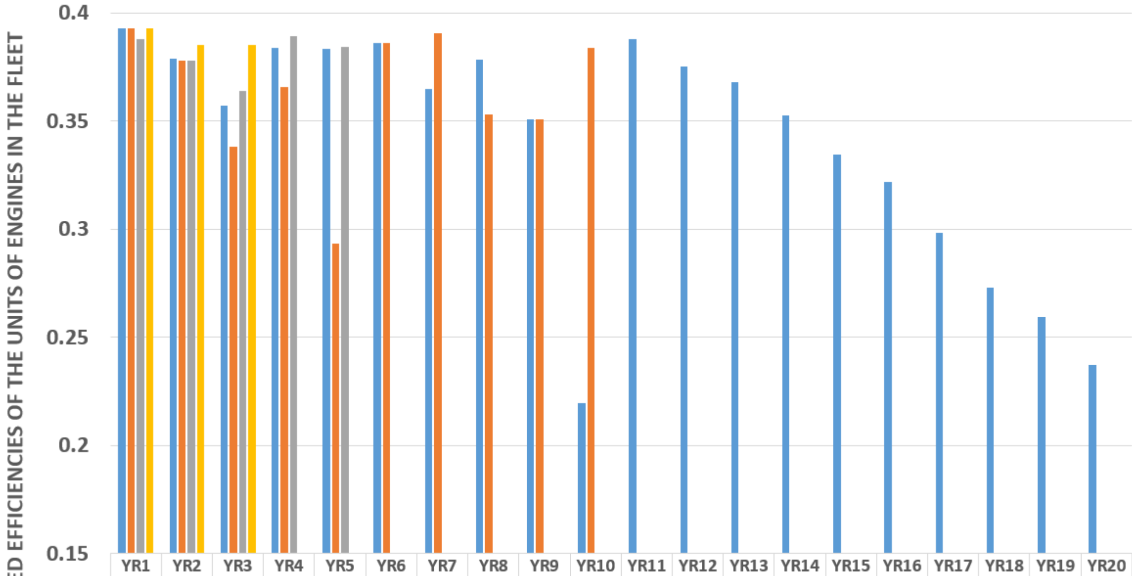
G.1.4 Screenshot of the optimised efficiencies in MATLAB Excel



G.1.5 Screenshot of the optimised fuel utilisation in MATLAB Excel



G.1.6 Optimised efficiencies for the Medium degraded RH296 fleet

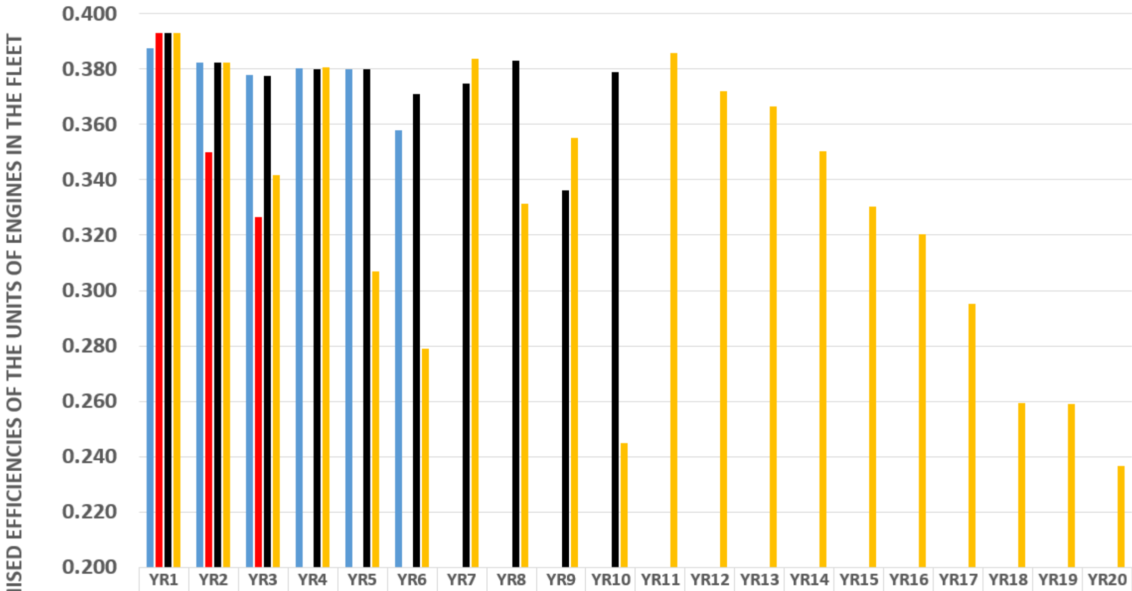


	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.393	0.379	0.357	0.384	0.383	0.386	0.365	0.378	0.351	0.219	0.388	0.375	0.368	0.353	0.334	0.322	0.298	0.273	0.259	0.237
GT2	0.393	0.378	0.338	0.366	0.293	0.386	0.391	0.353	0.351	0.384										
GT3	0.388	0.378	0.364	0.389	0.384															
GT4	0.393	0.385	0.385																	

PROJECT TIME [YRS]

GT1 GT2 GT3 GT4

G.1.7 Optimised efficiencies for the Pessimistic degraded RH296 fleet

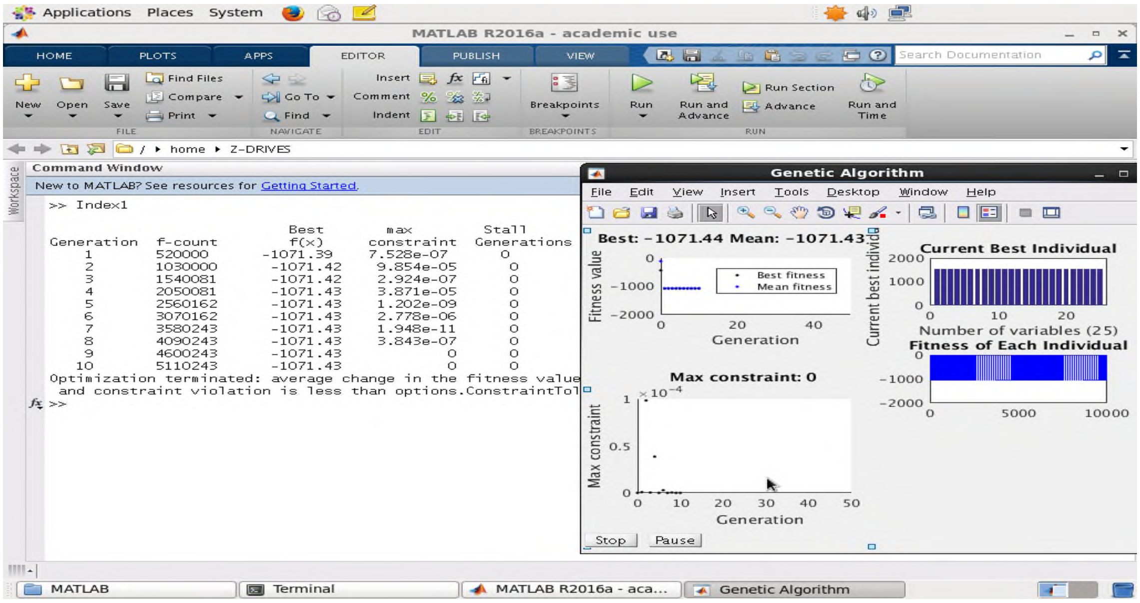


	YR1	YR2	YR3	YR4	YR5	YR6	YR7	YR8	YR9	YR10	YR11	YR12	YR13	YR14	YR15	YR16	YR17	YR18	YR19	YR20
GT1	0.388	0.382	0.378	0.380	0.380	0.358														
GT2	0.393	0.350	0.327																	
GT3	0.393	0.382	0.378	0.380	0.380	0.371	0.375	0.383	0.336	0.379										
GT4	0.393	0.382	0.342	0.381	0.307	0.279	0.384	0.331	0.355	0.245	0.386	0.372	0.366	0.350	0.330	0.320	0.295	0.259	0.259	0.237

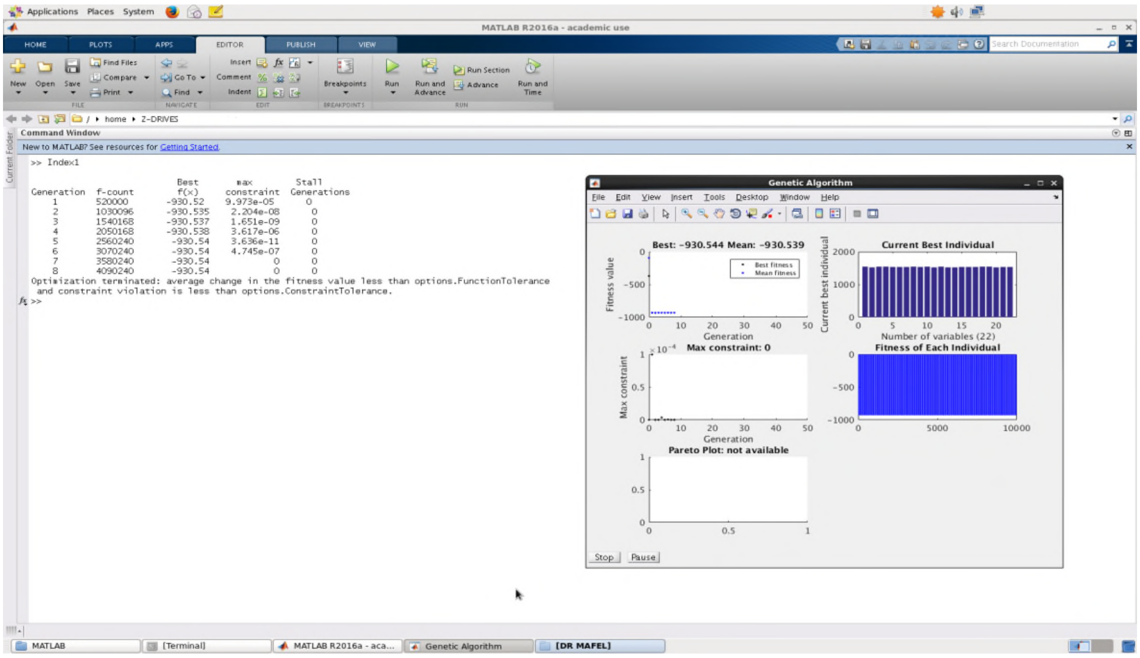
PROJECT TIME [YRS]

GT1 GT2 GT3 GT4

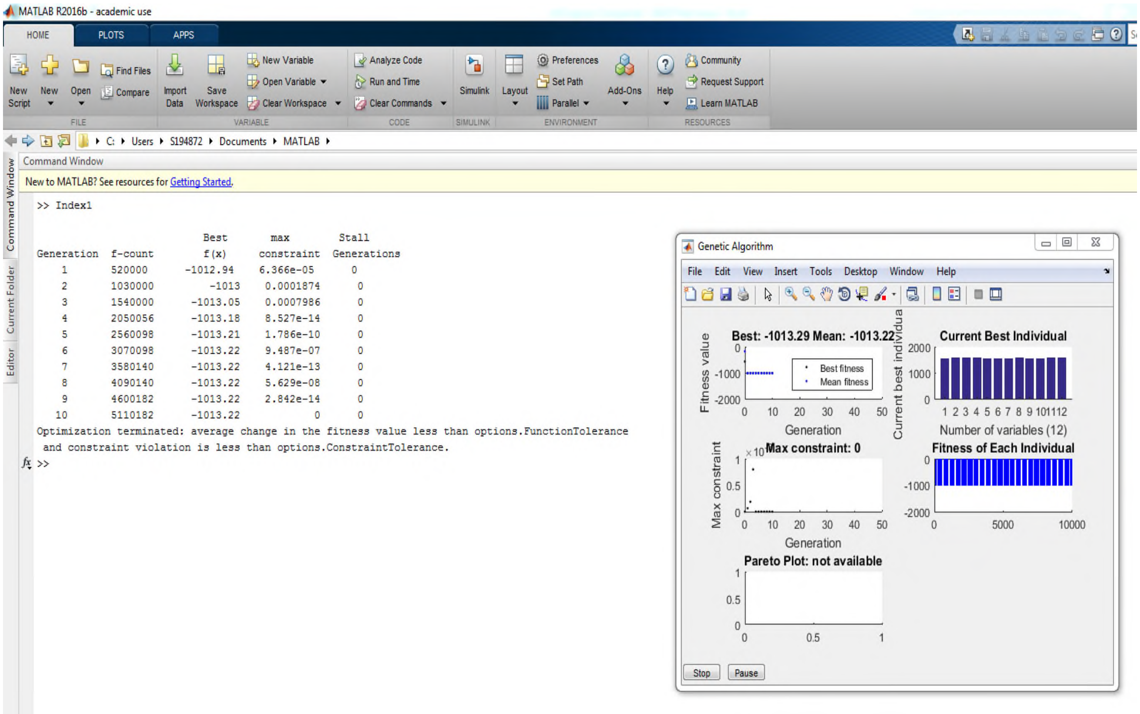
G.1.8 Screenshot of the optimised fleet composition and power production, AD43 Clean, Year 1



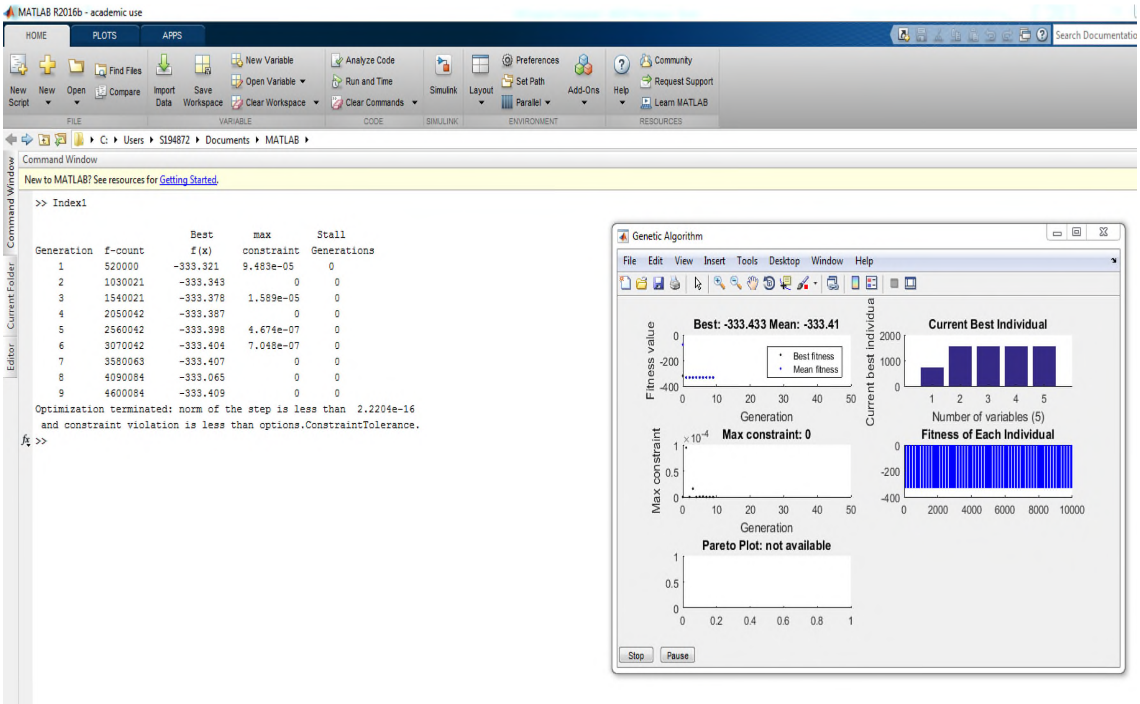
G.1.9 Screenshot of the optimised fleet composition and power production, AD43 Clean, Year 2



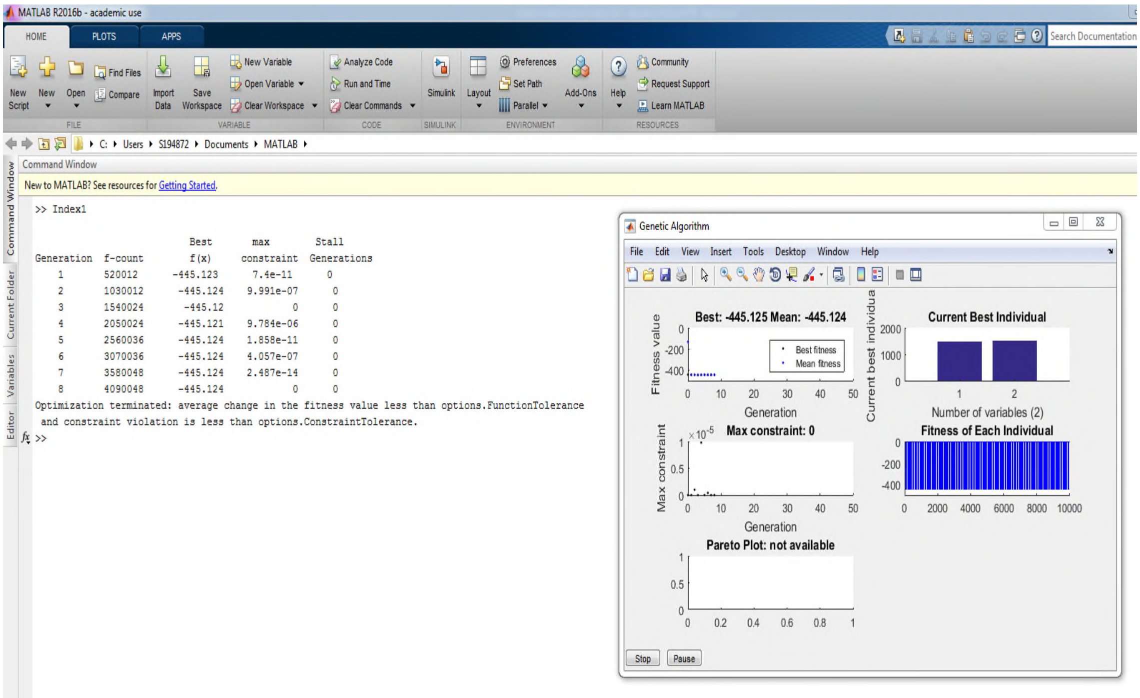
G.1.10 Screenshot of the optimised fleet composition and power production, IC100 OPT, Year 2



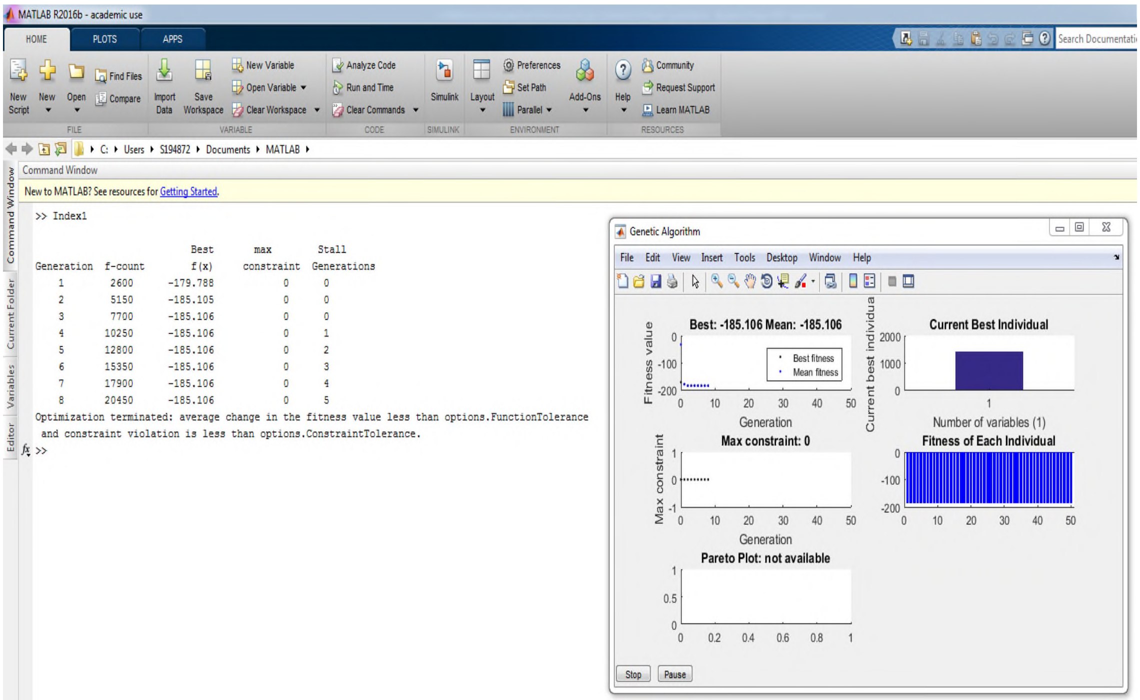
G.1.11 Screenshot of the optimised fleet composition and power production, IC100 OPT, Year 10



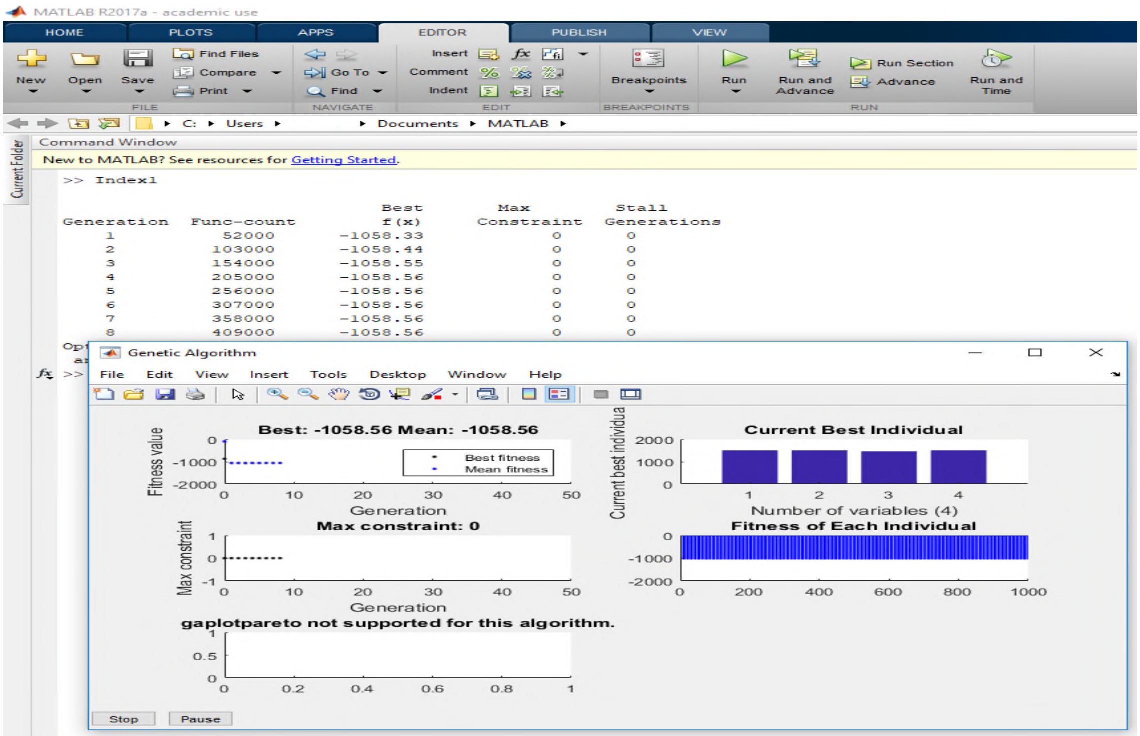
G.1.12 Screenshot of the optimised fleet composition and power production, SS296 OPT, Year 7



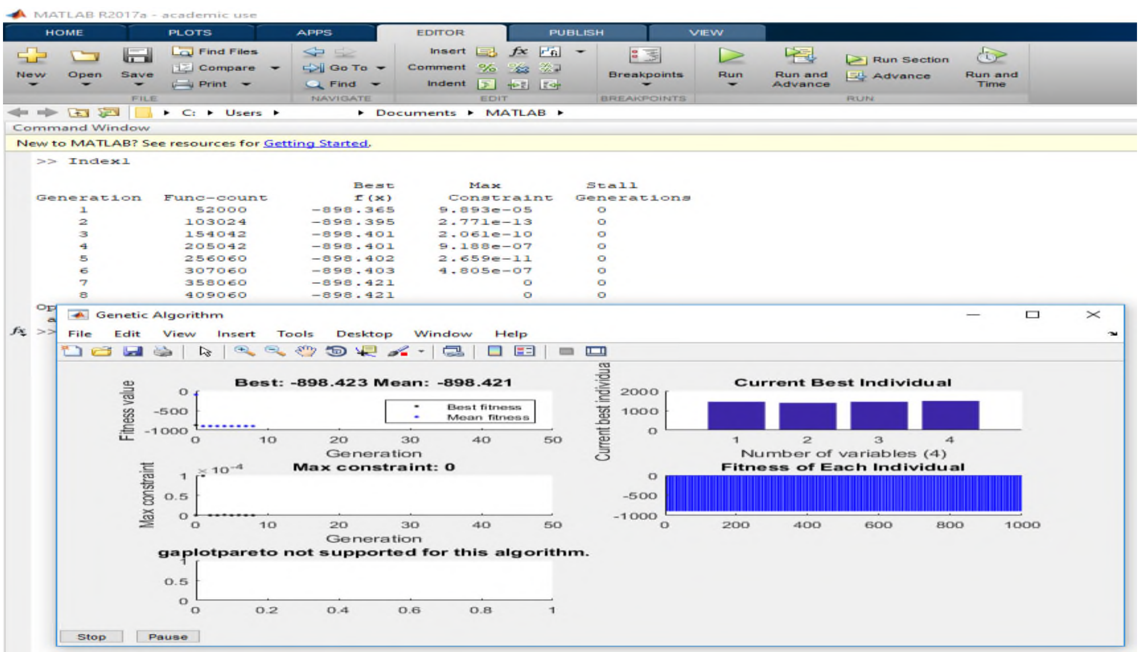
G.1.13 Screenshot of the optimised fleet composition and power production, SS296 PES, Year 13



G.1.14 Screenshot of the optimised fleet composition and power production, RH296 Clean, Year 1



G.1.15 Screenshot of the optimised fleet composition and power production, RH296 Clean, Year 2



Appendix H : Input and Output Files of Emission Prediction using Hephaestus

H.1 Input file used for predicting CO_2 emissions (Baseline fleet)

HephaestusInput - AD43 Baseline.inp - Notepad

File Edit Format View Help

```
!       **********************
!       HEPHAESTUS - Input file
!       **********************

!       Author: MAFEL OBHUO
!       Cranfield University (CU), 2017

!     This file contain the input data for the CU Gaseous Emissions Prediction Model HEPHAESTUS
!       Four slashes (////) indicate the data beginning
!       Everything before the four slashes (////) is ignored

!       Data is read sequentially. POINT must start at 1 (one), and follow a sequential order
!       This input data format is used in order to allow the computation of multiple points easily

!       Input file is divided in sections starting with a keyword 'METHOD' (sequential METHOD numbering is required)
!       Each section (except the first one) represents a different emissions prediction methodology
!       First section (METHOD 0) deals with the initial settings of HEPHAESTUS

!       Each section has two lines/rows of '==...' characters. Everything inside these two rows is ignored
!       Data is read inmediately after the second row of '==...' characters until a line of blank ones is found

!       Lines/rows of blank characters must be avoided between the keyword 'METHOD' and the first line/row of '==...' characters
!       Lines/rows of blank characters must be avoided between the second line/row of '==...' characters and the actual data lines/rows

!       Only the first section (METHOD 0) is read at all times
!       Other sections are read only when required (according to the first section settings)
!       Input data is required according to the particular emissions prediction method utilised

////
METHOD 0
==============================================================================================
!       MODEL 0 is NOT a model. It is a generic section dealing with HEPHAESTUS initial settings
!       Only one (1) line or row of data (first one) is need. All other data lines/rows are ignored


!       Description of the imput parameters:

!       POINT           Calculation point                               [---]
!       HAMB            Ambient (flight) altitude                       [m]
!       TAMB            Ambient temperature                             [K]
!       RHAMB           Ambient relative humidity                       [---]
!       TA              Air total temperature                           [K]
!       PA              Air total pressure                              [atm]
!       WA              Total air mass flow rate                        [kg/s]
!       FRAIRFF Flame front air mass flow rate fraction         [---]
!       FRAIRP  Primary air mass flow rate fraction             [---]
!       FRAIRI  Intermediate air mass rate flow fraction        [---]
!       FRAIRD  Dilution air mass flow rate fraction            [---]
!       WF              Fuel mass flow rate                             [---]
!       TF              Fuel total temperature                          [K]
!       FFIA            Flame front inlet area                          [m2]
!       FFOA            Flame front outlet area                         [m2]
!       FFL             Flame front length                              [m]
!       PZIA            Primary zone inlet area                         [m2]
!       PZOA            Primary zone outlet area                        [m2]
!       PZL             Primary zone length                             [m]
!       IZIA            Intermediate zone inlet area                    [m2]
!       IZOA            Intermediate zone outlet area                   [m2]
!       IZL             Intermediate zone length                        [m]
!       DZIA            Dilution zone inlet area                        [m2]
!       DZOA            Dilution zone outlet area                       [m2]
!       DZL             Dilution zone length                            [m]


POINT   HAMB            TAMB            RHAMB           TA              PA              WA              FRAIRFF   FRAIRP  FRAIRI  FRAIRD  WF
[---]   [m]             [K]             [---]           [K]             [atm]           [kg/s]    [---]         [---]           [---]           |
==============================================================================================
1       0.00000 288.15000       0.60000 830.45000       28.96   117.140 0.290000        0.210000        0.210000        0.290000        2.3958
2       0.00000 288.15000       0.60000 818.60000       26.45   111.600 0.290000        0.210000        0.210000        0.290000        1.8500
3       0.00000 288.15000       0.60000 818.82000       26.26   111.040 0.290000        0.210000        0.210000        0.290000        1.8135
4       0.00000 288.15000       0.60000 818.90000       26.19   110.900 0.290000        0.210000        0.210000        0.290000        1.7998
5       0.00000 288.15000       0.60000 819.03000       26.08   110.600 0.290000        0.210000        0.210000        0.290000        1.7797
6       0.00000 288.15000       0.60000 829.20000       25.09   107.270 0.290000        0.210000        0.210000        0.290000        1.6015
7       0.00000 288.15000       0.60000 831.72000       24.94   106.710 0.290000        0.210000        0.210000        0.290000        1.5762
8       0.00000 288.15000       0.60000 792.30000       22.97   116.100 0.290000        0.210000        0.210000        0.290000        1.3221
9       0.00000 288.15000       0.60000 847.59000       24.00   103.190 0.290000        0.210000        0.210000        0.290000        1.2562
```

H.2 Output file for predicted CO_2 emissions (Baseline fleet)

HephaestusOutput - AD43 Baseline.out - Notepad

File Edit Format View Help

```
*************************************************************************
*                                                                       *
*                          "HEPHAESTUS"                                 *
*     A GASEOUS EMISSIONS PREDICTION MODEL FOR GAS TURBINE COMBUSTORS   *
*                                                                       *
*     -   Author: MAFEL OBHUO                                           *
*                 Cranfield University, 2017                            *
*                                                                       *
*     HEPHAESTUS predicts gaseous emissions from gas turbine combustors. *
* The prediction process and the algorithms used depend on the particular*
* prediction methodology utilised. Thus, the input data required and the *
* main results obtained vary according to the method utilised to predict *
* the referred gaseous emissions.                                       *
*                                                                       *
*************************************************************************

Date (DD.MM.YYYY):      25- 7-2017
Time (HH.MM.SS)  :      13:25:27

                            CHEMICAL REACTORS-BASED METHOD RESULTS
                            ======================================

 POINT             TOTAL               FAR                 T               PHI               PHI               PHI
OT             SOOT            EICO2            EIH2O
    --              MEAN              STOI              STOI              OVER                FF              PRIM
ML            SAESN                --               --
    --              TIME                --                --                --                --                --
--                --                --               --
    --                --                --                --                --              CORE              CORE
--                --                --               --
  [--]              [ms]              [--]               [K]              [--]              [--]              [--]
1]              [--]     [g/kg fuel]     [g/kg fuel]

     1         33.762478          0.057757       2560.400146          0.354115          0.976868          0.141646
00          0.000000     2837.981445      2206.436279
     2         33.213245          0.057757       2552.184082          0.287016          0.791768          0.114806
00          0.000000     2844.035156      2207.558838
     3         33.169724          0.057757       2552.091553          0.282772          0.780061          0.113109
00          0.000000     2844.505127      2207.609619
     4         33.135952          0.057757       2552.056396          0.280990          0.775145          0.112396
00          0.000000     2844.706299      2207.630859
     5         33.103096          0.057757       2552.002930          0.278606          0.768568          0.111442
00          0.000000     2844.979492      2207.658447
     6         32.687538          0.057757       2555.807129          0.258492          0.713081          0.103397
00          0.000000     2847.470215      2207.855225
     7         32.607983          0.057757       2556.844971          0.255743          0.705499          0.102297
00          0.000000     2847.839355      2207.878662
     8         29.537167          0.057757       2535.689453          0.197165          0.543904          0.078866
00          0.000000     2858.016846      2208.433594
     9         32.537106          0.057757       2563.324463          0.210775          0.581449          0.084310
00          0.000000     2855.168701      2208.276855
```

H.3 Output file for predicted NOX and CO emissions (Baseline fleet)

EIMoutput - AD43 Baseline.out - Notepad

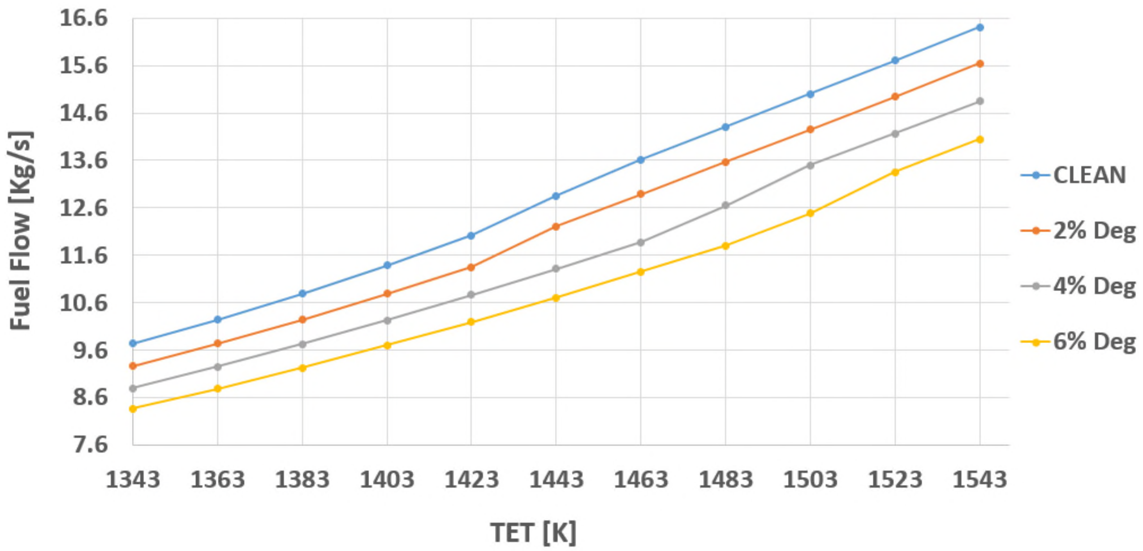
File Edit Format View Help

```
*****************************************************************************

        EMISSIONS PREDICTION FROM INDUSTRIAL GAS TURBINE COMBUSTORS

                        - Author: MAFEL OBHUO
                                  Cranfield University, 2017

 This code predicts emissions from industrial gas turbine combustors.
 For the case of the NOx, CO, and UHC, the emissions are calculated
 (EINOx, EICO, and EIUHC) in ppm.

****************************************************************************


                                  EMISSIONS
                                 ***********

Date (DD.MM.YYYY):       25- 7-2017
Time (HH.MM.SS)  :       13: 2:13


          SOOT              SOOT              SOOT              SOOT              SOOT
      SOOT              SOOT           EINOX             EICO             EIUHC
           GEN               OXI             SOOTF             WOXIF               SFV
     WOXIF             SFV                --                --                --
         INTER             INTER             INTER             INTER             INTER
        --                --                --                --                --
          CORE              CORE              CORE              CORE              CORE
        --                --                --                --                --
3 soot/s]E-12     [m3 soot]E-12     [m3 soot]E-12     [m3 soot]E-12 [m3 soot/m3]E-12
soot]E-12 [m3 soot/m3]E-12           [ppm]             [ppm]             [ppm]

      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          25.349844         1.676337          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          11.766289         0.264187          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          11.712610         0.238415          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          12.034255         0.228396          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          12.874285         0.215846          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          11.889972         0.149343          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000          12.328117         0.143941          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000           6.694602         0.102778          0.000000
      0.000000          0.000000          0.000000          0.000000          0.000000
 0.000000          0.000000           9.881748         0.074083          0.000000
```

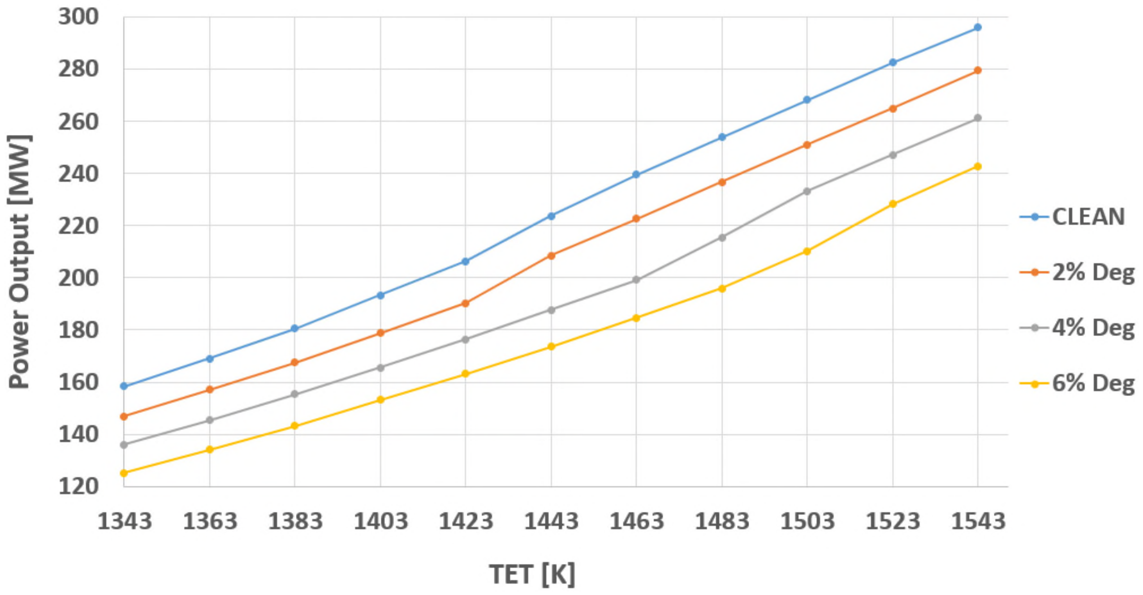
Appendix I : Off-design performance of the study engines

I.1 RH296 Engine

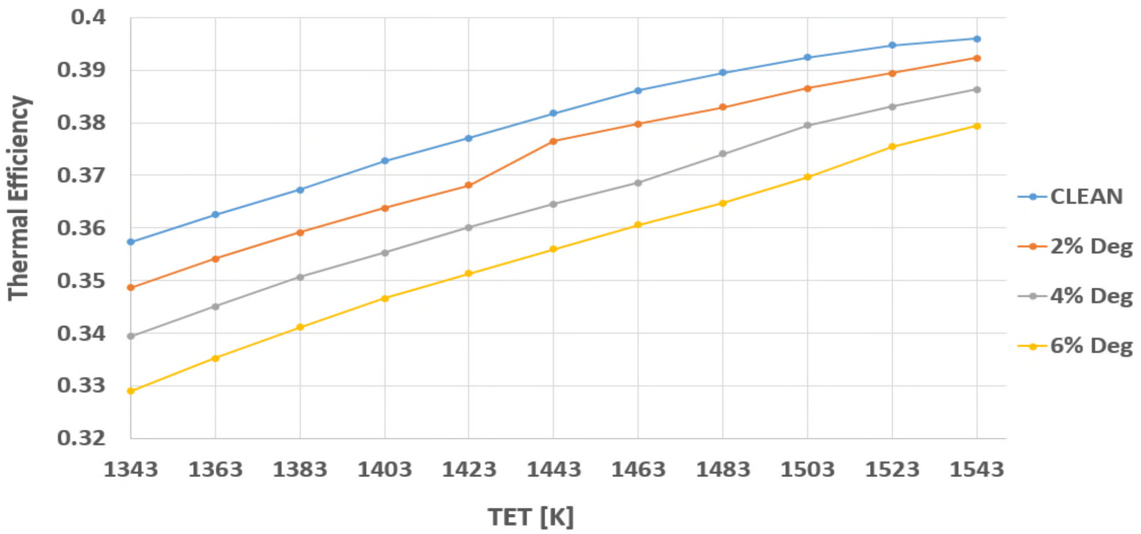
I.1.1 TET (K) versus Fuel flow (Kg/s)



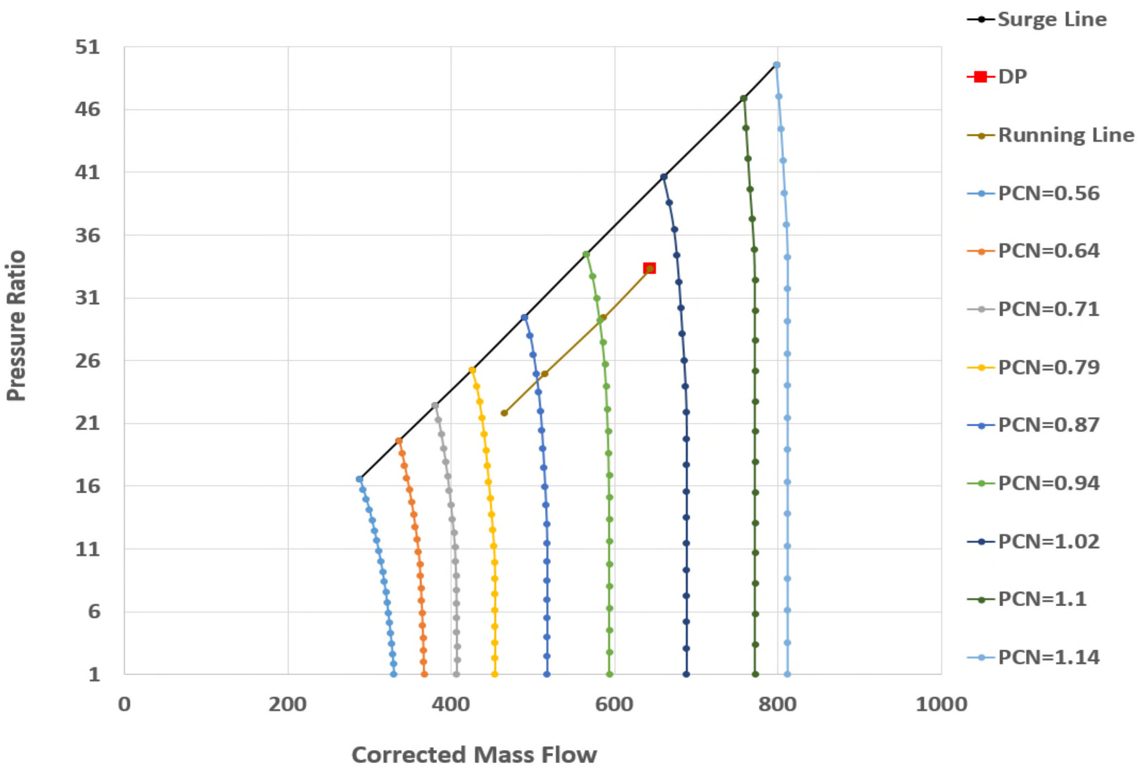
I.1.2 TET (K) versus Power output (MW)



I.1.3 TET (K) versus Thermal efficiency

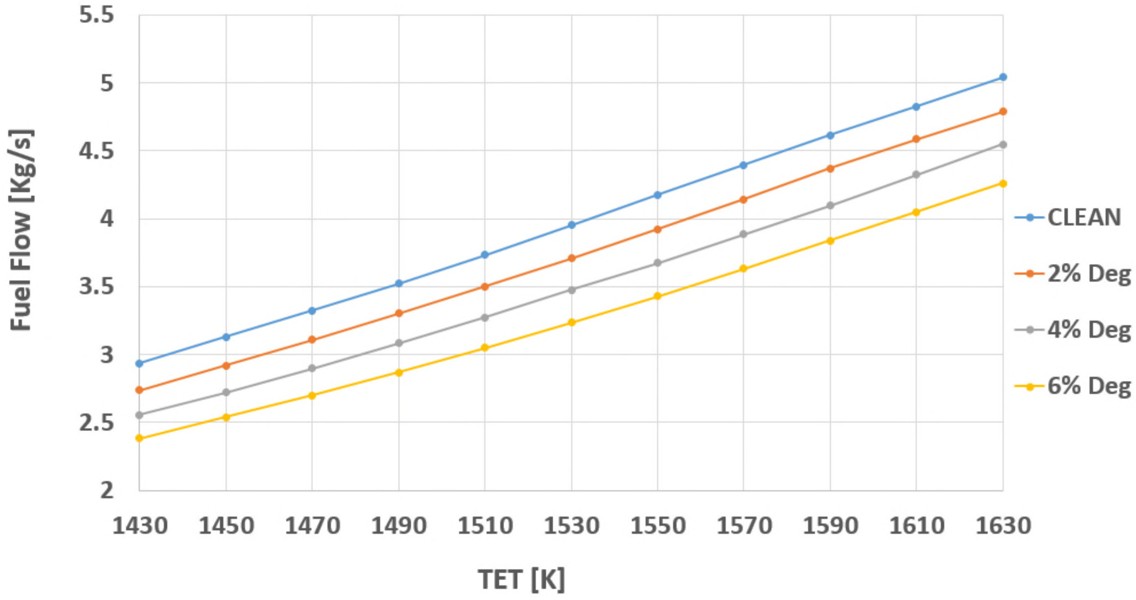


I.1.4 RH296 Compressor Map

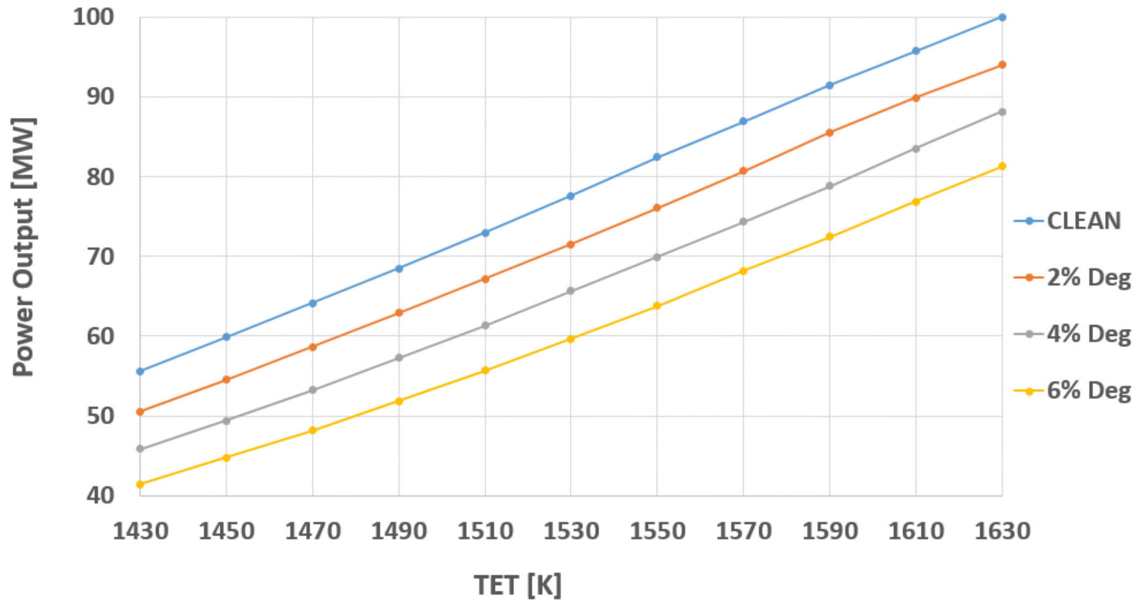


I.2 IC100 Engine

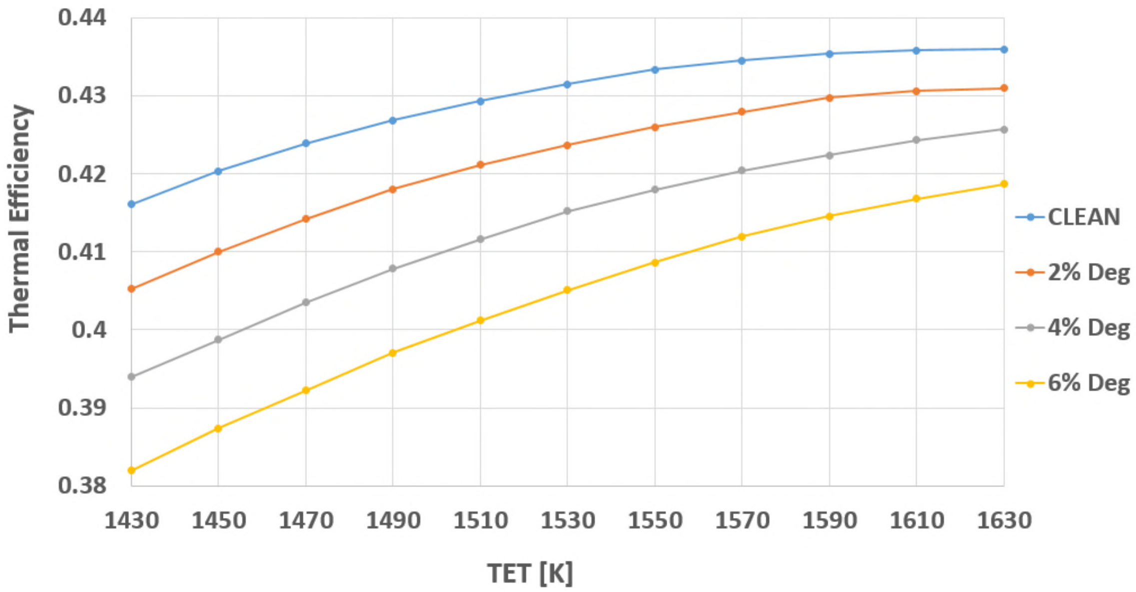
I.2.1 TET (K) versus Fuel flow (Kg/s)



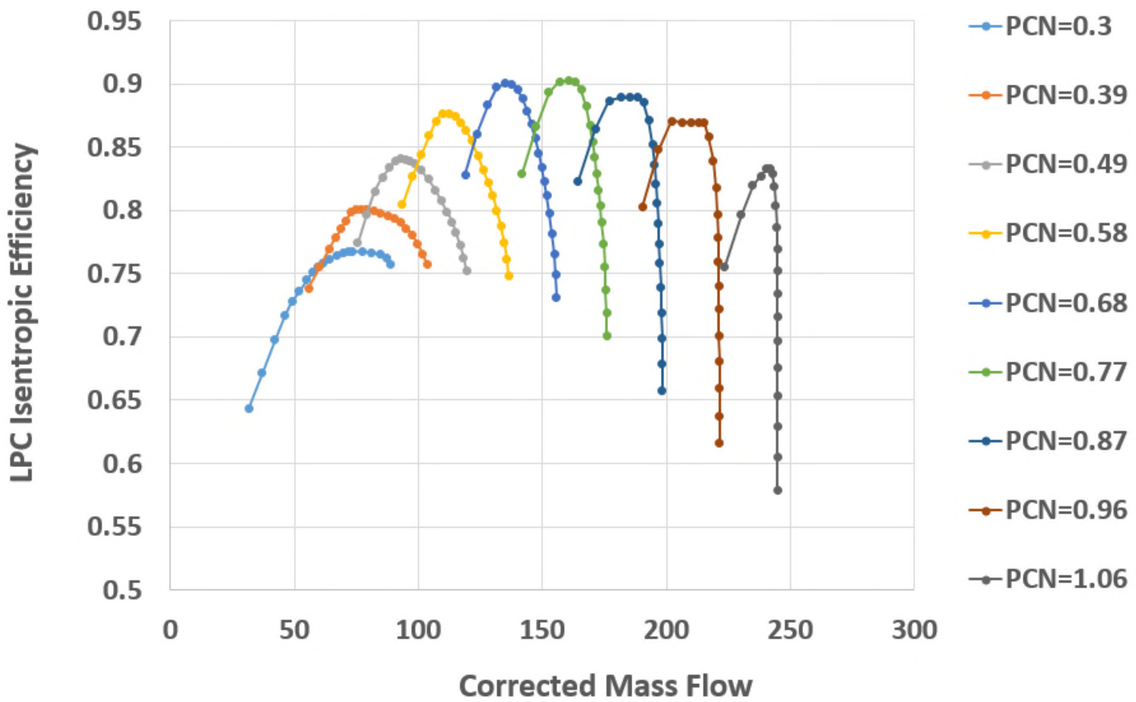
I.2.2 TET (K) versus Power output (MW)



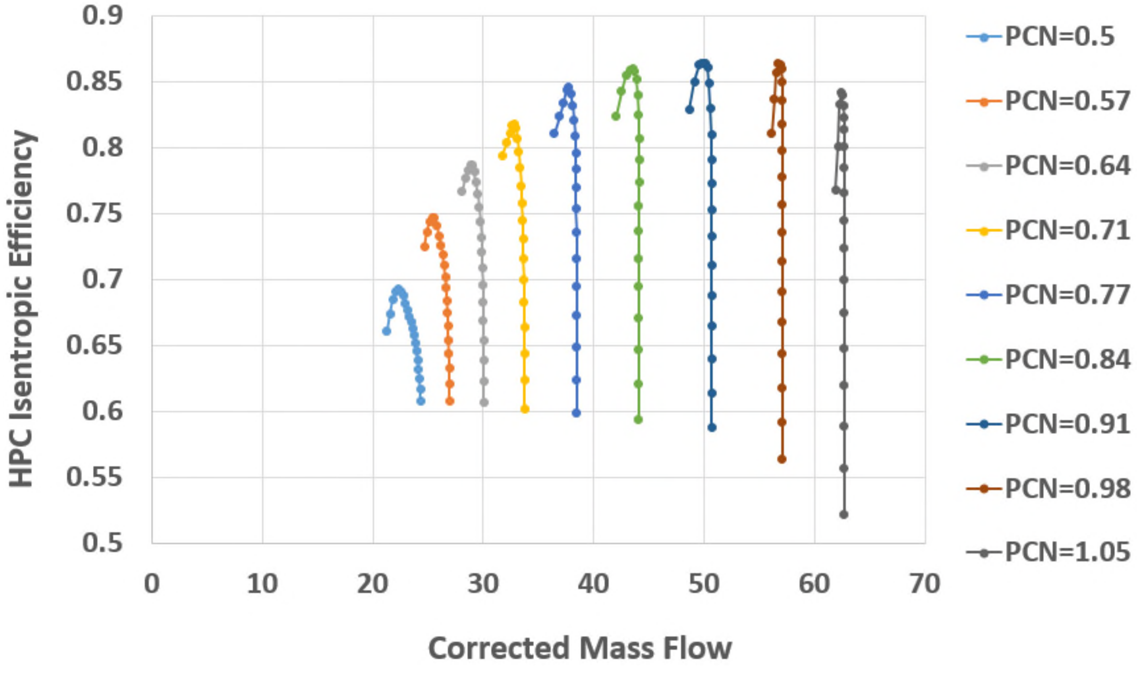
I.2.3 TET (K) versus Thermal efficiency



I.2.4 Low Pressure Compressor (LPC) Map

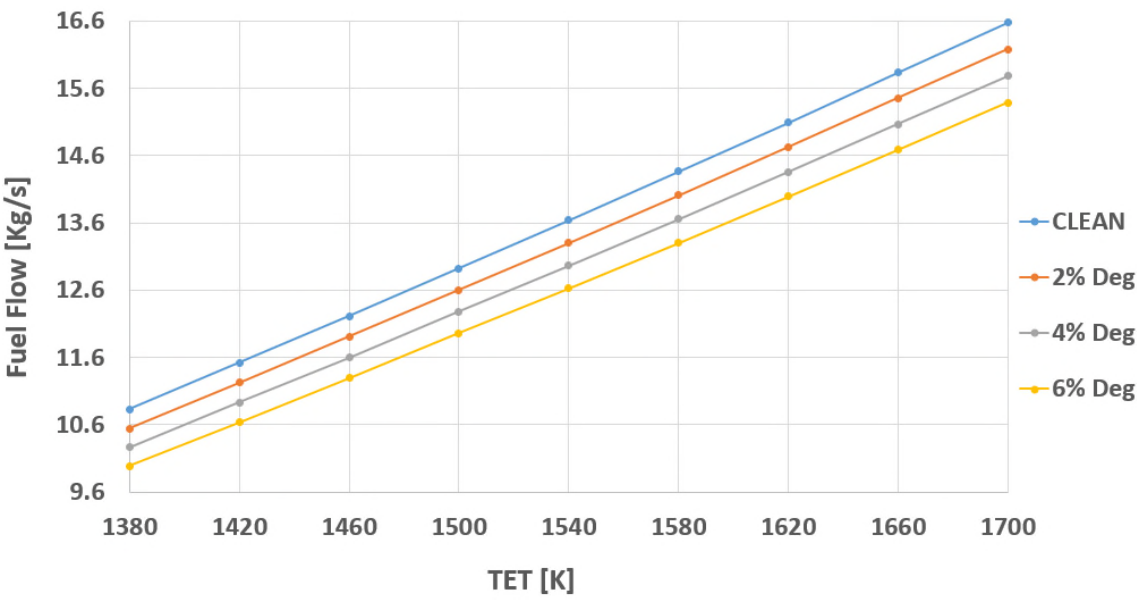


I.2.5 High Pressure Compressor (HPC) Map

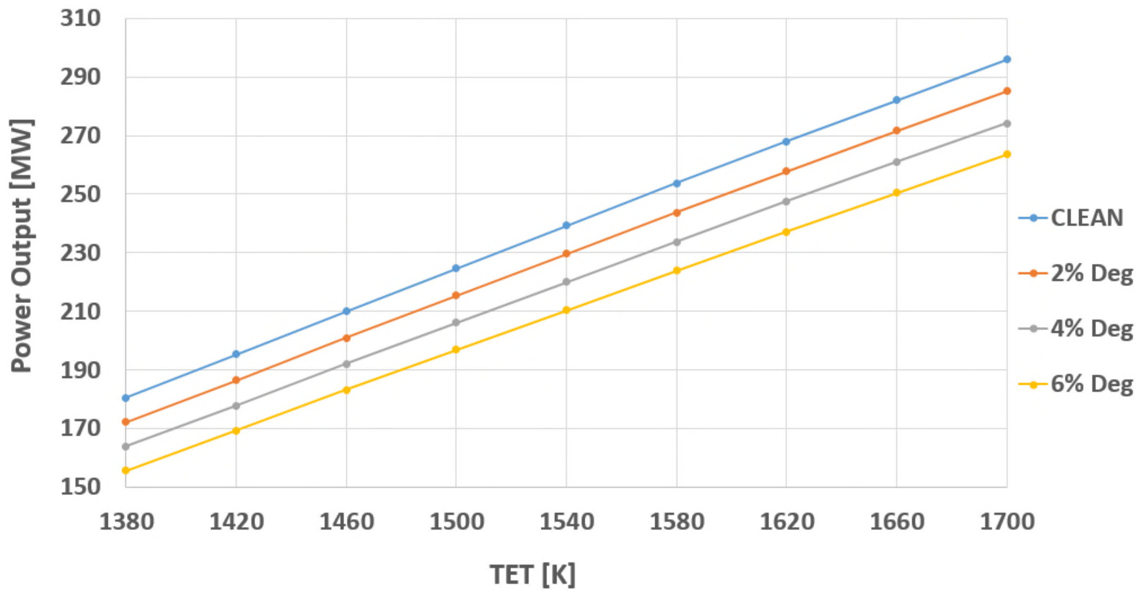


I.3 SS296 Engine

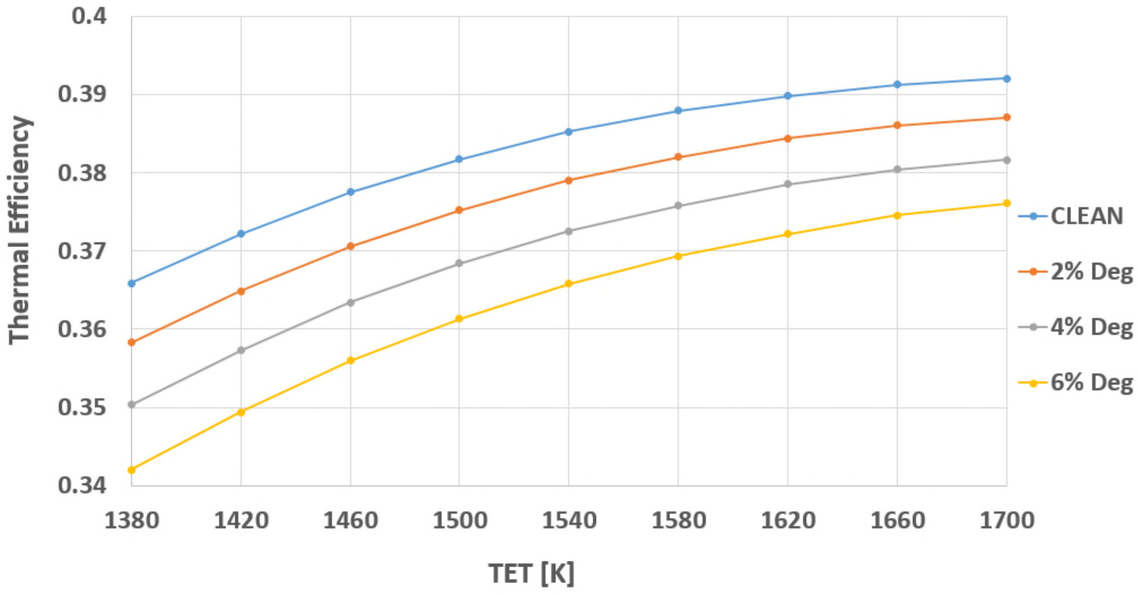
I.3.1 TET (K) versus Fuel flow (Kg/s)



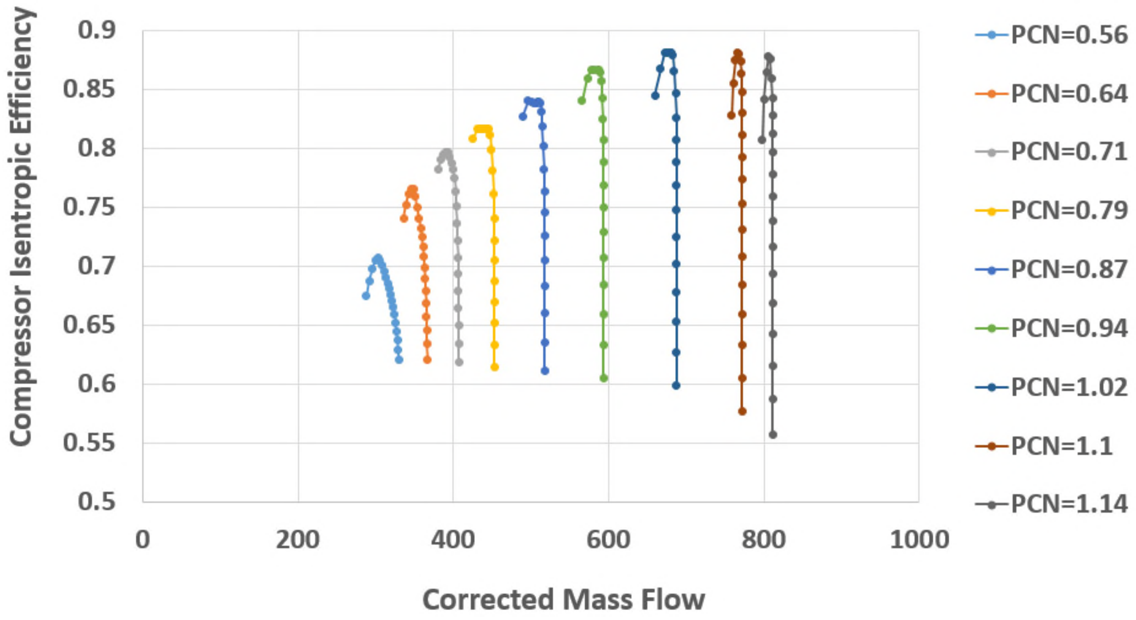
I.3.2 TET (K) versus Power output (MW)



I.3.3 TET (K) versus Thermal efficiency



I.3.4 SS296 Compressor Map



Appendix J : Economic Analysis of Associated Gas Utilisation

J.1 Economic analysis of the clean RH296 fleet, 2% loan interest rate

10% Discount Rate (d)	0.1
Engine Capital Cost $/Kw	689
Initial Cash flow (F_0)$	815776000
Conversion	1000
Number of Gas turbines	4
PO @DP (MW)	296

End of Year (t)	O&M Cost	Emission Tax	Staff Salaries	GT Divestment Sales	Revenue from sold electricity	Annual Loan repayment	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $F_t/(1+d)^t$
1	159985223.76	29465533.07	4459220		1112760897		918850920.56	835319018.7
2	138193882.38	26166950.24	4459220.00	0.00	963308896.68	312128150.5	482360693.57	398645201.3
3	125934275.43	23193417.97	3938504.50	190777592.03	877241206.40	104105270.5	810847330.04	609201600.3
4	109111291.87	20576951.45	3880300.00	0.00	758809107.75	104105270.5	521135293.94	355942417.8
5	93715810.75	11126266.85	3880300.00	0.00	653265345.05	104105270.5	440437696.96	273477157.5
6	87490354.73	16155288.62	3350900.70	172131892.91	609869522.66	50544731.87	624460139.65	352491469.2
7	75598712.58	14318414.97	3301380.00	0.00	526976383.87	50544731.87	383213144.44	196648936.1
8	64944616.85	12686287.64	3301380.00	0.00	452709816.97	50544731.87	321232800.62	149857472.3
9	55464986.90	11238533.03	3350900.70	0.00	386630105.58	50544731.87	266030953.08	112823093.6
10	60783067.51	9921794.76	2722460.00	149388390.43	379847769.54	22704377.4	433104460.29	166980518.3
11	47543538.51	8783403.92	2722460.00	0.00	331412019.38	22704377.4	249658239.55	87503689.92
12	41010100.31	7773920.98	2763296.90	0.00	285869343.90		234322025.70	74662218.66
13	35188276.44	6877588.79	2722460.00	0.00	245287122.48		200498797.25	58077359.74
14	29992894.26	6083790.07	2722460.00	0.00	209071641.85		170272497.51	44838070.34
15	25389793.96	5380301.60	2763296.90	0.00	176984783.90		143451391.44	34341122.58
16	21277670.47	4757866.81	2722460.00	0.00	148320380.85		119562383.57	26020258.21
17	17613468.60	4207758.37	2722460.00	0.00	122778307.65		98234620.67	19435196
18	14366457.31	3720087.78	2763296.90	0.00	100144347.20		79294505.21	14261813.75
19	11670708.45	3287311.73	2722460.00	0.00	81353075.00		63672594.83	10410978.05
20	9273527.63	2905278.42	2722460.00	97548574.09	64643032.77		147290340.81	21893770.63
∑	1224548658.71	228626747.08	63991676.60	609846449.46	8487283106.86	872031644.25		3842831363
						Initial Cash Flow [	815776000	
						NPV [$]	3027055363	3.027055363

J.2 Economic analysis of the optimistic degraded RH296 fleet, 2% loan interest rate

10% Discount Rate (d)			0.1					
Engine Capital cost $/Kw			689					
Initial Cash Flow (F_0)$			815776000					
Conversion			1000					
Number of Gas turbines			4					
PO @DP (MW)			296					
End of year (t)	O&M cost	Emission tax	Staff Salaries	GT Divestment Sales	Revenue from sold electricity	Annual Loan repayment	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $F_t/(1+d)^t$
1	159985223.76	29465533.07	4459220		1112760897		918850920.56	835319018.7
2	141073277.70	19269579.83	4459220.00	0.00	958352908.08	309274084.4	484276746.18	400228715.8
3	136088760.55	15239936.43	3938504.50	190777592.03	871377036.36	101251204.4	805636222.54	605286418.1
4	110604810.54	15591590.35	3880300.00	0.00	756758080.23	101251204.4	525430174.97	358875879.4
5	95499414.69	10527600.91	3880300.00	0.00	649246060.85	101251204.4	438087540.88	272017895.5
6	93045580.36	16151831.90	3350900.70	163246400.34	605718676.40	47690665.76	608726098.02	343610012.9
7	76382720.45	14317143.22	3301380.00	0.00	525368864.19	47690665.76	383676954.76	196886944.1
8	66199307.20	12684132.46	3301380.00	0.00	450051338.75	47690665.76	320175853.33	149364398.5
9	57255490.23	11235742.62	3350900.70	0.00	382910357.24	47690665.76	263377557.93	111697795.1
10	47479743.66	9952516.62	3301380.00	0.00	326570968.52	47690665.76	218146662.48	84104981.83
11	48885755.99	8782135.72	2722460.00	129590202.97	329983164.21	22704377.4	376478638.08	131953465.9
12	42437124.10	7772422.10	2763296.90	0.00	283808841.45		230835998.36	73551462.91
13	35527517.84	6877063.18	2722460.00	0.00	244362227.30		199235186.27	57711336.65
14	30562023.27	6082866.11	2722460.00	0.00	207773767.84		168406418.47	44346673.41
15	26179730.98	5379060.64	2763296.90	0.00	175083474.11		140761385.58	33697156.57
16	21464853.56	4757446.98	2722460.00	0.00	147637655.05		118692894.52	25831032.06
17	17890844.43	4207758.37	2722460.00	0.00	121629648.81		96808586.00	19153062.64
18	14767146.75	3719089.75	2763296.90	0.00	98758973.44		77509440.04	13940754.09
19	11560309.13	3287119.20	2722460.00	0.00	79513094.57		61943206.25	10128209.2
20	9162048.29	2904205.58	2722460.00	78913263.01	62287541.53		126412090.67	18790351.78
∑	1242051683.48	208204775.04	64570596.60	562527458.35	8389953576.32	874185403.68		3786495565
						Initial Cash Flow [$]	815776000	
						NPV [$]	2970719565	2.970719565

J.3 Economic analysis of the medium degraded RH296 fleet, 2% loan interest rate

MAIN WORK - 2% Loan Int. Rate - Excel

FILE HOME INSERT PAGE LAYOUT FORMULAS DATA REVIEW VIEW ADD-INS Nuance PDF TEAM Obhuo, Mafel

J64 | fx 1000000

10% discount rate (d)		0.1
Engine Capital cost $/Kw		689
Initial Cash flow (F_0)$		815776000
Conversion		1000
Number of gas turbines		4
PO @DP (MW)		296

End of year (t)	O&M cost	Emission tax	Staff Salaries	GT Divestment Sales	Revenue from sold electricity	Annual Loan repayment	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $F_t/(1+d)^t$
1	159985223.76	29465533.07	4459220		1112760897		918850920.56	835319018.7
2	144885584.20	26155994.62	4459220.00		954463497.75	206292460.6	572670238.33	473281188.7
3	130089550.76	26432244.74	4526108.30	0.00	814420826.13	206292460.6	447080461.72	335898168.1
4	111222627.68	21810309.46	3880300.00	172990475.96	755134836.25	101251204.4	689960870.69	471252558.4
5	97854067.94	23782439.74	3880300.00	0.00	645729772.59	101251204.4	418961760.54	260142290.7
6	103880195.89	16148346.21	3350900.70	154731692.87	601321097.41	47690665.76	584982681.72	330207473.4
7	77832973.47	14316085.62	3301380.00	0.00	524026298.58	47690665.76	380885193.73	195454329.3
8	67855713.99	12654581.48	3301380.00	0.00	447898998.87	47690665.76	316396657.64	147601375.9
9	58816042.94	11232598.41	3350900.70	0.00	379348217.51	47690665.76	258258009.71	109526606.8
10	47939766.47	9943129.01	3301380.00	0.00	325915134.05	47690665.76	217040192.81	83678389.87
11	51667977.35	8780887.11	2722460.00	116424262.85	328289036.04	22704377.4	358837597.03	125770388.7
12	43586932.66	7770695.91	2763296.90	0.00	281124407.29		227003481.83	72330305.04
13	35844183.63	6877063.19	2722460.00	0.00	243684163.97		198240457.15	57423199.06
14	31279479.05	6082782.84	2722460.00	0.00	206468203.32		166383481.42	43813970.86
15	26822543.42	5377728.45	2763296.90	0.00	172998446.09		138034877.32	33044452.17
16	21634795.43	2147930.78	2722460.00	0.00	147082636.62		120577450.42	26241166.33
17	18252789.59	4206190.58	2722460.00	0.00	120482207.04		95300766.88	18854748.67
18	15017060.66	3705469.45	2763296.90	0.00	96856145.14		75370318.14	13556014.21
19	11725323.49	3287119.20	2722460.00	0.00	79713787.88		61978885.19	10134042.99
20	9073163.49	2904182.91	2722460.00	63693139.33	59889736.69		108883069.62	16184774.5
∑	1265265995.86	243081312.76	65158200.40	507839571.01	8297608346.61	876245036.16		3659714462
						Initial Cash Flow |	815776000	
						NPV [$]	2843938462	2.843938462

MED RH296 Econs 2% Int | OPT RH296 Econs 2% Int | CLEAN RH296 Econs 2% Int ...

J.4 Economic analysis of the pessimistic degraded RH296 fleet, 2% loan interest rate

10% Discount Rate (d)	0.1
Engine Capital Cost $/Kw	689
Initial Cash Flow (F_0)$	815776000
Conversion	1000
Number of Gas Turbines	4
PO @DP (MW)	296

End of year (t)	O&M cost	Emission tax	Staff Salaries	GT Divestment Sales	Revenue from sold electricity	Annual Loan repayment	F_t (annual net cash flow) (£)	Present value (10% discount rate) (£) $F_t/(1+d)^t$
1	159985223.76	29465533.07	4459220		1112760897		918850920.56	835319018.7
2	150314298.74	26172120.19	4459220.00		948282030.54	196000353.5	571336038.09	472178543.9
3	145140195.40	23204467.44	4526108.30	0.00	807050174.75	196000353.5	438179050.08	329210405.8
4	112666566.71	20574380.81	3880300.00	167460515.35	753485737.96	90959097.29	692865908.50	473236738.3
5	99681705.07	18228852.69	3880300.00	0.00	641647988.44	90959097.29	428898033.39	266311934.4
6	91404392.60	16170516.87	3938504.50	0.00	541339202.17	90959097.29	338866690.92	191281412.8
7	78189789.01	14315539.74	3301380.00	137062991.37	522913696.51	47690665.76	516479313.37	265035552.6
8	70724068.53	12696638.11	3301380.00	0.00	444664738.59	47690665.76	310251986.19	144734841.3
9	62949460.69	11229708.57	3350900.70	0.00	374877692.44	47690665.76	249656956.72	105878920.8
10	48541858.58	9948652.54	3301380.00	0.00	324635774.43	47690665.76	215153217.55	82950879.22
11	56056153.09	8801770.58	2722460.00	104474651.12	326739229.36	22704377.4	340929119.42	119493576.5
12	47772220.74	7768573.97	2763296.90	0.00	278643879.72		220339788.10	70207046.86
13	36311637.30	6877063.19	2722460.00	0.00	242843122.21		196931961.72	57044174.54
14	31811621.89	6081002.46	2722460.00	0.00	205176707.84		164561623.49	43334218.72
15	28698175.23	5376411.98	2763296.90	0.00	170903858.29		134065974.18	32094328.31
16	21890550.63	2147930.78	2722460.00	0.00	146398511.79		119637570.38	26036621.05
17	18481327.43	4205422.09	2722460.00	0.00	119199767.08		93790557.56	18555961.81
18	15550186.89	3707128.68	2763296.90	0.00	92604735.85		70584123.38	12695175.02
19	11802230.40	3287119.20	2722460.00	0.00	78930356.56		61118546.96	9993370.815
20	9184636.42	2903926.96	2722460.00	51289388.41	59238521.99		95716887.02	14227705.35
Σ	1297156299.13	233162759.93	65745804.20	460287546.25	8192336623.93	878345039.33		3569820427
						Initial Cash Flow |	815776000	
						NPV [$]	2754044427	2.754044427

PES RH296 Econs 2% Int | MED RH296 Econs 2% Int | OPT RH296 Econs 2% Int