CRANFIELD UNIVERSITY

GALI HARUNA MUSA

TECHNO-ECONOMIC ANALYSIS OF GAS TURBINE COMPRESSOR FOULING AND WASHING

SCHOOL OF AEROSPACE, TRANSPORT AND MANUFACTURING
PhD Aerospace

PhD
Academic Year: 2015- 2019

Supervisor: Dr Uyioghosa Igie
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Gas turbine engines ingest large quantities of air from the surrounding atmosphere that often contains contaminants of different concentrations depending on the type of environment, atmospheric condition, seasonal changes, and wind direction. Deposition of contaminants and build-up on the compressor blades lead to compressor fouling. On-line and off-line compressor washing have been shown to relatively improve engine performance by decelerating or eliminating (in the case of off-line) the rate of engine degradation due to fouling during operation. There are a number of influencing parameters that determine the economic benefits of washing, some of which include the frequency of washing, effectiveness of washing liquid, and the power output produced.

This research explores the cost-benefit analysis for on-line washing from 72hrs to 480hrs frequency, focusing on the viability of compressor washing for various gas turbine engines or rated capacities, ranging from a 5MW single machine to a 300MW unit. Fouling degradation trends obtained from actual machine operation have been implemented in this study. The application of different washing frequencies and time-based recoveries of lost power shows a significantly higher return on investment for the larger engines in comparison to the smaller engines. This is partly because the washing equipment cost, though increases with engine size, does not increase proportionally. Some of the key aspects captured in this study are the capital and maintenance costs used for washing, relating to the different engine sizes, thus ensuring a more indicative basis for comparing the viability of the different engines. This also includes the estimation of washing liquids utilized based on their respective typical mass flows.

The study also presents an economic benefit for off-line washing from 720hrs to 4320hrs, focusing on costs that are related with off-line washing, specific cost of energy produced and net profit after deducting washing cost for different engines, related to their rated capacity. The result shows that at higher losses, off-line or on-line washing should be directly proportional to deposition or rate of degradation, and as the degradation rate increases, off-line or on-line washing is more frequent. However, when the degradation rate decreases, off-line or on-line washing should be less frequent. When off-line and on-line washing at different combinations are incorporated, the study shows that adopting the least possible off-line washing case combined with a fair amount of on-line washing case of 36 times a year provides higher net profit after deducting washing cost compared to other washing combinations.

The study also presents an optimization method for on-line and off-line washing capable of evaluating compressor washing performance and economics using non-dominated sorting genetic algorithms approach. The result shows an optimum on-line washing frequency ranging from 90hrs to 110hrs for all the engine sizes at 7.2% power drop except for light-duty engine that was found to be not viable.

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LIST OF PUBLICATIONS

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AP_w	Additional profit due to washing
B_I	Inlet flow angle
$B_{recovery}$	Benefit due to power recovery
B/t	Blade solidity
ΔB	Flow turning angle
$\beta(i,n)$	Capital charge factor at discount rate (i) and at $n\ years$
C_c	Capital cost of gas turbine
C_f	Fuel cost
C_0	Capital cost of the power plant
C_m	Maintenance cost of washing
C_p	Specific heat of gas at constant pressure
C_r	Cost for rinsing
C_w	Total cost of washing
C_{aw}	Washing cost
C_{ep}	Cost of energy production
C_{ff}	fuel cost per annum for fouled engine
C_{fl}	Cost of fluid
CF_P	Pressure correction factor (power)
CF'_P	Fuel flow correction factor using pressure
CF_t	Net cash flow at year t
CF_{T+RH}	Power output correction factor using (temperature + RH)
CF'_{T+RH}	Fuel flow correction factor using (temperature + RH)
C_{fuel}	Cost of fuel per annum
C_{fw}	fuel cost per annum for washed engine
C_{NG}	Fuel cost (natural gas)
CO_2	Carbon dioxide
COE_f	Cost of electricity fouled engine
COE_w	Cost of electricity washed engine
$C_{off-line}$	Cost of off-line washing
COF_f	Cost of fuel fouled engine
COF_w	Cost of fuel washed engine
C_{om}	yearly maintenance/operational cost
$C_{O\&M}$	Operation & maintenance cost per annum
$C_{O\&M/GT}$	Fixed and variable O&M cost of GT
C_{pp}	Personnel cost
C_{pw}	Capital cost Washing
D_c	Tip diameter of axial compressor first stage
DH_2O	Demineralized water
E_b	Economic benefit

E_c	Cascade entrainment coefficient
E_l	Economic loss
E_t	Electricity generation at year t
F_e	Fouled energy
ff	Fuel flow
ff_b	Excess fuel burn
FF_{corr}	Corrected fuel flow (standard)
FF_{crcit}	Corrected fuel flow (extended)
F_t	Fuel expenditures at year t
H	Operating hours
i	Discount rate
I_t	Investment expenditures at year t
kW	Specific power output
$\dot{m}$ or $\dot{m}_a$	Mass flow rate
m_f or $\dot{m}_f$	Fuel flow
m_{fcorr}	Corrected fuel flow
m_{fuel}	Fuel flow
M_t	Operation & Maintenance expenditures at year t
MW_{actual}	Design point value
$MW_{expected}$	Corrected new and clean (3 – 5% higher than the output)
n	Lifetime for the investment.
N_{corr}	Corrected speed
nCriteria	Number of criteria
NP_{ad}	Net profit after deducting washing cost
NP_{fe}	Net profit fouled engine
NP_{we}	Net profit washed engine
nVars	Number of decision variable
P_1	Compressor inlet pressure
P_2	Compressor outlet pressure
P_3	Turbine inlet pressure
P_4	Exhaust pressure
P_{amb}	Ambient pressure
P_{CIP}	Pressure correction factor (fuel flow)
P_{clean}	Clean power
P_{corr}	Corrected power output (standard)
P_{crcit}	Corrected power output (extended)
Pd	Frequency
P_{fl}	Power at full load
P_{fouled}	Fouled power
P_{inlet}	Inlet pressure (compressor)
P_{loss}	Yearly power loss cost

P_{std}	Pressure at ISO
P_m	Mutation probability
PO_A	Actual power output
PR_{corr}	Corrected pressure
$P_{\Delta T}$	Energy produced
P_{washed}	Washed power
R_f	income from selling electricity by fouled engine
r_h	Hub/tip ratio for the first stage
$R_{P.lost}$	Recovery of loss power
R_w	income from selling electricity by washed engine
SV_0	salvage value
t	Time for cash flow
T_1	Compressor inlet temperature
T_2	Compressor outlet temperature
T_3	Turbine entry temperature
T_4	Exhaust gas temperature
T_a	Ambient temperature
TC_{aw}	Total cost associated with washing
T_{CIT}	Temperature inlet temperature applicable to temperature
$T_{corr(EGT)}$	Corrected exhaust gas temperature
T_{inlet}	Inlet temperature (compressor)
T_{std}	Temperature at ISO
$TP_{\Delta T}$	Total profit
ΔT^*_{stage}	Average total temperature rise/stage
$\dot{W}$	Plant rating
W_{corr}	Corrected mass flow
W_e	Washed energy
$WEP_{\Delta T}$	Washed energy produced
W_{fl}	Washed fluid
$W_{fuelactive}$	Actual fuel flow
$W_{fuelcorr}$	Corrected fuel flow (extended)
ΔE	change in energy
δG	Mass flow
$\eta_{isentropic}$	Isentropic efficiency
ΔP	Pressure Drop
ΔP_{cc}	Pressure loss
η_T	Turbine efficiency
$\eta_{thermal}$	Thermal efficiency
$\Delta\pi$	Pressure ratio
$\delta\eta$	Compressor efficiency
γ	Gamma

LIST OF ABBREVIATIONS

ALR	Annual loan replacement
ANCF	Annual net cash flow
AOP	Annual operation profits
AS	Annual savings
ASCII	American Standard Code for Information Interchange
AT	Annual tax
B	Blade chord
BESP	Break-even selling price
BTU	British thermal units
C	capital cost of equipment
CDP	Compressor discharge pressure
CDT	Compressor discharge temperature
CFD	Computational fluid dynamics
CIP	Compressor inlet pressure
CoE	Cost of electricity
DPB	dynamic payback
E	Emission
EGT	Exhaust gas temperature
EOH	Equivalent operating hour
EPA	Efficiency particulate air filter
ES	Electricity sold
ETR	Emission tax rate
GA	Genetic Algorithms
GG	Gas generator
GT	Gas turbine
GTW	Gas Turbine world
HEPA	High efficiency particulate air filter
HR	Heat recovery
HRSG	Heat recovery steam generator
IGVs	Inlet guide vane
IRR	Internal rate of return
ISF	Index of sensitivity to fouling
ISO	International Organisation for Standardisation
LCC	Life cycle cost
LCOE	Levelised cost of electricity
LHV	Lower heating value
MP	Market price
N	life expectancy of the equipment
NPADWC	Net profit after deducting washing cost
NPV	Net present value
NRD	Non-recoverable degradation

NRPD	Non-recoverable performance degradation
O&MCWE	O&M cost of the washing equipment
OEM	Original equipment manufacturer
PPM	Parts per Million
PPM	Part per million
PWF	Present worth factor
RD	Recoverable degradation
RoI	Return on Investment
RPD	Recoverable performance degradation
SCEP	Specific cost of energy production
SPB	Simple pay back
Stk	Stokes number
STPP	Steam Turbine Power Plant
STPP	steam turbine power plant
T	Blade pitch
TET	Turbine entry temperature
TI	Taxable income
TIT	Turbine inlet temperature
TR	Tax rate
ULPA	Ultra-low penetration air filter
VIGV	Variable inlet guide vane
W	Mass flow

1 INTRODUCTION

1.1 Background

Gas Turbine (GT) engine produces a large amount of energy which depends on the size of the engine. Due to its small size and weight, the GT has become an appreciated machine for power generation, industrial and marine applications. In the last two decades, the use of GT in power generation and industrial applications has developed extensively; this is due to higher operating efficiencies, and reduced emission to the environment.

The GT engine consumes a large amount of air that contains a variety of contaminants to the GT system and needs to be clean to avoid damage to the turbine. Though dust and water are present everywhere, the quantities of these contaminants vary depending on the location. However, the air contains particles that stick to the components in the engines gas path. Inlet filtration systems are designed to remove particulates, but small particles usually escape and deposit on the compressor airfoils. The adhesion of the ingested particles on the compressor airfoils that mixed with oil mists reduces the compressor efficiency, flow capacity, power output and the thermal efficiency of the engine [1]. This reduces the overall performance of the engine [2–4]. The most common performance deterioration is due to compressor fouling, this causes an increase in tip clearance, changes blade geometry and changes airfoils surface quality [5]. According to Scheper et al. [6], about 70 – 85% of the overall performance losses during the life service of a gas turbine are due to compressor fouling. Its effect is very significant and has a direct impact on operating costs. Compressor fouling [5] can be characterized as “recoverable” and can be controlled by means of light maintenance practices such as washing. This makes it essential for periodic washing of the compressor. An appropriate air filtration system can also control fouling. The development of more efficient inlet air filters has been very successful. However, no filter is hundred per cent effective and fouling will build up despite an effective inlet filter as stated by Hamed et al. [7].

Inlet filtration systems protect the engine from ingesting large size particles, sometimes producing a large pressure drop (ΔP). However, the choice of filtration system can only be achieved based on the environmental condition, location of the site and most importantly the economic consideration. The other conventional way of recovery is by compressor washing and suggested measures of compressor cleaning procedure are reduced mass flow of 3% [8,9], reduced overall pressure ratio by 2%, and a reduced power output by 3% [10].

There are three different methods for wet cleaning that are commonly used in practice; these are manual hand washing, on-line washing and off-line washing [11]. Hand cleaning is necessary for a situation of the high accumulation of deposits in which the engine has to be disassembled, cleaned with brushes and detergent; this adds a significant benefit to the engine. As stated by Leusden et al. [12], Abdelrazik and Cheney [13] that highest power recovery is achieved by this method. The most advanced method is an on-line washing in which a liquid is injected into the compressor at base load with VIGVs at 100% open position [8]. Unfortunately, on-line washing cannot remove fouling completely but can only reduce or decelerate it to a degree. However, a high-performance recovery close to the original level can be achieved by off-line washing [14]. Off-line washing is performed at regular periodic intervals that require shutdown and is performed with the starter motor turning the engine [15]. It shows high effectiveness of performance recovery when the two methods are combined together.

1.2 Previous Work

A lot of work in the last 15 years at Cranfield University has been carried out on compressor fouling and washing. This is due to the influence of deterioration on gas turbine performance that reduces profit to the operator. Mustafa [16] analysed the water droplet trajectories in an axial compressor of a gas turbine. Mund [17] analysed the water droplet distribution in front of the IGV area of an industrial gas turbine compressor. Vigueras Zuniga [18] works on cost-benefit analysis of compressor on-line washing in a power plant. Vigueras Zuniga used a test rig to study the effect of fouling in the blade aerodynamics. The work presents a model of the fouling mechanism and the estimation of compressor on-line washing. The model for fouling was produced based on the experiment and CFD results and was used to calculate the engine performance using TURBOMATCH software. The results of the engine simulation showed that engine efficiency decreased in a period of 5 days by 3.5%. The recovery of the engine power was calculated with TURBOMATCH based on an economic scenario of a gas turbine operation for four years in a Power Plant. The study shows that on-line compressor washing is an economic solution to recover the power lost due to fouling. The power recovered for an engine of 240 MW in four years is equivalent to £6.5 million of electricity sale. Fouflias [19] works on experimental and computational analysis of compressor cascades with varying surface roughness (roughness of 63μm, 76μm, 102μm, and 254μm of particles diameter). Igie [20] works on the effect of compressor fouling and the impact of on-line compressor washing for industrial gas turbine engines. Igie investigated the fouling effect and economic evaluation of on-line washing on a heavy duty gas turbine engine of 240 MW and light duty gas turbine of 7.9 MW and assuming a power loss of 3.2% for both engines after 1 year of operation. Igie achieved a 30% recovery of loss power using a cascade experiment. It was observed that the majority of the research conducted on compressor fouling was done experimentally (lab-based experiment) and validating the experimental data by computational fluid dynamics (CFD). This research is purely on existing measured engine data of a power plant.

1.3 Aim and Objectives

1.3.1 Aim

The aim of the research is to investigate the performance of an existing gas turbine engine and assess the economic viability of compressor washing for different engine capacities by applying different washing schemes.

1.3.2 Objectives

- Quantify compressor fouling degradation using machine data taking into account the influence of ambient conditions and power settings.
- Obtain a degradation trend line for the power output from the analysis, to input into the compressor washing economic model for on-line and off-line washing.

- Develop a performance model that accounts for the changes in degradation trend when washing of various frequencies and recovery rates are applied.
- Investigate the economic viability of compressor washing at various wash frequencies and recovery rates from small to large gas turbine engines, also identifying when it becomes economically viable.
- Determine the best combination of crank soak and on-line compressor washing cycles that offer the greatest economic benefit.
- Calculate the break-even selling price of electricity (BESP) for different engine capacities at clean, washed and degraded conditions.
- Determine an optimum frequency for on-line & off-line washing using a multi-objective genetic algorithm (GA).
- Development of a tool (software program) for compressor washing (performance and economics) and compressor washing optimisation (on-line and off-line washing).

1.4 Scope of the Research

The study examines the analysis of gas turbine health/performance using machine-generated engine data. The output of this investigation that includes obtaining a degradation trend for power output as a function of time, serves as the basis (input) for the investigation of the economic analysis.

In the economic study, compressor washing is investigated. The compressor washing model consists of on-line and off-line washing cases or a combination of the two, it also includes optimization for on-line and off-line washing cases. This incorporates different wash frequencies, recovery rates, and accommodates different degradation trends and cost values (capital and recurring).

1.5 Contributions to Knowledge

For the first time, the capital cost of the washing equipment has been obtained as a function of power or capacity of the engine. This ensures that more realistic viability study is possible. This is particularly important given that the increase in the price of the equipment is not proportional to the increase in the size of the equipment.

- This relates the amount of liquid (washed fluid consumption) as a function based on the individual mass flow which has not been done previously.
- This study shows higher RoI with more advantage for heavy-duty engine compared to a light-duty engine all across the range from low to high. It is more economically viable to implement on-line compressor washing for larger engines than for smaller engines. At a lower level of deterioration, the viability begins to shifts toward a negative direction and this could reach unviable zone. However, at a higher level of deterioration, the viability shift toward a positive direction and that basically improves the RoI.
- The viability of applying compressor washing for different engine capacity has been identified. This considers the respective BESP for individual capacity and shows that with these prices the heavy-duty engines are more favourable economically in terms of RoI compared to the smaller engines.
- A method for finding an optimal frequency of on-line washing using non-dominated sorting genetic algorithm for different engine capacities has been identified. This shows an optimum on-line washing frequency ranges from 90hrs to 110hrs for all the engine sizes except for light-duty engine that was found to be not viable.
- The cost-benefit analysis shows that the least net profit has the least frequency of off-line wash and the least frequency of on-line wash. However, the best combination shown is with a most frequent off-line wash with a frequency of not most frequent (240hrs) on-line wash. The reason for this is that more frequent off-line wash does not bring about great improvement at the beginning of operation as a result of the effectiveness of on-line washing.

The other achievements include;

- The study relates the effectiveness of washing as a function of frequency which was obtained from the actual machine data.

- The optimal off-line washing frequency tends towards more frequent off-line washing in comparison to on-line washing case which also tends to more frequent washing.

1.6 Thesis Structure

The thesis is structured into seven chapters with the key work in chapter 3, 4, 5 and 6. The details of each chapter are outlined below.

Chapter One includes the background of the study, previous work carried out in the area, aim and objectives, scope of the research, contributions to knowledge, and lastly thesis structure.

Chapter Two presents the literature of previous studies that include forms and mechanisms of degradation, recoverable and non- recoverable performance degradation, causes of degradation rate and degradation effects on the gas turbine engine. The study also explores in detail the use and procedure of on-line compressor washing, off-line compressor washing and filtration system. Some case studies of different power plants have also been highlighted.

Chapter Three presents an approach of the research structure and the methods used for the implementation of the research work. This includes data correction, engine evaluation, and performance and economic models for on-line and off-line washing. The work also presents methods for on-line and off-line washing optimization.

Chapter Four involves engine evaluation and economic analysis of GT on-line compressor washing. The study presents the economic cost of compressor fouling and economic benefit of washing for different engines, related to their rated capacities ranging from a 5MW single machine to a 300MW unit. The study also investigates the cost-benefit analysis for on-line washing from 72hrs to 480hrs frequency, focusing on the viability of compressor washing for various gas turbine engines. The work also presents the LCOE for different engine capacities from heavy-to light-duty engines.

Chapter Five presents an economic analysis of GT off-line compressor washing from 720hrs to the 4320hrs frequency and a combination of the two methods (on-line and off-line). The work also presents the economic benefit, economic losses, cost related with washing (off-line and on-line), specific cost of energy produced, additional profit due to washing and net profit after deducting washing cost for different engines, related to their rated capacity.

Chapter Six involves compressor washing optimization. The study presents an optimization method capable of evaluating compressor washing performance and economics, for different engine capacities using a non-dominated sorting genetic algorithms approach/method.

Chapter Seven presents a summary of the thesis work and recommendation of further work.

2 GAS TURBINE PERFORMANCE DEGRADATION

This chapter provides a background and summary of the research analysis carried out by different authors in the field of compressor fouling, compressor washing and filtration systems. This also includes different power plant engine performance evaluation and investigation.

2.1 Introduction

Any prime mover exhibits natural effects of wear and tear over time. Each component part of a GT may show wear and tear over the lifetime of the system, and consequently affect the overall operation. Compressor, gas generator, turbine, and power turbine are aerodynamic components that operate in an environment that degrade their performance over time. Degradation is a process of a loss of the relevant properties of materials that proceeds gradually due to exposure to in-service conditions [21]. It is important to understand the mechanisms that cause degradation, and the effects that the degradation of certain components cause for the overalls system [22]. Losses in GT can be considered as any phenomenon that causes shaft power and efficiency to decrease with respect to design conditions [23].

2.2 Performance Deterioration of a GT

Performance deterioration of a GT can be considered as recoverable and non-recoverable. Gas turbines deteriorate mainly due to the amount of contaminants that enter the turbine, and pass through the inlet air filters, ducts, plus fuel, water from evaporative coolers and engine water washing. Unusual site conditions can really accelerate the GT degradation, such airborne contaminants are oil, smoke, dust storms, chemical releases, and sugar canes burning have been documented to hasten engine degradation.

2.2.1 Recoverable Performance Degradation (RPD)

Most of degradation can be recoverable; RPD is the deterioration in a GT performance that can be recovered by a compressor washing. However, Kurz and Brun [22] states that a substantial amount of degradation can be recovered by resetting variable geometry [22]. RPD is mainly occurs due to fouling, in which airborne particles contaminate with the incoming air, and combined with oil vapour that act as glue, that changes the aerodynamic profile of the blade and annulus dimension.

Deposition of contaminants and build-up on the compressor blades lead to compressor fouling. The effects of fouling on compressor blades and overall engine performance are well known. Studies such as Suder et al.[24], Gbadebo et al. [25], Morini et al. [26] and Igie et al. [27] show the impact on the compressor blade aerodynamics. These includes higher exit flow angles and early flow separation, higher total pressure loss coefficient, increase in drag due to increased friction caused by increased surface roughness and changes in shape of the airfoils as shown in Figure 2-1, the rise in the flow passage velocity due to a reduction in the flow passage area and an increase in blockage.

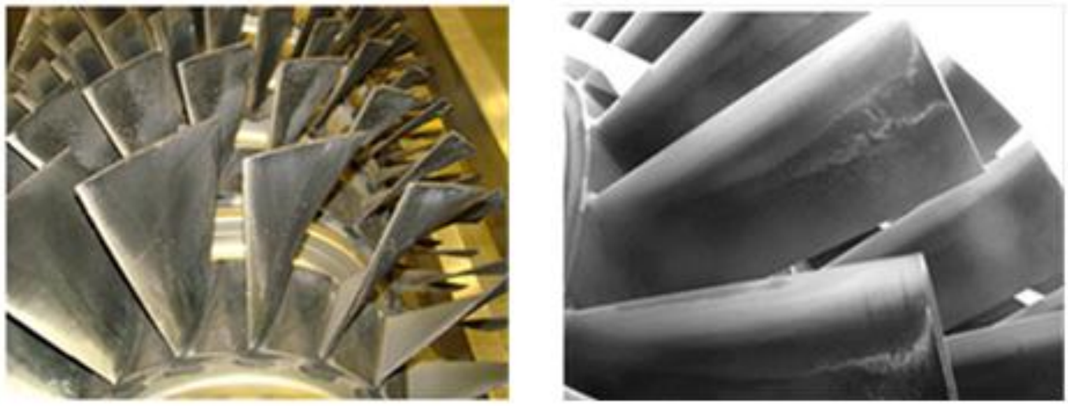


Figure 2-1 Salt deposits on compressor blades of about 18,000hrs of operation (left**) and compressor rotor (**right**)** [28]

Figure 2-2 Oil deposits on axial compressor blades [29]

The overall implications of these local changes on the stage are also propagated to subsequent stages in the compressor; the effects being a reduction in air mass flow, pressure ratio and compressor efficiency that causes a reduction in the power output. Meher-Homji et al. [29] also address the causes and effects of compressor fouling on GT performance, and proposed design parameters influencing the susceptibility and sensitivity to fouling. Compressor fouling is the main mechanism leading to performance deterioration in GTs over time. Kurz and Brun [28] defined fouling as the degradation caused by the adherence of particles to air foils and annulus surfaces. Kurz et al. [28] and Boyce et al. [11] states particles that cause fouling, are typically smaller than 0.2 to 10 μm. Though, small concentrations of foreign particles can accumulate to several tons of contaminants, that are ingested by the GT during the operating time between two major inspections [7].

The Gas turbine compressor consumes the highest turbine power. According to Boyce and Gonzales [11] the power consumption of a compressor amounts to about 60% - 65% of the turbine power. Hence, a small compressor efficiency change will have a major effect on the overall performance of the GT engine. With a decrease in efficiency, flow capacity, pressure ratio and stall margin; the power output is limited at constant TET. Figure 2-3 (left) shows the effect of mass flow, pressure ratio and surge line on the compressor map. Fouling can be partially controlled by an appropriate inlet air filtration system and compressor cleaning as stated earlier. The use of compressor washing can restore the performance of the fouled compressor with small degradation non-recoverable shown in Figure 2-3 (right). Fouling can be recovered by either off-line or on-line washing. Figure 2-4 shows the impact of compressor washing on efficiency. The 1st curve represents degradation rate with no washing at all, the 2nd curve represents degradation rate with only on-line washing, while the last curve has smaller slope that indicates a lower degradation rate due to performance combination of on-line and off-line washing. The figure illustrates a recoverable loss due to on-line and off-line washing that shows higher recovery at crank wash. However, higher recovery is achieved by hand cleaning due to hot section overhaul.

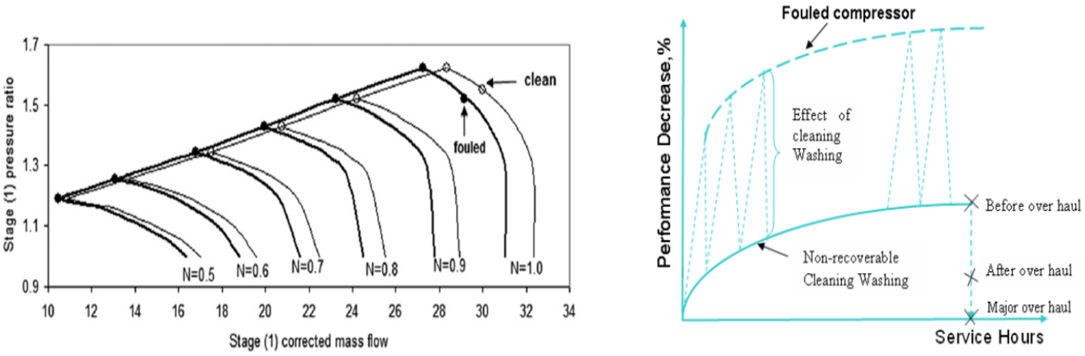


Figure 2-3 Effects of fouling (left**) and performance deterioration of GT (**right**)** [20,30]

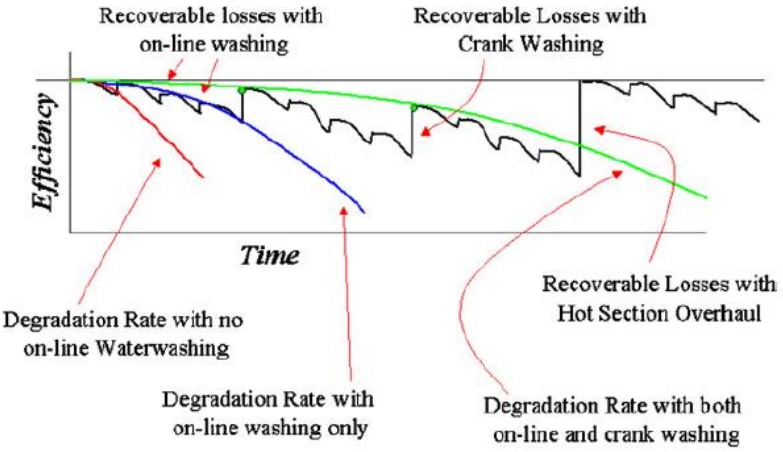


Figure 2-4 Impact of compressor washing on GT engine [31]

2.2.2 Non-Recoverable Performance Degradation (NRPD)

Non-recoverable performance degradation (NRPD) is the performance deterioration of a GT caused by internal engine component wear and tear. It is mainly occurs due to erosion, corrosion, foreign object damage, and hot end component damage. It can only be recovered by engine overhaul and shop inspection. Very few publications indicated the rate of degradation on GTs, and most of the published papers indicated the initial degradation on a new engine is more rapid than the degradation after several thousand hours of operation. This depends on the different performance test practices of different manufacturers. If the engine is subjected to a hot restart as part of the factory test process (the engine is shut down and restarted immediately which causes the largest clearances. During the later operation of the engine, the clearance will not be up to the first) and the performance data will reflect the clearance that will likely not worsen as later engine operation. This shows early sharp drop in degradation may be reduced. Another feature that slows degradation is the effort to thermally match stationary and rotating parts of the engine.

Veer et al. [32], indicated that both RD and NRD follow a logarithmic pattern. The NRD indicated a loss of power output of about 3.5% in the first 5000 EOH, followed by an additional of 0.5% for the next 5000 EOH. Though, this may not be applicable for other applications. The degradation mechanisms for aero and industrial engines are totally different. Aero-engines operate with no filtration system, and erosion is a key contributor, while Industrial engines operate with an advantage of an installed filtration system, and are subjected to fouling by small particles.

Kurz and Brun [22] defined hot corrosion as the loss of material from flow path components, caused by chemical reactions between the components such as mineral acids, salts and or reactive gases (Figure 2-5 left). Many oil and gas GT’s are placed near sea; sodium chloride (NaCl) is a potential offender. Cold engine parts are attacked by NaCl while hot engine parts can be attacked by sodium sulfate. GT materials in this environment need to be protected by coating, and it is the coating integrity that limits the lifetime of the components [22]. Figure 2-5 (right) is an example of corrosion on compressor blade. Typical particles size that causes erosion are greater than that of fouling with a value larger than 10 μm in diameter [22]. Erosion is the abrasive removal of material from the flow path by hard or incompressible particles impinging on the flow surfaces [22].

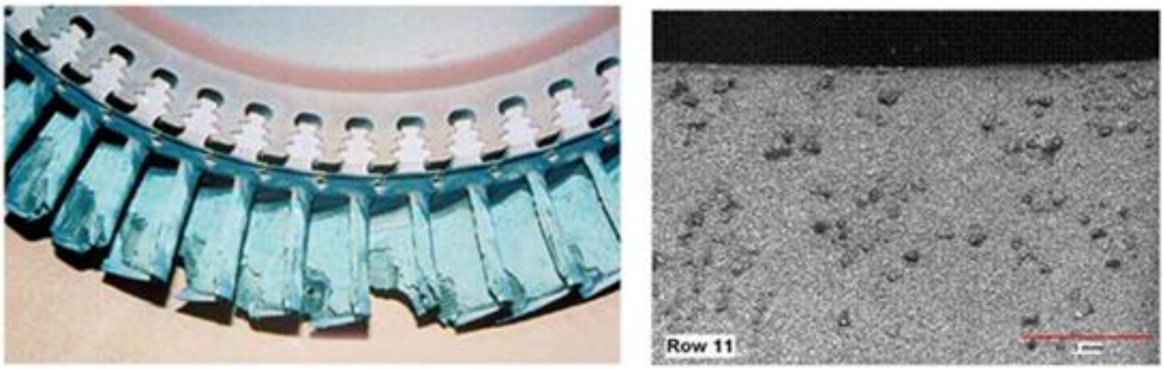


Figure 2-5 Hot corrosion on a turbine rotor [22] **(**left**) and corroded turbine blade** [33] **(**right**)**

Figure 2-6 Leading edge erosion

2.3 Causes of Compressor Fouling

Several studies in the past indicated that axial compressors will foul in most operating environments, such as rural, marine and industrial. The following are the causes of compressor fouling:

- Ingestion of gas turbine exhaust.
- Industrial pollution.
- Mineral deposits such as limestone and cement dust.
- Airborne salt.
- Airborne minerals such as soil, dust and plant matter.
- Insect causes a serious problem in tropical environments.
- Vapour plumes from adjacent tower.
- Internal gas turbine oil leaks
- Impure water from evaporative coolers.

Ambient air can contaminate solids, liquids, and gases. Particles up to $10\mu m$ cause fouling while above $10\ \mu m - 20\ \mu m$ cause erosion. Typical air loadings are as follows [34]:

- Desert 0.1 to 700 ppm by weight.
- Industrial 0.1 to 10 ppm by weight.
- Coastal 0.01 to 0.1 ppm by weight.
- Countryside 0.01 to 0.1 ppm by weight.

Felix and Strittmatter [35] reports about type of study to be carried out at a GT plant site in order to identify the causes of compressor fouling. The authors state that air quality of an industrial area may create acidic conditions in the axial compressor, such contributors are rain showers and relative humidity. Several operators identified a sharp drop in GT output due to rain showers. Due to high humidity, the air filters will exhibit a rapid growth in ΔP as the filters become saturated with water. This problem may cause a speedy compressor fouling.

Seddigh and Saravanumuttoo [36] studied the susceptibility of compressor fouling on different types of GT. The same study has also been done by Aker and Saravanumuttoo [37] which provided results pertaining to fouling based on stage stacking procedures. More recent findings by Tarabrin et al. [36],[37] shows that several beliefs are taken in the GT professional community, regarding compressor fouling and washing, based on findings at one site that generalized to global application. It causes a lot of argument such as choice of cleaning fluids, frequency of washing and effectiveness of online water washing. In marine and offshore environment, the relative humidity was found to be high. This is due to the wet form of the salt. Tatge et al. [40] states that salt will stay as supersaturated droplet except when the relative humidity drops below 45%.

2.4 Degradation of Components

2.4.1 Gas Turbine Compressor Section

Fouling and erosion generate an increased surface roughness of the blade. An increased in roughness may increase the friction losses. Kind et al. [41] investigated the change of turbine blade performance, which fellows alterations of the blade geometry due to fouling, erosion and corrosion. The deterioration of the turbine blades results in changes of exit angles and increased losses. Schmidt [42] reports the effect of a deliberate reduction of the chord length in a power turbine nozzle that reduced the work output of the turbine.

Clearances occur between stationary and rotating parts, which normally open up due to ageing of the equipment. The effect results in higher leakage flows, which reduces head capacity and efficiency of the components. Khalid et al. [43] reports that an increase of the rotor tip clearance from 1% to 3.5% of blade chord, reduces the pressure ratio of the stage by up to 15%.

Millsaps et al. [44] reports in their simulation of a fouled 3-stage axial compressor that the fouled first stage compressor has higher impact on the overall performance than the fouled later stages. Syverud et al. [45] performed tests on a GT, and spraying salt water at the inlet of the engine. It was observed that, a deposits causes increased surface roughness on the compressor airfoils. The majority of the deposits occur on the first stage, and become ineffective after the fourth compressor stage. Compressor condition couldn’t be separated from the turbine section of the engine due to turbine flow capacity that determines the operating point of the engine. Graf et al. [46] reports that an increased clearance of an axial compressor causes a reduced surge margin and compressor efficiency. A clearance was increased from about 2.9% to 4.3% and that caused an increase surge flow coefficient of about 20%, reduction in design pressure coefficient of 12%, and a loss of design point efficiency of 2.5%.

2.4.2 Combustion System Section

The combustion system is an indirect cause for performance deterioration. However, the combustion efficiency will only decrease in rear cases of combustor distress.

2.4.3 Turbine Section

Radtke and Dibelius [47] states that, a reduction in efficiency of a multi-stage turbine by 0.6% causes an increase in radial clearance from 0.5% of the blade height at the rotors, and 0.4% at the blade height at the stators to 0.8% of the blade height at both rotors and stators. According to Boyle [48] for a two-stage turbine, efficiency losses of 2.5% for a 10.2 μm surface roughness when compared with smooth blades. It is interesting to note that losses due to clearances were in the same order of magnitude as the profile losses.

2.5 Engine Degradation Type

Degradation of engine components has a serious effect on the engine performance due to change in component performance characteristics, which lead to mismatch of the components on the engine level. One point worth mentioning is the impact of the individual component degradation that is influenced by the control system and the control mode of the engine. Both the single shaft engines operating at constant speed and two-shaft engines that depend on the control mode show different degradation behaviour. Compressor degradation will impact flow capacity, efficiency, and pressure ratio. For a better understanding of the behaviour of the engine, the authors separate effects that occur together.

2.5.1 Case 1: Impact of compressor efficiency reduction on GT engine

The authors consider the case (1) of compressor efficiency reduction due to compressor fouling in a GT engine. Compressor degradation produces different results for both single and two-shaft engines. The single shaft machine operates at fixed (constant) speed, with a combination of turbine-choked nozzles. Loss of compressor efficiency will affect the pressure ratio to a very limited degree and the flow through the machine as shown in Figure 2-7. Two-shaft engines with reduced compressor efficiency will result in substantial changes in flow and pressure ratio. Syverud et al.[45] and Millsaps [44] observed a reduction in flow which shows the same finding as Spakovszky et al. [49].

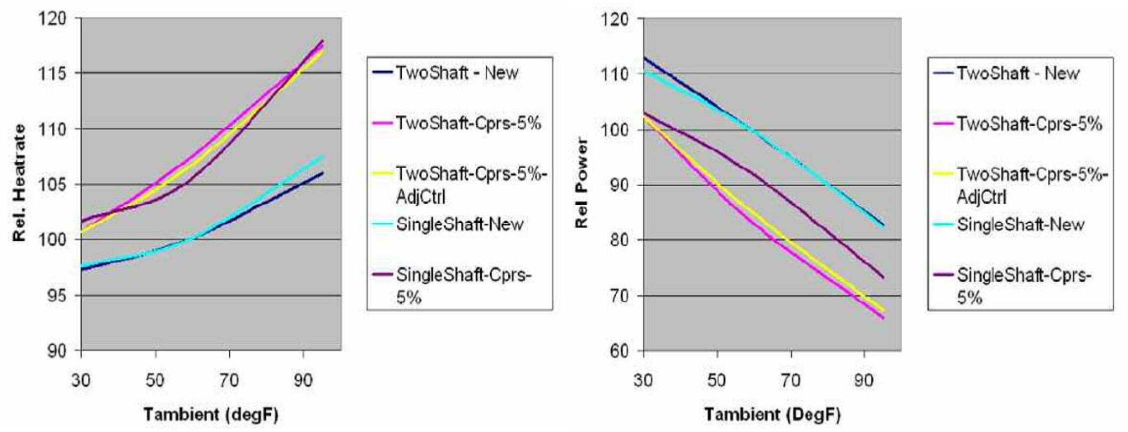


Figure 2-7 Effect of loss of compressor efficiency due to degradation on GT heat rate (left**) and power output (**right**)** [22]

The pressure ratio flow relationship of the compressor remains unchanged and with the engine running faster and the compressor consuming more power once it deteriorates. The power output for two-shaft engine is more susceptible to the effects of degradation, while the heat rates for both single and two-shaft engines are affected equally.

2.5.2 Case 2: Impact of flow capacity reduction on GT engine

The authors consider the case (2) of an engine with reduced compressor flow capacity due to reduced clearances. Using the same level of compressor blockage produces more power degradation in a two-shaft engine than in a single shaft engine. As stated earlier the effect of degradation for 2-shaft engine depends on the control mode. When the engine operates at T_a below the match temperature, the result will be in speed topping mode, while when the engine operates at T_a above the match temperature, the results will be in turbine entry temperature topping mode. Tarabrin et al. [38] reported that, the effect of degradation is more severe for two-shaft engines than for a single shaft engine. At high ambient temperatures, compressor degradation on the two-shaft engine results in a drop of gas generator speed. If there is presence of variable geometry like adjustable compressor inlet guide vanes (IGVs) as cited by Kurz and Brun [5] the drop in speed can be avoided by readjusting the settings and the effects of compressor degradation of both single and two-shaft engines are closer. Compressor deterioration cause higher power losses than heat rate, this is due to higher compressor exit temperature at a fixed turbine entry temperature that reduces the fuel flow.

Figure 2-8 shows the result of reverse effects of degradation on different engine parameters when the engine was returned to the factory after several thousand hours of operation. Without any adjustments, the initial run of the engine showed that TET was $22\ ℃$ below the design, T_3 and the GG was 3% below the design speed. After adjusting the inlet guide vanes the engine improved its power with a reduced heat rate. The engine continued to improve its performance by detergent washed. Individual stages were adjusted to the factory settings by variable vane. After all engine adjustments, when compared with the factory testing when it was new, the losses in power output and heat rate were 2.5% and 1.2% respectively, which shows that a significant amount of degradation can be reversed and some are non-recoverable due to engine wear and tear.

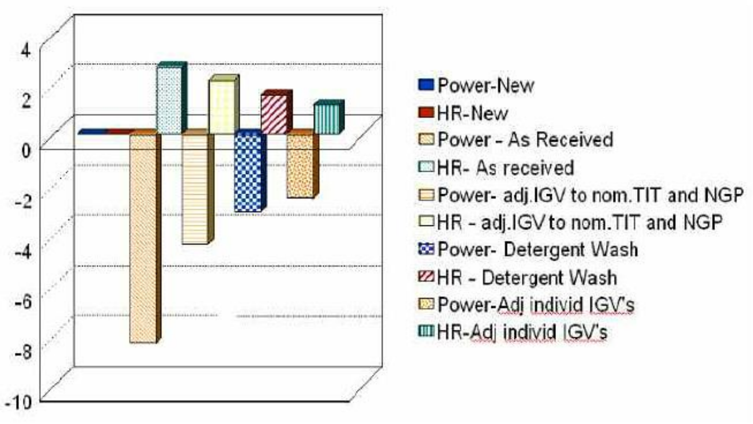


Figure 2-8 Performance recovery by adjusting the IGVs, Detergent wash, individual adjustment of IGVs [5]

Tarabrin et al.[38] reports that lighter engines are more susceptible to degradation, and the same study was carried out by Aker and Saravanamuttoo [37] that shows an opposite conclusion with Tarabrin finding.

2.6 Fouling Deterioration Rate in Axial Flow Compressors

Tarabrin et al. [38,39] states that the rate of particle deposition on blades increases with a growing angle of attack, and smaller GT engines are more sensitive to fouling than larger GT engines as stated above. However, an increase in compressor stage head ($C_p \Delta T$) increases the sensitivity to fouling. For a specific compressor design parameters such as pressure ratio, air inlet velocity at the IGV, aerodynamic and geometric characteristics are used to determine the sensitivity to fouling [38,39].

GT Sensitivity to Fouling

The index of sensitivity to fouling (ISF) presents a complex of parameters that are arguments of E and that determine the sensitivity to fouling. The value will reflect qualitatively the sensitivity of the axial compressor to fouling under similar environmental conditions. The index of sensitivity to fouling of axial compressor is available in Tarabrin et al. [38,39] and mathematically can be represented as follows:

$$\mathrm{ISF} = \frac{\dot{m} C_p \Delta T_{stage}}{(1 - r_h^2) D_c^3} \times 10^{-6} \qquad \textbf{(2-1)}$$

Tarabrin et al. [38,39] states that assuming an engines operating on similar environmental conditions, with the same level and quality of air filtration system, the GT engines with higher ISF values have a greater reduction in pressure ratio, airflow and efficiency than the engine with lower ISF. The coefficient entrainment is the ratio of number of particles sticking to surface to the number of particles in the flow for one pitch of the cascade. The coefficient of cascade entrainment is available in Tarabrin et al. [38,39] and can be represented as follows:

$$E_c = (0.08855Stk - 0.0055) * (b/t) * \sin(\Delta B/2) / \sin B_I \tag{2-2}$$

An increase in design compressor work/stage, leads to an increase in flow turning angle ΔB and blade solidity of the cascade. Seddigh and Saravanamuttoo [36] proposed a fouling factor that is non-dimensional coefficient which is defined as the ratio of the specific power output of an engine and the enthalpy rise for a stage represented mathematically as follows:

$$Fouling\ Index = kW/\dot{m}\, C_p \Delta T_{stage} \tag{2-3}$$

There finding shows that larger engine units tend to have higher values of fouling index compared with the smaller units. The result for the fouling index are not coincident with that of Tarabrin et al. [38,39].

Fouling Degradation Rate

Fouling follows an exponential law and occurs during the initial operation and stabilizes after 1000 to 2000 operating hours (OH) shown in Figure 2-9. An empirical formula was developed and proposed by Tarabrin et al. [39]:

$$\Delta Power = a[1 - e^{-bt}] \tag{2-4}$$

Where:
a = 0.07, b = 0.005

The influences of fouling are the result of changes in compressor efficiency $(\delta\eta)$, pressure ratio $(\Delta\pi)$, and mass flow (δG), as a function of time [39] and is shown in Figure 2-9.

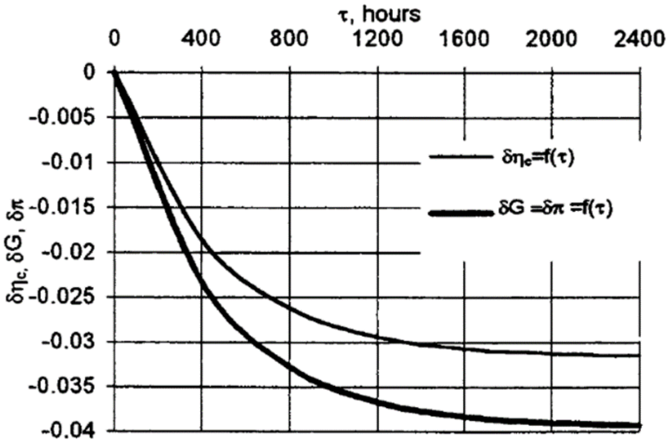


Figure 2-9 Influence of fouling on axial flow compressor as function of time [38]

Location of Fouling in an Axial Compressor

Tarabrin et al. [38] conducted an experimental test that shows stage one to five or six stages of the compressor tend to foul, and the degree of fouling reduces from the front to the back end of the compressor. A typical example of deposits on blades of a sixteen stage compressor of a Frame 5322 is shown in Figure 2-10 (left) for the rotor blades and Figure 2-10 (right) for the stator blades. A very small amount of deposits were noted on the seventh to sixteen stages.

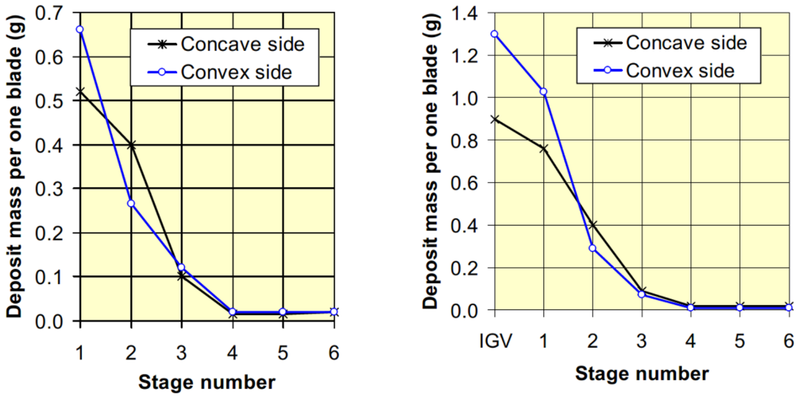


Figure 2-10 Deposits on axial compressor rotor blade of Frame 5 GT (left**) and stator blades of Frame 5 GT (**right**)** [38]

2.7 Detection of Compressor Fouling

Manufacturers of gas turbines normally give guidelines to the operators when fouling deterioration calls for corrective action. This is based on a combination of exhaust gas temperature (EGT) and load. Operators may also monitor compressor efficiency and compressor discharge pressure (CDP). Some operators usually detect fouled compressors by visual inspection. This interprets shutting down the unit, removing the casing or inlet plenum hatch, and inspecting the VIGVs bell mouth and inlet of compressor. This method is very expensive, as it requires shut down of the engine. However, the following factors can also be a guide for indicators of fouling [34]:

- Reduction in pressure ratio and compressor efficiency.
- Reduction in mass flow on a fixed geometry engine.

Boyce and Gonzalez [11] also highlights that deterioration in turbine performance is detected by the following conditions:

- Lower power output
- Engine compressor surge and slower acceleration
- Decrease of engine compressor discharge pressure (CDP)
- Increase in compressor discharge temperature (CDT)

The most sensitive and problematic parameter is the mass flow, and it is essential to detect fouling at the early stage to prevent a significant power drop. Some operators focused on regular washing while others are based on the certain requirement of the performance on the engine parameters. Boyce and Gonzalez [11] states that a site and specific test program should be conducted, in order to optimize the effectiveness of a turbine water wash program.

Power capacity factor is used as a trend in gas turbine output and mathematically can be represented as follows [34]:

$$Power\ Capacity\ Factor = MW_{Actual}/MW_{Expected} \tag{2-5}$$

Corrections should be made to the following parameters: Inlet pressure, inlet temperature, NO_x water injection rates, specific humidity, inlet and outlet pressure drops, and speed corrections.

2.8 Compressor Cleaning

Gas turbine installations contain an inlet air filtration system that may reduce or eliminate contaminants that can affect performance. Axial compressor fouling is unavoidable and depends on environmental conditions of the site, with a high percentage of overall performance loss during operation due to compressor fouling. It can be partially recovered by compressor cleaning. Compressor cleanliness can be maintained using a routine program of water washing either on-line or off-line washing. The on-line is performed with the machine at operating temperature while the off-line is performed in a cooled state using the crank speed.

2.8.1 Compressor On-line Washing

On-line compressor washing is performed during gas turbine base load operation with the VIGVs in 100% [50] open condition. On-line compressor washing as depicted in Figure 2-11 is a method of mitigating the effects of fouling when particles get past the air filter systems into the compressor section. This involves the injection of atomised droplets into the compressor during engine operation, thereby avoiding the need to shut-down. The spray nozzles are usually mounted around the periphery of the bellmouth intake or intake plenum as in the case shown in Figure 2-11. The number of nozzles and placement of the engines depends on the size and the design of the machine respectively.

Figure 2-11 On-line compressor washing set up with nozzle mounted on the intake plenum [Courtesy of R-MC]

Figure 2-12 is the picture of a wash system, consisting of a tank (typically 2 tanks - one contains the detergent and the other contains demineralized water) and pump, amongst other parts/components. On-line compressor wash is most beneficial for engines operating continuously in baseload mode and evidence indicating the benefits of on-line washing from actual engine operations are highlighted in Schneider et al. [50], Igie et al. [51] and Leusden et al. [12].

Comparable to most technology, the viability of on-line washing is essential to its success. Studies on the fouling cost have been briefly highlighted in Diakunchak [23]. Aretakis et al. [52] focus on the optimisation of compressor washing with emphasis on identifying the required number of washings and washing intervals. The study recommends taking into account engine ageing when considering the economics of the power plant since it has a noticeable effect on both total profit and optimum number of washings. Predictions on the total profit and the specific energy cost for an open cycle gas turbine plant for varying degradation rate is demonstrated. In a related study, Hovland and Antoine [53] addresses the scheduling problem of compressor washing by taking into account the maintenance and fuel costs. The study presents the economic benefit for an optimised compressor washing schedule compared to a fixed schedule in a combine cycle plant arrangement. This is based on model predictive control taking into account the future cost of fuel and power price in the context of on-line and off-line compressor washing.

Figure 2-12 Turbotect system for on-line and off-line compressor washing [Courtesy of Turbotect]

Sanchez et al. [54] present a tailored program for the washing schedule that have been developed through a trial and error method which depends on operator’s experience. This work also indicates that the economic benefit of washing can be doubled in terms of cash-flow when the washing schedule is appropriate and applied site specifically. Bromley et al. [55] , Stalder et al. [56], and Demircioglu

[57] report that online compressor cleaning effect is limited to the VIGVs and first few stages of the compressor. On-line compressor washing can only reduce the degree of compressor fouling but it cannot eliminate it completely. Henceforth, it shows high effectiveness of performance recovery when combine with off-line cleaning.

2.8.2 Compressor Off-line Washing

For off-line compressor washing the gas turbine must be shut down and allowed to cool, then run unfired with the motor rotating the engine [15]. Then demineralized water is used to flush the compressor in order to reduce the roughness of the blade, and in some cases detergent is applied. The gas turbine is sped up from 20% - 50% of the nominal speed and allowed to coast to a stop [11]. Other authors stated the minimum rotational speed is in the order of 20% [58–60] to a maximum of 30% [13] of the operational speed. Flushing period is repeated many times. Boyce et al. [11] and Saravanamuttoo et al. [61] states that rinse-cycles should be repeated until the water that pours out of the compressor through the opened blow-off valves does not show any sign of contaminants. Applying the above procedure, the effects of compressor fouling can be removed completely. In order to avoid non-availability of the gas turbine, the compressor off-line washing is recommended at the normal inspection intervals.

2.8.3 Compressor Hand Cleaning

Hand cleaning of the compressor includes cleaning of the VIGVs and the blades of the first compressor row with brushes and detergent. This method is very effective for removing particles on the blade surface, it is time consuming and requires shut down and cooling of the gas turbine engine. It is recommended to combine the hand cleaning with an off-line cleaning since cleaning the compressor by hand may show effectiveness only on the blades of the first compressor row and the VIGVs.

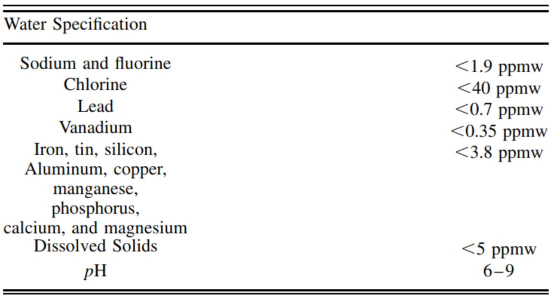
2.8.4 Abrasive Cleaning

Boyce and Gonzalez [11] states that compressor cleaning by use of abrasive materials is suspended in most plants as it causes serious damage to the engine, the erosion effects are high and there is possibility that these non-liquid materials may clog the passages of the secondary air system. According to Boyce and Gonzalez [11] particles may enter the lubrication system, or damage the coating of the compressor blades.

2.9 Wash Fluid

The water quality for on-line and off-line cleaning must satisfy the water specification requirement and guarantee impurities are not introduced. It is very significant to test the quality of water before performing a routine on-line water wash. The cleaning agent used to clean gas turbine engine compressors may be solvent base, water base, industrial cleaners, and demineralized water.

Table 2-1 Typical water specifications for GT washing [11]



Water Specification	
Sodium and fluorine	<1.9 ppmw
Chlorine	<40 ppmw
Lead	<0.7 ppmw
Vanadium	<0.35 ppmw
Iron, tin, silicon, Aluminum, copper, manganese, phosphorus, calcium, and magnesium	<3.8 ppmw
Dissolved Solids	<5 ppmw
*p*H	6–9

2.10 Engine Investigations

In order to analyze the power plant performance and understand the effects of degradation on GT engines and the type of maintenance practice observed, different case studies of power plant were investigated. In some plants, power loss and heat rate increase were highlighted to see how the degradation affects the engine performance and how it was translated into economics. Compressor efficiency performances for some power plants were highlighted and in order to understand the effects of cleaning the GT engine. The following are the power plant investigated;

Priprem et al. [62] investigated compressor performance of a 710 MW combined cycle power plant (CCPP), Namphong, Thailand. The power plant has two blocks; each block comprising of two GT 2*121 MW and one steam turbine 1*113 MW. According to Priprem et al. [62] that a field investigation was set up in order to understand the effects of cleaning duration on compressor efficiency on the GT.

The study involved operating all the four GT at 3000 hours base load condition. Off-line cleaning was conducted as scheduled according to the maintenance scheme of the plant. It is scheduled for each compressor as follows:

Table 2-2 On-line cleaning of each compressor [62]

Block	Compressor no	On-line Cleaning
1	GT-11	None
	GT-12	Every 4 days
2	GT-21	None
	GT-22	Every 12 days

The power plant facility recorded the data and was logged every 3 minutes. Irrelevant data were filtered out and the data were pre-treated by taking the hourly average representative before the analysis processes. The power outputs were corrected according to the correction curves provided by the manufacturer. Figure 2-13 shows the corrected power and the isentropic efficiency graph of unit GT-12, with the other unit following the same pattern.

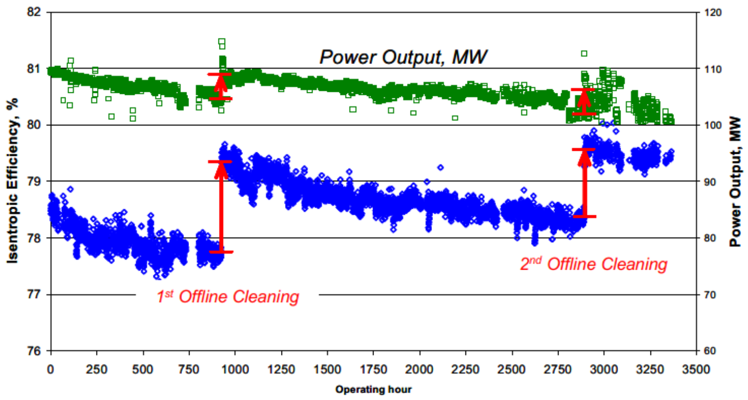


Figure 2-13 corrected power output and compressor efficiency curve [62]

It can be seen that efficiency of each compressor and corrected power output reduced with the operating hour in the same pattern. In both the two blocks the compressors were cleaned twice in 3000 operating hours except unit GT-21 that was mechanically cleaned at the beginning and washed once off-line. It can be observed that compressor efficiencies were recovered by off-line wet cleaning operations. Figure 2-13 shows the power gain after off-line cleaning. The efficiency gain after first off-line cleaning varies from 1.14% - 1.70% while the second one has a gain of 1.07% and 1.22% [62]. The second cleaning gave less efficiency gain compared with the first cleaning shown in Table 2-3**,** this confirmed that off-line cleaning couldn't fully recover the efficiency of a compressor due to wear and tear. Similarly the corrected power gains for the second cleaning were less than the first one.

Table 2-3 Isentropic efficiency gain (left) and corrected power gain (right) [62]

Engine	η_{before} 1^{st}	$\Delta\eta_{gain}$ 1^{st}clean	$\Delta\eta_{gain}$ 2^{nd}clean	$\Delta\eta_{1-2}$	P_{before} 1^{st}	ΔP_{gain} 1^{st}clean	ΔP_{gain} 2^{nd}clean	ΔP_{1-2}
GT-11	79.7	1.27	1.07	0.20	107.7	2.51	2.08	0.43
GT-12	77.7	1.70	1.22	0.48	104.5	3.65	3.13	0.52
GT-21	81.5	1.68	-	-	108.3	4.81	-	-
GT-22	80.0	1.14	-	-	102.4	2.75	-	-
	Avrg	**1.45**	**1.15**	**0.34**	**Avrg**	**3.43**	**2.60**	**0.48**

The author indicated that unit GT-21 that was mechanically cleaned gave remarkably higher gains in both power output and efficiency by 6.53 MW and 2.35% respectively. The values gained from off-line cleaning was 4.81 MW power and 1.70% efficiency that is lower than the values obtained by hand cleaning.

Schneider et al. [50] investigated six GT's operated at base load conditions. The power output and other parameters was corrected accordingly. Three - Alstom GT26 operated at Plant A, are analysed; they are named PA1-GT26, PA2-GT26, and PA3-GT26 and are identical single shaft CCPP units. The other 3 Alstom operated at plant B are GT13E2; they are named PB1-GT13E, PB2-GT13E, and PB3-GT13E in a multi-shaft arrangement. The environmental conditions of Plant A are: industrialized area, maritime conditions and petrochemical industry while for Plant B are: high air humidity, industrialized area, maritime condition and high concentration of particles. On-line washing schedules for about 7 months were investigated for plant A.

Table 2-4 Analysis of schedule compressor washing at plant A

Plant A	Alstom GT26	Compressor Washing
1	PA1	None
2	PA2	Weekly on-line + demineralized water
3	PA3	Daily on-line + demineralized water

Figure 2-14 shows the power output remain relatively constant at the beginning, and then reduce gradually and become stable at lower level. After a certain time a stable degradation level have been reached, this is confirmed by Stalder [63] and Tarabrin et al. [39]. The signs of degradation on the compressor efficiency for all units can be seen after about 6 weeks, and for power output degradation can be seen for PA1-GT26 after about 6 weeks, PA2-GT26 after about 9 weeks and for PA3-GT26 after about 12 weeks.

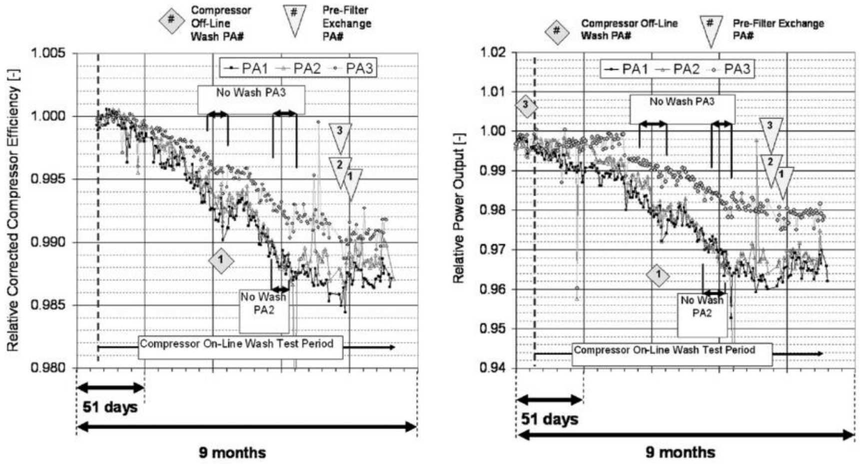


Figure 2-14 Relative corrected compressor efficiency Plant A (left) and relative power output Plant A (right) [50]

As expected, the GT without compressor washing indicates the maximum degradation rate while the GT with a daily compressor washing has the minimum degradation rate. This shows that on-line cleaning retains the power output at upper level for a longer period of time. At the end of the test period, the corrected compressor efficiency degradation was about 1.4%, 1.2% and 1.0% for gas turbine engines PA1-GT26, PA2-GT26 and PA3-GT26 respectively. The actual power output degradations for PA1-GT26, PA2-GT26, and PA3-GT26 were 3.6%, 3.4% and 2.0% respectively. On-line washing schedules for about 6 months were investigated for plant B with different washing fluids.

Table 2-5 Analysis of schedules compressor washing at plant B

Plant B	Alstom GT13E2	Compressor Washing
1	PB1	Twice-a-week on-line + detergent
2	PB2	Daily on-line with demineralized H_2O+weekly detergent
3	PB3	None

At the beginning of the analysis, when comparing the two plants, the compressor efficiency degradation trends observed at plant B progresses quicker without a relatively balanced phase after the off-line washing. As stated by Schneider et al. [50] that compressor fouling is larger at plant B due to highly polluted environment and the degradation trends are different. PB2-GT13E gas turbine has the minimum efficiency degradation rate. PB3-GT13E had the highest power loss of about 4% in 6 weeks and PB2-GT13E lost only 1.5% in 11 weeks. The result shows the usefulness of compressor cleaning with a detergent diminishes over time and daily on-line washing with demineralized water only became more effective.

Boyce and Gonzalez [11] conducted 5 tests on 3 similar GT (identical) next to each other. The aim of the tests was to select the proper solvents to use and to determine the wash frequency that affect performance for baseline operation over a period of one year. The washing was conducted once per week (test 1) on 3 similar GT next to each other using two-different soap + demineralized H_2O and the crank wash was done after 45 hrs of operation. It was observed that washing with water alone was as good as soap solutions [11]. A test 2 was conducted with the aim to find the most efficient soap between solvent base and water base soap with Demineralized water. It was observed, that solvents base were more active at the first week and the efficiency diminishes after some time and reached a point where the plain demineralized water is more effective [11]. The authors [11] conducted a test 3 with the aim to find If there is a better water base soap between different vendors. The results of the analysis showed that all the soaps had exactly the same effects. The aim of the test 4 was to find an optimal frequency to perform the on-line water wash tests. Based on all the tests it shows that washing with water twice a week is most active over time than all other frequencies.

Lastly the two aims of the test 5 were; to find the degradation in compressor efficiency and the total turbine heat rate with and without on-line water wash, while the second was to evaluate the effects of operating a GT for longer hours without an off-line washing. The analysis was performed at 4000 hrs of operation. Turbine 2 washed two times a week with $\mathrm{D.H_2O}$, and Turbine 3 was not washed for the duration of operation. Before the operation, 2-turbines were crank washed with the recommended off-line cleaning agent and efficiency was found to be approximately 81%. At the end of 3000 hrs of operation, turbine 2 had a reduction of 0.2% with an efficiency of 80.8% while turbine 3 had a compressor efficiency of 79.0% with a reduction of approximately 2.5% shown in Figure 2-15. Another washing was applied for turbine 2 with different cleaning agent and efficiency was restored to 82%. At the end of the other 1000 hrs, the turbine was found to be 0.5% less in efficiency. Turbine 3 was also measured and found to be 78.5%.

Leusden et al. [12] evaluated performance data of Siemens V64.3 unit in Obernburg, Germany. The plant is located near a chemical plant, and produces fibres for industrial application. This site condition leads to high level of fouling [12]. Monthly mean for efficiency and power output was calculated by taking the average measured values after correction to ISO conditions.

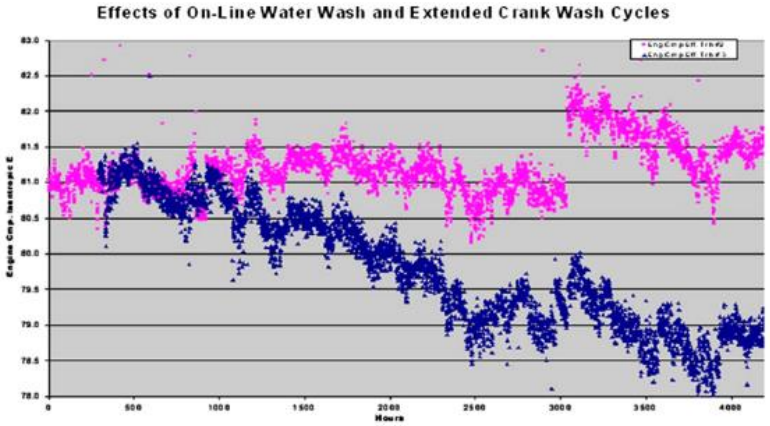


Figure 2-15 Degradation of turbine compressor efficiency [11]

Table 2-6 Output & efficiency measured with calibrated instrumentation [12]

Parameter	Unit	Test 1	Test 2	Test 3	Test 3 (corrected)
Date		Sept. 1996	Aug. 1999	June 2002	June 2002
EOH	H	2586	24,350	49,200	49,200
Gross power output	MW	62.5	63.4	60.9	61.6
Gross efficiency	%	35.3	35.7	35.2	35.4

The performance level recorded after the major outage is 24,350 hrs (Table 2-6) which is the start value for normalization. Figure 2-16 show the evolution of the monthly efficiency and power output relative to initial values. Both the power output and efficiency shows a similar behaviour with performance recovery due to off-line cleaning. None of the seven off-line washes leads to the original performance line. Nevertheless, towards 25,000 hrs inspection intervals, off-line compressor washing leads to performance level that is similar to the level reached with 1st off-line washing. This is due to the hand cleaning which leads to an optimal condition. To differentiate the losses labeled, performance levels following each off-line wash was used to fit a line using linear regression. The lines displayed in Figure 2-16 and the slopes of the regression lines for power output and efficiency are 0.02%/1000hrs and 0.03%/1000hrs respectively. With the correction to ISO condition, a power loss of 900 kW was observed (approximately 1.4%) compared to the acceptance test one (1).

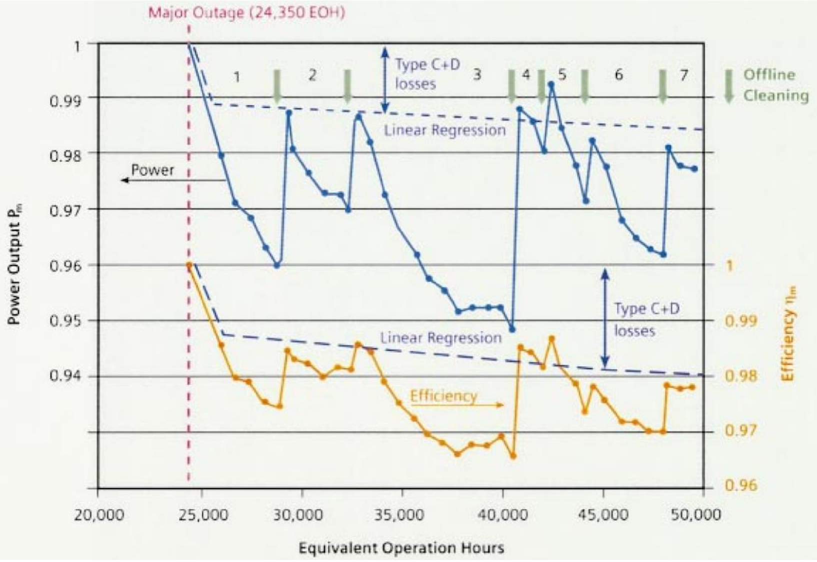


Figure 2-16 Estimation of mean monthly performance on the engine [12]

There are no losses for the efficiency after 50,000 hrs of operation, indicating values are very low. When test 2 and test 3 (corrected) are examined, the power losses between major outages and efficiency are 1.8 MW (2.8%) and 0.3% $(\Delta\eta/\eta = 0.8\%)$ respectively. This shows that test 2 is above the acceptance test performance, and recorded with hand-cleaned compressor.

Lastly, the Eemshaven power plant investigated is located in the North East of Netherland. It has two plants: the first is steam turbine power plant (STPP), which was upgraded with Siemens V94.2 GT that gives a power output of 697 MW. The second is an extension that gives a total power output of 1775 MW for commercial purposes. It consists of 5*225 MW GT Frame 9-FA engines with heat recovery (HR) boiler and 1×steam turbine on the same shaft. Each unit has a total power output of 355 MW with natural gas as it fuel [64]. Due to continued increase of the price of natural gas, the plant is running on the cycling mode. A 2-stage filtration system was adopted for the plant. It consists of a G3 class coarse filter and F9 class filter. It was changed from F9 to F8 filtration class due to cost optimization. The fine filter elements F8 are replaced every 3 years, and the coarse filter G3 elements are replaced twice/year. All GT compressors were on-line washed daily in summer. During the winter months, the frequency of washing increased to 3 times, per week for an average of 30 – 40mins [64]. An off-line cleaning was introduced in 2001 and performed at an average of once per year on annual inspection of each engine. Table 2-7 is a typical on-line cleaning schedule for the plant.

Table 2-7 Wash frequency for on-line [64]

Period	Summer Period	Winter Period
1995 to Jun 2001	Daily 35 min	3*35 min/week
Jun 2001 to Aug 2002	3*10 min/week	3*10 min/week
Sep 2002 frontward	3*17 min/week	2*17 min/week

Table 2-8 shows the power loss and power gain after off-line washing on unit EC-6. The fouling rate or power degradation pattern is steeper, following off-line wash and clean compressor blades.

Table 2-8 Power loss and recovery after off-line washing [64]

Time/Period	EOH hrs.	P (MW) corr. clean	P (MW) corr. fouled	Power loss (%)
Jun 04-Jun 05	7,902	359	343	4.4%
Jun 05 –Dec 05	4,083	357	348	2.5%
Dec 05-Mar 06	1,922	353	343	2.8%

2.11 GT Inlet Filtration System

Inlet filtration systems play a significant role in the operation and life of GTs. During the operation, gas turbines ingest large amounts of ambient air. Due to this, the quality of air ingested by the turbine is a key factor in the performance and life of the GT. A major concern for the manufacturers and operators is the purity of the combustion air, since the machines are reacting with progressively rising sensitivity to staining on the blades. High-quality air filters at the intake system will reduce staining at the blade, thus increasing the power output and efficiency of the GT. Many factors are to be considered when selecting and installing a new filtration system and sometimes upgrading an existing system. These are; particles sizes to be filtered, efficiency of the filtration system, maintenance over the life of filtration system, pressure losses of the filtration system, availability and reliability of the GT. Modern filtration systems comprised of multi-stage filtration and each stage is selected based on performance goals and operating environment. Sometimes, filters are selected without fully investigation of the type of contaminants present in the surrounding environment.

A life cycle cost analysis (LCC) is a technique used to evaluate upgrades or changes to the inlet filtration system. The analysis quantifies various factors in terms of net present value (NPV). There are several consequences that occur when the inlet air quality is not well controlled; some of the common mechanisms are fouling, corrosion and erosion.

2.12 Filtration System Characteristics

These consist of filtration mechanisms, filter efficiency and classification, filter pressure loss, filter loading and face velocity.

Filtration Mechanisms

A Filtration system uses filters of different mechanisms to remove contaminants from the air. Each filter type has different mechanisms working together to remove contaminants. The 4-filtration mechanisms are inertial impaction, diffusion, interception and sieving.

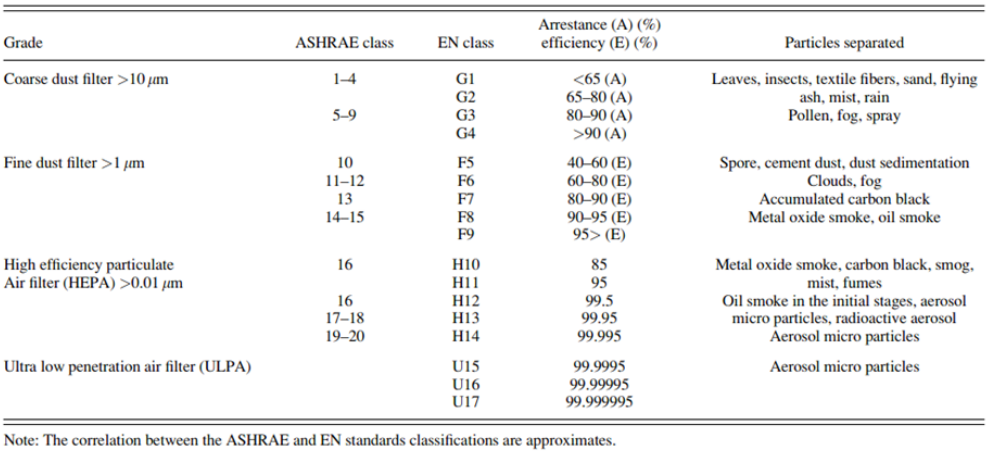
Classification of Filter Efficiency

Filter efficiency can be defined as the ratio of weight captured in the filter to the weight entering the filter respectively. It can be represented mathematically as follows [65]:

$$\eta = \frac{W_{entering} - W_{exiting}}{W_{entering}} * 100\% \tag{2-6}$$

At the beginning of life, filters have poor performance against small particles, but as the filter media become loaded with particles, it can catch smaller particles. Wilcox et al. [65] show the average efficiency is higher than the initial efficiency. The pressure loss of a filtration system increases with an increase of a filter efficiency. Filters become more efficient when less dust penetrating through them, leading to higher pressure loss. Wilcox et al. [65] studies have indicated that higher pressure loss due to high efficiency filtration has a lower effect on GT power degradation than poor inlet air quality. Table 2-9 shows a summary of grades, class and efficiency of filter media.

Table 2-9 Summary of grade, class, & efficiency filter media (EU & ASHRAE) [66]



Grade	ASHRAE class	EN class	Arrestance (A) (%) efficiency (E) (%)	Particles separated
Coarse dust filter >10 μm	1–4	G1	<65 (A)	Leaves, insects, textile fibers, sand, flying ash, mist, rain
		G2	65–80 (A)	
	5–9	G3	80–90 (A)	Pollen, fog, spray
		G4	>90 (A)	
Fine dust filter >1 μm	10	F5	40–60 (E)	Spore, cement dust, dust sedimentation
	11–12	F6	60–80 (E)	Clouds, fog
	13	F7	80–90 (E)	Accumulated carbon black
	14–15	F8	90–95 (E)	Metal oxide smoke, oil smoke
		F9	95> (E)	
High efficiency particulate Air filter (HEPA) >0.01 μm	16	H10	85	Metal oxide smoke, carbon black, smog, mist, fumes
		H11	95	
	16	H12	99.5	Oil smoke in the initial stages, aerosol micro particles, radioactive aerosol
	17–18	H13	99.95	
	19–20	H14	99.995	Aerosol micro particles
Ultra low penetration air filter (ULPA)		U15	99.9995	Aerosol micro particles
		U16	99.99995	
		U17	99.999995	

Note: The correlation between the ASHRAE and EN standards classifications are approximates.

Filter Pressure Loss

Pressure losses cause a drop in compressor inlet pressure (CIP), power output, and consumes more fuel, this has a direct effect on the performance of the engine. An increase in pressure loss due to degradation results in power output drop and linearly increase heat rate. An example of pressure loss on inlet filtration systems varies from 500 to 1500 Pa [67].

Filter Loading

As the filter collect particles during operation, the particles loaded slowly until it reaches a full state and is specified as pressure losses. The Filters can be loaded either surface or depth loading. Depth loading is when particles are captured inside of the filter material and filter must be changed. For a surface loading, particles collect on the surface of the filter. Few of the particles penetrate on the fibre material and no replacement of the filter should be carried out [68,69].

2.13 Individual Components of a Filtration System

A gas turbine ingests large amounts of air and needs to be protected from variety of contaminants existing in the ambient air. Several filtration devices used in modern filtration systems are; the weather protection, anti-icing protection system, inertial separators, moisture coalesces, pre-filters, self-cleaning filters and high-efficiency filters.

The Weather hood (Figure 2-17 left) or trash screens are used to reduce the amount of moisture and solid contaminants that enter the main filtration system.

Figure 2-17 Example of weather hood (left**)** [70] **and pulse cartridge filters on ice (**right**)** [33]

They are part of the filtration systems that made up of sheet metal on the entrance of the filtration systems, and help in removing large objects or contaminants along the flow stream. The weather hood are very effective for minimizing water and snow penetration; it is low-priced and has negligible pressure loss [71].

Anti-icing is applied in freezing weather condition to protect the filters. When the climatic condition of a place is freezing with rain and snow, it causes icing at the inlet of the compressor. This result in physical damage to the inlet of GT compressor and the performance of the engine may be affected. When ice is formed on the filter elements, it causes a blockage of the flow path and the velocity of the other filters increases. This causes a filter efficiency to decrease.

Figure 2-17 (right) shows an ice formation in filter housing. Compressor bleed air, heaters and self-cleaning filters are used to avoid build-up of ice on the filter elements [65].

Inertial separators are the type of filter that change the direction of air from the streamline of the air path and result in dust particles separation. It has a low maintenance cost.

Coalescers are used in an environment with high concentration of liquid moisture. They are designed to allow the droplet to drain down, or released back into the flow stream [71,72].

Using one-stage high efficiency filter, the build-up small and large solid particles may quickly increase pressure loss and filter loading. Pre-filters are mainly used to increase life of the downstream high efficiency filter, and capturing the larger solid particles. The advantage of a pre-filter is that it can be changed without the shutdown [71,72].

There are three types of high efficiency filters; EPA, HEPA and ULPA and their grade, class and efficiency of the filter media are shown in Table 2-9 [73–78]. For high efficiency filters the initial pressure loss can be up to 250 Pa with a final pressure loss in the range of 625 Pa for rectangular filters and 2000 Pa for cartridge filters [71,72]. An example of high efficiency rectangular filters and high efficiency cartridge filters are shown in Figure 2-18.

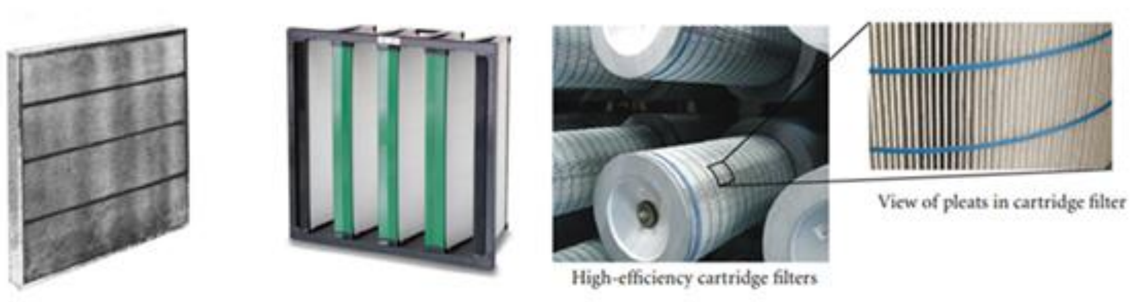


Figure 2-18 Rectangular filters (left**)** [79,80] **and cartridge filters (**right**)** [33]

The system operates with surface loaded high-efficiency cartridge filters. The surface loading helps for easy removal of dust, and has accumulated with reverse pulses of air.

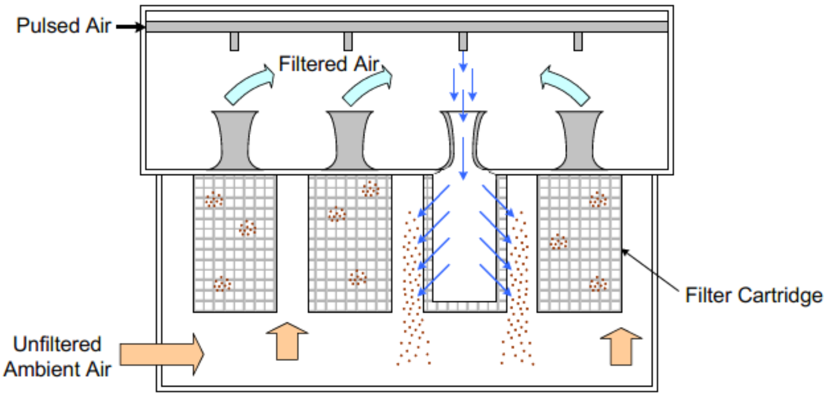


Figure 2-19 Typical of self-cleaning filters [33]

For any application, GT needs more than one filter for an operation. No single filter can be used to serve all the purposes. Therefore, two-stage or three-stage filters are required for the filtration systems. Figure 2-20 shows a typical over view of a three-stage filter.

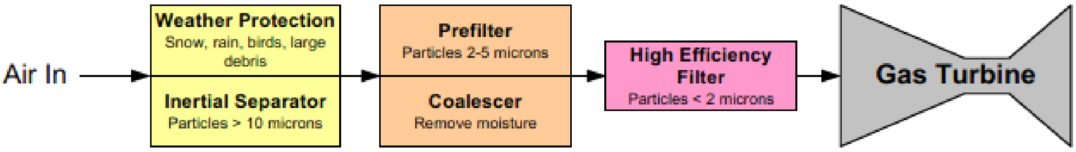


Figure 2-20 Example of three-stage filtration system [65]

2.14 Two and Three-Stage Filter System

The best way to reduce the amount of particles entering into a GT is by fixing a highly efficient 3-stage instead of 2-stage filter system. This increases the average pressure drop (ΔP) of the filters; however the amount of fouling on the blades reduces. These causes a small reduction of output due to an increase in ΔP, while an increase in output power occur due to reduction of fouling on the blade. Figure 2-21 illustrates an example of a 2 and 3-stage filter systems defined under EN 779: 2003 [73] and EN 1822 [74–78]. For the effect of increased pressure drop, Schroth and Cagna [81] states that for a 50 Pa increase ΔP the turbine's output power decreases by 0.1% (Figure 2-22 left). The diagram in Figure 2-22 (right) is a comparison of Pressure drop on 2 and 3-stage filtrations operating at base load condition of approximately 9000 hours. The pressure drop curve is monitored on the machines after an installation of 3-stage filter system.

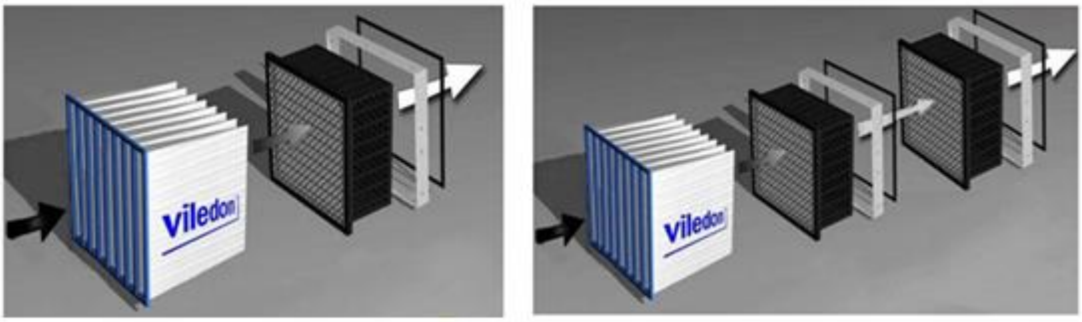


Figure 2-21 2-stage F6+F8 filter system (left) and 3-stage F6+F9+H11 filter system (right) [81]

The result shows a lower value of ΔP in the 2-stage system of approx. 300 Pa compared to a 3-stage system of approx. 670 Pa [81] at the end of 9000 hours of operation. Comparing the particles concentrations for both the 2-stage and 3-stage filter system in a sequence of **F6+F8** and **F6+F9+H11** respectively, assuming the system was installed as new with three particles size ranges. For example, in a 2-stage system approximately 7.2 million particles of the size range 0.3 – 0.5 μm reach the clean-air-side of the final filter stage, while for the 3-stage system approximately 0.22 million particles of the same size range reaches the clean-air-side of the final filter stage [81].

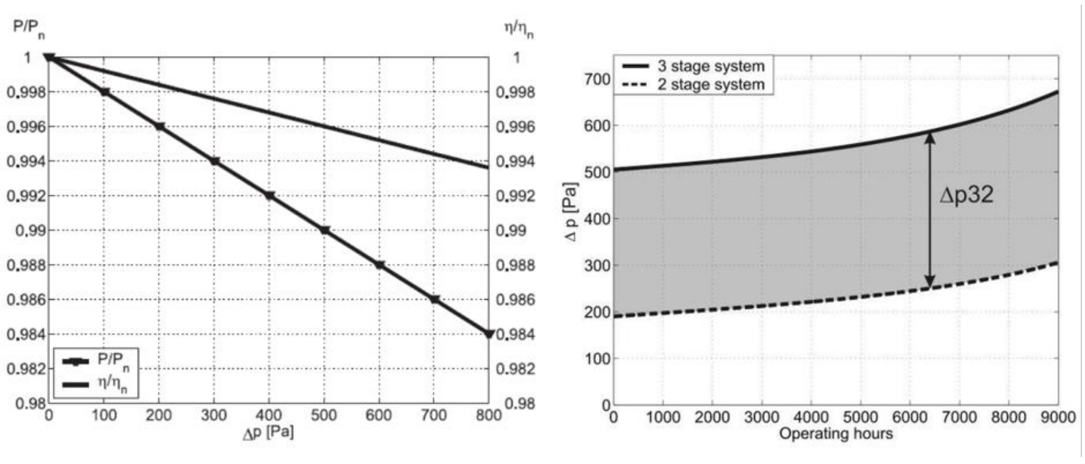


Figure 2-22 Effect of pressure drop on output and efficiency (left**) and comparison of Pressure drop on 2 and 3-stage filtration (**right**)** [81]

The efficiency of the filter for both the 2 and 3-stage is approximately 64% and 98.9% respectively [81]. This shows that 3-stage filter holds back approx. 97% of the particles reaching the clean-air-side of the final filter with low penetration through the filter, this was the reason for decreased fouling level.

2.14.1 Benefit of Improved Filtration System

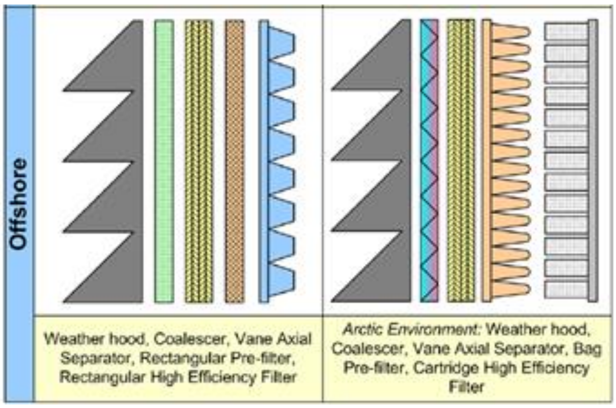
Improved filtration system may reduce the downtime for off-line water washing. This analysis is based on 25 MW engine operated over 8000 hrs of operation. The washing interval for F7/F8 filter was 750 hrs with a total of 11 off-line washing per year and cost impact of $8,862,239. Installing F9 filter the cost benefit over F7/F8 filter was $5,527,649 with about 4 off-line washing per year. Installing high efficiency H12 filter the cost benefit over F7/F8 filter was approximately $8,064,342 shown in Table 2-10.

Table 2-10 Cost Analysis for 25 MW Engine [82]

Filtration Efficiency	F7/F8	F9 Filter	H12 Filter
Engine wash frequency – Hours	750	2000	8000
Expected filter life –months	24	24	12
Filter costing (filter + labour) per year	$10,000	$15,000	$40,000
Annual washing cost (12h off-line/event)	$29,167	$10,938	$2,497
Annual production loss (20,000 bbl /$75)	$8,823,072	$3,308,652	$755,400
Total annual cost impact	**$8,862,239**	$3,334,590	$797,897
Net annual cost benefit for F9/machine		**$5,527,649**	
Net annual cost benefit for H12/machine			**$8,064,342**

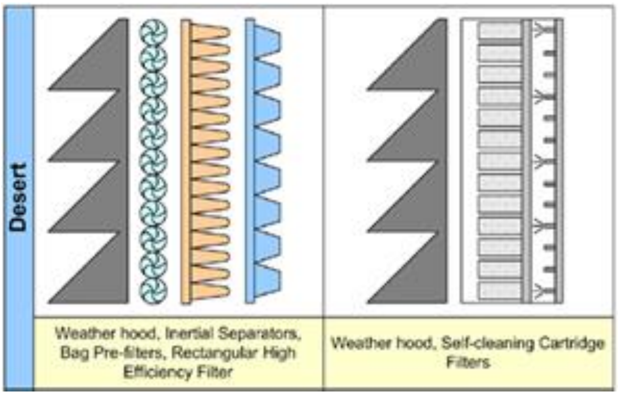
2.15 Operating Environment of Inlet Filtration System

The environmental condition where the GT operates is the main factor to be considered when selecting the inlet filtration systems. This includes, particulates, gaseous contaminants, moisture, seasonal changes, location and environment. Several different environments with their typical contaminants are presented:



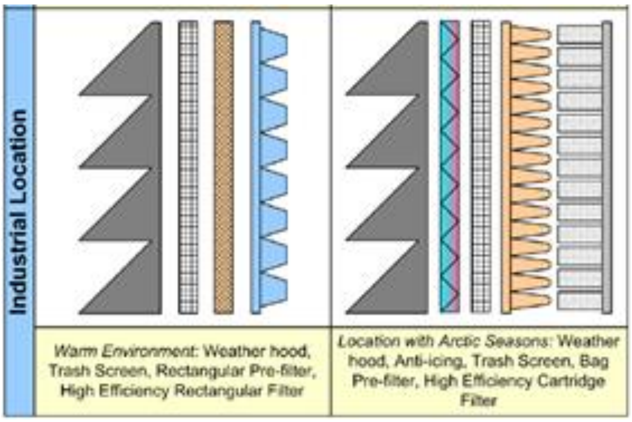
Contaminants: Hydrocarbons, salt, water and cooling tower aerosols

Figure 2-23 Filter systems for offshore environment [33]



Contaminants: Dust, sand storm, fog, humidity and sticky substance

Figure 2-24 Filter systems for desert environment [33]



Contaminants: Exhaust particles, leaves, rain, snow, ice, pollen, hydrocarbon & soot.

Figure 2-25 Filter systems for industrial environment [33]

3 METHODOLOGY

This chapter presents the mathematical approaches that includes estimation of the calculated parameters, data correction for the standard method that takes into account the compressor inlet temperature (CIT) and pressor (CIP) only and extended method that takes into account the CIT, CIP and relative humidity and engine data performance and evaluation (as shown in Figure 3-1).

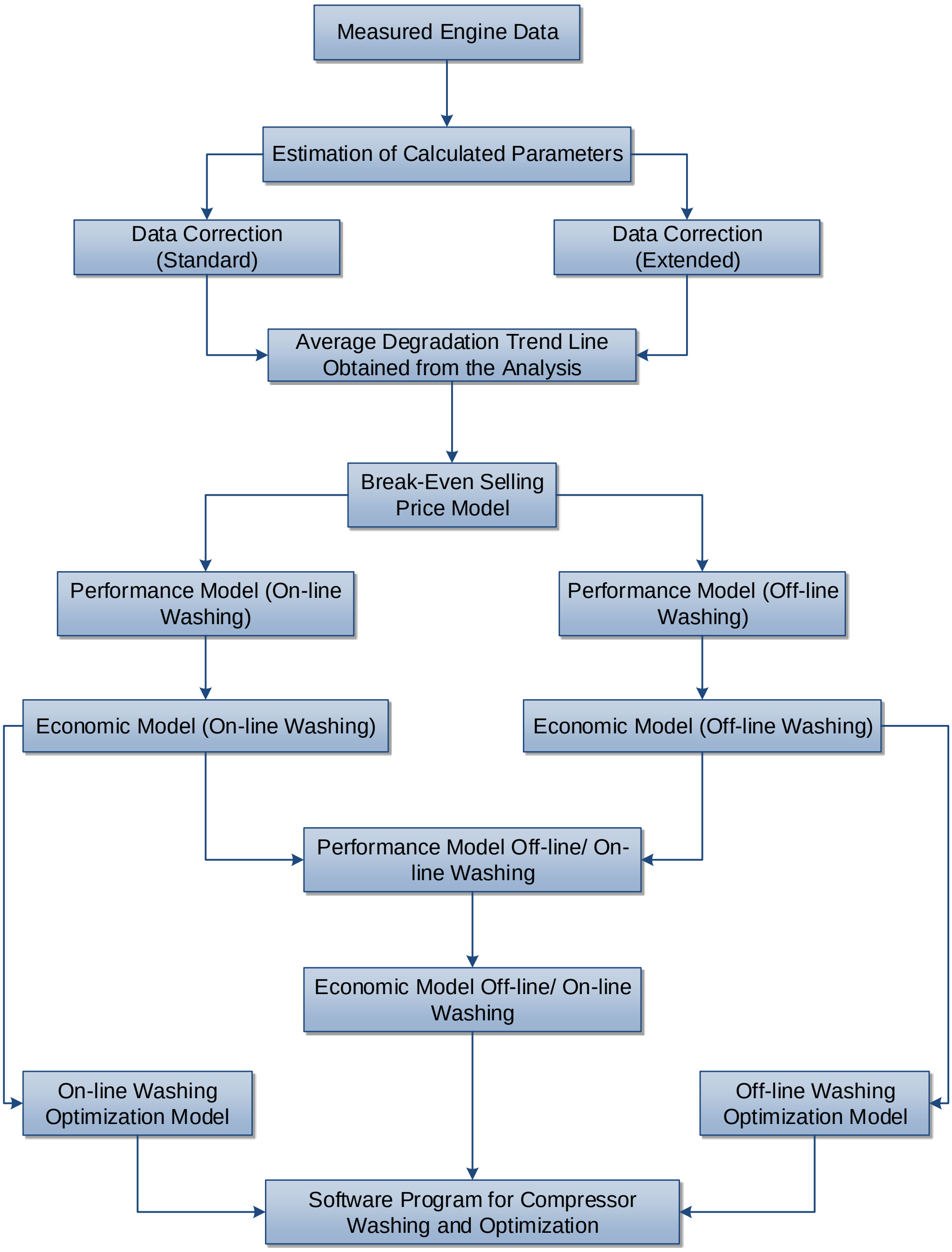


Figure 3-1 Structure of the work

It also includes the break-even selling price model, performance model for on-line and off-line washing, economics model for on-line and off-line washing, performance and economics model of the combination of two methods. The work also presents on-line washing optimization, off-line washing optimization and a computer programme for compressor washing performance and economics and compressor washing optimization for on-line and off-line washing for different engine sizes. Figure 3-1 shows the flow chart of the research work.

3.1 Engine Data Evaluation

The power plant investigated consists of two (2) GE 7FA class units referred as Engine -1 and Engine -2 operated for about 4 years. The Engine 1 has been operated and washed off-line only. The Engine 2 has been operated and washed on-line at an average of 55hrs frequency. **R-MC** Power Recovery LTD provided the operating data (measured engine data) for the power plant that includes General Electric (GE) 7FA engine of 211MW capacity in a combined cycle arrangements operated for approximately 4 years, the plant experiences 4 seasons in a year. The operational data was studied and unknown parameters were calculated using equations (3-1) to (3-9) and with the performance calculation flow chat shown in Figure 3-2.

Due to the variation of temperature along the cycle, the working fluid changes throughout the cycle. The values of γ and C_p at the cold section of the compressor are assumed to be 1.4 and 1.005 kJ/kgK respectively [61]. The efficiency of the compressor can be written as follows;

$$\eta_{isentropic} = \frac{\left(P_2/P_1\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(T_2/T_1\right) - 1} \tag{3-1}$$

An assumed pressure loss of 5% for industrial engines were experienced at the outlet of the combustor. This is due to momentum changes produced by exothermal reaction [61].

$$P_3 = P_2 * (1 - \Delta P_{cc}) \tag{3-2}$$

$$P_4 \approx P_{amb} \tag{3-3}$$

To estimates TET, some of the assumptions are made and these are; $\dot{m}_f \ll \dot{m}_a$, C_{Pc} and C_{Pt} are constant, C_{Pc} is the constant specific heat in the compressor and C_{Pt} is the constant specific heat in the combustor and turbine. The turbine power is approximately equal to the sum of the compressor power and the active power. TET has been obtained from the turbine power equation. This is the equation used to estimate the value of TET.

$$P_t \approx P_c + P_a \tag{3-4}$$

$$\dot{m}_a = \frac{\dot{m}_f * LHV}{C_{Pt}(T_3 - T_2)} \tag{3-5}$$

$$TET = \frac{\dot{m}_f * LHV[C_{Pt} * T_4 + C_{Pc}(T_2 - T_1)] - C_{Pt} * T_2 * P_a}{C_{Pt}\left(LHV * \dot{m}_f - P_a\right)} \tag{3-6}$$

The values of γ and C_p at the hot section of the engine are 1.333 and 1.148 kJ/kgK respectively [61].

$$\eta_{Turbine} = \frac{1 - \left({}^{T_4}/_{T_3}\right)}{1 - \left({}^{P_4}/_{P_3}\right)^{\frac{\gamma-1}{\gamma}}} \tag{3-7}$$

The following equations can be used to determine the thermal efficiency and heat rate of the engine according to [61,83].

$$\eta_{thermal} = \frac{P}{m_{fuel} * LHV} \tag{3-8}$$

$$Heat\ rate = \frac{2544.4}{{}^{\eta_{thermal}}/_{100}} \quad BTU/hp - hr \tag{3-9}$$

Where; Btu = British thermal units = 1.05506kJ, hp = Horse power = 0.746kW, hr = hours.

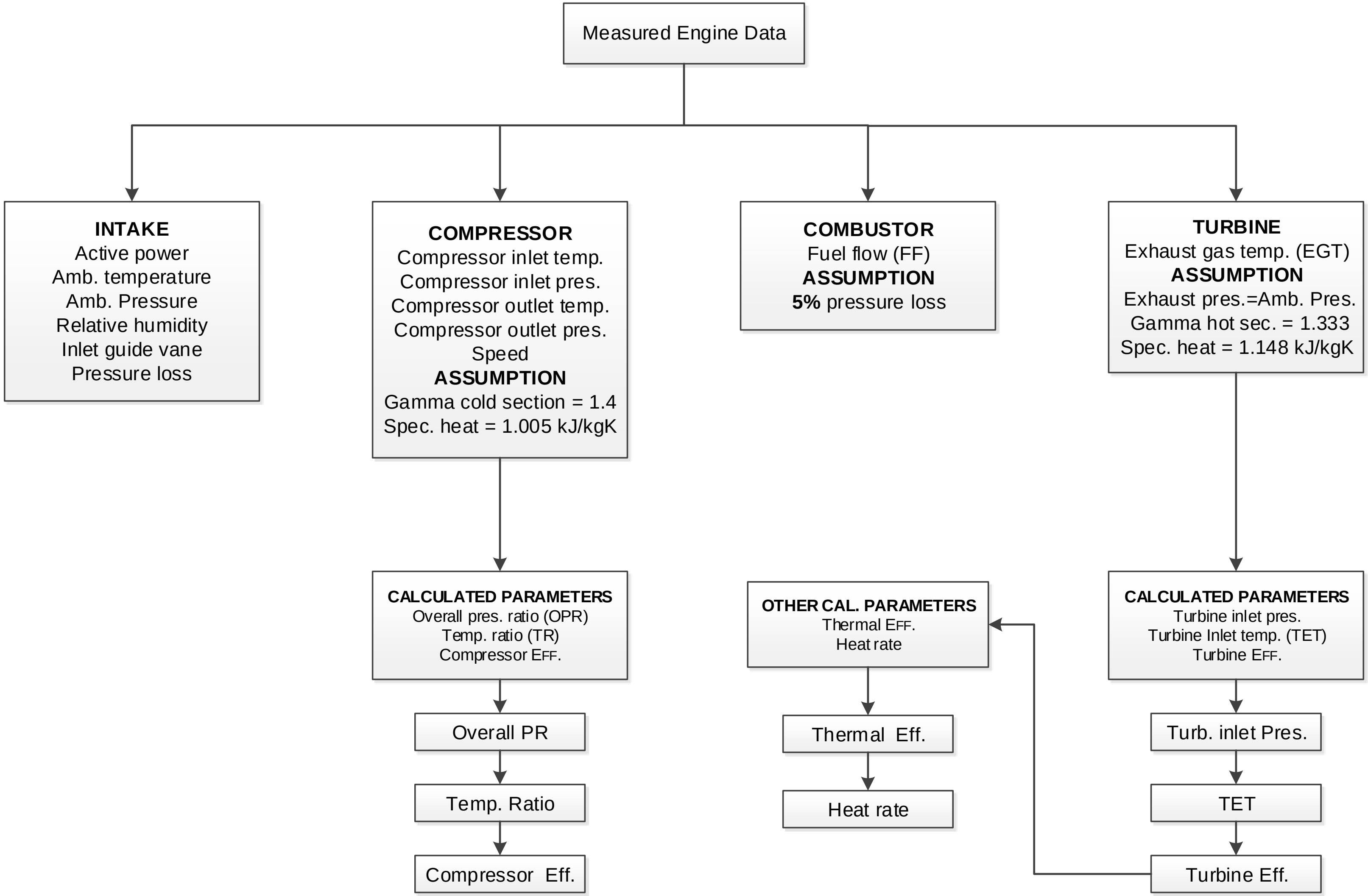

Measured Engine Data
INTAKE
Active power
Amb. temperature
Amb. Pressure
Relative humidity
Inlet guide vane
Pressure loss
COMPRESSOR
Compressor inlet temp.
Compressor inlet pres.
Compressor outlet temp.
Compressor outlet pres.
Speed
ASSUMPTION
Gamma cold section = 1.4
Spec. heat = 1.005 kJ/kgK
COMBUSTOR
Fuel flow (FF)
ASSUMPTION
5% pressure loss
TURBINE
Exhaust gas temp. (EGT)
ASSUMPTION
Exhaust pres.=Amb. Pres.
Gamma hot sec. = 1.333
Spec. heat = 1.148 kJ/kgK
CALCULATED PARAMETERS
Overall pres. ratio (OPR)
Temp. ratio (TR)
Compressor Eff.
OTHER CAL. PARAMETERS
Thermal Eff.
Heat rate
CALCULATED PARAMETERS
Turbine inlet pres.
Turbine Inlet temp. (TET)
Turbine Eff.
Overall PR
Temp. Ratio
Compressor Eff.
Thermal Eff.
Heat rate
Turb. inlet Pres.
TET
Turbine Eff.

Figure 3-2 Engine model performance calculation flow chart

3.2 Data Corrections

Data corrections to ISO conditions are used to eliminate the uncertainties and scatter of measurement and it can be categorized into standard or extended method. Data corrections to ISO conditions for both standard and extended methods were performed to the reference conditions to remove the bias effect of ambient conditions and estimate the values that do not depend on the climatic condition according to equations (3-10) to (3-15) for the standard method. The parameters corrected are; power output, non-dimensional mass flow, rotational speed, ambient temperature, ambient pressure, compressor efficiency, thermal efficiency, exhaust gas temperature and fuel flow. Figure 3-3 shows the data corrections model calculation for standard and extended corrections.

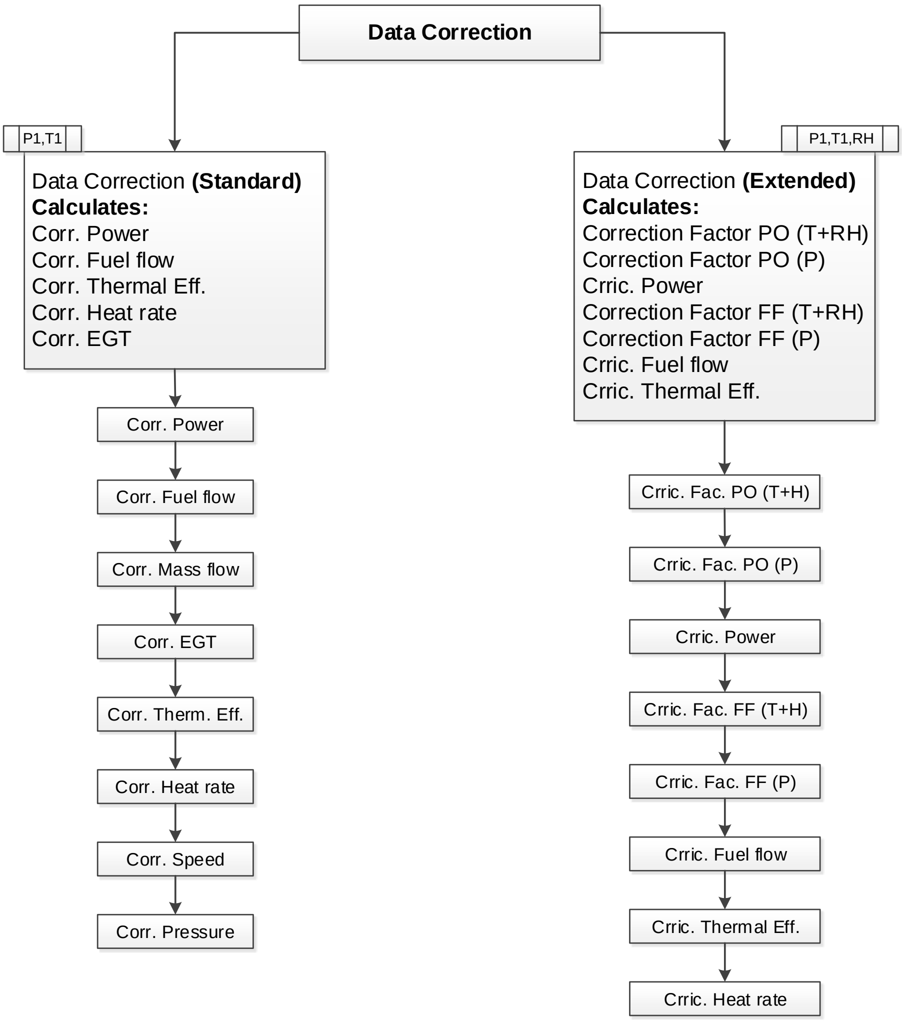


Figure 3-3 Data corrections model

The standard correction is the method used for correcting the data that takes into account the compressor inlet temperature and pressure only. The equations used for the standard data correction are available in Boyce and Veer [32,83];

Corrected Power Output:

$$P_{corr} = P * \left(\frac{1.01325bar}{P_1}\right) * \sqrt{\frac{T_1}{288K}} \tag{3-10}$$

Corrected Mass Flow:

$$W_{corr} = W * \left(\frac{1.01325bar}{P_1}\right) * \sqrt{\frac{T_1}{288K}} \tag{3-11}$$

Corrected EGT:

$$T_{corr(EGT)} = T_{EGT} * \frac{288K}{T_1} \tag{3-12}$$

Corrected Pressure:

$$PR_{corr} = \frac{P_1}{1.01325bar} \tag{3-13}$$

Corrected Speed:

$$N_{corr} = N * \sqrt{\frac{288K}{T_1}} \tag{3-14}$$

Corrected Fuel Flow:

$$m_{f\,corr} = \frac{m_f}{\left(\frac{P_{inlet}}{P_{std}}\right) \Big/ \sqrt{\left(\frac{T_{inlet}}{T_{std}}\right)}} \tag{3-15}$$

However, the extended correction is the method used for correcting the data that takes into account the compressor inlet temperature, compressor inlet pressure and relative humidity. Equations (3-16) to (3-21) are used for the extended data correction to estimates the corrected power output and fuel flow according to Igie et al. [51] equations. The parameters in equations (3-17) and (3-20) are compressor inlet temperature and relative humidity. The equations are derived using the 3 different possible combinations of compressor inlet temperature and compressor inlet pressure and relative humidity using Turbomatch software for off-design point simulation.

$$PO_{Corr} = \frac{PO_A}{CF_{T+RH} \times CF_P} \tag{3-16}$$

Where;

$$CF_{T+RH} = 2.7048 * 10^{-7} * T_{CIT}^3 + 1.4032 * 10^{-7} T_{CIT}^2 * RH - 1.0725 * 10^{-6} * T_{CIT}^2 - 1.0729 * 10^{-8} * T_{CIT} * RH^2 + 3.7352 * 10^{-6} * T_{CIT} * RH - 0.007 * T_{CIT} - 1.5464 * 10^{-10} * RH^3 + 1.1605 * 10^{-7} * RH^2 + 2.683 * 10^{-5} * RH + 1.0971 \tag{3-17}$$

$$CF_P = 1.4461 \times \left(\frac{P_{amb}}{101325}\right) - 0.4456 \tag{3-18}$$

The corrected fuel flow can also be estimated using Igie et al. equation:

$$W_{fuelcorr} = \frac{W_{fuelactive}}{CF'_{T+RH} * CF'_P} \tag{3-19}$$

Where;

$$CF'_{T+RH} = 2.186 * 10^{-7} * T_{CIT}^3 + 2.3183 * 10^{-7} * T_{CIT}^2 * RH + 3.9875 * 10^{-6} * T_{CIT}^2 - 7.4896 * 10^{-9} * T_{CIT} * RH^2 + 3.9004 * 10^{-6} * T_{CIT} * RH - 0.0058 * T_{CIT} - 4.7166 * 10^{-10} * RH^3 + 1.8571 * 10^{-7} * RH^2 + 2.6014 * 10^{-5} * RH + 1.076 \tag{3-20}$$

$$CF'_P = 1.0016 * \left(\frac{P_{CIP}}{101325}\right) - 0.0016 \tag{3-21}$$

The analysis of the engine data (corrected) was performed using Tableau software to visualize the behaviour of the engine and quantify the compressor fouling degradation level taking into account the influence of ambient conditions and power settings. The output of this investigation is the degradation trend line of the power output as a function of time, the trend lines serves as the input for the performance and economic analysis.

3.3 Performance Model (On-line/Off-line)

A performance model for on-line and off-line washing have been developed, the washing model that consists of on-line and off-line cases were investigated at different wash frequencies, recovery rate that accommodates different degradation trends and cost values. Based on the available information provided, in which the performance was monitored during the operation shows about **19 events** of off-line washing at base load operating conditions.

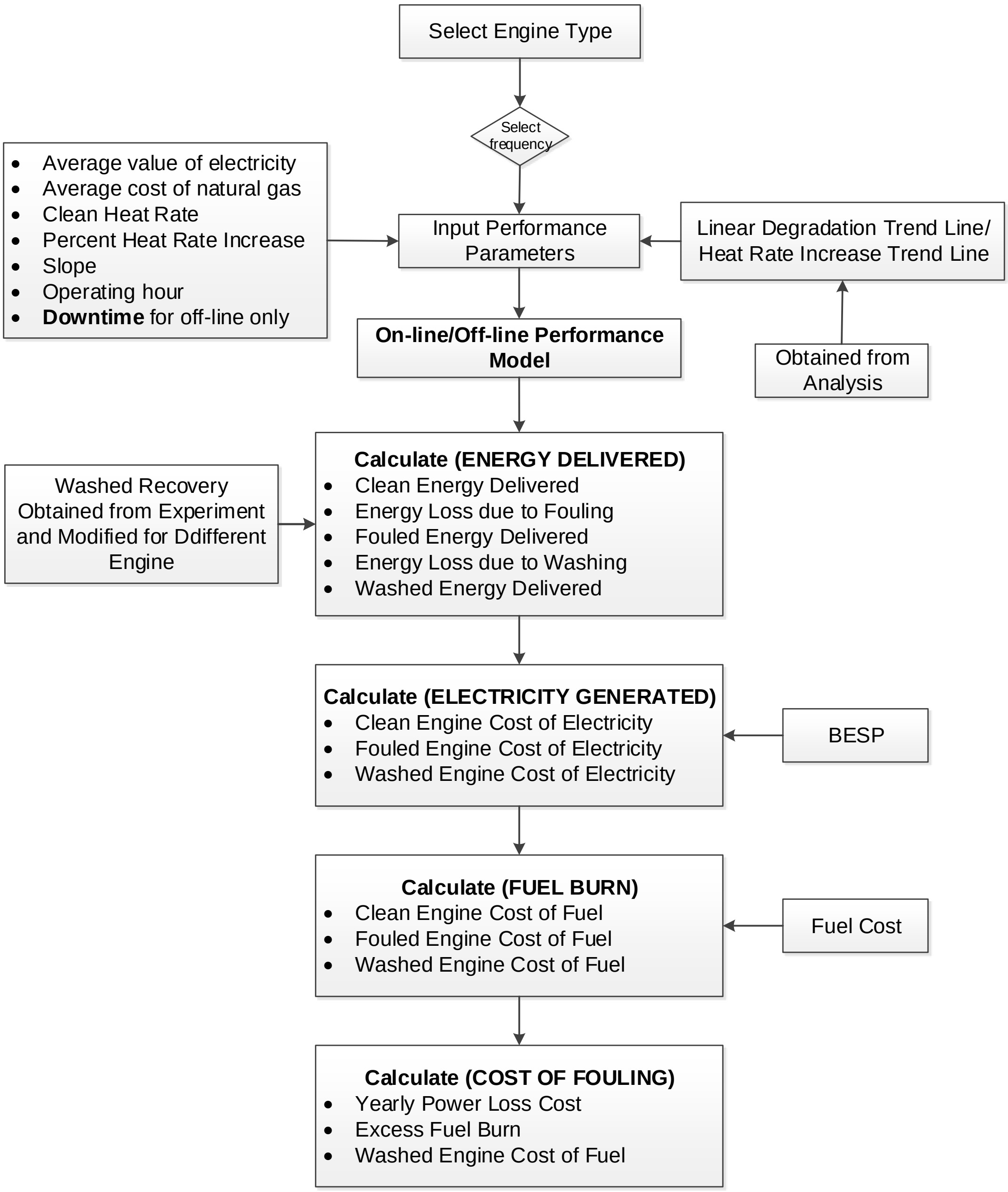


Figure 3-4 On-line/Off-line performance model calculation

The performance section deals with estimating the energies at clean, fouled and washed condition. The selling value of electricity generated at clean, fouled and washed engine are also estimated. However, the heat rate and fuel consumption at clean, fouled and washed condition were accounted in the analysis. As the engine operates for a certain period of time, the rate of degradation increases with time and the excess fuel burn due to fouling has to be accounted. Finally, the loss of revenue due to fouling has to be estimated which is the sum of yearly power loss cost and the yearly excess fuel burn due to fouling shown in Figure 3-4. Equation (3-22) is used for estimation of the power recovery due to washing.

$$R_{P.lost} = \left[1 - \frac{P_{clean} - P_{washed}}{P_{clean} - P_{fouled}}\right] \times 100 \tag{3-22}$$

3.4 Break-Even Selling Price Model

To estimate the break-even selling price (BESP) or levelised cost of electricity (LCOE) there is need to estimate the life of the project and the time the plant start operation to the end of plant useful life. There is a direct cost that relates to the equipment costs and is expressed in ($/kW) and indirect cost that relates to the general facilities costs, engineering, home office overhead, and project or process contingencies. The capital investment cost is spread over the construction period, assuming 3 years for project completion of all the engines investigated.

The input model data consists of electricity price, fuel price, fixed and variable O&M cost, discount rate, income tax rate, plant availability, construction time, plant lifespan, investment cost, depreciation and escalation rate for fuel and electricity. The economic input data includes clean engine power output, fuel burn and the energy produced per annum. Two tax are paid annually and it includes tax on the profit and tax on emissions CO_2. Depreciation is used to reduce the taxable income for an assets [84,85]. A straight line method for depreciation have been adopted for this analysis.

The economic model output parameters consist of annual net cash flow (ANCF), annual operation profits (AOP), annual tax (AT), plant depreciation, net present value (NPV), pay-back period (PBP), internal rate of return (IRR), unitary cost of electricity (CoE) and break-even selling price (BESP). It is important to accept a project when its IRR is larger than the required rate of return [86]. The payback period most satisfies equation (3-28).The ANCF, AOP, AT are calculated according to the following equations [84].

$$ANCF = AOP - ALR - AT \tag{3-23}$$

$$AOP = ES - fuel\ cost - O\&M\ cost \tag{3-24}$$

$$AT = TR * TI + ETR * E \tag{3-25}$$

The cash flow and break-even selling price applicable yearly over the investment is shown in Figure 3-5. The economic parameters for NPV, IRR and PBP are calculated using the following equations:

$$NPV = \sum_{t=0}^{n} CF_t * (1+i)^{-t} \tag{3-26}$$

$$IRR = i^* \ni' NPV(i^*) \tag{3-27}$$

$$\underset{[0,n]}{min}\{n'\} \ \ni' \ \sum_{t=0}^{n'} CF_t \times (1+i)^{-t} \geq 0 \tag{3-28}$$

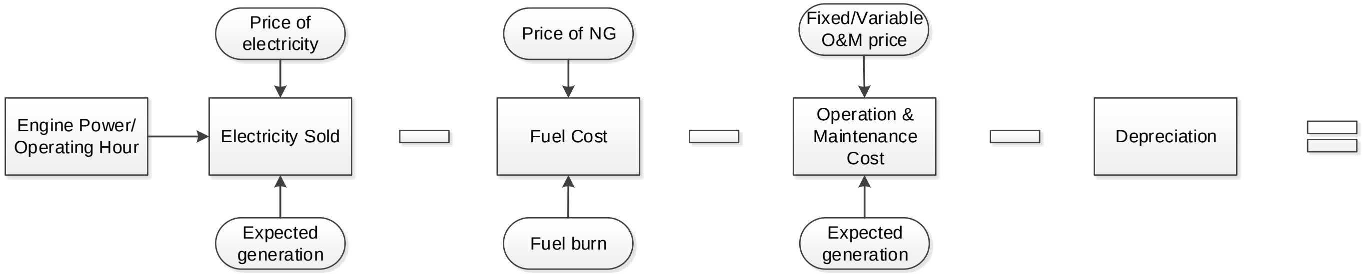
Break-even selling price (BESP) is the selling price that the generator supposed to charge for the generated electricity which is transmitted to the grid over the lifetime of the power station and NPV must be equal to zero. The economic parameters for CoE and BESP are calculated according to the following equations:

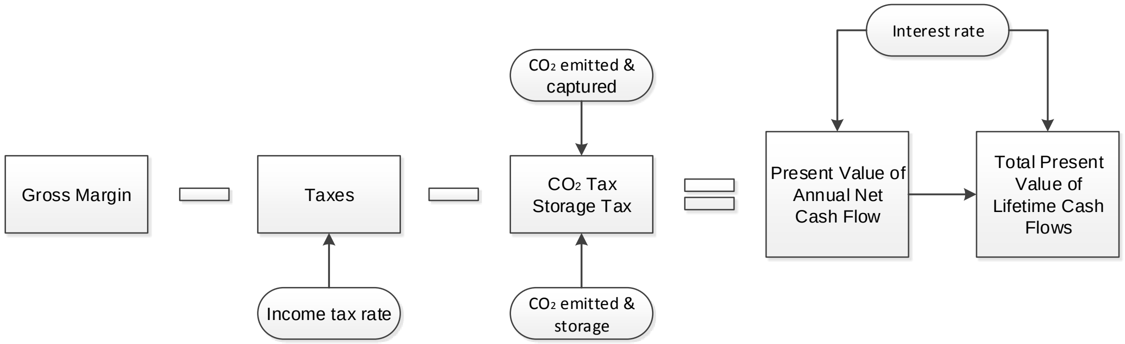
$$CoE = \frac{\beta * C_o + C_{fuel} + C_{O\&M}}{\dot{W} * H} \tag{3-29}$$

$$\beta = \frac{i \times (1+i)^n}{(1+i)^n - 1} \tag{3-30}$$

$$BESP = \frac{\sum_{t=0}^{n}[(I_t + M_t + F_t) \times (1+i)^{-t}]}{\sum_{t=0}^{n}[E_t \times (1+i)^{-t}]} \tag{3-31}$$

A simple cycle gas turbine cost depends purely on the unit size and equipment supply scope. The plant price estimates adopted are in gas turbine world (GTW's) and are based on standard bare bones gas-only (natural gas) plant. The plant prices covers only the equipment and do not include transportation, plant construction, plant engineering and customized specific options. The equipment supply scope in GTW handbook has been categorised into two segment of different sizes and plant type.


Price of electricity
Price of NG
Fixed/Variable O&M price
Engine Power/ Operating Hour
Electricity Sold
Fuel Cost
Operation & Maintenance Cost
Depreciation
Expected generation
Fuel burn
Expected generation


Interest rate
CO₂ emitted & captured
Gross Margin
Taxes
CO₂ Tax Storage Tax
Present Value of Annual Net Cash Flow
Total Present Value of Lifetime Cash Flows
Income tax rate
CO₂ emitted & storage

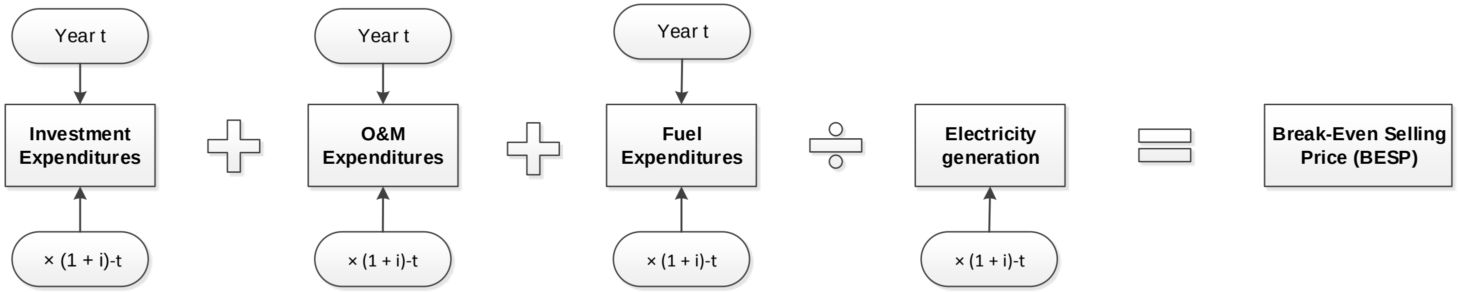

Year t
Year t
Year t
Investment Expenditures
O&M Expenditures
Fuel Expenditures
Electricity generation
Break-Even Selling Price (BESP)
× (1 + i)-t
× (1 + i)-t
× (1 + i)-t
× (1 + i)-t

Figure 3-5 Cash flow and break-even selling price model

The first segment is from 0 kW down to 100,000 kW shown in Figure_Apx B-22. The second segment is beyond 100,000 kW down to 450,000 kW shown in Figure_Apx B-23.

3.5 On-line Washing Economic Model

To investigate the economic analysis of washing, the cost of fouling for a given degradation rate has to be calculated.

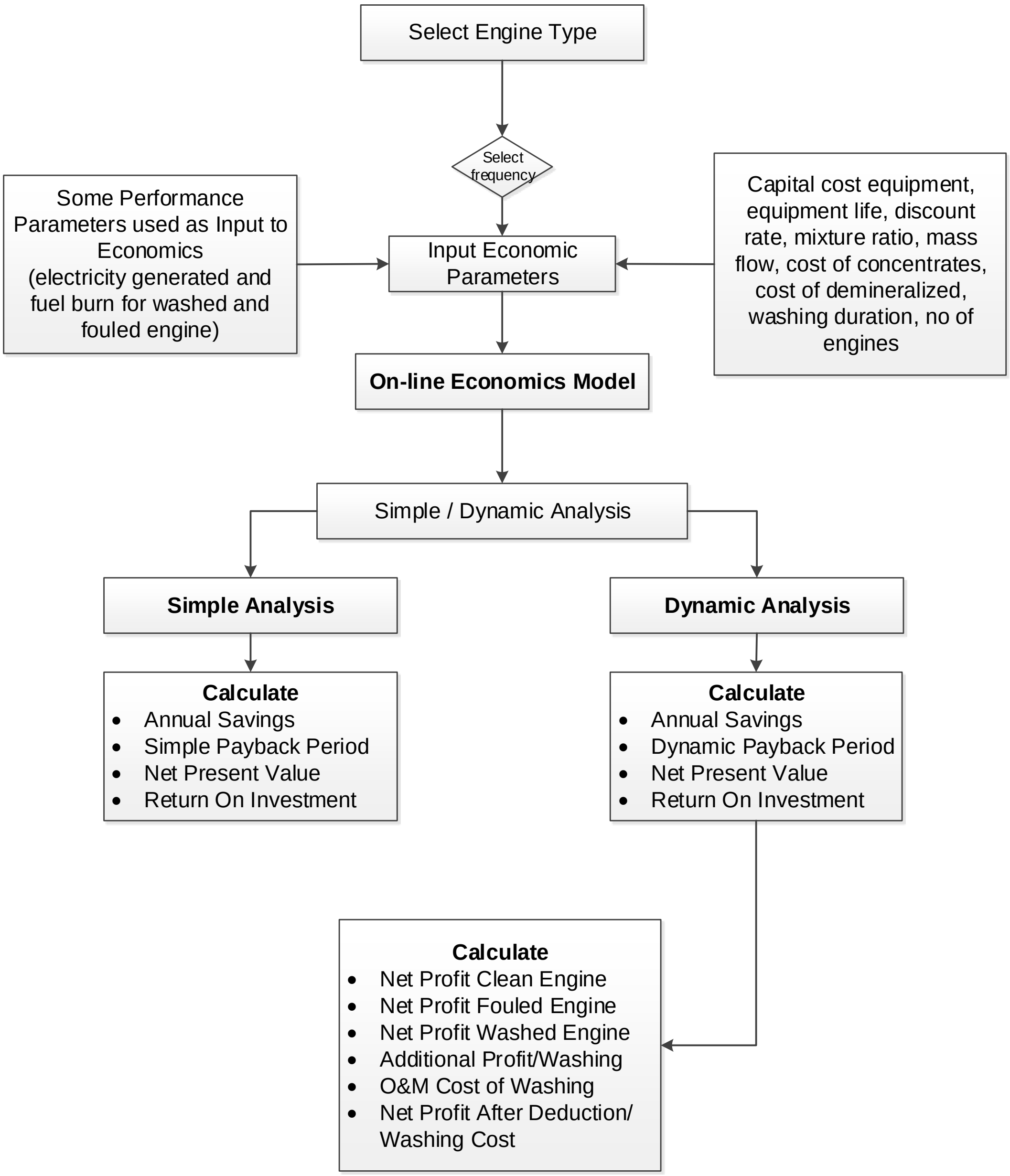


Figure 3-6 On-line washing economic model calculation

This has to be made in comparison with the cost of washing associated with the respective washing frequencies to identify whether the performance benefit of washing outweighs the capital investment and recurring cost (note the possible marginal increase in cost for higher recovery is not accounted for). To achieve these, the Payback period (PB), Return on Investment (RoI), Annual Savings (AS) and Net Present Value (NPV) are to be calculated. A simple and dynamic analysis (approach) is considered here (Figure 3-6), for which in the simple analysis the change in the value of money with respect to time is ignored (i.e. the market interest rate is considered equal to zero ($i = 0$)). For the dynamic analysis, the interest rate (or discount rate) is applied to obtain the present value of the cash flow each year, over the life of the equipment. The sum of these present values and the scrap value, deducting the capital investment is the NPV. It is the "now" value of the whole cash flow stream for the entire life of the washing equipment. Equations (3-32) to (3-41) are used for calculating the economic analysis for on-line washing. Equations (3-32) to (3-35) are used for simple analysis:

$$AS = \left(R_w - C_{fw} - C_{om}\right) - \left(R_f - C_{ff}\right) \tag{3-32}$$

$$NPV = -C + SV_0 + AS \times N \tag{3-33}$$

$$SPB = \frac{C - SV_0}{AS} \tag{3-34}$$

$$RoI = \frac{1}{SPB} = \frac{AS}{C - SV_0} \tag{3-35}$$

For the dynamic analysis it is considered an interest rate of 8% and the following formulas are used for the analysis:

$$NPV = -C + SV_0 + \sum_{i=1}^{N} \frac{AS_t}{(1+i)^t} \tag{3-36}$$

Here, it is considered that AS_t = AS (t = 1, 2, N). The following equation is valid:

$$PWF = \sum_{i=1}^{N} \frac{1}{(1+i)^t} = \frac{(1+i)^N - 1}{i(1+i)^N} \tag{3-37}$$

Where; PWF is the present worth factor. Equation (3-36) can be written as

$$NPV = -C + SV_0 + AS \times PWF \tag{3-38}$$

The Dynamic Payback period (DPB) is the smallest value of *N* that makes the net present value non-zero:

$$NPV = -C + SV_0 + \sum_{t=1}^{N_{min}=DPB} \frac{AS}{(1+i)} \geq 0 \tag{3-39}$$

$$DPB = \frac{-ln\left[1 - \frac{i(C - SV_0)}{AS}\right]}{ln(1+i)} \tag{3-40}$$

The return of investment (RoI) is the value that makes the net present value zero:

$$NPV = -C + SV_0 + \sum_{t=1}^{N} \frac{AS}{(1+RoI)^t} = 0 \tag{3-41}$$

3.6 Off-line Washing Economic Model

To examine the economic analysis of off-line washing in term of net profit after deducting washing cost, the cost of fouling for a given degradation rate has to be estimated. The off-line washing model consists of economic losses and economic benefit/gain that are associated with off-line washing process. The economic losses consists of the following:

- Cost of off-line washing.
- Loss of revenue (power loss and excess fuel burn)
- Cost of increase for number of start due to off-line washing

The economic benefit with respect to off-line washing consists of the following:

- Benefit due to power recovery.
- Benefit due to engine being off for a particular time without increasing the hours of operation.

3.6.1 Cost of Off-line Washing

The off-line washing cost consists of capital cost of the equipment, cost of wash fluid per year, cost of liquid used for rinsing, and maintenance cost of the equipment.

$$C_{off-line} = C_c + C_{fl} + C_r + C_m \tag{3-42}$$

3.6.2 Cost of Increase of Number of Start due to Off-line Washing

When an off-line washing is being conducted the number of engine starts increases with an increase in the maintenance cost. Mathematically this can be represented using De Backer et al. [87] and Bohrenkamper et al. [88] equation.

$$EOH = OH + K \cdot Start \tag{3-43}$$

3.6.3 Benefit due to Recovery of Power Output

The economic benefit due to washing is an important parameter for off-line washing that improves the performance of an engine; this is due to recovery of the power output loss. Mathematically this can be represented as;

$$B_{recovery} = (W_e - F_e) \times LCOE \tag{3-44}$$

3.6.4 Benefit for not increasing hours of operation due to shut down

There is a significant gain for not increasing the hours of operation when the engine is down for a particular period covered. The cost of increase for the number of starts and the benefit for not increasing hours of operations have been removed from the calculation due to insufficient data/information. The loss of power production due to shut down and benefit due to fuel saved as a result of shut down has been removed from the calculation as the power station used off-line washing as an opportunity. The other equations that are used in calculating the total operation profit are highlighted below. Figure 3-7 shows the off-line washing economic model calculation steps. Equations (3-45) to (3-56) are used for calculating the net profit after deducting washing cost, total operation profit, specific cost of energy production and energy produced according to Aretakis et al. [52].

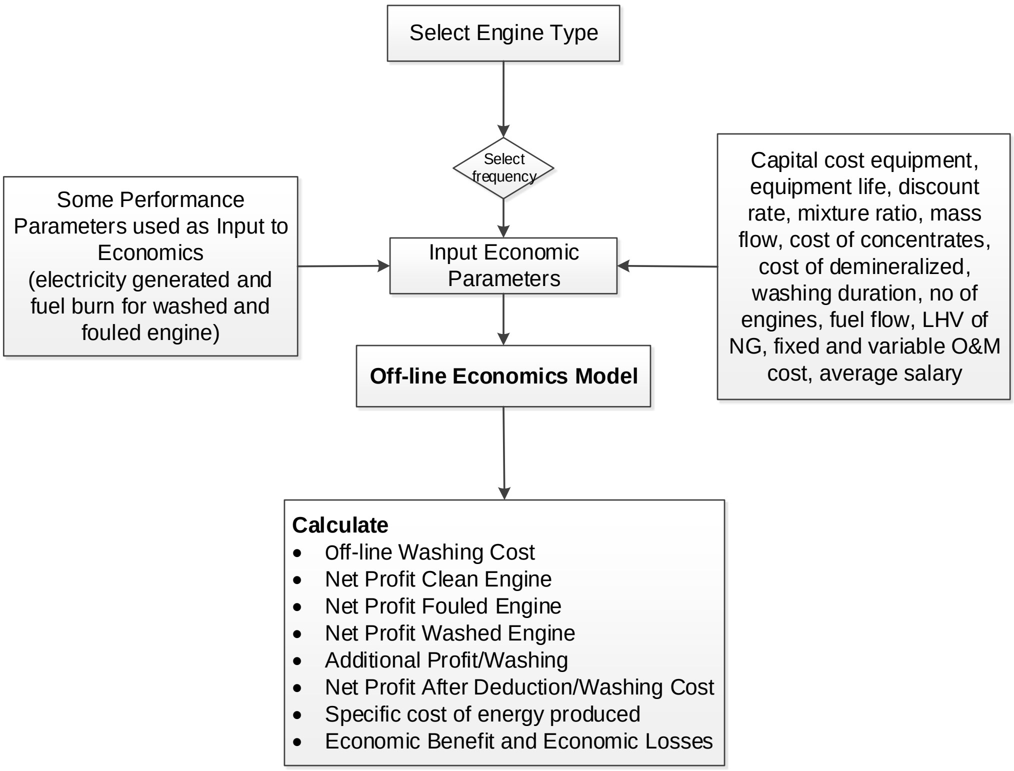


Figure 3-7 Off-line washing economic model

The input model assumptions for the off-line washing are as follows; average monthly salary = \$1,500 [52], O&M cost for GT engine \$17.825/kW/year [89], lower heating value LHV = 43MJ/kg

$$C_{aw} = E_l - E_b \tag{3-45}$$

$$C_{ep} = \frac{C_c + C_{pp} + C_{aw} + C_f + C_{O\&M/GT} + C_i + C_{rf}}{P_{\Delta T}} \tag{3-46}$$

$$P_{\Delta T} = P_{fl} \times hrs \tag{3-47}$$

$$SCEP = \frac{Cost\ per\ energy}{P_{\Delta T}} \tag{3-48}$$

$$(TP_{\Delta T}) = \left(MP - C_{ep}\right) \times P_{\Delta T} \tag{3-49}$$

$$(TP_{\Delta T}) = LCOE_{avg} \times WEP_{\Delta T} - \left(C_{aw} + C_c + C_f + C_{O\&M/GT} + C_{pp}\right) \tag{3-50}$$

$Where;$

$$E_l = C_{off-line} + C_{Pl} + ff_b + P_{loss} \tag{3-51}$$

$$E_b = B_{recovery} + B_{fs} \tag{3-52}$$

Other off-line washing economic equations include the following;

$$NP_{we} = COE_w - COF_w \tag{3-53}$$

$$NP_{fe} = COE_f - COF_f \tag{3-54}$$

$$AP_w = NP_{we} - NP_{fe} \tag{3-55}$$

$$NP_{AD\ washing\ cost} = AP_w - C_{offline} \tag{3-56}$$

3.7 On-line Washing Optimization Model

On-line washing optimization model is used to evaluate compressor washing performance and economics for different engine sizes using non-dominated sorting genetic algorithm (NSGA II) approach. The algorithm for on-line washing is capable of estimating the net profit after deducting the washing cost and the operation and maintenance cost of the washing equipment at an optimum frequency. The NSGA II has three features that need to be followed and these are; non-dominated sorting that are sorted according to the level of non-domination, elitism being used for storing the solutions while the crowding distance is used for maintaining the diversity of the solutions.

To determine the fitness of a function there is need to rank the solutions. There are different ways of ranking used to rate the population in terms of Pareto dominance. Goldberg [90,91] proposed a method called non-dominated sorting. It involves finding all the Pareto optimal points within a population, rank them one and remove them [91]. After removing rank 1, the remaining population are treated and found non-dominated individuals and given a name rank 2 and removed them again, and the same process applied until all populations are ranked. This method of ranking has been implemented by Richardson et al. and Ritzel et al. [92,93]. Another ranking method has been proposed by Fonseca [94] called multi-objective ranking. The method involves that every single individual is given a rank according to how many individuals dominate it. For non-dominated individuals in the scheme are given a rank 1, if other individuals dominate rank 1 then it is given a rank of that numbers plus one individual. This method gives higher ranking and penalises areas of high density solutions. A typical method used is to determine which individuals are dominant (Pareto solutions) and which are dominated (non-optimal solutions). Pareto solutions are called Rank 1 solutions and the two ranking methods are shown in Figure 3-8 while other solutions are ranked using the number of solutions which dominate them [95]. Based on the two methods highlighted the non-dominated sorting method developed by Goldberg et al. was chosen for the analysis.

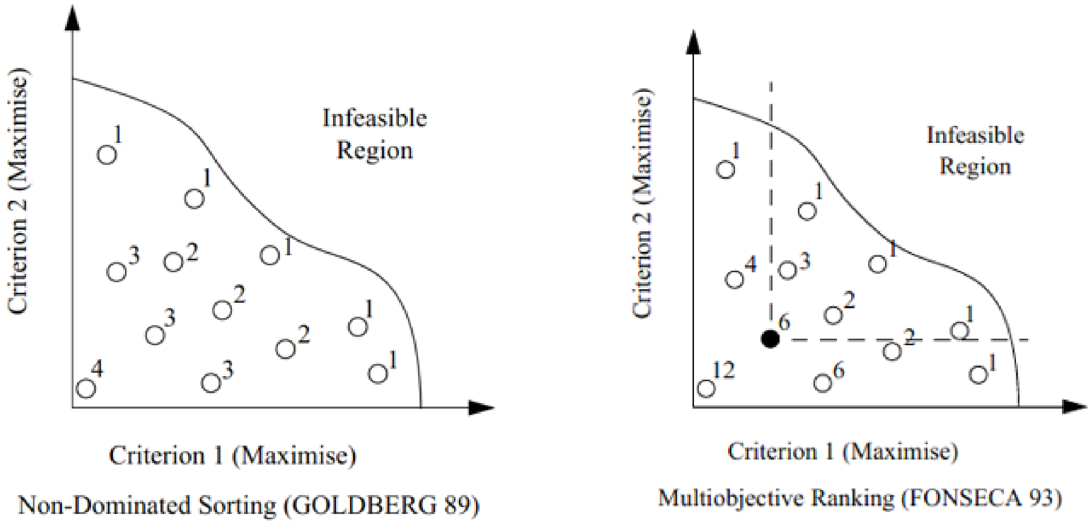


Figure 3-8 Goldberg and Fonseca ranking method [90,94]

3.7.1 Design Operation Procedure

The NSGA II is divided into; initialisation of the population, sort the initialized population, evaluation of the fitness function or criteria, begin the evolution process, non-domination sorting mod, tournament selection, genetic operator, replace chromosome and display the final results. A full description of how the NSGA II operates are as follows [95–102]:

- Select a starting population of chromosomes for a problem in the first generation and this has to be a systematic guess.

- Random values within the stated range of population are initialized. The decision variables are been initialized based on minimum and maximum likely values. A random number has been created that is chosen between the upper and lower possible values for each decision variable.
- Evaluate the selection of population on each criterion. The chromosomes of the generated population is decoded into model input and mapped into forms accepted by the model. All the criteria are assessed and returned the encoded model outputs as chromosomes.
- The current population are sorted by means of non-domination-sorting in order to determine for each individual population the rank and the crowding distance equivalent to the position in the front they belong. Individual population at the first front are assigned a rank 1 while individual at the second front are given a rank 2 and the process continues accordingly until all the population has been ranked. At this phase the rank and the crowding distance for each chromosomes is added to the chromosomes vector.
- The selection process employed here is a binary tournament selection of two individuals selected at random and the fitness values are compared. The best fitness with highest fitness value among the individuals is selected as a parent. The tournament selection process continues until the pool size is full. A pool size is determine based on the number of parent selected. The tournament selection uses information on ranking and the crowding distance from the chromosomes vector. Selection is done on the basis of ranking an individual and if individual of the same rank are met, crowding distance are compared and the selection criteria are based on the lower rank and higher crowding distance.
- Parent chromosomes are utilized to produce off-springs with the help of genetic operators (crossover and mutation).
- Evaluate the fitness functions of the off-springs population on each criterion in the first generations.
- Combined the population of parents and off-springs with the size twice the population size.

- Sort the population of the generated parents and off-springs by non-dominated sorting method in order to determine its fitness.
- Replace chromosomes are based on ranking and the crowding distance, the front is added one by one until the complete front is reached which is higher than the population size. The chromosomes in the front is added consequently to the population based on the crowding distances.
- Create the second generation using the 1st individual population from the combined population of parents and off-springs or copying the best solutions by elitism.
- The number of generation increases until it reach the maximum number of generations defined by the user and then the algorithm terminates.

The fitness function equations selected for optimization are stated using equation (3-57) to (3-62);

$$C_{OM} = W_{fl} \times C_f \times \left({}^{EOH}/_{Pd}\right) + C_m \tag{3-57}$$

$$NP_{after\ deduction} = \ AP_w \ - C_w \tag{3-58}$$

$Where;$

$$AP_w = NP_{we} - NP_{fe} \tag{3-59}$$

$$NP_{we} = COE_w - COF_w \tag{3-60}$$

$$NP_{fe} = COE_f - COF_f \tag{3-61}$$

$$C_w = C_{OM} + C_{pw} \tag{3-62}$$

3.8 Off-line Washing Optimization Model

The off-line washing optimization model similar to on-line washing model that uses non-dominated sorting genetic algorithm approach in order to find an optimum washing frequency. The algorithm for off-line washing estimates the net profit after deducting washing cost and the total cost related with off-line washing at an optimum frequency. The fitness functions selected from the model for optimization are highlighted from equations (3-63) to (3-64).

$$C_{off-line} \ = C_c + C_f + C_r + C_m \tag{3-63}$$

$$NP_{AD\ washing\ cost} = AP_w - C_{offline} \tag{3-64}$$

3.9 Software Programme for Compressor Washing/Optimization

This is the section where all the models are combined together and result to a computer programme for compressor washing/optimization shown in **Appendix A**.

4 ENGINE EVALUATION AND ECONOMIC ANALYSIS OF GT ON-LINE COMPRESSOR WASHING

This chapter presents an engine performance evaluation of the actual machine data of frame 7FA and economic analysis of GT on-line compressor washing. The study investigates the economic viability of compressor washing for different engines from light to heavy-duty engine for on-line washing from 72hrs to 480hrs frequency with the same level of time based degradation. A time-based recovery has been applied which determines the magnitude of the power output increase for the varied wash frequency. The economic analysis of these includes an assessment of the return-on-investment, dynamic payback period, net present values, net profit after deducting washing cost, annual savings and additional profit due to washing. A break-even selling price model has been developed and applied to determine the cost of producing electricity of each respective engine.

The main objective of this chapter is to demonstrate the economic viability of on-line compressor washing. Most studies focus on the immediate cost benefit analysis without taking into account the capital investment and the variation in value for different engine power capacity. This is particularly important, as the cost of washing equipment is not linearly related to the size of the engine or capacity. This brings about differences in the viability of on-line compressor washing, also in the context of the life of the equipment considered in this study. Apart from washing frequency variation demonstrated in other studies, a key aspect highlighted here included changes in the effectiveness of washing that is not constant. A key aspect highlighted is that effectiveness of washing changes in a time base degaration from a high percentage of power recovery to a lower percentage value. Another aspect considered is quantifying the compressor fouling degradation using machine data taking into account comparing both standard and extended methods. The study also presents a model that calculates the break-even selling price of electricity (BESP) or levelised cost of electricity (LCOE) for different engine capacity at clean, fouled and washed condition. This is important, as different sizes of engine have different cost of electricity generation. In an effort to demonstrate the viability of online washing for different engine capacities, the study answers the following questions:

- What is the average yearly cost of fouling for different engines for a period of 8640hrs (engine hours of operation)?
- What are the cost implication/ benefit of washing for a period of 8640hrs of operation for different engines?
- Does the performance benefit outweigh the economic cost for different engines (viability)?
- What are the payback period, NPV, annual savings and internal rate of return when washing is applied?
- How does the economic viability vary with increase in the number of engines and for different levels of degradation?
- What is the break-even selling price of electricity for different engine capacity at clean, fouled and washed condition?

4.1 Engine Description

The gas turbine engine used for this research is a frame 7FA class that has been developed by General Electric (GE). The advance GE frame 7FA class has been successfully operated in different applications. It is the first GE that reached 55% thermal efficiency in a combined cycle arrangement with very low emissions value of single digit of CO and NO_x. The GT engine has a reliability of 99.2% with a fast capability of 160MW in 10 minutes. The GT engine is a single spool heavy-duty engine that produces nominal power of 211MW in a single cycle plant arrangement with a thermal efficiency of 38.5%. The engine consists of 14-stage axial compressor with an overall pressure ratio of approximately 15.2, radial compressor diffuser with 3-dimensional aerodynamic airfoils. The engine also consists of dry low NO_x (DLN) combustion system with a model based control system [103]. The GE 7FA class engine has a fuel flexibility and can operates in either natural gas or distillate fuel which gives the operator an opportunity to choose the lowest available fuel price.

The power plant investigated experiences four seasons in a year 1. The research work focus on 2 - GE 7FA class units (Engine 1 and Engine 2) operated for about 4 years in a combined cycle arrangement. Figure 4-1 is a single-spool arrangement used for power generation application.

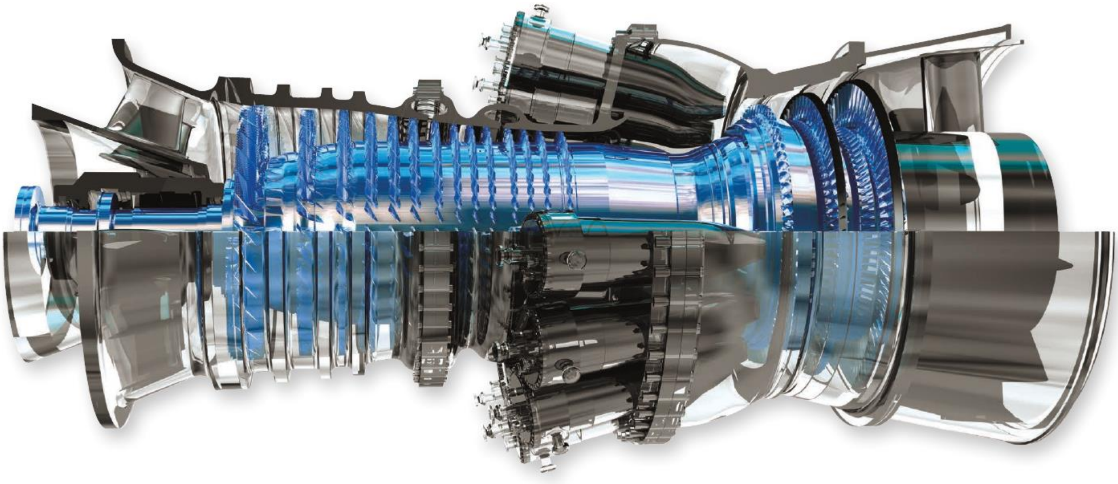


Figure 4-1 GE frame 7F.05 single-shaft heavy duty engine [Courtesy of GE]

4.2 Evaluation of Measured Data

With the help of sensors the engine data can be measured and recorded. The data for the GT engine investigated has been recorded every 5 minutes using gas turbine’s data acquisition system. The measurable parameters are; ambient pressure and temperature, relative humidity, active power, compressor inlet pressure (CIP) and temperature (CIT), compressor outlet pressure (COP) and temperature (COT), shaft speed, exhaust gas temperature (EGT), variable inlet guide vane (VIGV) and fuel flow shown in Figure 4-2. Other parameters that has been calculated are; turbine entry pressure and temperature, turbine outlet pressure, thermal efficiency, heat rate and compressor efficiency. The parameters can be calculated using equations (3-1) to (3-9).

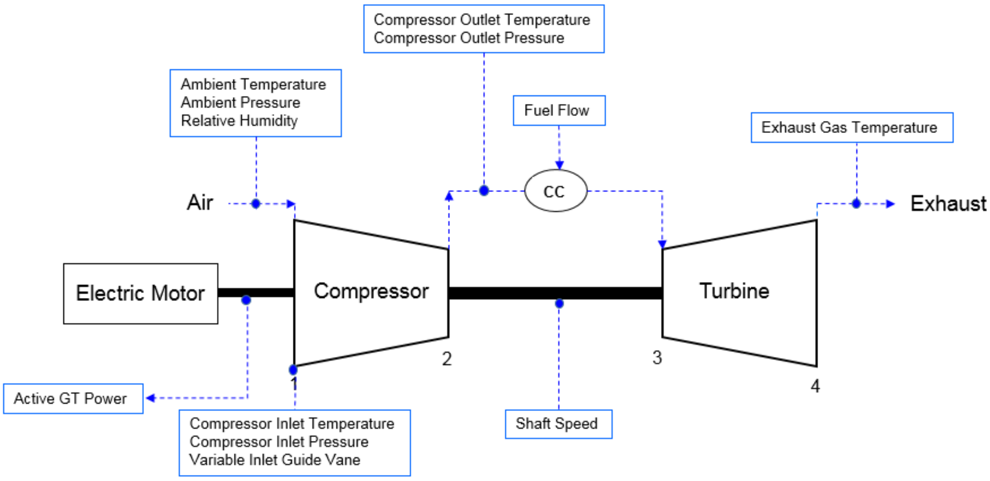


Figure 4-2 Engine schematic diagram GE 7F.05

4.3 Measured Data Investigation

This investigation covered a period of about four years with several off-line washings only. Based on the available information provided on this engine, in which the performance was monitored during the operation, there were about **19 events** of off-line washings for the period of 4 years of continuous operation. The measured engine parameters are indicated in Table 4-1. Figure 4-3 shows the variation of the T_1 over the seasons for the year 1, from the average coldest temperature of 259K in the winter month to the hottest average temperature of 322K in the summer.

Table 4-1 Measured and calculated engine data

Engine Parameters	Values
Ambient temperature (K)	258 - 310
Ambient pressure (kPa)	98.97 – 105.97
Exhaust gas temperature (K)	875 - 920
Fuel flow (kg/s)	10.85
Calculated Parameters	
Thermal efficiency	38%
Turbine entry temperature (K)	1539
Compressor efficiency	86%
Overall pressure ratio	15.2

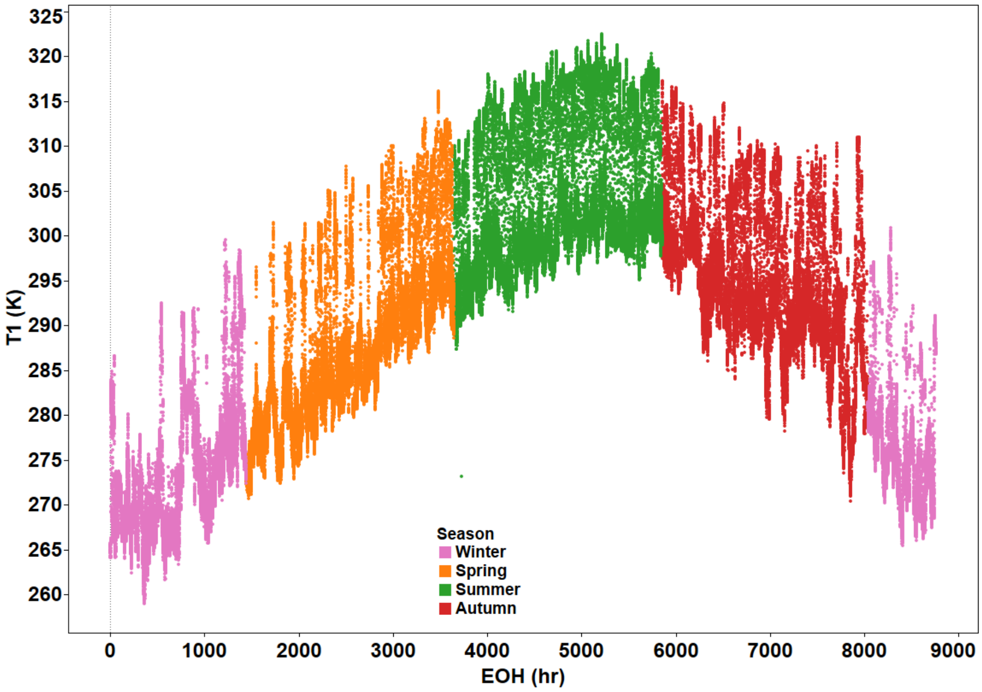


Figure 4-3 Temperature variations for year 1

Figure 4-4 shows the active power against time for a year 1 of operation. This shows a data concentration of the active power lies between 100MW – 180MW. Other data points may be due to shut-down, unloading, sensor fault, or even transient operation. It is clearly observed in Figure 4-4 at a lower inlet temperature from (259 – 300K) and Figure 4-5 at temperature from (257 – 286K) in winter it results in a higher engine performance (165–185MW). At higher T_1 in summer, the density of air drop and less mass flow is been ingested into the engine, this result to a sharp drop in power output of the engine to about 145MW and thermal efficiency to about 36% (Figure 4-6).

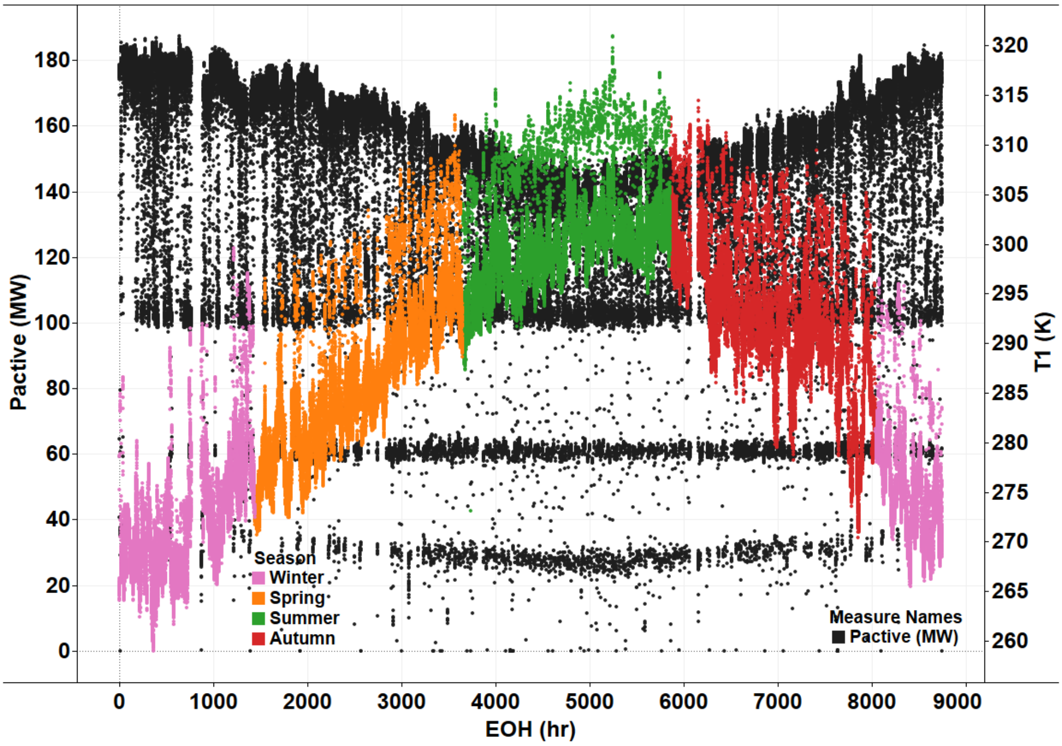


Figure 4-4 Active power and T1 against time (seasons)

In order to maintain a constant power output, TET and fuel flow have to be increased within the acceptable safe limit. This shows that GT engine maintained fixed EGT in a combined cycle plant arrangement shown in Figure 4-7. The other data in the figure are due to transient operation and sensor fault.

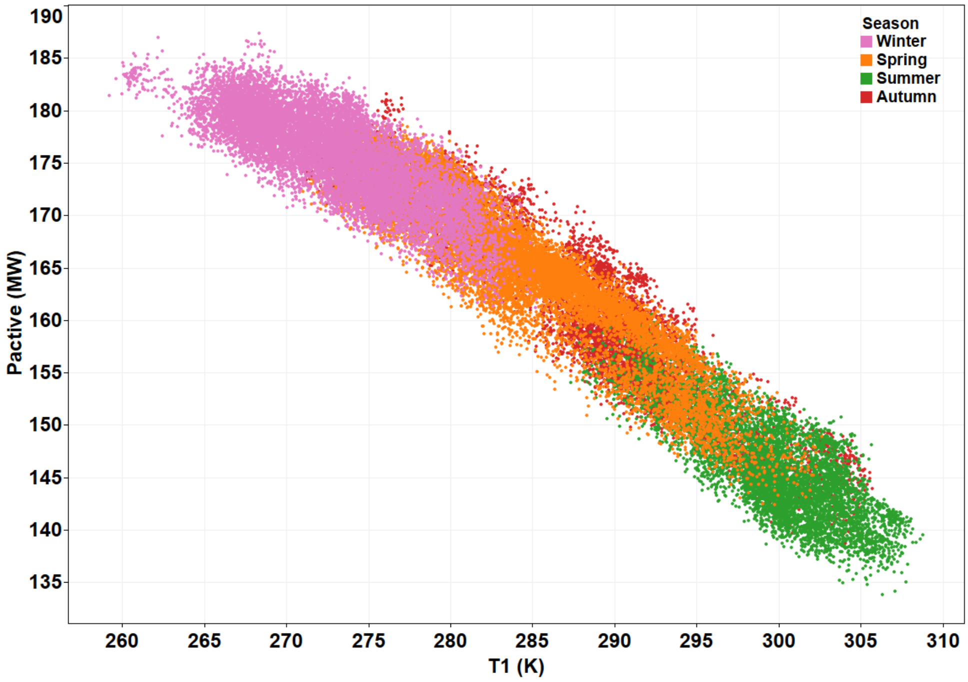


Figure 4-5 Influence of T_1 on corr. Power (VIGV 80 – 84%)

A sharp drop of power output was observed during the raining season, this is also due to higher relative humidity. Humidity increases to 93% during the raining season; this causes higher pressure drop as the filters get saturated with water, and lower inlet pressure (Figure 4-8). This problem causes compressor fouling.

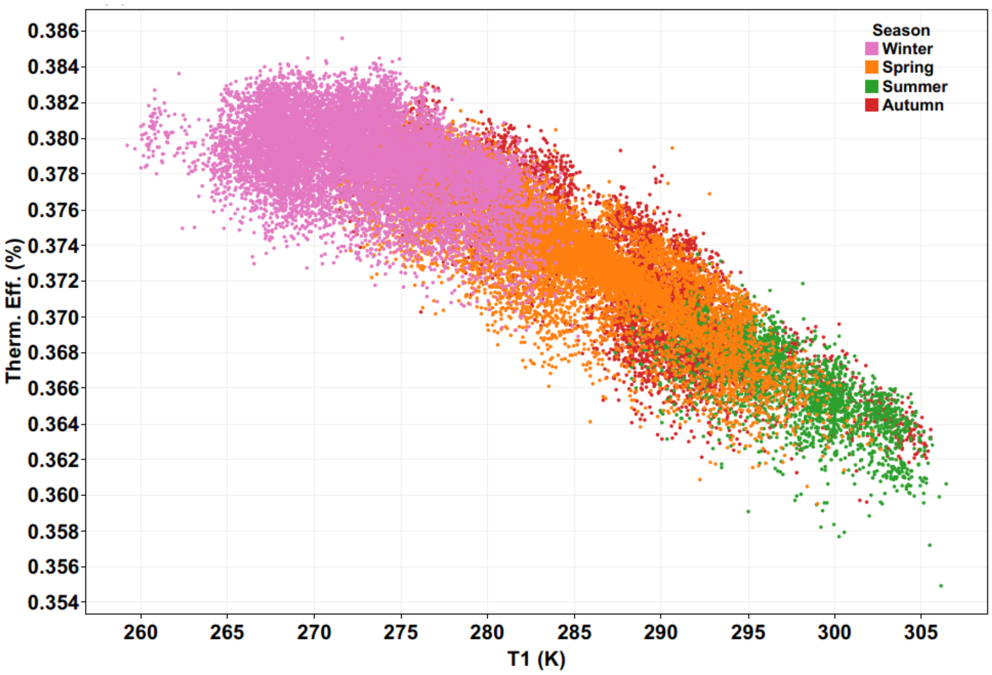


Figure 4-6 Influence of T_1 on thermal efficiency (VIGV 80 - 84%)

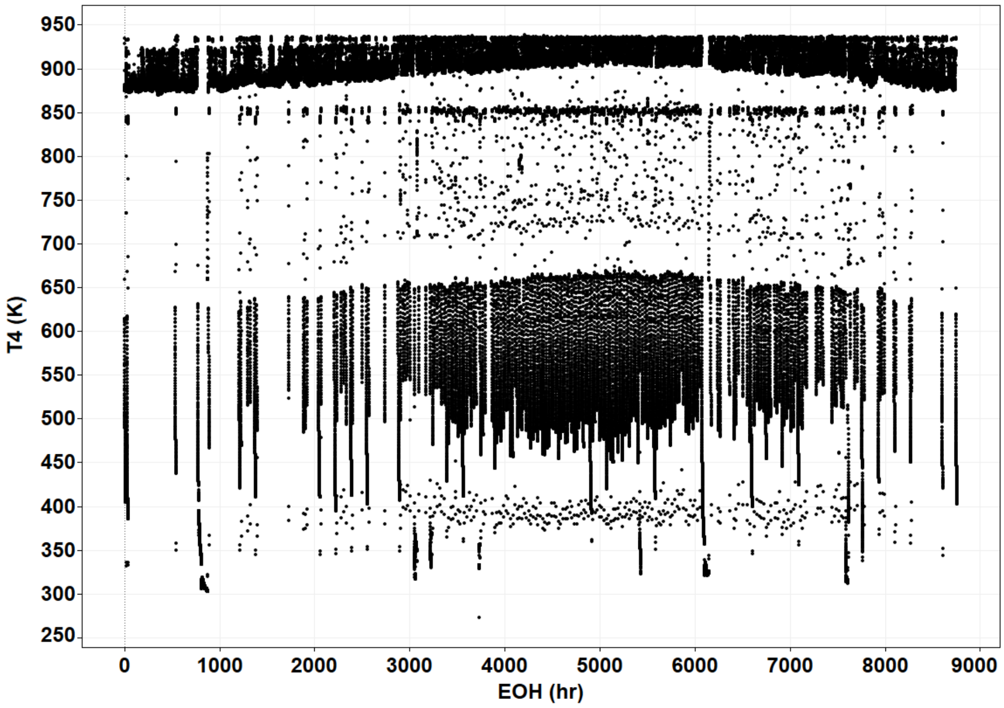


Figure 4-7 Exhaust temperature against engine EOH for year 1

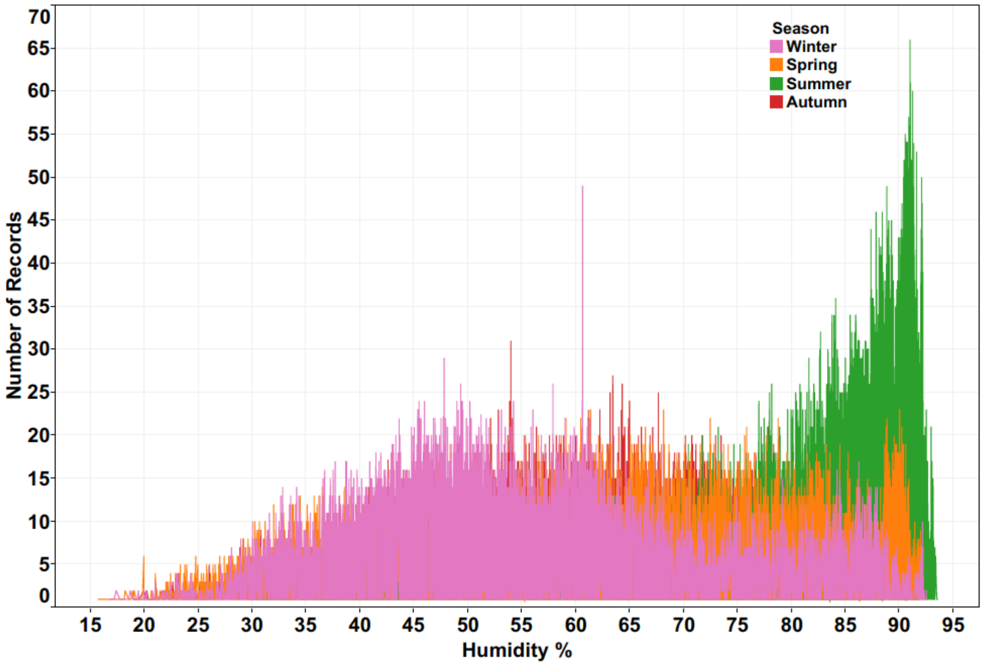


Figure 4-8 Influence of humidity for year 1

4.3.1 Data Correction to ISO Conditions

A performance data for the (Engine-1 that washed off-line only) were analysed. The study investigates the GT application for power generation. Despite all the instruments and sensors for high accuracy in collecting the data, the values present a scatter measurement which is very difficult to analyse directly for the performance losses [104–107]. However, calculating the average data did not help seriously, this may be due to a change in the operating conditions. To use the data more accurately, it is necessary to correct the data to the reference conditions (ISO condition: T_a = 15℃, P_a = 101.325 kPa, relative humidity = 60%) in order to exclude the uncertainties and scatter of measurements [32]. This method does not include the relative humidity. However, it is applied for extended correction. The operating condition of a GT engine is different for every location and with different ambient conditions, and is subject to data correction [5,104,108]. The standard data correction equations used were highlighted previously according to equations (3-10) to (3-15).

A reasonable decrease of the scatter measurement was obtained in Figure 4-9 compared to the active power of the machine data. As can be seen the average corrected power is higher than the active power, this is due to the inlet temperature and pressure effects taken into consideration. It can also be observed that the period in which the active power is optimum lies in the winter, this is due to lower CIT. However, a higher CIT results in a lower active power.

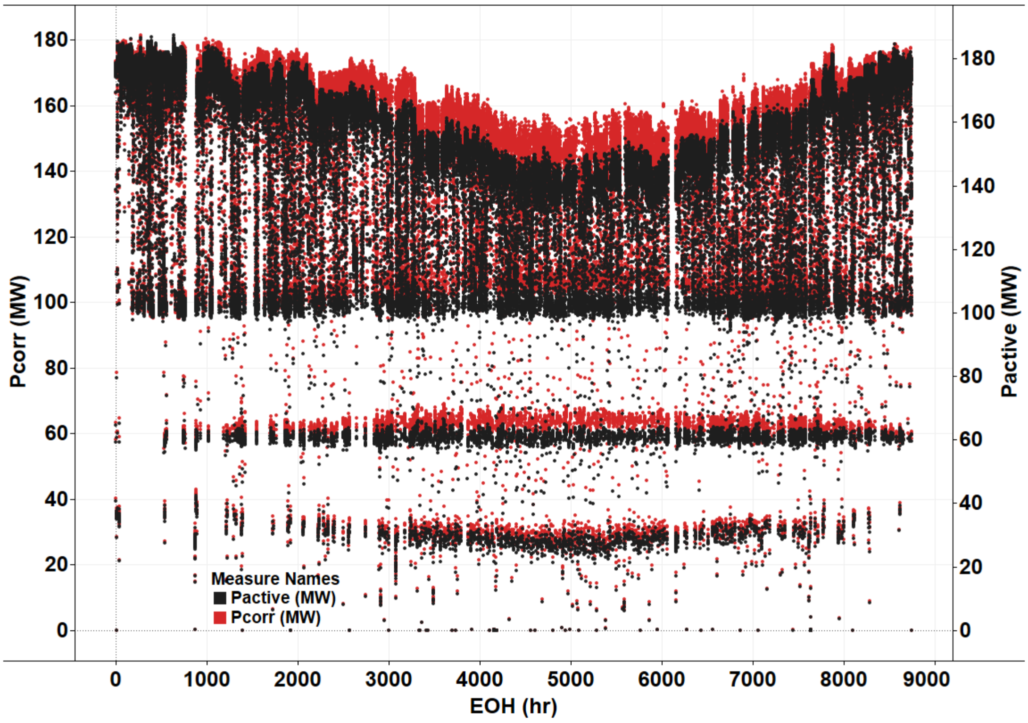


Figure 4-9 Influence of data correction (standard)

4.3.2 Extended Data Correction to ISO

This correction considers not only the external effects but other factors that are not influenced by external effects [32]. The most important and crucial effects are: ambient temperature and pressure, and variable inlet guide vane angle, load variation, fouling of the compressor, fuel change and degradation of the entire unit. Veer et al. [32] present a method for correcting power output, that can be used for other engine parameters sensitive to degradation. It has been proven including the relative humidity for correcting the data to ISO condition help in eliminating the scatter measurements further. It is significant to include relative humidity for the extended data correction, especially at the environment that experience higher ambient temperature, this increases the accuracy of the data. A method that combined the 3 effects has been developed by Igie et al. [51] using equations (3-16) to (3-21).

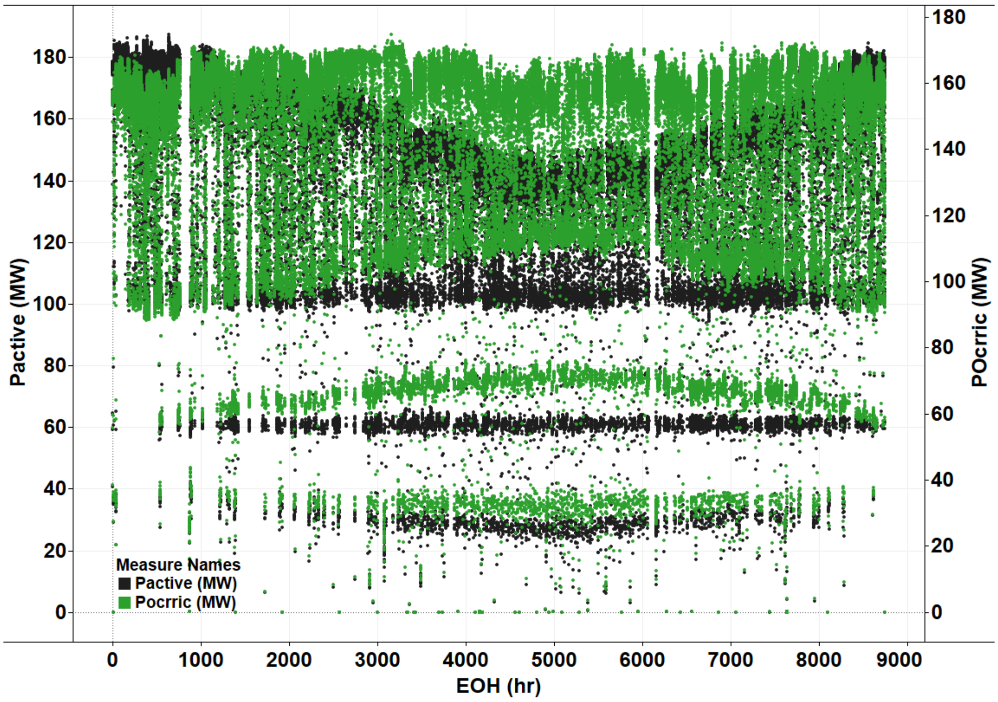


Figure 4-10 Influence of data correction (extended)

To use the data more accurately, relative humidity has been included for the extended (Figure 4-10) which shows a significant increase in corrected power output compared with the active power. As can be seen the average corrected power (extended) is higher than the active power, this is due to the effects of inlet pressure, temperature and relative humidity taken into consideration. Figure 4-11 shows the importance of extended correction over the standard one. This difference is due to the influence of humidity. It is also important to state that, corrected power output is approximately constant for extended data correction.

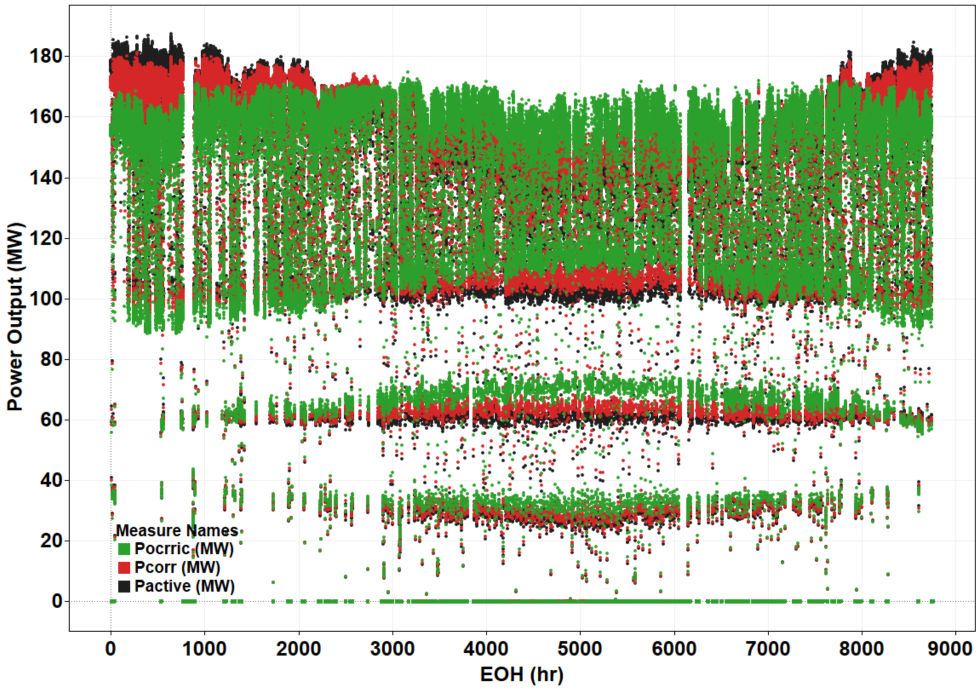


Figure 4-11 Influence of data correction (extended and standard) on active power

4.3.3 Engine Degradation (Extended Method)

Extended data correction makes it more reliable to demonstrate degradation that occurred along the equivalent operating hour. Load is controlled by VIGV and this controls the amount of fuel fed to the engine. This method includes the relative humidity in correcting the data to the reference conditions and this demonstrated and estimated previously. Figure 4-11 shows the importance of extended correction that differs from the standard one. This difference is due to the influence of relative humidity.

A filter of the engine data used has been selected (to find the control mode of the engine) using Tableau software at VIGV opening from 80% - 84% for the analysis (Figure 4-12). This selection is based on the concentration of data (approximately 36,370 occurrences of the VIGV ranges selected) shown in Figure 4-13. To demonstrate degradation occurred along the year, corrected fuel flow has been used as the handle and the values ranges from 8.9kg/s to 9.1kg/s based on the corresponding IGV opening selected. However, Turbine entry temperature and corrected power output were also selected independently as the handle with the VIGV opening in order to demonstrate degradation that occurred during operation when using different handle. The same procedure has been applied for corrected fuel flow against fuel flow between 80% to 84% VIGV opening, and this shows an average corrected fuel flow of 9.05kg/s shown in Figure_Apx A-1.

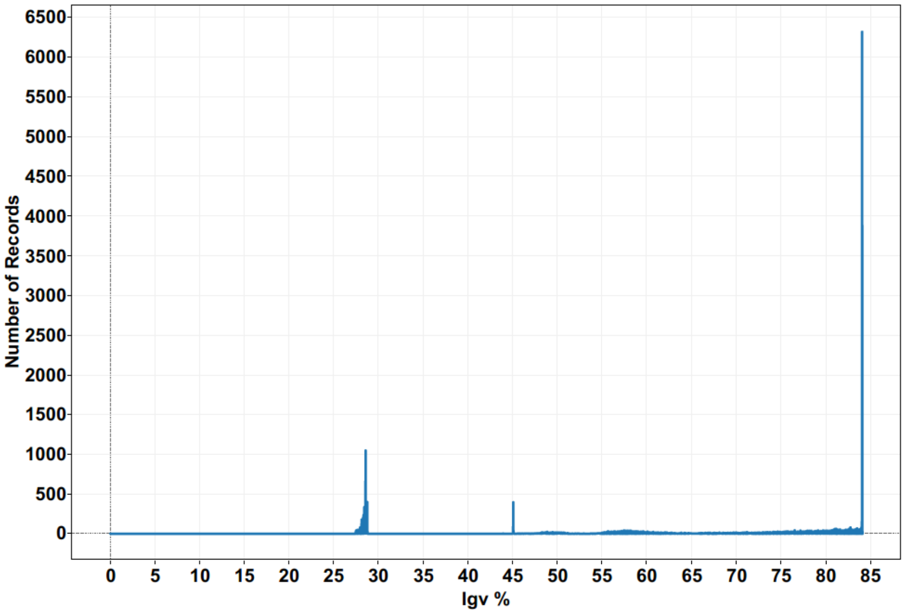


Figure 4-12 Data concentration of VIGV

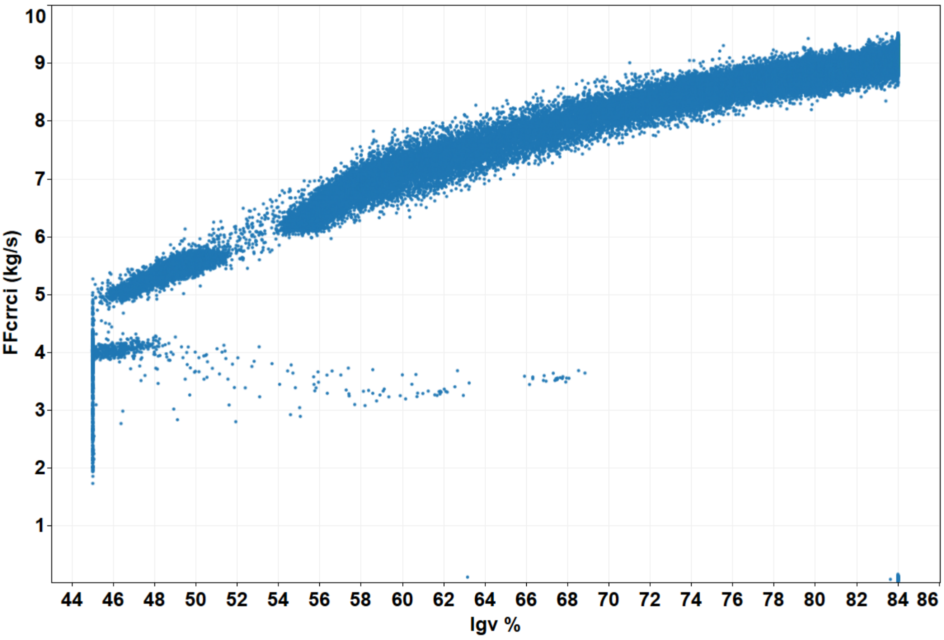


Figure 4-13 Corrected fuel flow against IGV per year

Seven degradation trend lines were presented that covered one year of operation with 6 off-line washing shown in Figure 4-14. There are 7 period in the 1st year and each period represent an hours of GT operation before an off-line washing. The gap between each period (different colours) represents an off-line washing duration.

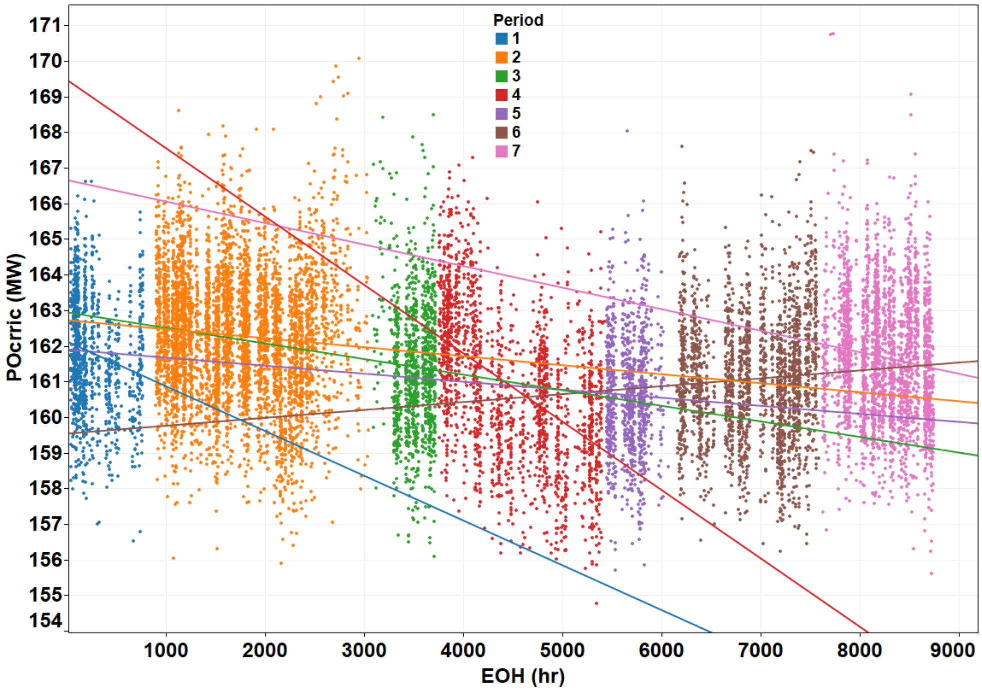


Figure 4-14 Trend lines for corrected power along the EOT for year 1 (VIGV 80 – 84%, FF_{corr} 8.9 – 9.1kg/s)

Each period has a different degradation trend line which depends on the rate of deterioration of the engine. Improvement were observed after each washing except the 6th off-line, this could be due to sensor fault. As expected the average corrected power output before off-line washing takes place were lower than after off-line washing, this indicates the effectiveness of washing procedure. Periods 1-5 and 7 shows negative slopes which were used for the analysis while period 6 has a positive gradient and cannot be used for the analysis. Adjusting the VIGV and corrected fuel flow higher shows more negative gradient, this is due to reduced data points which also reduces the root mean square (RMS) value. All trend lines were assumed to be linear and this represents a linear equations. The 1st to 7th trend lines with the exception of the 6th were extended for each period of operation to 8640th hours. The corrected power has now been estimated at each

1 hour of operation for a period of 8640th hour. An average trend line were obtained for each year. The same method applied and estimated for other years of operation. Figure 4-15 shows the corrected fuel flow against EOH, with the corrected power output at 160MW to 166MW as the filter, these show positive slopes from period 1 to 6 and this indicates a sign of degradation due to over consumption of fuel burn.

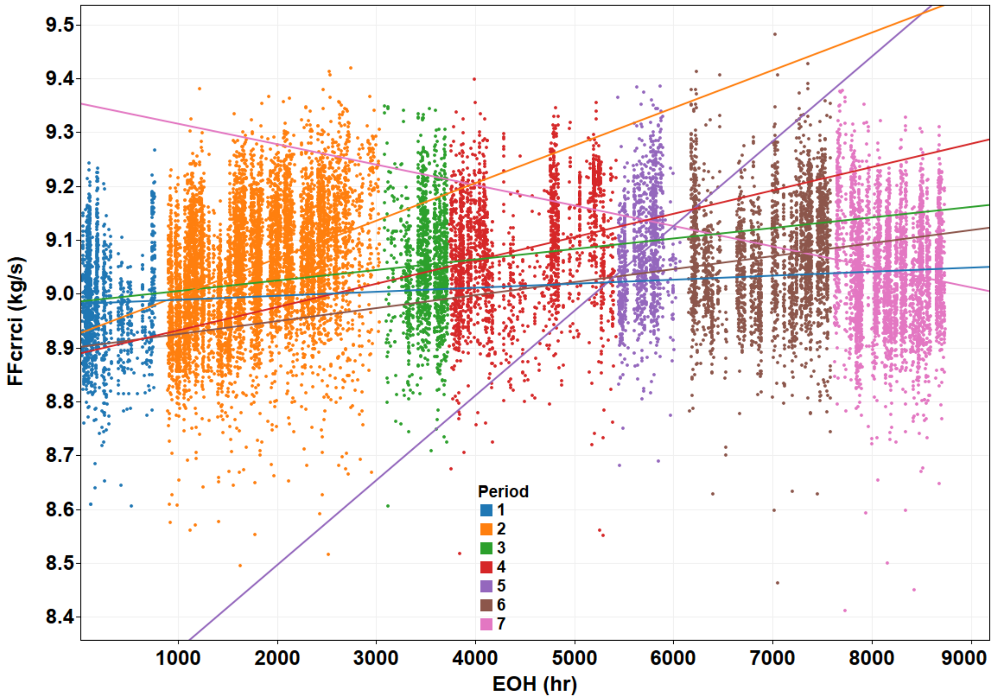


Figure 4-15 Trend lines for corrected fuel flow along the EOT for year 1 (VIGV 80 – 84%, P_{crcit} 160 – 166MW)

To analyse the effect of degradation on thermal efficiency of the engine, VIGV filter and corrected fuel flow have also been selected as the handle shown in Figure 4-16. This shows a decrease in efficiency for about 6 periods of each corresponding degradation trend line and this is also an evidence of degradation. Figure 4-17 shows the percentage degradation trend lines for the 15 periods (negative gradient only) of operation of 4 years with only off-line washing. This shows 6 degradation trend lines for the 1st year with the highest hours of operations between shutdown at 2279hrs and lowest hours of operation at 650hrs, 3 degradation trend lines for the 2nd year with the highest hours of operation at 3783hrs and lowest hours of operation at 2257hrs.

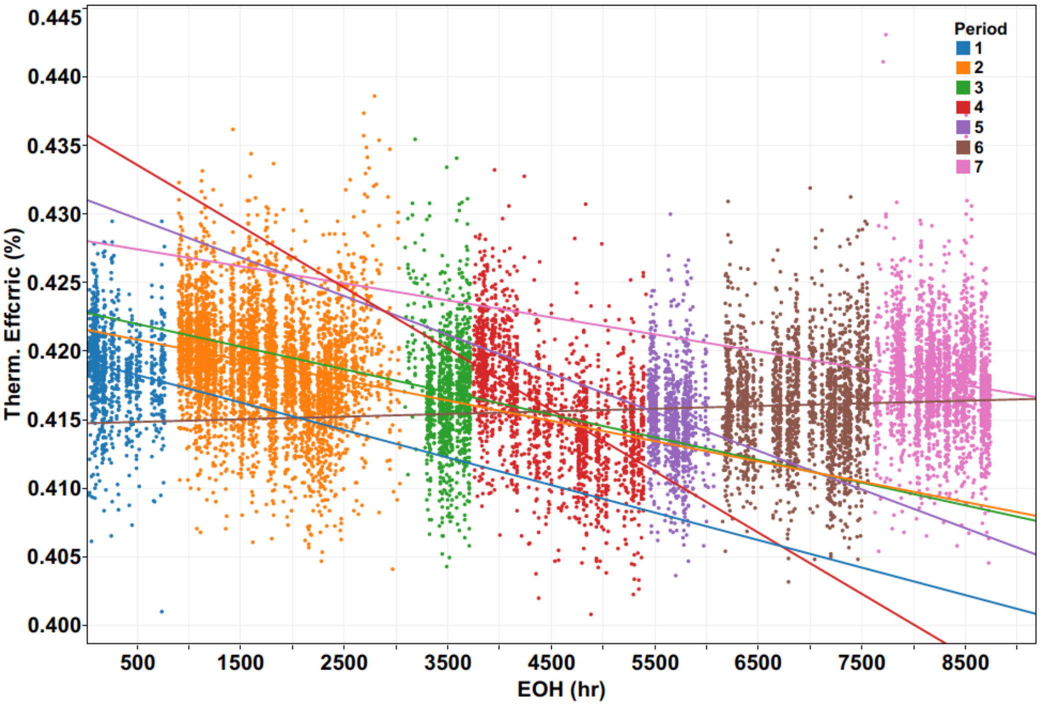


Figure 4-16 Trend lines for thermal efficiency along the EOT for year 1 (VIGV 80 – 84%, FF_{corr} 8.9 – 9.1kg/s

However, for the 3rd year there are 4 degradation trend lines with highest hours of operations at 3014hrs and lowest of 1001hrs, while on the 4th year only 2 degradation trend lines are available with highest at 798hrs and lowest at 670hrs. Since the corrected power outputs are calculated at each 5-minutes interval of EOT for a total of 8640hrs of operation, it is now easy to calculate the rate of degradation at each EOT for the duration of one year. It was found that the highest percentage degradation in period 18 with 22.6% degradation while the lowest is at period 5 with degradations are of 1.2% shown in Figure 4-17. This shows that the percentage degradation for the extended correction are lower and realistic. Figure 4-18 shows the percentage degradation for each year with the 1st year has the lowest percentage degradation with an average value of 4%, followed by 3rd and 2nd year, while the average highest percentage degradation falls on the 4th year with an average value of 15%. Figure 4-19 shows the average degradation trend line for the 4 years of operation, with the average percentage degradation value of 7.2% at the 8640th hour of operation. A step by step procedure for obtaining a degradation trend line equation for power output with respect to equivalent operating time and calculation of the cost of revenue due to fouling has been presented in Figure 4-20.

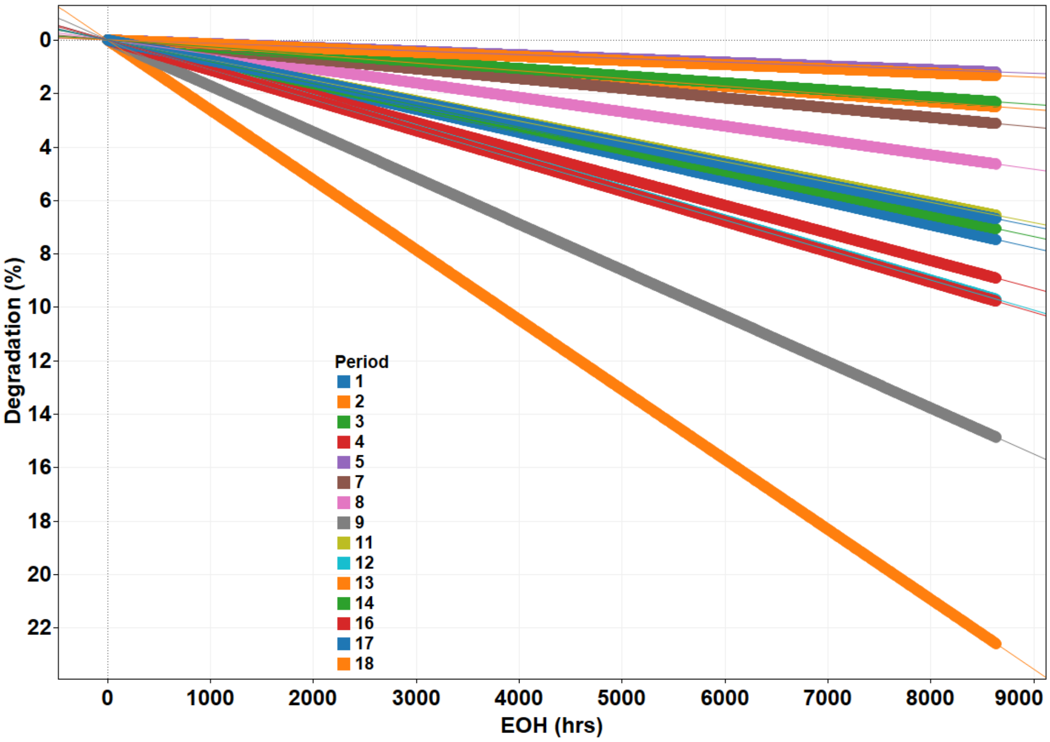


Figure 4-17 Degradation trends for all period for 4 years of operation

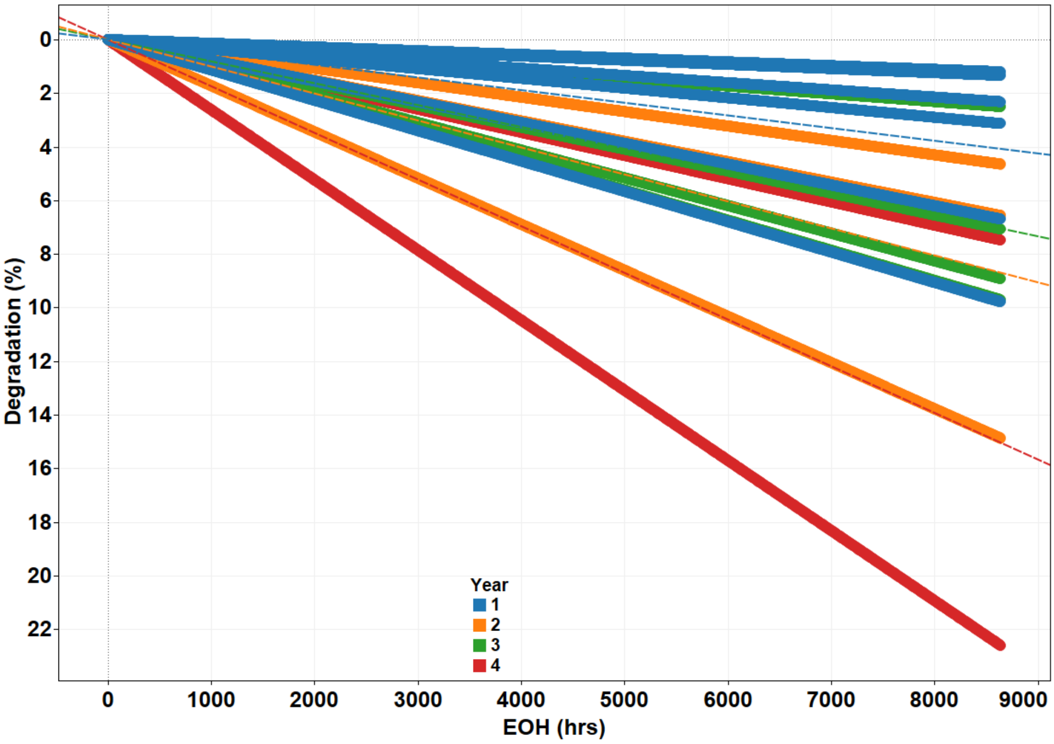


Figure 4-18 Average degradation trends for every year of operation

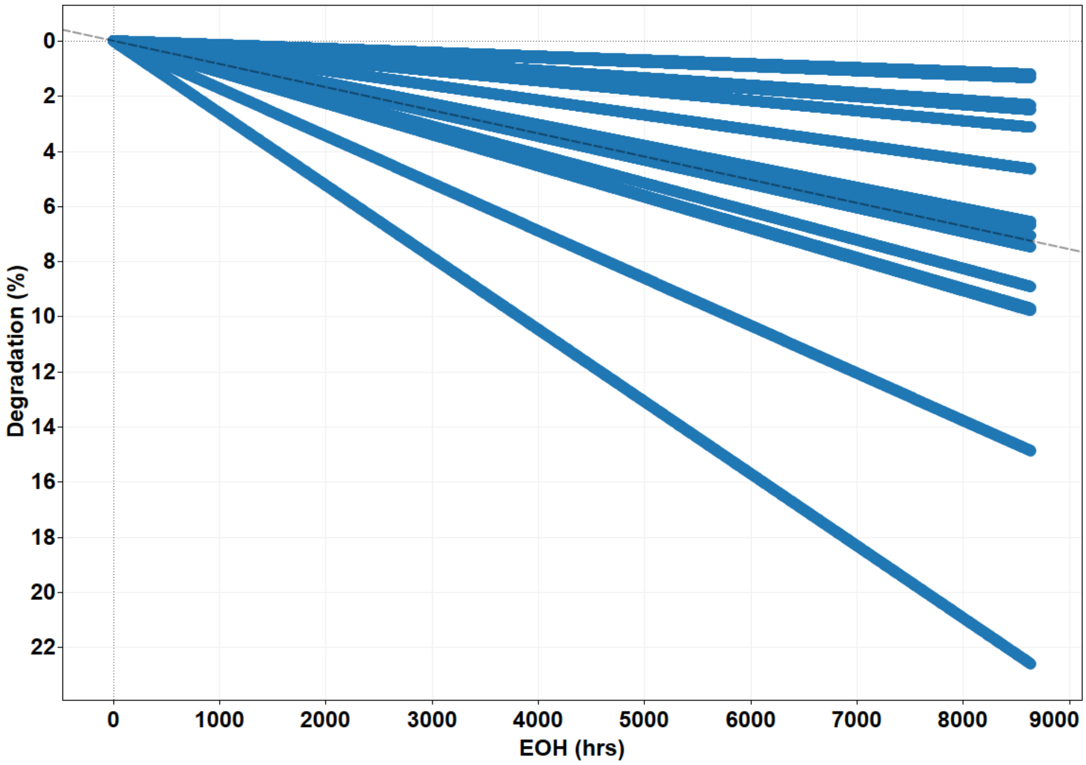


Figure 4-19 Average degradation trends of 4 years of operation

4.3.4 Engine Degradation (Standard Method)

Corrections of the data by a standard method have been done to analyse the data for the performance losses. Several gas turbine engines load are controlled by use of the variable inlet guide vane (VIGV) which controls the mass flow, this also control the amount of fuel burn into the engine. A filter has been selected (in order to find the control mode of the engine) using Tableau software at VIGV opening from 73% - 84% for the analysis, this selection is based on the concentration of data (approximately 55,600 occurrences of the VIGV ranges selected), higher ranges of VIGV has been selected due to influence of ambient temperature difference in the summer. A corrected fuel flow have been selected as the handle in order to see the changes on the power output (degradation) along the equivalent operating time. Values selected for the corrected fuel flow range from 8.8kg/s to 9.2kg/s. This selection is based on the average corresponding values of the VIGV opening from 73% - 84% shown in Figure_Apx C-1.

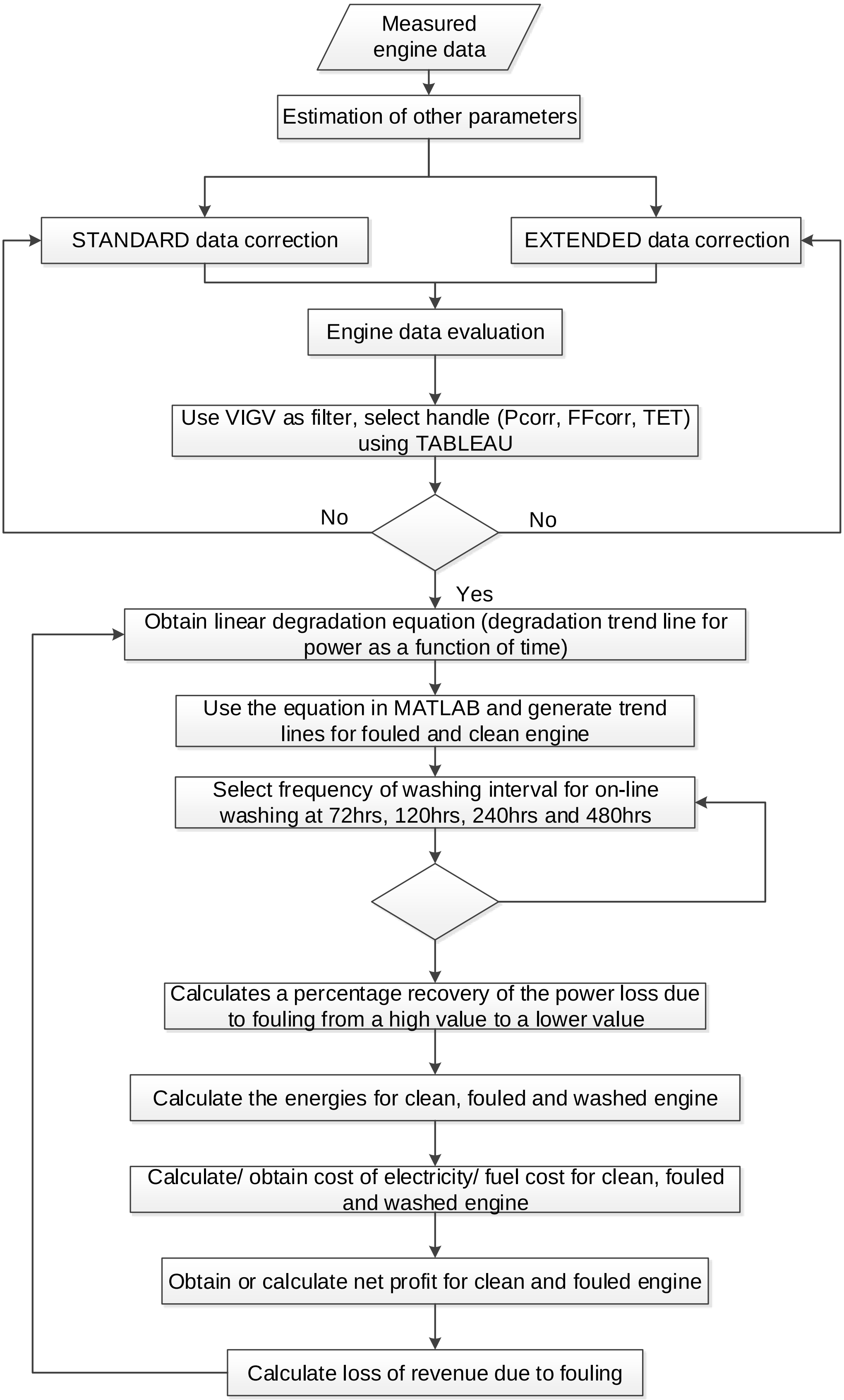


Figure 4-20 Flowchart for obtaining degradation equation and cost of fouling

Corrected power output and turbine entry temperature were also selected separately as the handle together with the VIGV opening at 73% to 84% to demonstrate degradation that occurred during operation. The same procedure has been applied for corrected fuel flow against fuel flow between 73% to 84% VIGV opening, and this shows an average corrected fuel flow of 9.18kg/s shown in Figure_Apx C-2.

Figure_Apx C-3 shows the trend lines for corrected power output along the equivalent operating time for year 1. This uses a combination of the VIGV opening and corrected fuel flow ranges previously estimated. The trend lines has 5 negative slopes that represent different deterioration rates as well as washing for each period. The gap between each period represents an off-line washing. However, period 6 and 7 represents a positive slope that cannot be used for the analysis. To analyse the effect of degradation on thermal efficiency of the engine, VIGV filter and corrected fuel flow has also been selected as a handle shown in Figure_Apx C-4. This shows a decrease in efficiency of about 5 periods of each corresponding degradation trend line and this is an evidence of degradation. To investigate the effect of degradation on corrected fuel flow, VIGV opening and corrected power output, (160MW to 170MW) has been selected as the handle and the ranges are shown in Figure_Apx C-5. This shows 4 positive slopes, and which indicates a sign of degradation due to over consumption of the fuel burn. A change in the load affects the performance of a gas turbine. If a load increases from part load to full load it raises the power output and fuel consumption, as it degrades for the same level of load the consumption of fuel will be higher. The same procedure have been applied to the 2nd, 3rd and the 4th year of operation and the degradation trend lines for the corrected power output has been obtained.

Figure_Apx C-6 shows the percentage degradation trend lines for the 13 period (negative gradient only) of operation for 4 years with off-line washing only. This shows 5-degradation trend lines for the 1st year as previously highlighted with the highest hours of operations between shutdown at 2125hrs (period 2) and lowest interval of operation at 630hrs (period 5), 3-degradation trend lines for the 2nd year with the highest hours of operation at 2985hrs (period 2) and lowest hours of operation at 320hrs (period 3) this value is very short for the analysis and has been removed. However, for the 3rd year there are 3-degradation trend lines with highest interval of operations at 2954hrs (period 3) and lowest interval of 922hrs (period 1), while on the 4th year there are 3 degradation trend lines with highest at 4208hrs and lowest at 625hrs respectively. Since the corrected power outputs are calculated at each 5-minutes interval of EOH for a total of 8640hrs of operation, it is now easy to calculate and extend the rate of degradation at each EOH for the duration of one year. It was found that the highest percentage degradation is in period 9 with 28.9% degradation while the lowest is at period 1 with degradation of 1.5% shown in Figure_Apx C-7.

A percentage degradation for each year (Figure_Apx C-7) with the 1st year have the lowest percentage degradation with an average value of 12%, followed by the 4th and 2nd year, while the average highest percentage degradation falls on the 3rd year with an average value of 24%. Figure_Apx C-8 shows the average degradation trend line for the 4 years of operation, with the average percentage degradation value of 11.35%. It can be noticed from Figure_Apx C-8 that higher percentage degradation trend lines of more than 20% reduction of output at the end of 8640th hours has been removed, as it is very difficult to experience such high level of deterioration and removing the trend lines is more realistic. It can be noticed from extended results lower percentage degradation trend lines are obtained at the end of 8640th hours, and it is very common to experience such type of deterioration hence using this average trend line in the analysis is more realistic than the standard one.

4.4 The Case Study and Considerations

The engine operational data for fouling degradation in use is that of a heavy duty gas turbine (Engine-1) in which the performance was monitored during its operation. The operation that consists of no on-line washing, and the average trend line obtained for this study is demonstrated in Figure 4-19**.** The reductions in power output with respect to time implemented in this study is a result of the extensive analysis that accounts for the isolation of the effects of inlet conditions demonstrated previously (compressor inlet temperature, pressure and relative humidity) and bias effect of power setting (load variation). Figure 4-21 indicates the degradation trend from the study that is applied to different power capacity/engines as indicated. Applying this extrapolated degradation trend (extended) amounts to 7.2% reduction in the power output in 8640hrs.

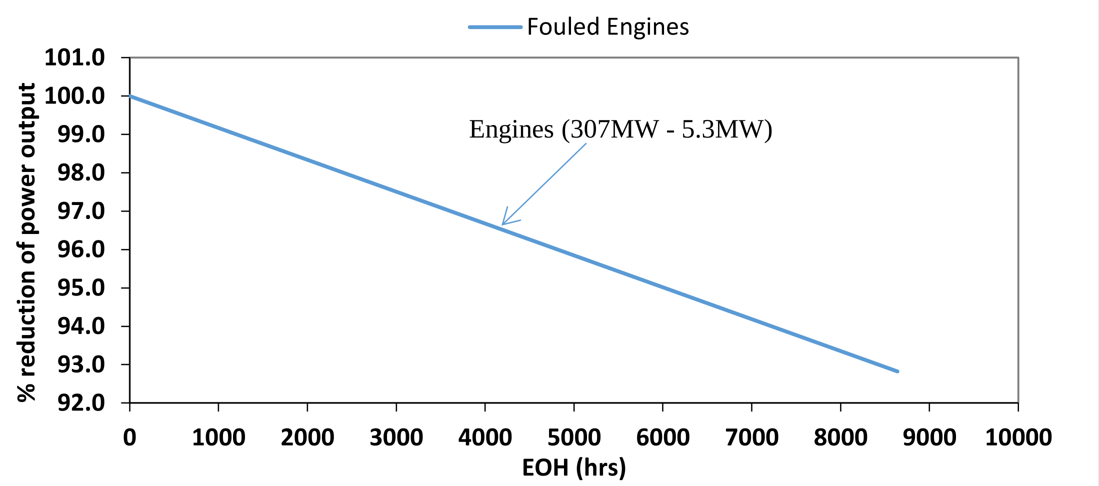


Figure 4-21 Percentage reduction of power (degradation) applicable to all engines (Extended)

Figure 4-22 indicates the energy produced in the fouled condition as a consequence of the power reductions. As power output dropped with respect to time in Figure 4-21, heat rate increases this is due to engine deterioration.

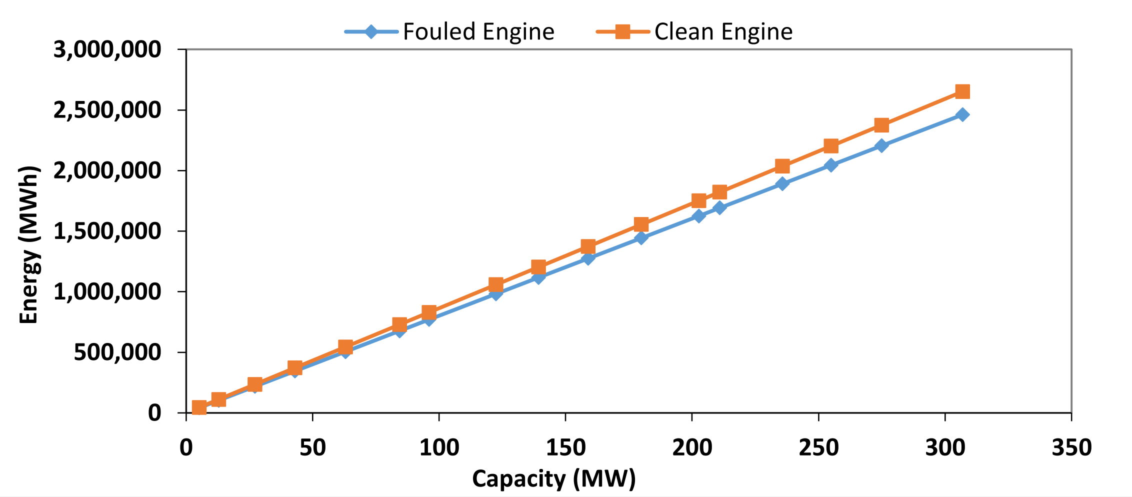


Figure 4-22 Energy produced in a year for the various engines/rated output (clean and fouled)

This shows that excess fuel has been burnt for the same level of power generated shown in Table 4-2. The reasons for the heat rate increasing with time implemented are as the result of extensive analysis, and selection of only the positive trend lines period from the periods calculated. To account for the increase in heat rate, an average percentage heat increase of 1.6% rise has been estimated and applied here. In this study, an average heat rate increase of 1.6% has been applied/adopted to all power capacity/engines.

Table 4-2 Heat rate increase for 211MW capacity

Year	Period	EOH (hrs)	Cal. HR (Btu/kWhr)	Percent Increase
1	1	770	8977	0.28
1	2	2279	9117	2.94
1	4	1701	9050	2.43
1	5	650	8898	0.75
2	8	2411	9250	2.84
4	17	798	9240	1.22
4	18	670	9113	0.68
			Average	**1.60**

4.4.1 Quantity of Liquid Utilised for Washing

Estimates on the amount of liquid utilised for washing is based on the water-to-air ratio by mass flow. In this study 0.2% [27,45] of water-air-ratio is assumed, justifying the relatively small amount of water used for high-pressure on-line washing. With publicly available data on individual engine mass flow [109–111], and shown in Figure 4-23, it is convenient to calculate the quantity of liquid in use.

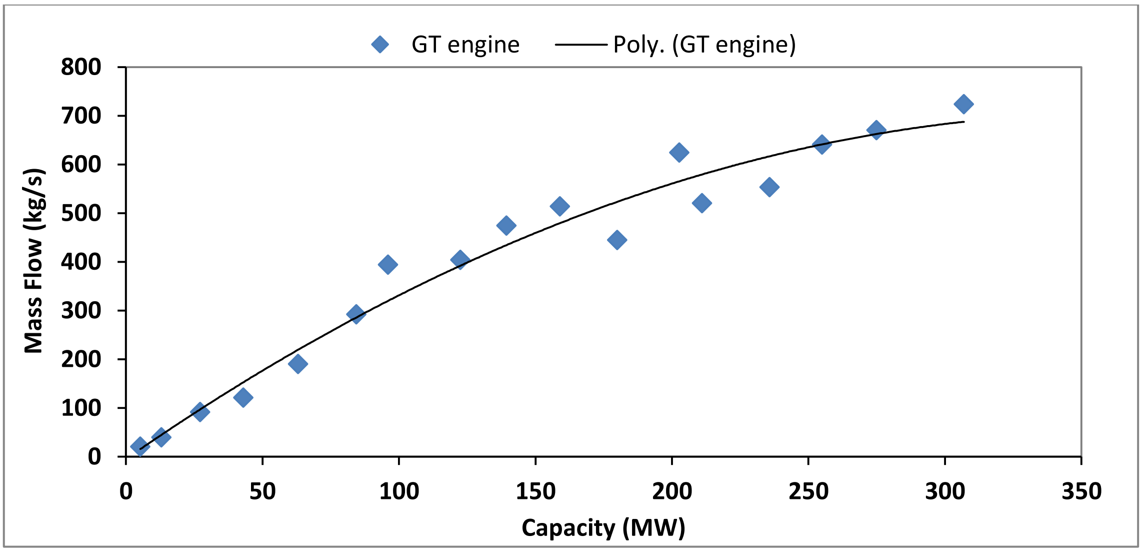


Figure 4-23 Inlet air as a function of engine capacity (0 to 307MW)

The amount of fluid depends on the mass airflow through the inlet plenum, the position of the nozzles relative to the front of compressor depends on plenum shape and ambient dirt loading. The optimum liquid used will purely depend on the site, ambient and GT conditions. The duration considered for washing is 10 minutes, applying a concentrated mixture of detergent and demineralized water. Figure 4-24 show the quantity of liquid used for one wash, per engine or in relation to mass flow. Table 4-3 indicates the wide-ranging engines into account in the study, from 5.3 to 307MW with estimated amount of liquid consumed. These figures are a guide based on the mixture ratio for the fluid (concentrates and demineralized water) of 1:4 for all the engines.

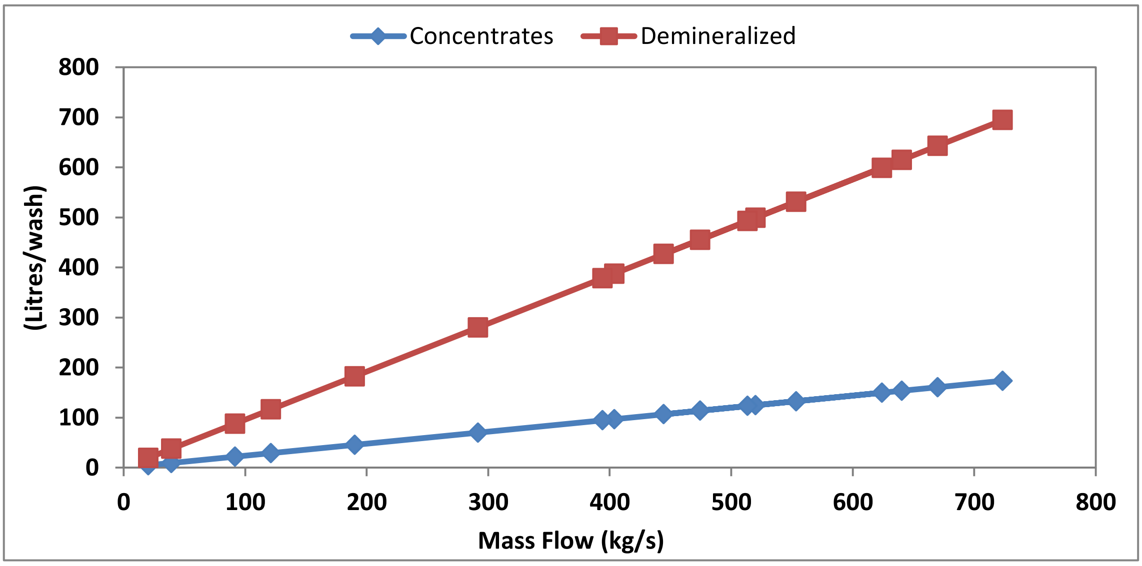


Figure 4-24 Liquid used per wash as a function of mass flow

4.4.2 Power Recovery and Frequency of Washing

To account for the improvement in performance after online washing, 30% recovery of lost power after every washing has been achieved experimentally by Igie et al. [27]. The referred study investigated is a multi-stage compressor fouling in a gas turbine engine model, assuming only the first stage of the compressor is washed. The measure of effectiveness due to washing was obtained from compressor cascade experiments similar to that explained in Igie et al. [112], for which a higher recovery (50%) of lost power was obtained; though in this other study, the model implemented was relatively less detailed, with a different foulant and level of fouling. It is also important to state that the effectiveness of washing is influenced by the fouling levels and nature of foulant which differ with environments and seasons as highlighted in Igie et al. [51]. Varied frequency of washing such as, every 72hrs, 120hrs, 240hrs and 480hrs are implemented in this study.

Table 4-3 Amount of liquid consumed per wash per engine

Manufacturer	Engine Type	Capacity (MW)	Mass Flow (kg/s)	Litre/Wash (l)
Siemens	SGT5-4000F	307	723.48	868
GE Industrial	PG9001FB	275	669.96	804
Siemens	V94.3A	255	640.47	769
Siemens	501G	236	553.38	664
GE Power	7F.05	211	510.31	624
Alstom	GT13E2	203	624.14	749
Siemens	V84.3A	180	444.52	533
Siemens	V94.2	159	513.47	616
Siemens	701D	139	474.37	569
GE Industrial	PG9001EA	123	403.70	484
Alstom	GT13D	96	394.17	473
GE Industrial	PG7001EA	84	291.66	350
Siemens	V64.3	63	190.06	228
Alstom	GT100	43	121.11	145
Royce Rolls	RB211	27	91.63	110
Alstom	Cyclone	13	39.19	47
Alstom	Typhoon5.3	5	20.32	24

The engine operational data for washing in use are of Engine-2 (another GT engine that has been washed on-line in the same power station) in which the performance was monitored during its operation for 4 years. This is the operation that consists of on-line washing only. The on-line washing operation has been conducted experimentally from the actual GT engine in a plant at a frequency of 55hrs on average with a mixture ratio of 4:1 of demineralised water to concentrates. The trend line used here is the average (on-line washing at every 55hrs of operation) obtained from several trend lines that relates to a given period at about 8640th hours of operation. The engine that has been washed every 55 hours intervals does not have information on the degradation trend line. The other engine that was discussed previously is the operation that consists of no washing with the power reduction of about 7.2% at 8640th hours of operation. This engine does not have trend line for the on-line washing. Using the trend lines for the two engines together and assuming the two trend lines for the degraded and washed engine are for the same engine, and applying the extrapolated washed and degraded (no washing) trend line amount to 4.02% and 7.2% reduction in the power output at 8640hrs respectively shown in Figure 4-25. The improvement in the power output due to washing of about 3.18% with respect to time implemented is a result of the washing at an average of 55hrs frequency of washing.

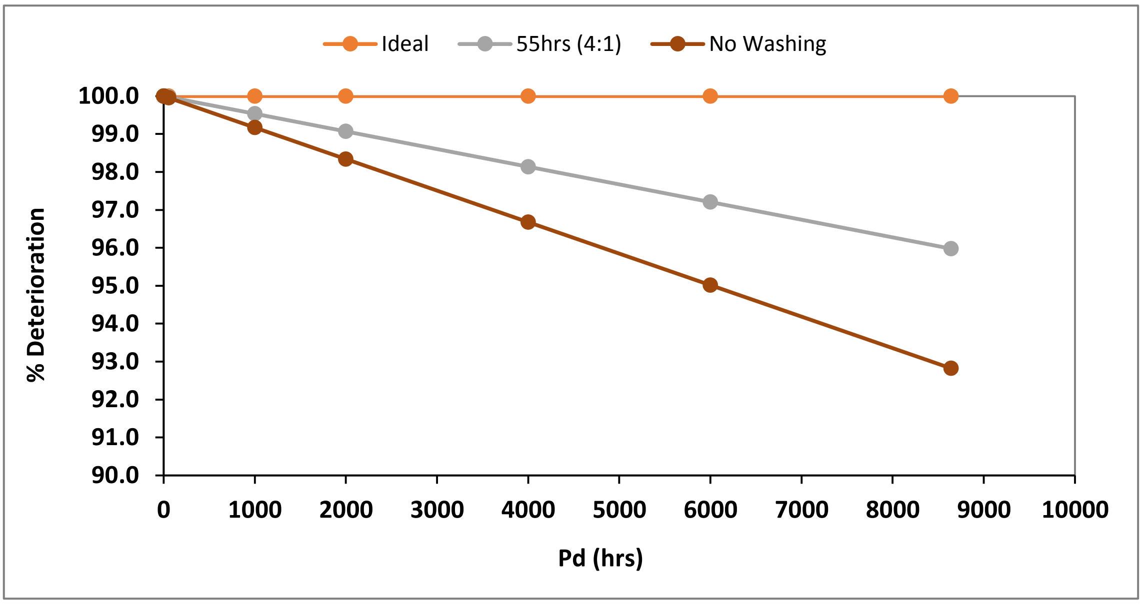


Figure 4-25 Washed and degraded engine percentage deterioration

Figure 4-25 shows the clean, average washed at 55hrs frequency and degraded trend line. To account for the improvement in performance when different frequencies of washing have been applied such as 72hrs, 120hrs, 240hrs and 480hrs, different degradation trend lines of the washed frequencies has been achieved (shown in Figure 4-26). The power output reductions of the washed frequencies at 8640hrs amount to 4.05%, 4.07%, 4.11% and 4.20% respectively. This shows a significant improvement in the performance when compared with no washing. However, when different frequencies of washing have been compared it shows the washing at 72hrs has lower level of power drop compared to 120hrs, 240hrs and 480hrs respectively. As expected, the washing at 480hrs frequency has the highest level of power drop compared to other frequencies of washing. The deterioration of the GT engine increases as time progresses (lower deterioration leads to higher recovery at lower EOH while higher deterioration yields lower recovery at higher EOH).

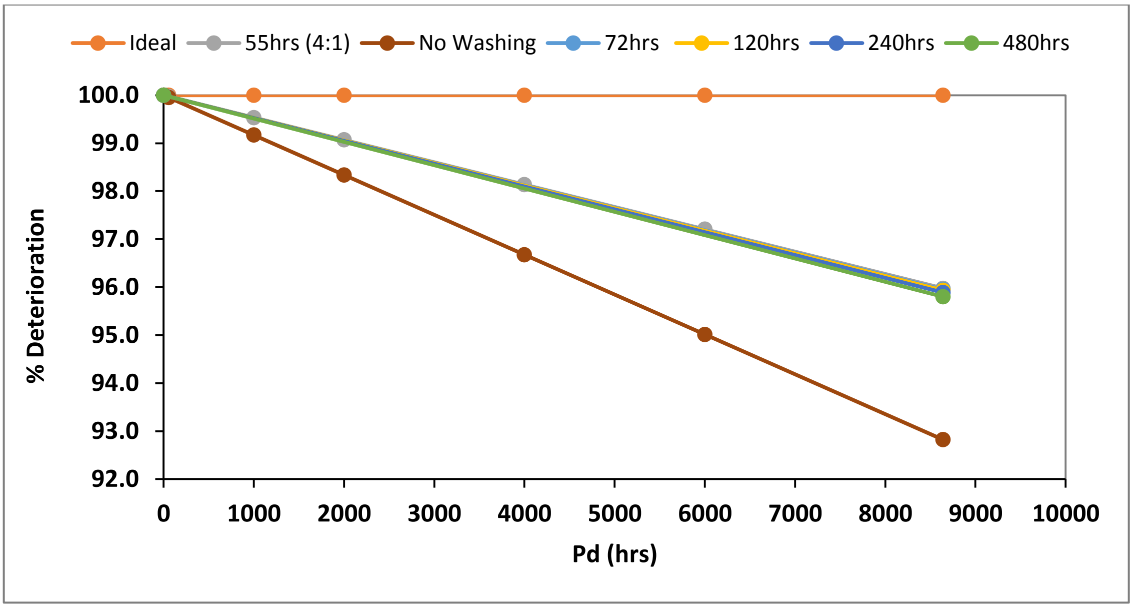


Figure 4-26 Washed and degraded GT engine percentage deterioration with different frequencies of washing

The measure of effectiveness due to washing for the 55hrs frequency of washing to the end of year was obtained from the actual engine data of an approximate values of 99.53% and 43.95% recovery (shown in Figure 4-27) of the loss power according to equation (3-22) [27]. To account for the improvement in performance when different frequencies of washing has been applied during operation in a year such as 72hrs, 120hrs, 240hrs and 480hrs yields a percentage of power increase/recovery of 99.53%, 99.21%, 98.41% and 96.75% (shown in Figure 4-28) respectively at the first washing interval of each frequencies, the higher recovery obtained at the beginning of washing could be due to lower deterioration and engine condition (new and clean), this could also be due to the absence of degraded trend line for washed engine and washed trend line for the degraded engine. However at the end of a year of 8640hrs of operation yields a percentage of power increase/recovery of 43.58%, 43.34%, 42.73% and 41.51% respectively with reference to the degraded condition, the reason for the lower recovery compared to the beginning of washing (first washing) is due to higher deterioration that will lead to off-line washing as on-line can only decelerate the rate of deterioration but cannot eliminate it completely. This has proven that more washing gives higher effectiveness/recovery of power loss and less deposits built up. However, less washing gives lower effectiveness/recovery of power loss and more deposits built up. The result also shows that recovery rate is not constant and it varies with different EOH (recovery rate decreases as the time progresses along the equivalent operating time).

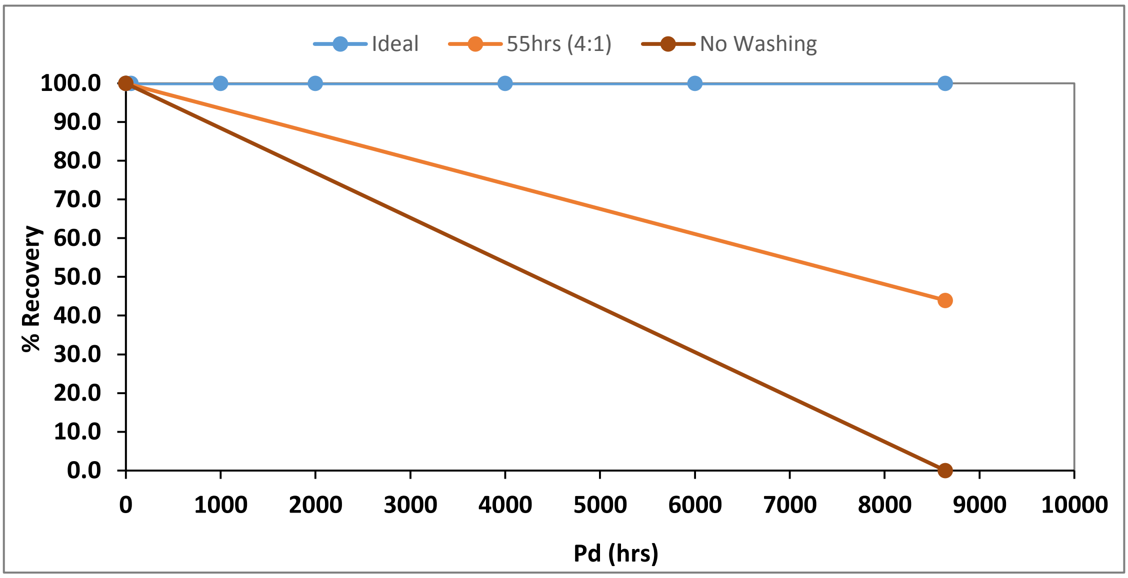


Figure 4-27 Washed and degraded engine percentage recovery

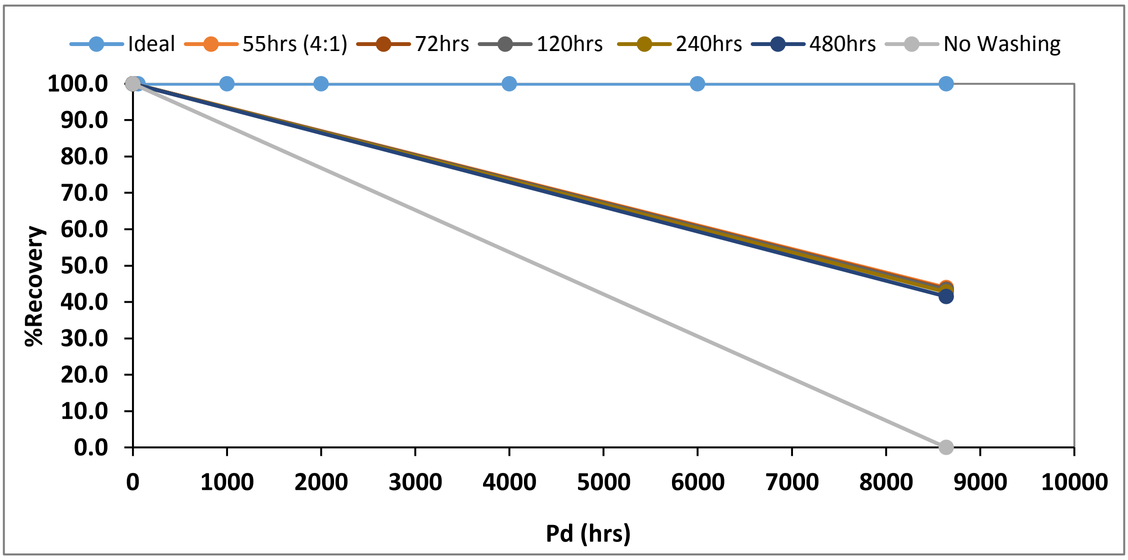


Figure 4-28 Washed and degraded GT engine percentage recovery with different frequencies of washing

4.4.3 Capital and Operational Cost of Washing

The associated capital, maintenance cost and salvage cost of the washing equipment for small to large engines has been provided by **R-MC Power** Recovery Ltd and is shown in Table 4-4. This table shows that the $/MW of the three items is a lot more expensive for the smaller engines in relation to the larger engines. The larger engines would consist of more washing nozzles, a larger tank for liquid storage, piping and a bigger pump. The washing equipment is available in both manual and automatic modes for engines below 150MW, while for heavy-duty engines above 150MW the process of operation is automated and the manpower cost is negligible. The operational/running cost of the liquid that includes the washing liquid has also been accounted for. R-MC Power Guard concentrate mixture with demineralized water in the ratio of 1:4 is used at the cost of $3.9 and $0.065 per litre of the concentrates and demineralized water (UK price) respectively, and this value may vary on different locations due to cost for transporting the concentrates. Table 4-5 shows the total cost of washing for a large engine of 307MW and light engine of 5.3MW, when the washing frequency is every 72hrs. The costs of liquid per wash for the 307MW and 5.3MW engines are $722 and $20 respectively shown in Table 4-5. The average washing period here is for 10 minutes but can vary based on the level of degradation and site condition. The annual cost of wash liquid for both engines at a frequency of 72hrs with 120 intervals is $86,679 and $2,434 respectively. The total cost/expenditure for the first year that includes the capital cost is $357,079 and $63,274. These values are not 4 times the cost when 4 units of engines are applied to the respective engines. Table 4-6 highlights this, indicating that the increased cost is 1.9 and 1.3 times for the largest and smallest engine respectively.

Table 4-4 Capital, maintenance cost and salvage value of washing equipment for different engine size

Parameter	GT Engine up to 20MW	GT Engine 21 – 50MW	GT Engine 51 – 100MW	GT Engine 101–150MW	GT Engine > 150MW
Capital cost of equipment/ installation - **C**	$58,500	$91,000	$130,000	$195,000	$260,000
Yearly maintenance/ installation - C_{O+M}	$2,340	$3,640	$5,200	$7,800	$10,400
Salvage value of equipment SV_o	$5,850	$9,100	$13,000	$19,500	$26,000

The reduced cost is mainly attributed to the fact that one washing equipment can serve more than one engine within the proximity, making it more cost effective. Cost related to additional nozzles, a larger tank and piping connection and increased maintenance cost is marginally increased for 4 engines when compared to one. The only variable with 4 times increase for 4 engines is the liquid wash cost.

Table 4-5 First year cost of washing 1-heavy and 1-light-duty engine

Description/ Cost of Washing/ Maintenance	**1-Heavy-Duty 307MW**	**1-Light-Duty 5.3MW**
Capital cost of equipment/ installation	$260,000	$58,500
Total amount of wash fluid used	868l	24l
Cost of concentrates / wash	$677	$19
Cost of demineralized / wash	$45	$1
Cost of fluid/ on-line wash	$722	$20
Cost of fluid (**72hrs-120 intervals**)	$86,679	$2,434
Maintenance/ installation of equipment	$10,400	$2,340
Total cost per 8640hrs 1 heavy-duty	**$357,079**	**$63,274**

Table 4-6 First year cost of washing 4-heavy and 4-light-duty engine

Description/ Cost of Washing/ Maintenance	**4-Heavy-Duty 307MW**	**4-Light-Duty 5.3MW**
Capital cost of equipment/ installation	$312,000	$70,200
Cost of fluid/wash/year/ **120 interval**	$346,716	$9,736
Maintenance/ installation of equipment	$12,480	$2,808
Total cost per 8640hrs 4 heavy-duty	**$671,196**	**$82,744**

Figure 4-29 shows the total cost of washing for 1 and 4 engines for different engines at a frequency of 72hrs. However, the cost reduces with a decrease in the frequency of washing but more deposits are built up. Due to the use of one wash skid of the 4-engines, it is cost effective. The cost of washing for different engine capacity at different frequency of washing is shown in Figure 4-30. It can be seen the cost of washing for 307MW at a frequency of 72hrs is $357,079, however at 480hrs it reduces to $283,402 due to lower number of washing (frequency of washing) and more deposits build up. It can also be observed for a light-duty engine of 5.3MW capacity; the cost of washing at 72hrs interval is $63,274 and reduces to $61,205 at 480hrs interval, the cost reduction is due to lower number of washing.

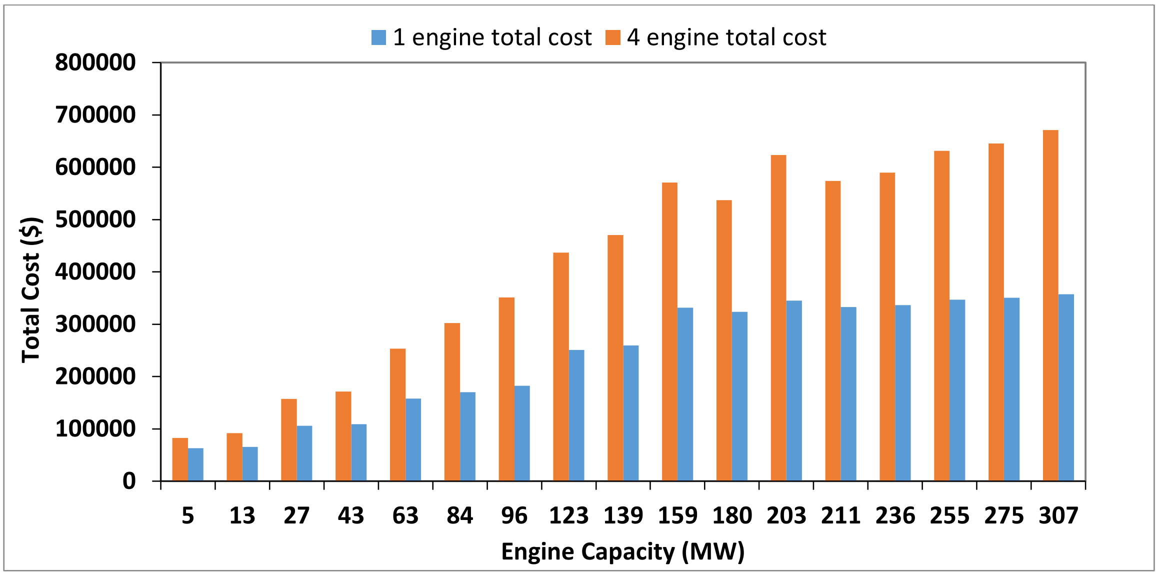


Figure 4-29 Total cost of washing for 1 and 4-engines

4.4.4 Cost of Fuel and Electricity Generation

It is important to highlight that the cost of electricity depends on the source and type of electricity production. This varies for thermal, nuclear, hydro, and renewable energy plant. The average cost of electricity produced or cost of electricity generated by thermal (natural gas only) power plant is achieved by developing a break-even selling price model, as different engine have different costs of electricity generation. The average price of natural gas is $6/MMBTU according to year 2015 for the United Kingdom.

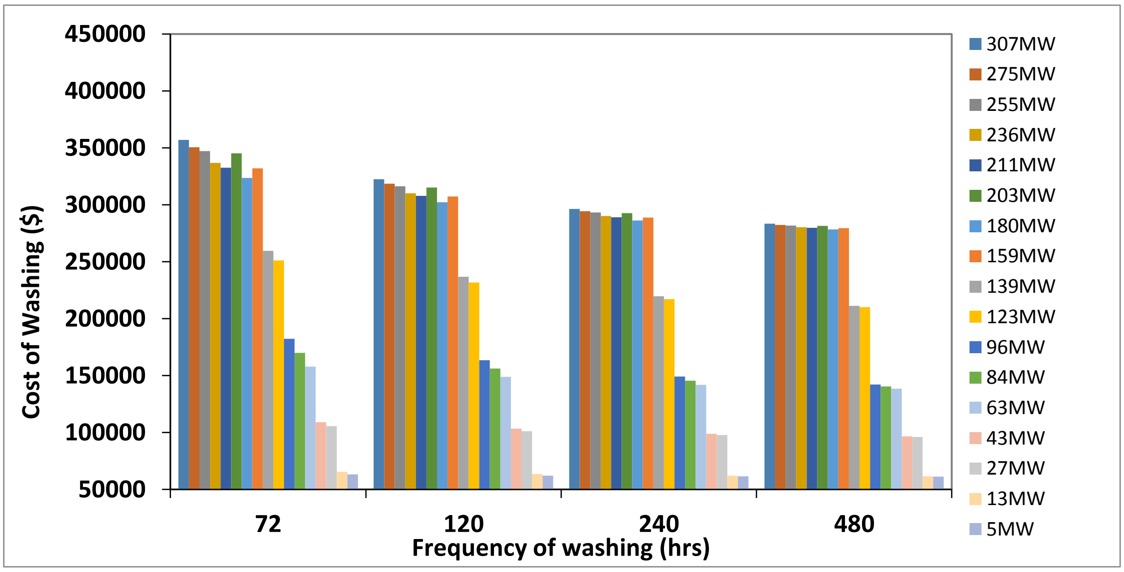


Figure 4-30 Cost of washing for different frequency of washing

4.5 Break-Even Selling Price (BESP) Model

The economic parameter for beak-even selling price model consists of ANCF, AOP, AT and plant depreciation, NPV, PBP, IRR, CoE and BESP. NPV is used to evaluate the profitability of a project and can be defined as the present value of cash inflows minus the present value of cash outflows. IRR measures the profitability of an investment and it is represented in percentage, it also measures the discount rate that makes the cash flows of a project a zero NPV [84]. It is important to accept a project when its IRR is larger than the required rate of return [86]. Break-even selling price (BESP) is the selling price that the generator supposed to charge to the generated electricity which is transmitted to the grid over the lifetime of power station and NPV must be equal to zero. The BESP is calculated in order to estimates the price of electricity to be sold for different engine sizes. The mathematical equations for the break-even selling price model can be represented using equations (3-23) to (3-31).

A simple cycle gas turbine cost depends on the unit size and equipment supply scope. The estimate prices adopted are in gas turbine world (GTW's) and are made on standard bare bones gas-only plant. The plant prices cover only the equipment. The economies of scale for the plant allow original equipment manufacturer (OEM's) to reduce the price of manufacture as GT engines grow in size with increase in output. With the recent advancement of new technology, F-, H- , G- and J- class GT engines, prices are beginning to go up for the larger machines. A 20% of the equipment cost has been assumed as the cost for plant construction, plant engineering and transportation for all the engine capacity. The equipment cost $/kW for a 307 MW engine is $245/kW down to $730/kW for the smaller engine of 5.3 MW capacity shown in Table 4-7.

These values have been obtained using the equations for the best fits. It can be noticed that small GT plants cost significantly more $ per kW (expensive) than larger GT plants. The capital cost is the product of genset price with power rating of each GT engine and is shown in Table 4-7. Table 4-8 shows the input data model assumption for the economic analysis for all the GT engines from 307MW down to 5.3MW capacity. The technical economic data include power output, fuel burn, availability and energy produced per annum.

Table 4-7 Capital cost for different engine sizes

Capacity (MW)	Genset Price ($/kW)	Capital Cost ($)
307	245.1	75,256,523
275	249.8	68,685,558
255	253.0	64,513,060
236	256.4	60,450,525
211	261.3	55,128,190
203	263.1	53,322,181
180	268.4	48,316,501
159	274.1	43,589,201
139	280.4	39,068,621
123	286.6	35,105,264
96	328.4	31,523,713
84	340.3	28,703,823
63	368.7	23,228,043
43	409.5	17,609,838
27	464.5	12,637,726
13	570.1	7,361,410
5	730.1	3,834,654

As an example the economic input data for 307 MW engine are as follows; Power output = 307,000 kW, fuel burn = 555,508,170 kg/year, energy produced = 2,652,480,000 kWhr, Availability = 98.6%. In order to run the model there is need to guess for the electricity price in ($/kWhr) and the value selected is $0.065/**kWhr** shown in Table 4-8 in order to find the cost of electricity at which the NPV is zero. The lifespan of the plant has been assumed to be 25 years. Escalation rate at 2% fuel price, 2% O&M costs and 2.5% electricity price has been applied that gives more realistic results for the lifespan of the plant. The methods used for the economic module calculation is the discounted cash flow technique (DCF). This is a dynamic approach that has taking an account the time value of money, it has taken the cash inflow and outflow over the lifespan of a project. Once all the input parameter assumptions are defined and calculated by the user it’s now ready to input and run the model algorithm and generate an output result. The parameters in the output results includes NPV, IRR, ANCF, PBP, BESP and these guided the user to assess the viability of the project. It can be seen that the BESP for 307 MW at clean condition is $55.49**/MWh** while using the BESP value (minimum selling value of electricity in the plant) gives NPV = 0, IRR = 8%, PBP = 25yrs. For light-duty engine of 5.3 MW capacity the minimum selling value of electricity (BESP) at clean condition is $79.97**/MWh** and using the minimum BESP value also gives NPV = 0, IRR = 8%, PBP = 25yrs respectively.

Table 4-8 Input model assumptions for the economic analysis

Parameter	Value
Power plant lifespan (year)	25
Operating hour (hr)	8640
Interest rate (%)	10
Electricity price ($/kWhr)	0.065
Fuel price of natural gas ($/kg)	0.2445
Time period for depreciation (year)	20
Construction time (year)	3
Specific and variable O&M cost ($/kW)	17.825
Actual fuel price escalation rate (%)	2
Actual electricity price escalation rate (%)	2.5
Actual O&M escalation rate (%)	2

It can be noticed that the BESP for heavy-duty engine are lower than the light-duty engine this is due to higher cost of production for the smaller engine. A profit margin has been applied for the project of the cost of electricity production of all the engine capacity. A sample of economic output results for the NPV of 307MW and 5.3MW capacity at clean, fouled and at different frequency of washing are shown in Figure 4-31 and Figure 4-32 respectively**.**

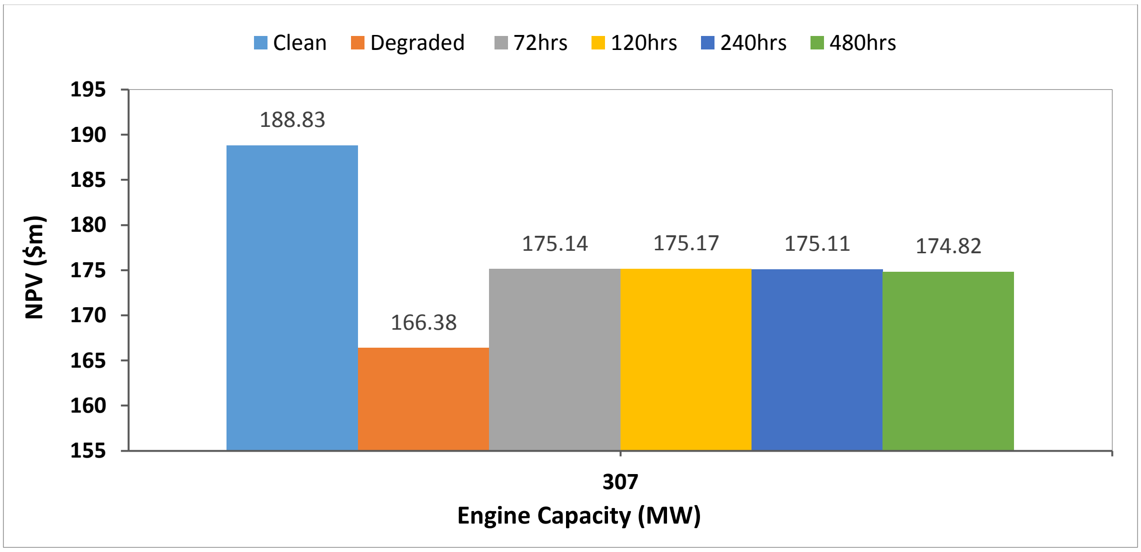


Figure 4-31 Sample of economic output result of NPV for 307MW

The clean engine has the highest NPV as no energy has been lost during operation in a hypothetical scenario while the fouled engine has the lowest NPV as a lot of energy have been lost; this is due to lower energy production because of fouling. It can be noticed at 307MW and 5.3MW capacity the NPV at 120hrs is higher than at 72hrs and then followed by the sequence of 240hrs and 480hrs respectively. As expected, the NPV for the 480hrs are lower compared to other frequencies and this is due to lower recovery of power loss and lower number of washing. This highlights the benefits of washing along the equivalent operating hours.

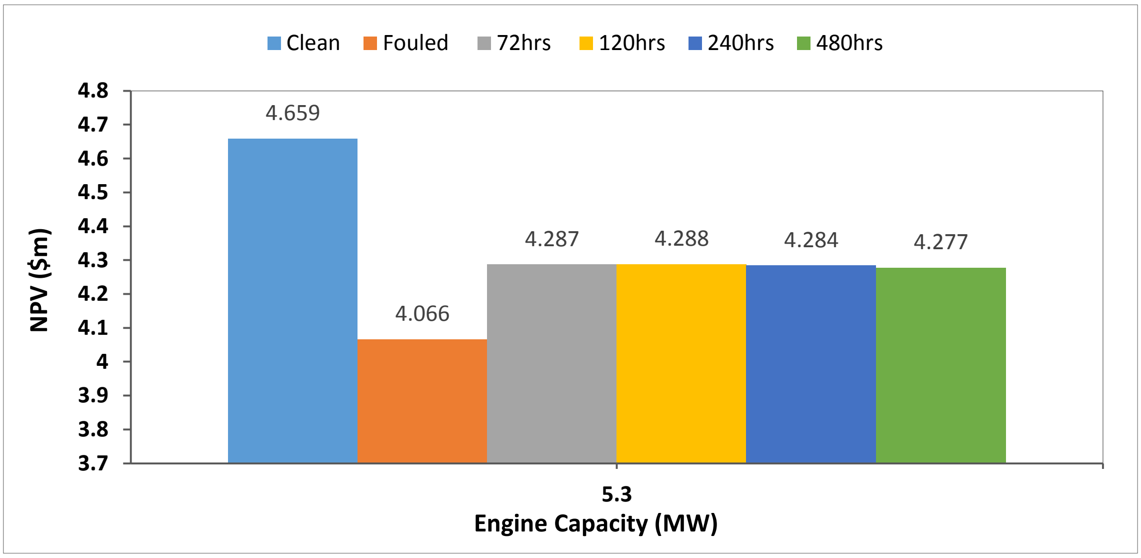


Figure 4-32 Sample of economic output result of NPV for 5.3MW

The same method has been applied for all other engines down to 5.3 MW in order to get the economic parameter results. The BESP with the profit margin for all the engines at clean condition are shown in Table 4-9. A sample of economic output results for the annual savings of 307MW and 5.3MW capacity at different frequencies of washing is shown in Figure 4-33 and Figure 4-34 respectively**.** The annual savings at 72hrs frequency provides higher profit compared to the other washing frequencies. It can be observed that annual savings decrease (from 72hrs washing frequency), with an increase of the frequency of washing (480hrs washing frequency). The annual savings at 12hrs washing frequency are lower compared to 72hrs down to 480hrs, this is due to higher number of washing with lower degradation. As mentioned earlier washing is directly proportional to the rate of degradation. As the number of washing intervals (frequency) increases, the degradation rate also increases.

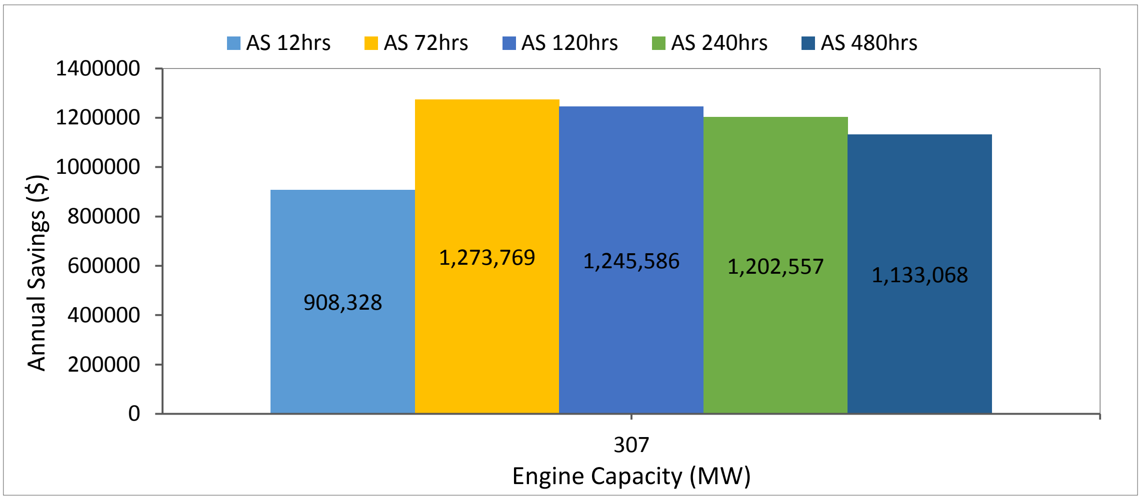


Figure 4-33 Sample of economic output result of AS for 307MW

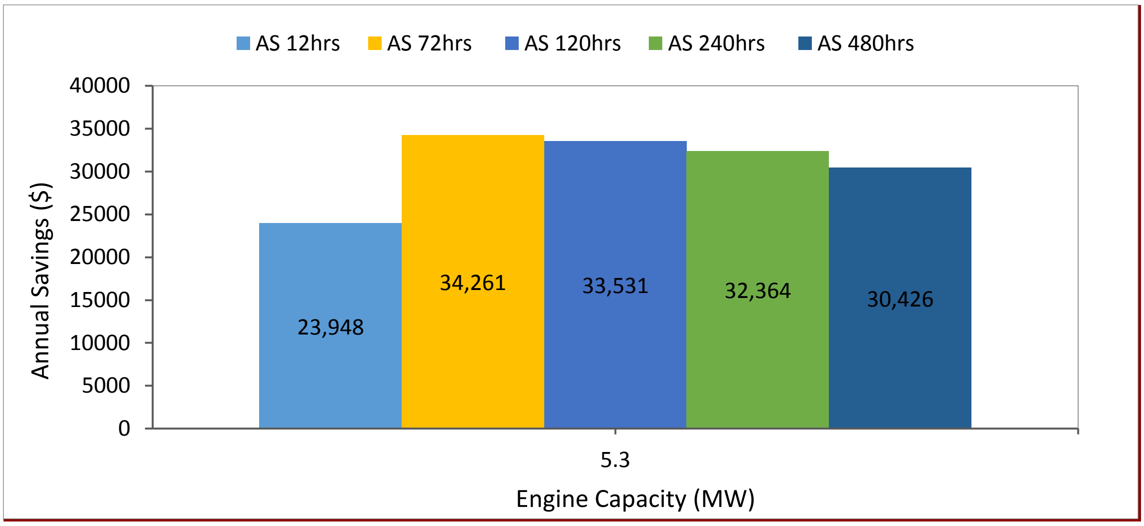


Figure 4-34 Sample of economic output result of AS for 5.3MW

To identify the impact of compressor washing on BESP or LCOE, the clean, fouled and washed engine LCOE for different engine capacity has been obtained. It can be observed that the clean engine LCOE after the profit margin for 307MW is $66.6/MWh which is lower than the degraded engine with the LCOE of $67.7/MWh shown in Figure 4-35. This translates to a total cost of energy production for the degraded engine is higher than the clean engine by a difference of $1.1/MWh, excess fuel having been burnt for degraded engine to produce the same amount of energy. This means that operating at degraded condition reduces the total profit to the operator. However, implementing on-line washing at a certain frequency reduces the loss to the operator as degradation cannot be eliminated completely. On-line washing at 72hrs frequency reduces the cost of energy production for the degraded engine by $0.3/MWh.

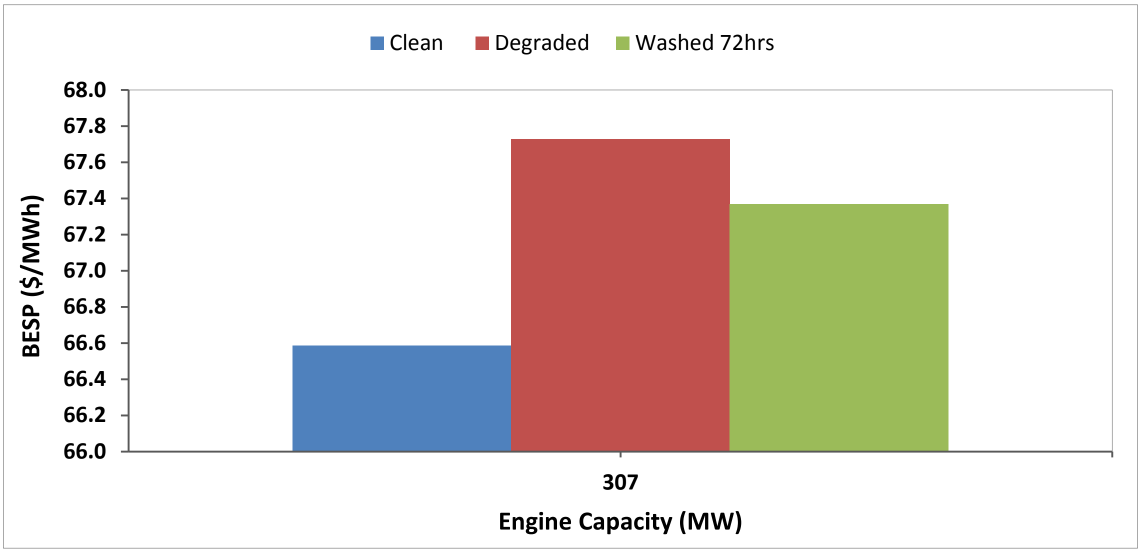


Figure 4-35 BESP for clean, fouled and washed engine of 307MW capacity

The LCOE for the washed engine at 72hrs frequency is $67.4/MWh, this value being lower than for the degraded engine as it gives more profit to the operator when implemented. Figure 4-36 shows the clean, fouled and washed engine LCOE for 5.3MW capacity; it can be observed the LCOE for the light engine of 5.3MW is higher than for heavy-duty engine of 307MW, and this is due to the cost of energy production for the light-duty engine is higher and more expensive.

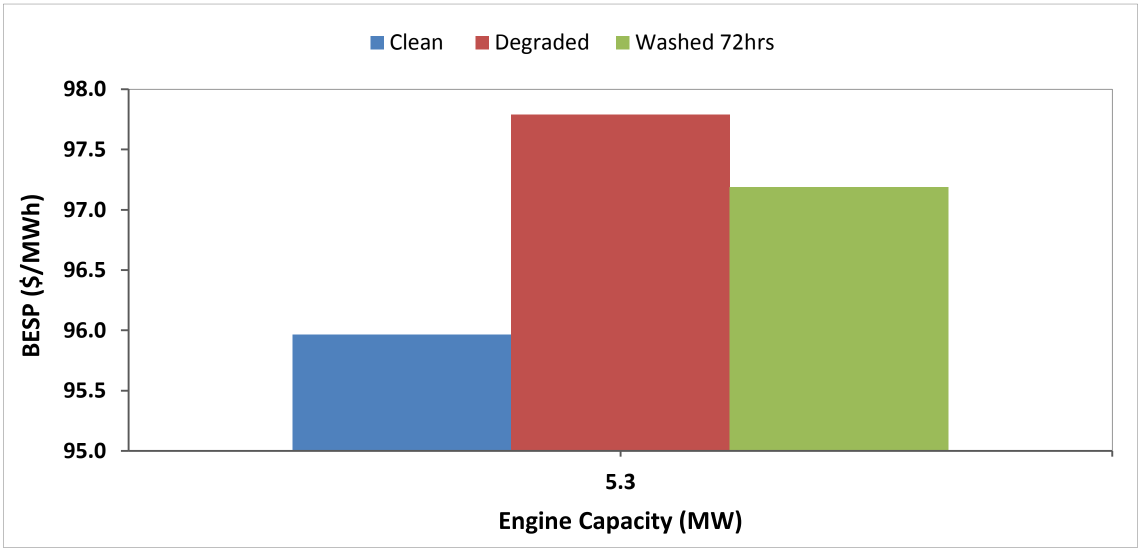


Figure 4-36 BESP for clean, fouled and washed engine of 5.3MW

Table 4-9 Economic Parameters for clean and BESP for different engine capacity at clean, fouled and washed condition

Capacity (MW)	**NPV ($) (Clean)**	**IRR (%) (clean)**	**PBP (yr) (Clean)**	BESP ($/MWh) **(Clean)**	BESP ($/MWh) **(Degraded)**	BESP ($/MWh) **(Washed)**
307	188.83	29.06	4.18	66.6	67.7	67.4
275	164.15	28.12	4.35	64.6	65.7	65.3
255	162.58	29.14	4.17	69.1	70.3	69.9
236	149.34	28.76	4.23	68.7	69.9	69.5
211	135.01	28.58	4.26	69.4	70.6	70.2
203	131.28	28.69	4.25	70.2	71.4	71.0
180	123.60	29.44	4.14	74.4	75.7	75.3
159	113.86	29.86	4.05	77.6	78.9	78.5
139	92.62	27.97	4.37	72.1	73.3	72.9
123	88.94	29.25	4.15	78.7	80.1	79.7
96	73.48	27.65	4.43	83.0	84.4	84.0
84	63.98	26.85	4.56	82.2	83.6	83.1
63	45.22	24.61	5.08	77.8	79.2	78.7
43	29.75	22.55	5.65	75.0	76.4	75.9
27	19.41	21.32	6.04	77.3	78.7	78.3
13	9.84	19.71	6.66	82.6	84.2	83.7
5	4.65	18.69	7.11	96.0	97.8	97.2

4.6 Economic Analysis of Different GT Capacity

The trend lines for a clean, washed and fouled engine were generated for the year of 307MW and 5.3MW capacity as shown in Figure 4-37 and Figure 4-38 respectively. The ideal clean engine power output of the largest engine unit is 307MW. This output is maintained throughout the year in this hypothetical scenario. In actual operation, it’s usually not the case due to natural wear and tear, alongside other variabilities. The estimated energy produced per year for the idealised clean engine is 2,652,480 MWh as shown in Table 4-10. Based on the degradation trend, the energies produced in the fouled condition is 2,557,292 MWh. The trend for online compressor washing has been obtained by applying a varying recovery rate of lost power every 480 hours (washed data) and the energy produced for the washed engine is 2,628,690 MWh. The selection of this wash interval is due to the fact that it best highlights the changes in the power outputs for visual purposes, compared to other combinations. For a rated output of 307MW, 8 cases have been investigated. These are varying recovery rate of the lost power obtained (washed data) and the modified recovery rate, with 72hrs, 120hrs, 240hrs and 480hrs intervals of wash, respectively. A degradation trend line has been obtained from engine one (Engine-1) of the actual engine data as previously mentioned. An estimated recovery trend line for washing has also been obtained from engines two (Engine-2) of the actual engine data indicated in Figure 4-37. Nevertheless, these two trend lines are for different engines, in order to try an estimate, the washing trend for the degradation of GT engine one. The degraded trend for the washed engine does not exist as no idea of what was lost for the wash engine.

Once the washed engine trend line is known, then the fouled engine trend line will be unknown and vice versa. The degradation trend for the washed engine has been adjusted or modified (Figure 4-37) using in the time based recovery rates which are associated on the degradation trend, in order to obtain a new trend which reflects the distribution of recoveries with time, the two trends obtained are neither from the same engine. The idea is to be able to develop or devise a washing recovery which is more reflective of recovery rate obtained during operation with respect to the degradation trend. The only thing effectively used is the degradation of an estimated recovery as a function of time. A calculation of recovery based on degradation on a similar engine in the power station has been obtained and this enable working out the washed trend, and assuming this washed engine had that degradation. The kind of distribution experienced from the experiment is not expected as time progressed, the suggestion is that a high level of recovery is not expected for a very long period, and adjusting it further is more realistic. The reason for the adjustment/modification is that the degradation trend should have been more than that obtainable. The recoveries obtained at the first phase are expected for a short period of time as previously mentioned. An adjustment has been made in a way that only the highly dominant recoveries occurred at the beginning of the washing operation. There is less recovery at the rear stage of the compressor and this is due to accumulation of deposits. The overall accumulation of energy level for 307MW and 5.3MW capacity before the adjustment appears to be 2,628,690 MWh and 44,970 MWh respectively at 480hrs, and this is very high for on-line washing (sense of quantity between degraded and washed engines).

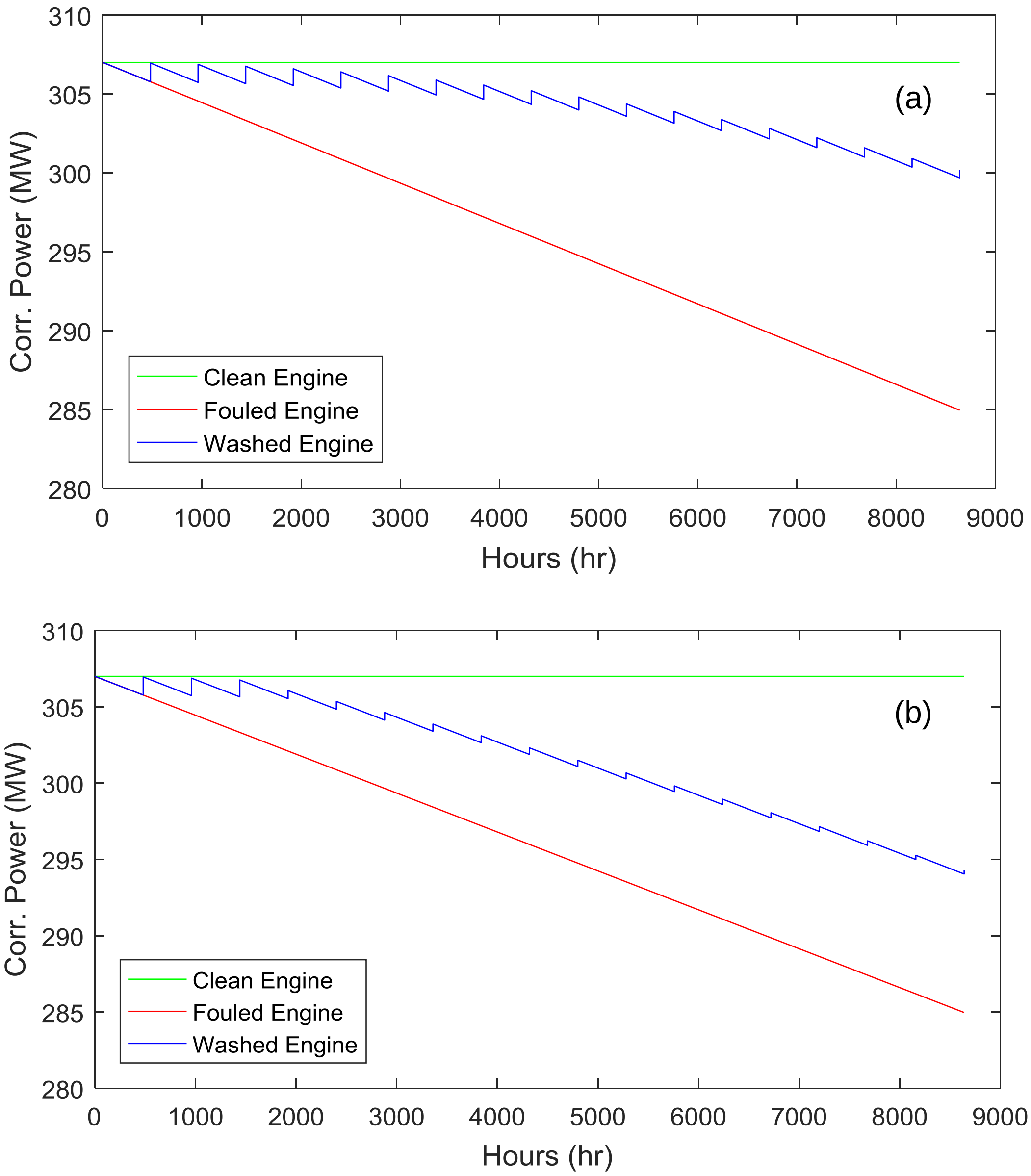


Figure 4-37 Trend lines for clean, fouled and washed engine of 307MW at 480hrs interval (washed data (a) and modified (b))

Figure 4-37 and Figure 4-38 indicated that as time progresses the recovery rate reduces/decreases drastically, and this is less visible at the extreme end but the actual value changes with time. This change in recovery appears to be less in the graph especially for 72hrs frequency. The modified or adjusted trend for online compressor washing has now been obtained by applying varying recovery rate at every 480 hours and the energy produced for the washed engine are 2,606,195 MWh and 44,585 MWh for 307MW and 5.3MW respectively. Table 4-10 indicates the resulting energy produced for these cases, as well as that of a significantly smaller engine with the same rate of degradation and washing schemes.

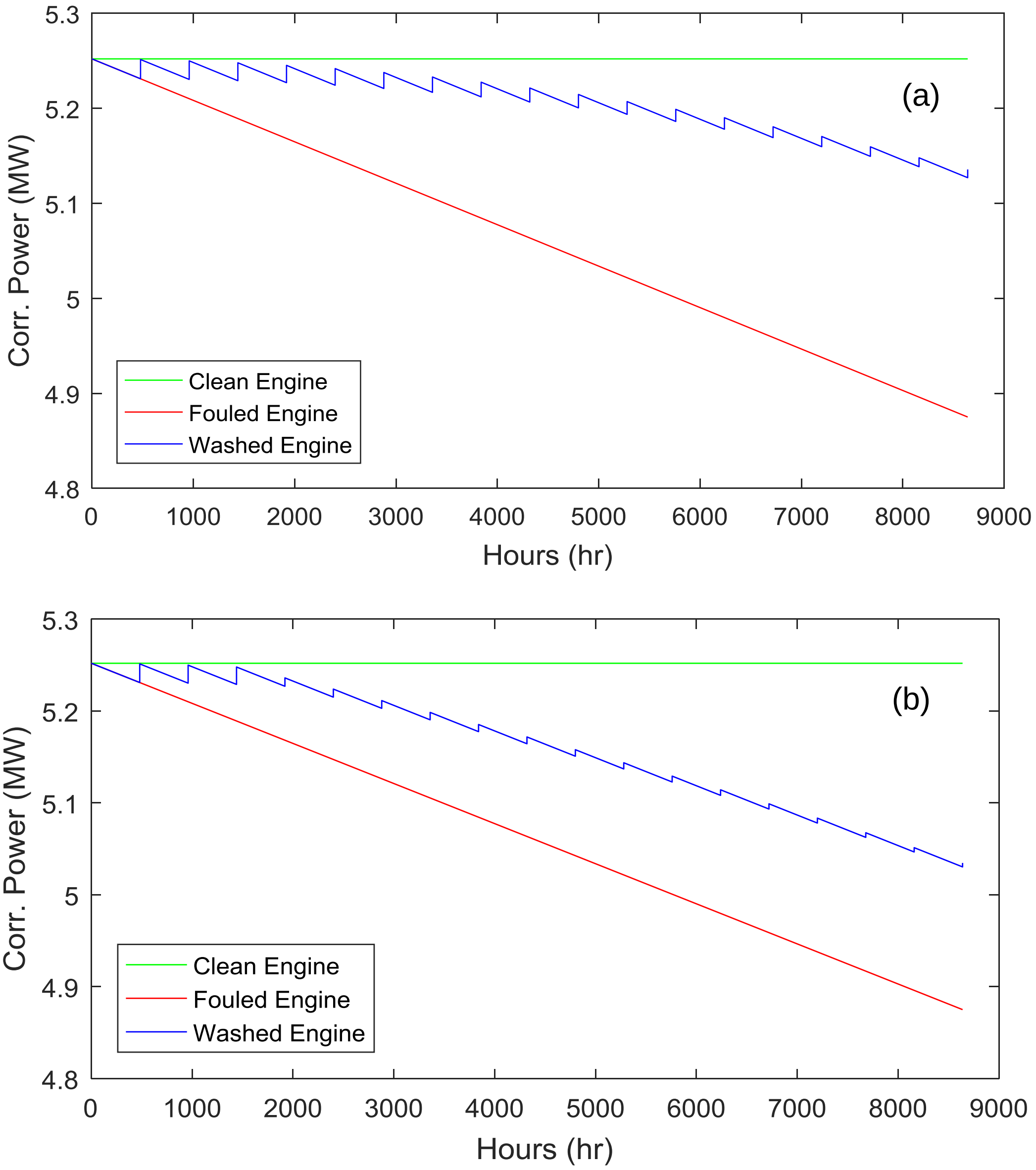


Figure 4-38 Trend lines for clean, fouled and washed engine of 5.3MW at 480hrs interval (washed data (a) and modified (b))

As would be observed from the table, increasing the number of intervals (frequency) of washing would increase the energy produced. Figure 4-39 and Figure 4-40 show the energy delivered due to washing for 307MW and 5.3MW at different frequencies of washing with varying recovery rate for washed data and modified recovery rate. It can be observed the energy delivered decreases with an increase in the number of frequency of washing interval from 72hrs to 480hrs, and this is due to effectiveness of washing is higher at 72hrs. The same method applied at 120hrs, 240hrs and 480hrs shows the same trend with higher energy supplied at 72hrs.

Table 4-10 Heavy and light-duty engines of 307MW and 5.3MW capacity

Description	**Frequency** (hrs)	**307MW Washed Data**	**Modified**	**5.3MW Washed Data**	**Modified**
Clean (MWh)	**72**	2,652,480	2,652,480	45,377	45,377
Fouled (MWh)		2,557,292	2,557,292	43,749	43,749
Washed (MWh)		2,633,787	2,613,639	45,057	44,713
$\Delta E\ (MWh)$		**76,495**	**56,347**	**1,309**	**964**
Washed (MWh)	**120**	2,633,183	2,611,645	45,047	44,679
$\Delta E\ (MWh)$		**75,892**	**54,353**	**1,298**	**930**
Washed (MWh)	**240**	2,631,677	2,609,274	45,021	44,638
$\Delta E\ (MWh)$		**74,385**	**51,983**	**1,273**	**889**
Washed (MWh)	**480**	2,628,690	2,606,195	44,970	44,585
$\Delta E\ (MWh)$		**71,398**	**48,904**	**1,221**	**837**

However, it is important to note that the recovery rate (effectiveness) is more important than the frequency/intervals of washing. This is demonstrated by the higher energy produced with changes in the recoveries. The table clearly shows that the most optimistic recoveries for the light and heavy-duty engine (72hrs wash frequency) provides higher energy produced compared to the case of most pessimistic recoveries (480hrs wash frequency) for the (experimental) washed engine data and modified washed engine results. These calculations have been made for all the rated capacities, amounting to 136 cases for the 17 engines. Table 4-11 shows the calculations made on the energy for the case of 72hrs frequency and with the varying modified recovery rate.

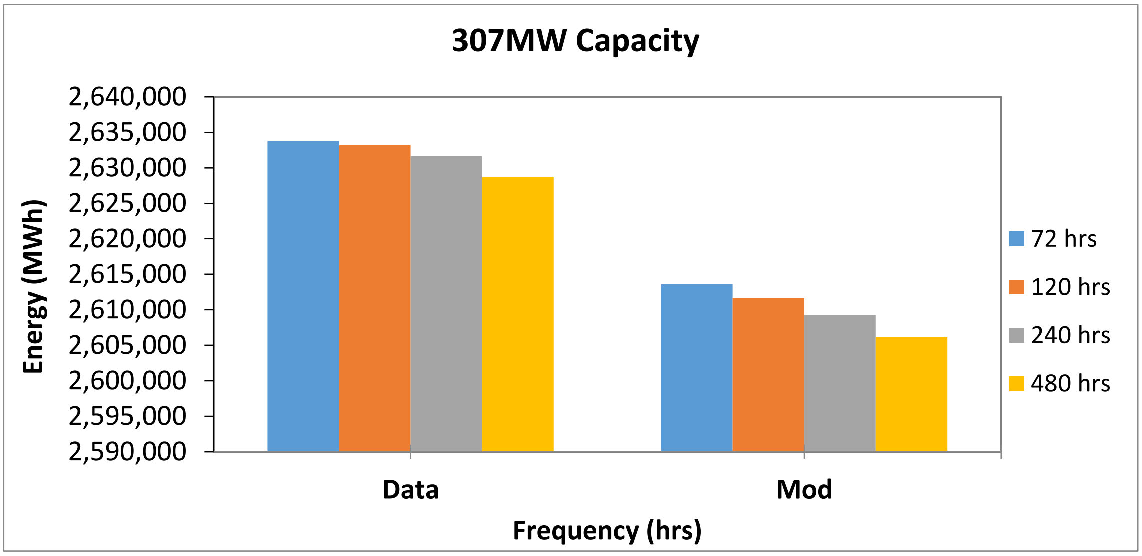


Figure 4-39 Energy delivered due to washing against frequency of washing

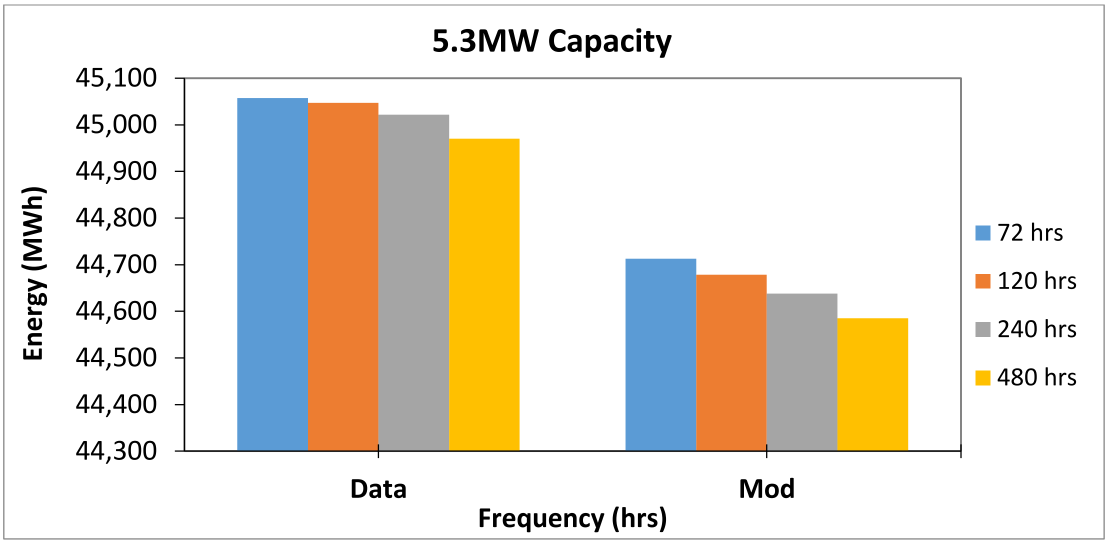


Figure 4-40 Energy delivered due to washing against frequency of washing

Table 4-11 Sample calculation for the cost of fouling of 307MW engine

Energy delivered in a year at 72hrs interval		
1.	Clean engine energy delivered [MWh]	2,652,480
2.	Fouled engine energy delivered [MWh]	2,557,292
3.	Washed engine energy delivered [MWh]	2,613,639
Average power delivered per 8640 hours		
4.	Average power delivered for clean engine [MW]	307.00
5.	Average power delivered for fouled engine [MW]	284.97
6.	Average power delivered for washed engine [MW]	295.68
Selling value of electricity generated		
7.	Average cost of electricity [$/MWh]	66.6
8.	Clean engine cost of electricity ($)	176,655,200
9.	Fouled engine cost of electricity ($)	170,315,600
10.	Washed engine cost of electricity ($)	174,068,400
Cost of fuel ($)		
11.	Average cost of fuel (natural gas) [$/MMBTU]	6
12.	Heat rate of 307MW engine [BTU/kWh]	8,532
13.	Average heat rate increase [%]	1.6
14.	Clean engine cost of fuel ($)	135,785,756
15.	Fouled engine cost of fuel ($) (inclusive of excess fuel due to higher rate)**	133,007,474
16.	Washed engine cost of fuel ($)	135,389,363
Cost of power loss and heat rate increase ($)		
17	Yearly power loss cost ($)	6,339,552
18.	Yearly excess fuel cost ($)	2,094,606
19	**Loss of revenue due to fouling ($)**	**8,434,158**

** Related to higher heat rate, inclusive of excess fuel - $ 2,094,606

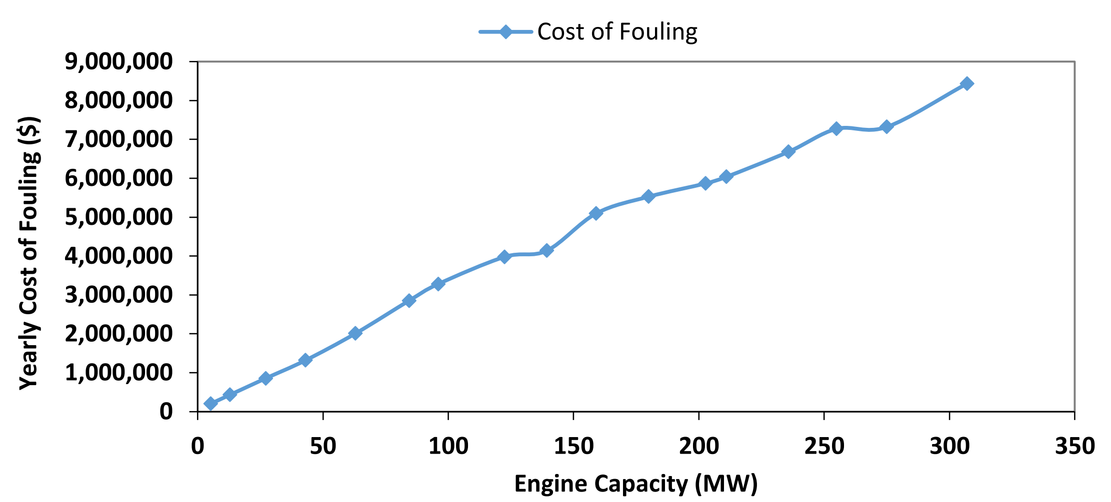


Figure 4-41 Yearly cost of fouling from 5.3MW to 307MW GT

The table shows the cost of power loss due to fouling and additional fuel cost due to increase in heat rate. These are $6,339,552 and $2,094,606 respectively, and considered high values that need to be compared in the context of the scale of operation. The same method is applied for other engines, down to 5.3MW rated capacity shown in Table 4-12. This also indicates that the cost of fouling increases with an increase of engine capacity for the same level of degradation and application (power generation) shown in Figure 4-41.

Table 4-12 Cost of fouling for gas turbine engines

Engine Capacity (MW)	Cost of Less Energy ($)	Cost of Excess Fuel ($)	Total Fouling Cost ($)
307	6,339,552	2,094,606	8,434,158
275	5,508,218	1,812,062	7,320,279
255	5,463,413	1,807,316	7,270,729
236	5,022,379	1,658,084	6,680,463
211	4,540,334	1,496,984	6,037,318
203	4,412,012	1,455,604	5,867,616
180	4,152,324	1,375,360	5,527,683
159	3,825,646	1,268,939	5,094,585
139	3,115,217	1,024,084	4,139,301
123	2,989,211	989,397	3,978,608
96	2,470,560	811,062	3,281,621
84	2,150,077	702,939	2,853,016
63	1,519,728	490,192	2,009,921
43	999,943	317,211	1,317,153
27	652,161	204,253	856,414
13	330,689	101,375	432,063
5	156,330	47,051	203,381

4.6.1 Simple and Dynamic Analysis

Table 4-13 indicates the parameters applied in calculating the stated economic criterion for the 307MW and 5.3MW engines for a period of 13 years. This also extends to the application of 4 engines for each of these.

Table 4-13 Parameters for 1 and 4-heavy-duty engines of 307MW and 5.3MW capacity at 72hrs frequency

Description	**1-Heavy-duty 307MW**	**4-Heavy-duty 307MW**	**1-Light-duty 5.3MW**	**4-Light-duty 5.3MW**
Capital cost of equipment/ installation - **C**	\$260,000	\$312,000	\$58,500	\$70,200
Yearly maintenance/operational cost of equipment- **C_{om}**	\$97,079	\$359,196	\$4,774	\$12,544
Fuel cost per annum for fouled engine - **C_{ff}**	\$133,007,474	\$532,029,896	\$2,987,761	\$11,951,045
Fuel cost per annum for washed engine - **C_{fw}**	\$135,389,363	\$541,557,452	\$3,041,266	\$12,165,064
Income from selling electricity by fouled engine - **R_f**	\$170,315,616	\$681,262,464	\$4,199,889	\$16,799,556
Income from selling electricity by washed engine - **R_w**	\$174,068,352	\$696,273,408	\$4,292,429	\$17,169,716
Salvage value of equipment - **SV_0**	\$26,000	\$31,200	\$5850	\$7,020
Life expectancy of the equipment - ***N***	13	13	13	13
Interest rate - ***i***	8%	8%	8%	8%

The life span of the washing equipment depends purely on the equipment usage and could even last for over 20 years. Equations (3-32) to (3-41) were used for calculating the economic analysis for on-line washing. Table 4-14 shows that as the engine size or capacity increases, the PB reduces and RoI increases. This relates to the AS, indicating that with higher potential for loss in revenue associated with bigger engines or higher capacity (also shown in Table 4-12), the greater the economic viability. This is mainly due to the fact that the cost of washing equipment does not increase proportionally with the size of the machine; the economy of scale for the washing equipment is in favour of the larger engines. It is also shown as expected, that the values for DPB are more conservative than the SPB, due to the changing value of money accounted. For a less, frequent washing case (480hrs) as shown in Table 4-15, it can be observed that the AS, NPV and RoI are lower. This is about 0.89 times lower than the case of more frequent wash (72 hrs). This is attributed to the fact that the washing liquid cost is significantly less with 480 hrs of washing and consequently less recovery has been experienced. In fact, at 72 hrs frequency, this is 120 washes in the year, while for the other, it is 18 washes. Nevertheless, the operation at a wash frequency of 72 hrs provides a higher energy production than the case of 480 hrs by a difference of 7,444MWh and 128MWh using Table 4-10 for 307MW and

5.3MW capacity. This amounts to a higher operational profit of $495,800 and $12,300 with a slightly shorter payback time. The same method applied for 120hrs and 240hrs interval for simple and dynamic analysis. Table 4-16 shows that increasing the number of engines from 1 to 4, with respect to the varying recovery rate and with 72hrs frequency, increases the RoI by 3.4 times on average. This also highlights the benefits of higher power capacity favorability for online washing economics. The main increased cost with 4 engines is due to the liquid utilised with respect to the size of the engine, as one wash equipment serve all machines. It is important to highlight using Table 4-14 and Table 4-16, that to achieve a total of approximately 255MW using more than one engine (e.g. 4 units of 63MW) provides better economic viability than with one engine at 255MW. This increases the RoI by 1.9 times with an increased annual savings of about $179,700. Figure 4-42 highlights the RoI for all the engines, considering the most optimistic recovery with the highest number of intervals alongside the most pessimistic combinations (pessimistic recovery and lowest number of intervals) for single unit machines. This figure indicates the maximum and minimum RoI of 520% and 462% for the 307MW engine.

Table 4-14 Simple and dynamic analysis for 1 engine of different capacity at 72hrs frequency

72hrs Size	**Simple Payback Period**				**Dynamic Payback Period**		
(MW)	**NPV ($)**	**AS ($)**	**SPB (yrs.)**	**ROI (%)**	**NPV ($)**	**DPB (yrs.)**	**ROI (%)**
307	16,324,999	1,273,769	0.18	544	9,833,586	0.19	520
275	14,187,737	1,109,364	0.21	474	8,534,168	0.22	452
255	**13,959,044**	**1,091,773**	**0.21**	**467**	**8,395,126**	**0.22**	**445**
236	12,906,834	1,010,833	0.23	432	7,755,401	0.24	412
211	11,645,910	913,839	0.26	391	6,988,780	0.27	372
203	11,092,849	871,296	0.27	372	6,652,529	0.28	354
180	10,560,446	830,342	0.28	355	6,328,837	0.30	338
159	9,512,337	749,718	0.31	320	5,691,605	0.33	304
139	7,818,164	614,897	0.29	350	4,684,510	0.30	333
123	7,471,355	588,220	0.30	335	4,473,656	0.31	319
96	6,223,574	487,736	0.24	417	3,737,959	0.25	397
84	5,515,376	433,260	0.27	370	3,307,387	0.28	352
63	3,967,835	314,218	0.37	269	2,366,509	0.39	254
43	2,687,821	213,055	0.38	260	1,602,042	0.41	246
27	1,727,246	139,165	0.59	170	1,018,029	0.63	160
13	902,062	73,439	0.72	139	527,798	0.77	130
5	392,747	34,261	1.54	65	218,144	1.70	59

Table 4-15 Simple and dynamic analysis for 1 engine of different capacity at 480hrs frequency

480hrs	Simple Payback Period				Dynamic Payback Period		
Size (MW)	NPV ($)	AS ($)	SPB (yrs.)	ROI (%)	NPV ($)	DPB (yrs.)	ROI (%)
307	14,495,887	1,133,068	0.21	484	8,721,518	0.22	462
275	12,639,489	990,268	0.24	423	7,592,859	0.25	403
255	12,409,014	972,540	0.24	416	7,452,734	0.25	396
236	11,429,255	897,173	0.26	383	6,857,058	0.27	365
211	10,320,024	811,848	0.29	347	6,182,665	0.30	330
203	9,975,849	785,373	0.30	336	5,973,412	0.31	319
180	9,329,517	735,655	0.32	314	5,580,453	0.33	299
159	8,518,946	673,304	0.35	288	5,087,640	0.37	273
139	7,067,633	557,164	0.31	317	4,228,200	0.33	302
123	6,694,787	528,484	0.33	301	4,001,516	0.35	286
96	5,650,218	443,632	0.26	379	3,389,369	0.28	361
84	4,943,292	389,253	0.30	333	2,959,571	0.32	316
63	3,530,533	280,579	0.42	240	2,100,637	0.44	227
43	2,385,568	189,805	0.43	232	1,418,278	0.46	219
27	1,542,260	124,935	0.66	153	905,561	0.70	143
13	794,800	65,188	0.81	124	462,585	0.87	115
5	342,890	30,426	1.73	58	187,832	1.94	52

Table 4-16 Simple and dynamic analysis for 4 engines of different capacity at 72hrs frequency

72hrs	Simple Payback Period				Dynamic Payback Period		
Size (MW)	NPV ($)	AS ($)	SPB (yrs.)	ROI (%)	NPV ($)	DPB (yrs.)	ROI (%)
307 (4)	66,333,757	5,124,197	0.06	1,825	40,219,702	0.06	1,752
275 (4)	57,784,708	4,466,578	0.06	1,591	35,022,028	0.07	1,526
255 (4)	56,869,934	4,396,210	0.06	1,566	34,465,861	0.07	1,502
236 (4)	52,661,097	4,072,454	0.07	1,450	31,906,961	0.07	1,391
211 (4)	47,617,399	3,684,477	0.08	1,312	28,840,479	0.08	1,258
203 (4)	45,405,154	3,514,304	0.08	1,252	27,495,473	0.08	1,200
180 (4)	43,275,543	3,350,488	0.08	1,193	26,200,706	0.09	1,144
159 (4)	39,083,108	3,027,993	0.09	1,078	23,651,778	0.10	1,034
139 (4)	32,047,975	2,481,429	0.08	1,178	19,402,058	0.09	1,130
123 (4)	30,660,739	2,374,718	0.09	1,128	18,558,642	0.09	1,081
96 (4)	25,411,174	1,965,506	0.07	1,400	15,394,517	0.07	1,343
84 (4)	22,578,383	1,747,599	0.08	1,245	13,672,229	0.08	1,194
63 (4)	**16,388,219**	**1,271,432**	**0.11**	**906**	**9,908,716**	**0.12**	**867**
43 (4)	11,113,098	862,414	0.11	878	6,718,045	0.12	840
27 (4)	7,270,798	566,852	0.17	577	4,381,992	0.18	551
13 (4)	3,840,843	300,309	0.21	475	2,310,398	0.22	453
5 (4)	1,803,583	143,597	0.44	227	1,071,780	0.47	215

The maximum value for the 5.3MW is 59%, while in the other case it has a minimum value of 52%. This again points to higher energy levels that can be obtained with more frequent washing but not necessarily more economical when compared to the increased cost of washing associated and especially with a lower degradation. The figure also indicates that for all other cases, washing is economically viable.

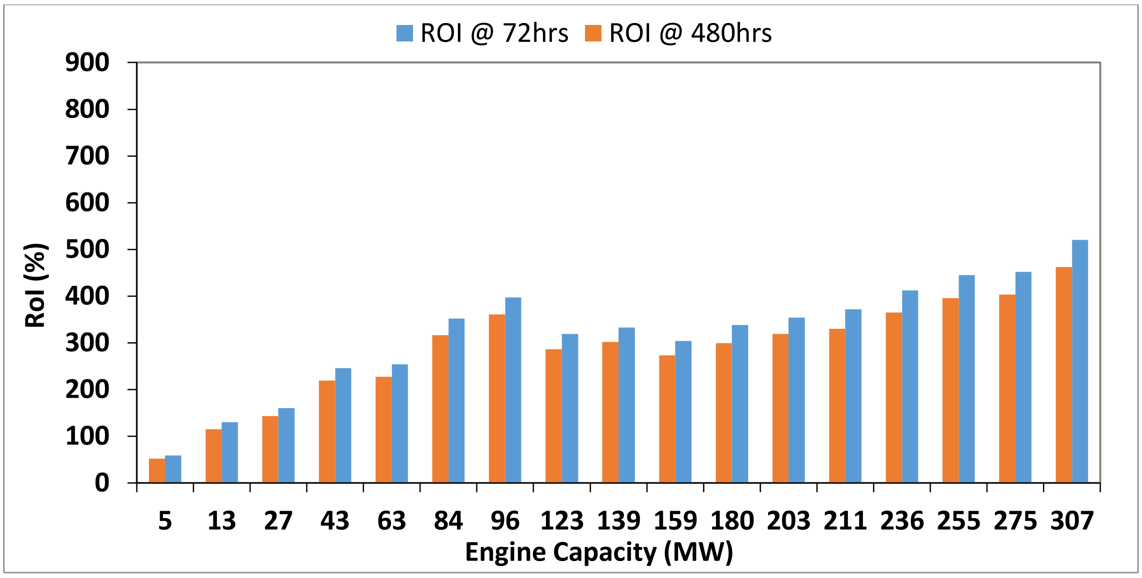


Figure 4-42 RoI for best and worst washing recovery and frequency

Further to the investigation described, the degradation rate is subsequently halved, to investigate the economic viability. This amounts to a 3.6% reduction in the power output by the 8,640th hour. However, there are no occasions when washing isn't viable as shown in Table 4-17. A further reduction in the level of degradation by another half, amounting to 1.8% reduction in power output in the 8,640th hour shows that washing is viable but with a very lower RoI. Consistent with previous cases the more frequent washing amounts to relatively higher RoI with the same level of degradation. The results also indicated that RoI reduces with a decrease in the level of deterioration. When the level of deterioration is lower and more frequent washing has been applied, it becomes expensive to the operator as demonstrated in Table 4-17. Table 4-18 and Table 4-19 highlights all the benefits/profits for more frequent washing case in comparison to less frequent washing of all the engine capacity, as previously stated the energy production for more frequent washing is higher compared to less frequent washing, this translates to a better economic benefit for more frequent washing, however the washing cost is higher for more frequent washing in comparison to the least frequent washing, this is due to higher number of washing intervals.

Table 4-17 RoI for different degradation rates with best & worst wash frequency

	RoI (%) (72hrs frequency)			**RoI (%) (480hrs frequency)**		
Size (MW)	**7.2% Loss**	**3.6% Loss**	**1.8% Loss**	**7.2% Loss**	**3.6% Loss**	**1.8% Loss**
307	520	353	269	462	317	244
275	452	305	231	403	275	211
255	445	301	230	396	272	209
236	412	279	212	365	250	192
211	372	251	191	330	225	173
203	354	237	179	319	218	167
180	338	229	175	299	204	157
159	304	205	155	273	187	143
139	333	222	166	302	205	156
123	319	214	162	286	195	150
96	397	264	197	361	245	187
84	352	235	176	316	214	163
63	254	167	124	227	151	114
43	246	160	117	219	144	107
27	160	101	72	143	92	67
13	130	81	57	115	73	52
5	59	34	22	52	31	20

The net profits for the clean and fouled engine have been estimated at 72hrs 120hrs, 240hrs and 480hrs frequency of washing and the values are the same for all the frequencies as the net profits for the clean engine is the difference between the clean engine cost of electricity and the clean engine cost of fuel, while the net profits for the fouled engine is the difference between the fouled engine cost of electricity and fouled engine cost of fuel. The net profits for the washed engine at 72hrs frequency are $38,678,990 and $1,251,164 for the large and small engine while at 480hrs frequency it is $38,464,612 and $1,245,259 for large and small engine respectively. Comparing the two washing frequency results shows that the washing at 72hrs frequency has more net profits of $214,378 and $5,905 for the large and small engine respectively. This highlights the benefit for the washing on the degraded engine and consistent with previous cases the more frequent washing amounts to relatively higher profits.

Table 4-18 Net profit for different engine capacity at 72hrs frequency

	Net Profit (72hrs frequency)				
Size (MW)	Clean ($)	Fouled ($)	Washed ($)	Additional ($)	After Deduc. ($)
307	40,869,412	37,308,142	38,678,990	1,370,848	1,013,769
275	36,020,160	32,915,458	34,115,489	1,200,031	849,364
255	35,079,350	35,079,350	33,192,063	1,178,906	831,773
236	32,463,850	29,640,750	30,728,282	1,087,533	750,833
211	29,474,911	26,920,173	27,905,551	985,378	653,839
203	28,581,673	26,100,371	27,056,844	956,473	611,296
180	26,547,264	24,219,214	25,113,213	893,999	570,342
159	24,343,027	22,200,500	23,022,136	821,636	489,718
139	20,419,569	18,662,696	19,342,226	679,531	419,897
123	19,157,040	17,480,162	18,124,549	644,386	393,220
96	16,265,318	14,870,550	15,410,711	540,161	357,736
84	14,344,169	13,126,468	13,599,871	473,403	303,260
63	10,570,694	9,701,156	10,043,345	342,189	184,218
43	7,300,368	6,721,172	6,952,378	231,205	122,055
27	4,931,810	4,550,571	4,704,354	153,783	48,165
13	2,643,072	2,446,846	2,527,321	80,475	14,939
5	1,306,049	1,212,128	1,251,164	39,036	-24,239

Table 4-19 Net profit for different engine capacity at 480hrs frequency

	Net Profit (480hrs frequency)				
Size (MW)	Clean ($)	Fouled ($)	Washed ($)	Additional ($)	After Deduc. ($)
307	40,869,412	37,308,142	38,464,612	1,156,470	873,068
275	36,020,160	32,915,458	33,928,166	1,012,708	730,268
255	35,079,350	32,013,157	33,007,606	994,450	712,540
236	32,463,850	29,640,750	30,558,268	917,518	637,173
211	29,474,911	26,920,173	27,751,592	831,419	551,848
203	28,581,673	26,100,371	26,907,360	806,990	525,373
180	26,547,264	24,219,214	24,973,258	754,044	475,655
159	24,343,027	22,200,500	22,893,431	692,931	413,304
139	20,419,569	18,662,696	19,236,185	573,489	362,164
123	19,157,040	17,480,162	18,023,701	543,539	333,484
96	16,265,318	14,870,550	15,326,466	455,916	313,632
84	14,344,169	13,126,468	13,526,163	399,695	259,253
63	10,570,694	9,701,156	9,701,156	289,195	150,579
43	7,300,368	6,721,172	6,916,794	195,622	98,805
27	4,931,810	4,550,571	4,680,793	130,222	33,935
13	2,643,072	2,446,846	2,515,079	68,233	6,688
5	1,306,049	1,212,128	1,245,259	33,131	-28,074

Considering the additional profit due to washing only from the total profit of the plant which is the difference between the net profits for the washed engine and the net profits for the fouled engine. Table 4-18 and Table 4-19 show that additional profits due to washing at 72hrs are $1,370,848 and $39,036 while at 480hrs are $1,156,470 and $33,131 for large and small engine respectively. This also highlights the benefits for the washing and the frequency of the washing itself. The net profits after deducting the washing cost are considered and can be defined as a difference between the additional profits due to washing and the total cost of washing (O&M + Capital) per 8640th hours. The net profits after deducting the washing cost at 72hrs frequency are $1,013,769 and $-24,239 while at 480hrs frequency of washing are $873,068 and $-28,074 for the large and small GT engine respectively. It can be noticed from the output results the net profits after deduction for a small GT engine are negative for the 72hrs and 480hrs frequency, thus the 72hrs frequency has lower negative value (loss) compared to the other frequency and this is due to washing benefit. This indicated that washing for small GT engine is not viable and that evidenced by lower RoI.

4.6.1.1 Sensitivity Analysis

The effect of changing the cost of electricity on RoI and NPV at 72hrs frequency of large engine of 307MW and small engine of 5.3MW is indicated in Figure 4-43 and Figure 4-44. The RoI increases with an increase in the cost of electricity from the reference value of $66.6/MWh and $96.0/MWh for 307MW and 5.3MW respectively. An increase in the cost of electricity by $1 increases the value of NPV by $445,357 and RoI by 23% for the large engine while NPV increases by $7,617 and RoI by 2% for smaller engine respectively.

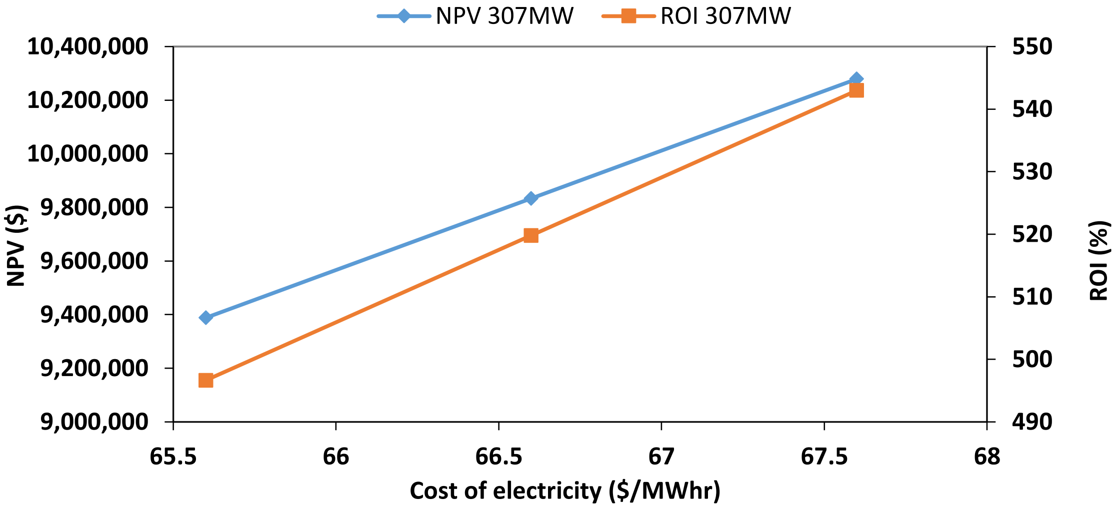


Figure 4-43 Effect of increase in cost of electricity for 307MW capacity

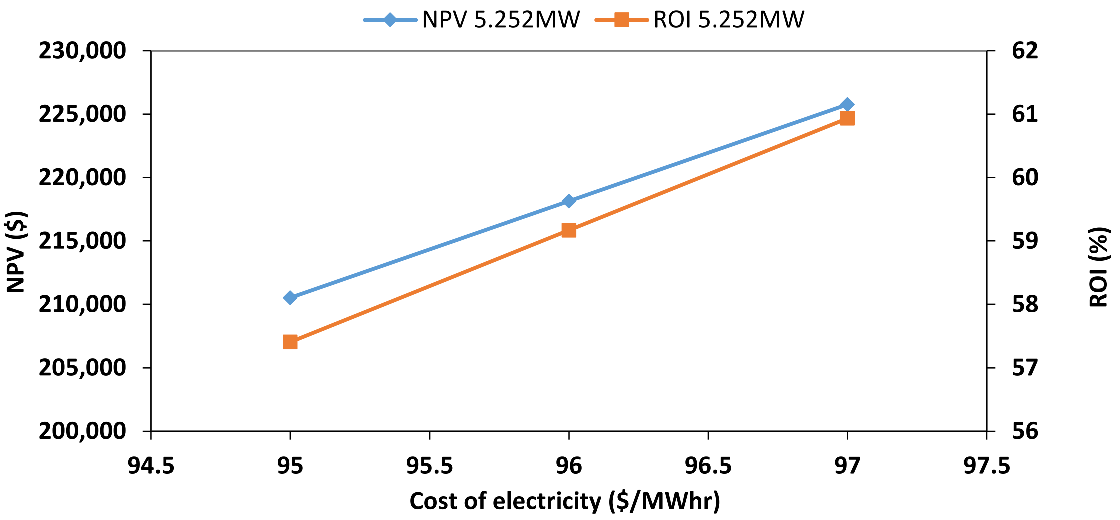


Figure 4-44 Effect of increase in cost of electricity for 5.3MW capacity

This increase in the cost of electricity increases the gains for the operator but this makes the electricity cost more expensive to the end user as the market price is highly competitive. The effect of changing the liquid cost on RoI is indicated in Figure 4-45. This is applicable to 72hrs interval for all the engines capacity. When the running cost of washing is higher, it reduces the gains for the operator, as every improvement in washing becomes relatively more expensive. This is shown in Figure 4-45 that shows RoI values for washing liquid cost from $2.9 per litre to $4.9 per litre. This also shows it’s more expensive to buy fluid at $4.9/litre for small engine of 5.3MW.

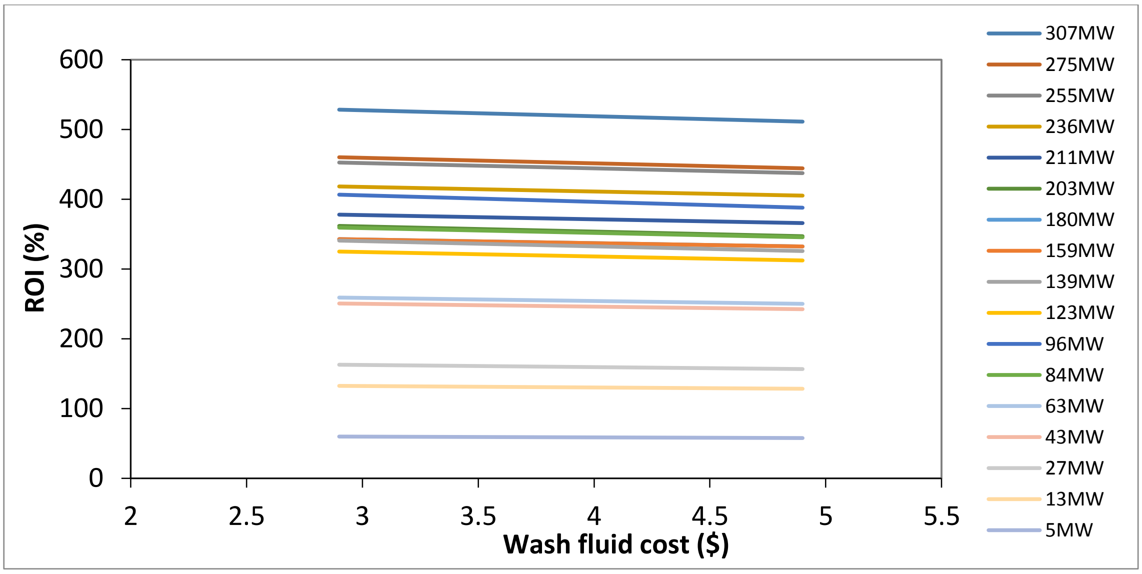


Figure 4-45 Effect of change in wash fluid cost for different capacity on RoI

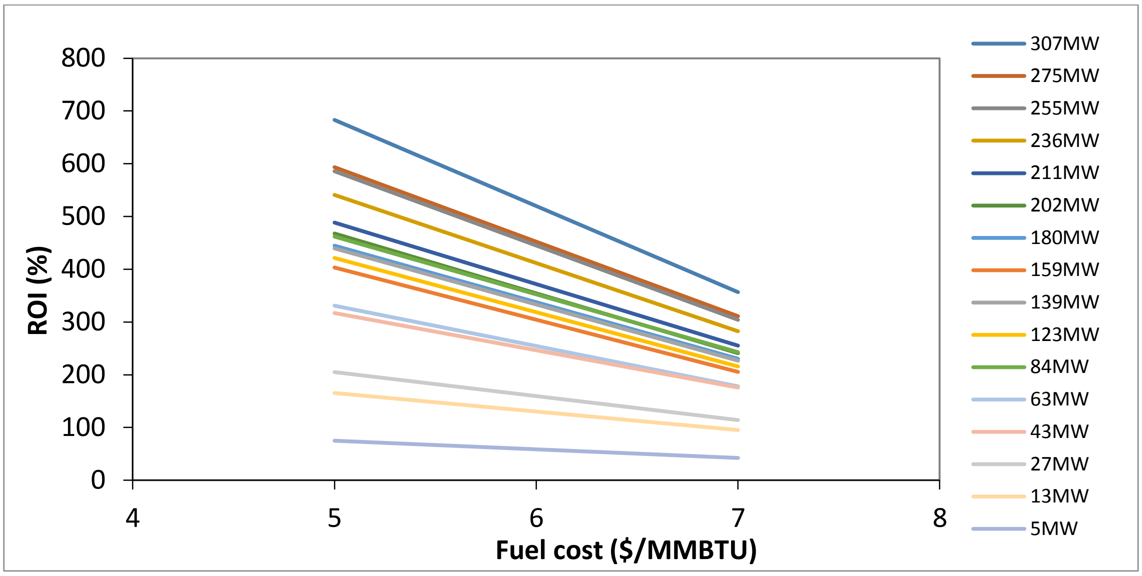


Figure 4-46 Effect of increase in fuel cost for different engine capacity on RoI

Likewise, an increase in fuel cost for the same selling cost of electricity is seen to penalize the gains in RoI as shown in Figure 4-46. This shows the implications of $1 per MMBTU increase on the RoI.

4.7 Summary

In summary, the study has presented the economic cost of compressor fouling for different engines, related to their rated capacities. This is on the assumption that all engines have similar existing levels of deterioration and percentage heat rate increase. All of the initial set questions have been addressed indicating the following:

- Cost of fouling can vary significantly, from $203,000 to $8,434,000 in one year depending on the engine size and level of deterioration.
- The cost of on-line washing equipment is not proportional to the size of the equipment. The economics is more favourable for larger engines due to economy of scale. This is due to a higher value of power production and significantly more penalty per MW of electricity generated for the same percentage losses. This can be overcome by implementing more than one single small engine unit.
- The increased performance benefit or higher power outputs promised by on-line washing typically outweighs the increased financial cost.

- On-line compressor washing is a lot more viable, when the expected level of degradation is high, as demonstrated in the study.
- The study also shows that on-line washing is viable for electric power generation. It was observed for smaller light-duty engines, the return on investment is very low especially in situations when the level of fouling is relatively low.
- Higher return on investment is achieved when more than one relatively small engine is used to obtain a higher total power output. This is about 1.9 times higher for four 63MW engines versus one 255MW, as relatively cheaper washing equipment is implemented for the same total operational capacity. This increases the annual savings to about $179,700.
- When the number of engines increases to 4 for a given operations, the return on investment increases by a factor of 3.4 on average. This is possible as one wash unit can be applied to more than one engine within proximity.
- The overall accumulation of energy level of washed data (experimental) for all the engines appears to be very high for on-line washing and adjustment has been made in a way that only high dominant of recoveries occurred for a short period of the washing with less recoveries at the end of washing operation due to the accumulation of deposits at the rear stage of the compressor.
- The additional profit with respect to washing from the total profit of the plant shows that profits at 72hrs frequency are $1,370,848 and $39,036 while at 480hrs are $1,156,470 and $33,131 for large and small engine respectively. This highlights the benefit for the washing and consistent with previous cases the more frequent washing amounts to relatively higher profits. The net profit for the washed engine at 72hrs frequency is relatively higher than that of 480hrs by a difference of $214,378 and $5,905 respectively.
- The net profits after deducting the washing cost at 72hrs frequency are $1,013,769 and $-24,239 while at 480hrs frequency are $873,068 and $-28,074 for the large and small GT engine respectively. It can be noticed

from the output results that net profits after deduction of washing and equipment cost for a small GT engine are negative, however the 72hrs frequency has lower negative value (loss) compared to other frequency and this is due to washing benefit. This also indicates that the viability of washing for small GT engine is lower.

- The results for the standard method show higher power drop and heat rate increase compared to the extended method by 4.14% and 0.8%, the reason for lower value for the extended method is due to accounting for the effect of humidity and compressor inlet pressure and temperature in correcting data.
- Higher cost of fouling for the standard method has been observed due to higher percentage of power output reduction and heat rate increase.

5 ECONOMIC ANALYSIS OF GT OFF-LINE COMPRESSOR WASHING

This chapter provides an economic analysis of GT off-line compressor washing from 720hrs to 4320hrs frequency and a combination of the two methods (on-line and off-line), using four years data of a power plant. The work presents the economic benefit, economic losses, cost associated with off-line/on-line washing, specific cost of energy produced, additional profit due to washing and net profit after deducting washing cost for different engines, related to their rated capacity. The main objective of the chapter is to analyze the economic benefit of combining off-line and on-line washing in order to recover the power loss due to degradation using different scenario for off-line washing frequency. However, no study demonstrates the economic benefit of combining off-line and on-line compressor washing. Most studies focus on the indivdual cost benefit analysis (on-line or off-line washing) without considering the capital investment for different engine power capacity. In an effort to demonstrate the economic benefit of off-line and on-line washing or a combination of the two methods for different engine sizes, the study answers the following questions:

- What is the specific cost of energy produced for different combination of off-line and on-line washing of different engine sizes?
- What is the total cost associated with (off-line and on-line) washing for a period of 8640hrs for different engine sizes?
- What is the net profit after deducting washing cost and additional profit due to washing for off-line or a combination of the two methods of different engine sizes?

5.1 Off-Line Washing Economics

The off-line washing model consists of economic losses and economic benefit that are associated with the washing process. The off-line washing economics that are accounted in this study includes the following;

- Cost of off-line washing.
- Loss of revenue (power loss and excess fuel burn previously calculated).
- Benefit due to power recovery.

Equations that are used in calculating the net profit after deducting washing cost are highlighted in the off-line washing model using equations (3-42) to (3-56). Figure 5-1 show a step procedure for obtaining the degradation trend line equation and the calculation of the cost of revenue due to fouling and the net profit after deducting washing cost.

5.2 Impact of Off-Line Cleaning

The engine operational data in use is of (Engine-1) heavy duty gas turbine in which the performance was monitored during its operation.

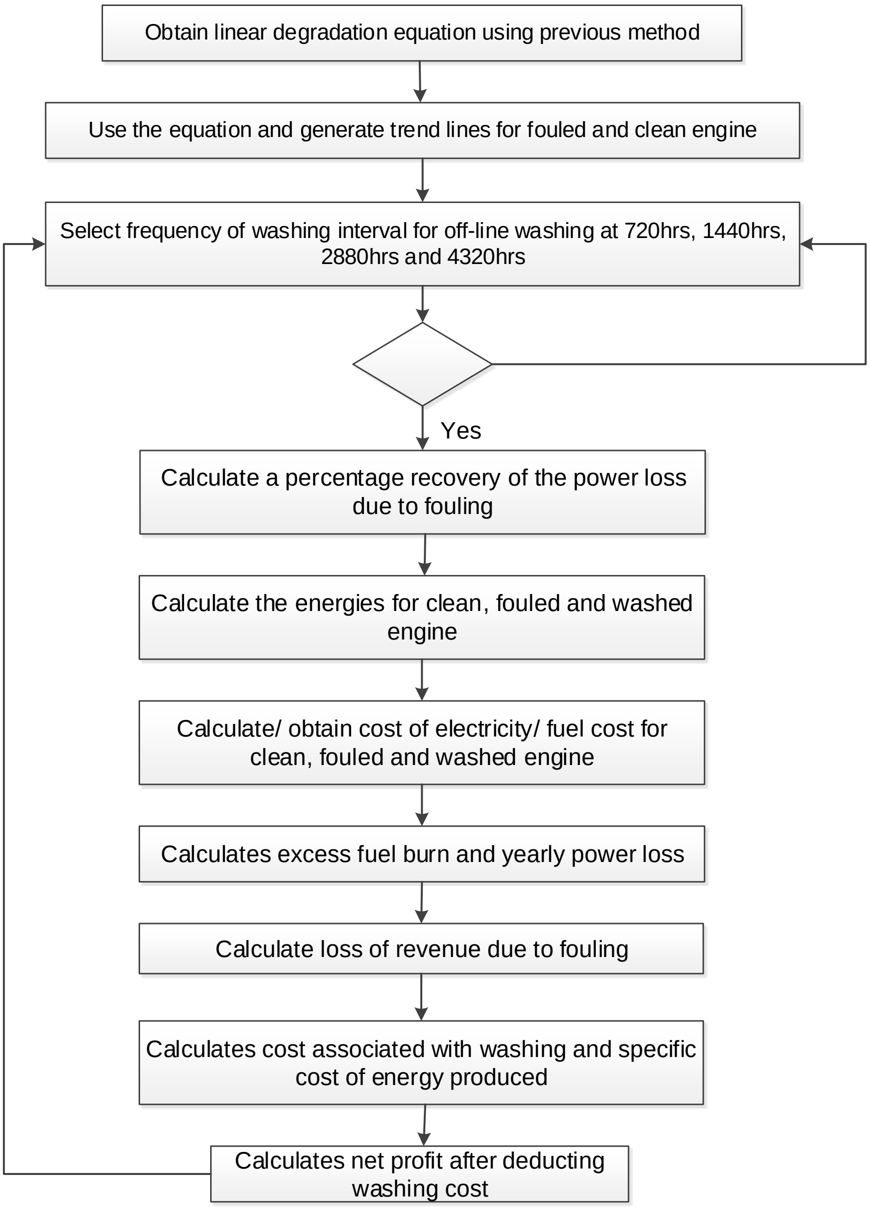


Figure 5-1 Flowchart for estimating net profit after deducting washing cost

The engine experienced six off-line washings for the 1st year (Figure 5-2), while the 2nd, 3rd and 4th year the engine experienced 3, 4, and 2 off-line washes respectively. Improvement has been observed after each washing in the 1st year except 2nd off-line washing, this could be due to sensor fault. As expected the average corrected power output after off-line washing were higher than before off-line washing, this indicates the effectiveness of washing procedure. The 1st EOH of each year's period are unknown as a result of each data start date might not be the starting period. The 2nd off-line washing for year 1, 2nd off-line washing for year 2, 3rd off-line washing for year 3, and 2nd off-line washing for the fourth year for the extended method has higher power recovery and shutdown duration and this could be due to higher operating hour.

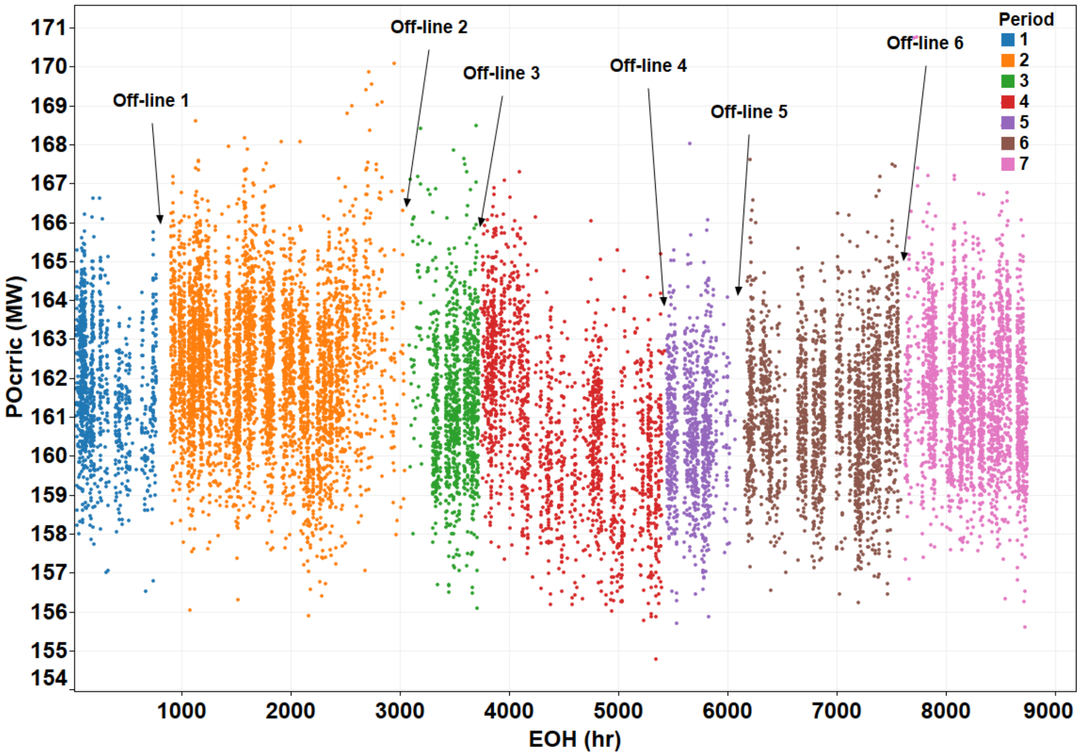


Figure 5-2 Corrected power against EOH for year 1

5.3 The Case Study and Consideration

The gas turbine performance has been monitored for approximately 4 years that shows about 19 events of off-line washing operation. To investigate the trend lines of degradation, an average trend lines for each year were obtained. Then an average trend line from the 4 lines of the 4 years was also obtained at 8640hrs of operation. For example, seven trend lines were obtained for the first year that show 6 periods with negative slopes and one positive slope at period six. An average trend line was obtained from the 6 periods which represent the trend line for year one. The highest durations for the operation before an offline washing lies at period 2 with 2280hrs while the lowest at period 5 with 650hrs. The duration for all the six periods were extended to 8640hrs and an average was obtained from it. The trend line equations were used to calculate the percentage degradation for each period for the particular hours. An average degradation trend line was obtained for other years. Then an average linear trend line was obtained from the average trend lines of the 15 events that show negative slope for the durations. The average reductions in power output with respect to time implemented in this work is as a result of extended data correction highlighted and discussed previously.

5.3.1 Duration and Quantity of Liquid Consumed per Washing

As stated previously, the estimates on the amount of liquid utilised for the washing cycle is based on the water-to-air ratio by mass flow. In this off-line washing analysis 0.1% of water-air-ratio is assumed, justifying the relatively large amount of water used for low-pressure off-line washing system. The droplet sizes produced from the nozzle for off-line washing are large with low pressure and low pump power. With publicly available data on individual engine mass flow [109–111], it is convenient to calculate the quantity of liquid in use. The duration considered for off-line washing is approximately 25 - 30 minutes, applying a mixture of detergent and demineralized water in the ratio of 1:4. For the washing, the injection, drain and pulse time are approximately at 1, 4 and 5 minutes respectively. This procedure is repeated for about 5 to 6 times for the washing. The duration for washing depends on; GT type and model, nozzle system installed and the plant specific procedure. Most power plants have their own washing procedure and this is adopted in this study as follows:

- Wash cycle(s)
- Soaking
- Rinse cycle(s)

Washing cycle is largely dependent on the level of deterioration and can take up to a maximum of 6 washes. The number of washes can be determined based on the evaluation of the effluent water from the drain. The duration considered for the rinse cycle is approximately 25 minutes; this depends on the nozzle system installed and plant specific procedure. It has been proven experimentally that rinsing the GT for more than one cycle with demineralized water is appropriate. It has been assumed that 2 rinse cycles with demineralized water for this study is appropriate. The cycle might be higher based on the rinse effluent water from the drains. The duration considered in this study for the soaking is approximately 15 minutes. There are certain conditions that OEM specifies which allow for an off-line wash. The main important criterion to be considered is the allowable temperature of the blades and cooling down the GT is influenced by various factors such as ambient temperature and rotational speed. Table 5-1 indicates the wide-ranging engines taken into account in the study, from 5.3 to 307MW.

Table 5-1 Amount of liquid consumed per wash per engine

Capacity (MW)	Mass Flow (kg/s)	Washing Cycle(s) (l)	Rinse Cycle(s) (l)
307	723.48	1302	2605
275	669.96	1206	2412
255	640.47	1153	2306
236	553.38	996	1992
211	510.31	919	1837
203	624.14	1123	2247
180	444.52	800	1600
159	513.47	924	1848
139	474.37	854	1708
123	403.7	727	1453
96	394.17	710	1419
84	291.66	525	1050
63	190.06	342	684
43	121.11	218	436
27	91.63	165	330
13	39.19	71	141
5	20.32	37	73

5.3.2 Power Recovery and Frequency of Off-line Washing

Off-line compressor washing plays a substantial role in recovering of GT power loss due to fouling. The degradation of a GT engine due to fouling comprises of losses that are recovered by washing, losses that are recovered due to major inspection or overhaul and the losses that cannot be recovered due to wear and tear. To account for the effectiveness due to off-line washing, 1.2% loss of non-recoverable degradation from the total percent reduction of power output for a year that includes losses recovered by major inspection and losses that are not recovered due to wear and tear has been applied in order to estimates the effectiveness of off-line washing according to Leusden et al. [12]. An 80% recovery of loss power due to fouling has been estimated using non-recoverable degradation percentage. To account for the improvement in performance in the analysis, 70% and 80% recovery of lost power after every washing is adopted. It is important to state that the effectiveness of washing is influenced by the fouling levels and nature of foulant which differs with environments and seasons. This is highlighted in Igie et al. [51] and as such, variations in washing effectiveness from 70% to 80% are implemented in this study. Varied frequencies of washing interval such as, every 720hrs, 1440hrs, 2880hrs and 4320hrs are implemented.

5.3.3 Capital and Operational Cost for Off-line Washing

The related capital, maintenance cost and salvage cost of the washing equipment for small to large engines has been provided by **R-MC** Power Recovery Ltd and is shown in previous chapter. The operational cost of the liquid that includes the washing liquid has also been accounted by R-MC Power Guard concentrate mixture with demineralized water in the ratio of 1:4. The cost of the concentrates is set at $3.9 per litre while the demineralized water per litre is set at a cost of $0.065 (UK price), this values may vary in different locations due to cost for transporting the concentrates. Figure 5-3 shows the quantity of liquid used for one wash, per engine or in relation to mass flow. Table 5-2 shows the total cost of washing a large engine of 307MW and small engine of 5.3MW, when the washing frequency is every 720hrs. The costs of liquid per wash for the 307MW and 5.3MW engines are $1,253 and $35 respectively. The washing period for off-line washing is approximately 25 - 30 minutes, applying a mixture of detergent and demineralized water. Two rinse cycles adopted and the duration considered for the rinse cycle is approximately 25 minutes; this depends on the nozzle system installed. The rinse cycle can be higher based on the level of effluent water from the drain. The annual cost of wash liquid for both engines at a frequency of 720hrs with 12 washing intervals are $15,033 and $422 respectively. The total cost/expenditure for the first year that includes the capital cost is $285,433 and $61,262 respectively. These values are not 4 times the cost when 4 units of engines are applied to the respective engines. Table 5-3 highlights this, indicating that the increased cost is 1.35times and 1.22times for the heavy and light duty engine respectively. The reduced cost is primarily attributed to the fact that one washing equipment can serves more than one engine within proximity, making it more cost effective. Cost related to additional nozzles, a larger tank and piping connection and increased maintenance cost are marginally increased for 4 engines when compared to one. The only variable with 4 times increase for 4 engines is the liquid wash cost.

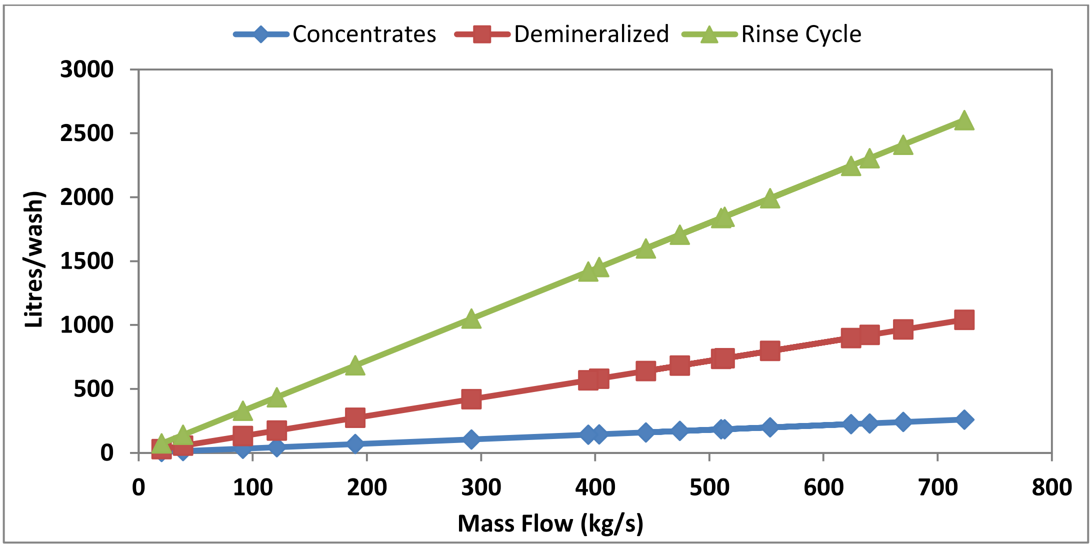


Figure 5-3 Litre used per wash as a function of mass flow (off-line)

Table 5-2 First year cost of washing 1-heavy and 1-light-duty engine

Description/ Cost of Washing/ Maintenance	1-Heavy-Duty 307MW	1-Light-Duty 5.3MW
Capital cost of equipment/ installation	$260,000	$58,500
Total amount of concentrates / wash	261l	7l
Total amount of demineralized	1,042l	29l
Total amount of demin. used for rinsing	2,605l	73l
Cost of fluid/ litre	$3.9	$3.9
Cost of demineralized water/ litre	$0.065	0.065
Cost of fluid/ off-line wash	$1,253	$35
Cost of fluid/ wash/year/ **12 interval**	$15,033	$422
Maintenance/ installation of equipment	$10,400	$2,340
Total cost per 8640hrs 1 heavy-duty	**$285,433**	**$61,262**

Table 5-3 First year cost of washing 4-heavy and 4-light-duty engine

Description/ Cost of Washing/ Maintenance	4-Heavy-Duty 307MW	4-Light-Duty 5.3MW
Capital cost of equipment/ installation	$312,000	$70,200
Cost of fluid/wash/year/ **12 interval**	$60,132	$1,688
Maintenance/ installation of equipment	$12,480	$2,808
Total cost per 8640hrs 4 heavy-duty	**$384,612**	**$74,696**

Figure 5-4 shows the total cost of washing for 1 and 4 engines for different engines at a frequency of 720hrs. However, the cost reduces with an increase in the frequency of washing but more deposits are built up. Due to the use of one wash skid of 4-engines, it is more reliable and cost effective.

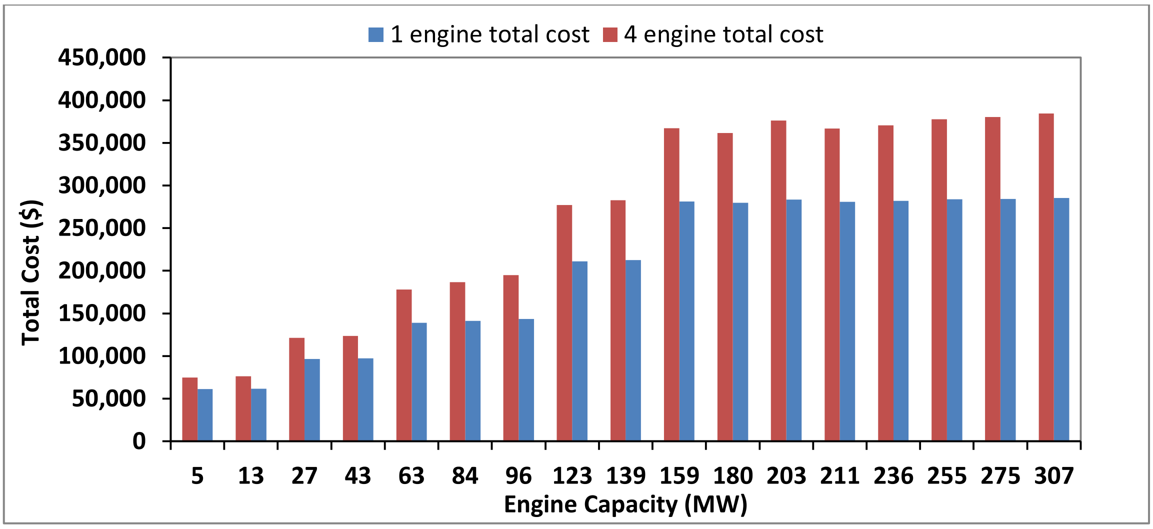


Figure 5-4 Total cost of washing for 1 and 4-engines 720hrs recovery

5.4 Economic Analysis for Off-Line Washing of Different GT Capacity

A performance model for off-line washing that suits all types of GT engine has been developed. The performance model comprises of degradation trend line, clean engine trend line and the washed engine trend line. In order to recover the energy loss due to fouling during operation, an off-line washing has been introduced and the following are outlined steps;

- Obtain degradation equation using extended or standard method
- Select interval of washing
- Calculate a percentage recovery
- Estimate the washed energy of the engine

The trend lines for clean, fouled and washed engine were generated for the year as shown in Figure 5-5 and Table 5-4. The ideal clean engine power delivered for SGT5-4000F engine is 307MW and it’s usually not the case due to natural wear and tear, the estimated energy produced per year for the idealised clean engine is 2,652,480 MWh shown in Table 5-4. Based on the degradation trend line, the energy produced for the fouled condition is 2,557,292 MWh. The trend for off-line compressor washing has been obtained by applying 80% recovery the lost power, every 720hrs with the total energy produced of 2,627,096 MWh. At a rated output of 307MW, 8 cases have been investigated. These are 70% and 80% recovery of the lost power, with 720hrs, 1440hrs, 2880hrs and 4320hrs intervals of wash respectively. Table 5-4 indicates the resulting energy produced for these cases, as well as that of a significantly smaller engine with the same rate of degradation and washing schemes. As would be observed from the table, increasing the number of intervals of washing (frequency) or recovery lost power would increase the energy produced. However, it is important to note that the recovery rate (effectiveness) is more important than the frequency/intervals of washing. This is demonstrated by the higher energy produced with changes in the recoveries. These calculations have been made for all the rated capacities, amounting to 136 cases for the 17 engines.

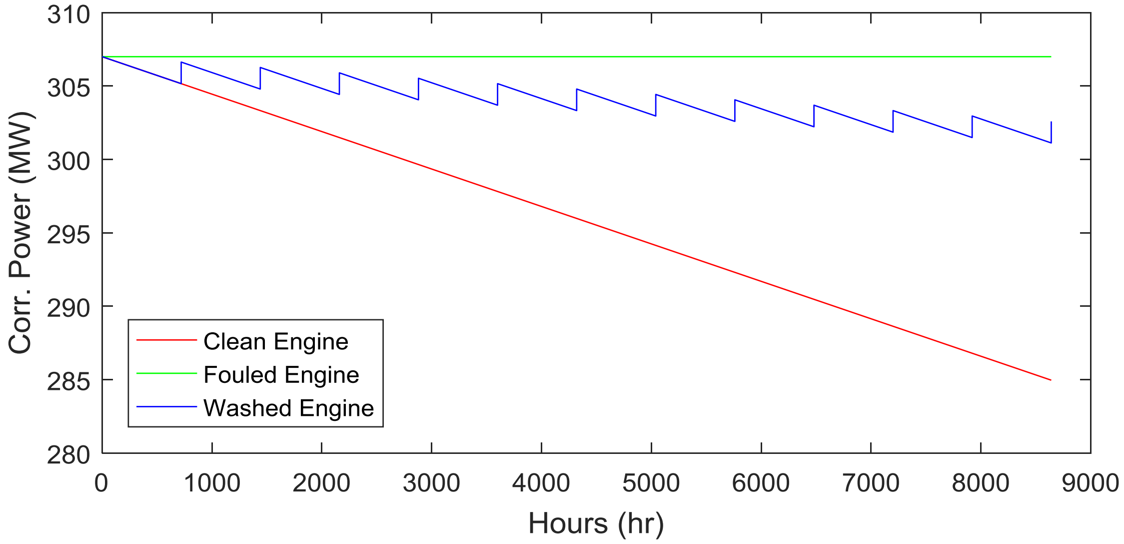


Figure 5-5 Trend lines for clean, fouled and washed engine of 307MW at 720hrs interval 80% recovery

Table 5-4 Heavy and light-duty engines of 307MW and 5.3MW engine

Description	**Frequency** (hrs)	**307MW** **70%**	**80%**	**5.3MW** **70%**	**80%**
Clean (MWh)	**720**	**2,652,480**	**2,652,480**	**45,377**	**45,377**
Fouled (MWh)		**2,557,292**	**2,557,292**	**43,749**	**43,749**
Washed (MWh)		2,618,371	2,627,096	44,794	44,943
$\Delta E\ (MWh)$		**61,079**	**69,805**	**1,045**	**1,194**
Washed (MWh)	**1440**	2,612,818	2,620,751	44,699	44,834
$\Delta E\ (MWh)$		**55,527**	**63,459**	**950**	**1,086**
Washed (MWh)	**2880**	2,601,713	2,608,059	44,509	44,617
$\Delta E\ (MWh)$		**44,421**	**50,767**	**760**	**868**
	4320	2,590,608	2,595,367	44,319	44,400
		33,316	**38,075**	**570**	**651**

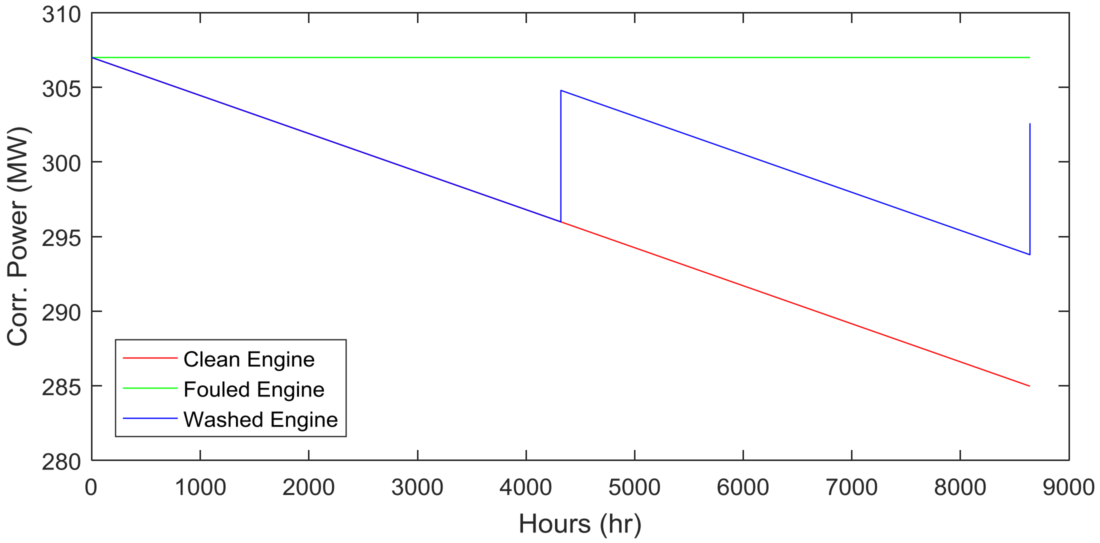


Figure 5-6 Trend lines for clean, fouled and washed engine of 307MW at 4320hrs interval 80% recovery

5.4.1 Economic/Financial Losses

The economic losses that are associated with the washing process consists of the following:

- Cost of off-line washing

The total cost of washing comprises of capital and maintenance cost of the washing equipment. It also contains the operational cost of the liquid that includes the washing liquid that has been accounted for R-MC Power Guard concentrate mixture with demineralized water. The total cost of off-line washing calculated is shown in Table 5-5. The off-line washing cycle is carried out with a mixture of detergent and demineralized water followed by rinse cycles and it’s very effective and gives promising results. It involves stopping the machine and allowing it to cool down to OEM recommended temperature typically below 93℃. The total shutdown duration for washing is largely dependent on the time required for cooling. The downtime required for heavy-duty engines may take 8 to 10 hours or even longer in some cases [113]. However the washing and rinsing period is assumed to be 2 hours for heavy and light-duty engines. The downtime required for light and aero-derivative engines may cool down between 1.5 to 3 hours due to lower metal mass [113]. However, the total losses for each GT engine is the sum of off-line washing cost and loss of revenue, and the total losses for the 307MW and 5.3MW engine are $8,719,591 and $264,643 respectively. The loss of power production due to shut down and benefit due to fuel saved as a result of shut down has been removed from the calculation as the power station used off-line washing as an opportunity.

Table 5-5 Economic losses for different engine capacity at 720hrs

Capacity (MW)	Off-line Washing Cost ($)	Loss of Revenue ($)	Total Losses ($)
307	285,433	8,434,158	8,719,591
275	284,321	7,320,279	7,604,600
255	283,708	7,270,729	7,554,437
236	281,899	6,680,463	6,962,362
211	281,004	6,037,318	6,318,322
203	283,369	5,867,616	6,150,985
180	279,637	5,527,683	5,807,320
159	281,069	5,094,585	5,375,654
139	212,657	4,139,301	4,351,958
123	211,189	3,978,608	4,189,797
96	143,391	3,281,621	3,425,012
84	141,260	2,853,016	2,994,276
63	139,149	2,009,921	2,149,070
43	97,157	1,317,153	1,414,310
27	96,544	856,414	952,958
13	61,654	432,063	493,717
5	61,262	203,381	264,643

** Loss of revenue due to fouling is the same with the previous chapter

5.4.2 Economic Benefit

The economic benefits that is associated with the recovery of loss performance due to washing includes the following:

- Benefit due to power recovery.

Off-line compressor washing shows a considerable role in recovering power loss. As earlier determined, 80% recovery of lost power after every washing is adopted. Varied frequencies of washing interval such as, every 720hrs, 1440hrs, 2880hrs and 4320hrs are implemented. The benefit due to power recovery for 720hrs and 4320hrs interval is shown in Table 5-6. This is obtained by deducting the fouled energy from the washed energy and multiplies with the cost of electricity which gives the benefit due to washing at 720hrs and 4320hrs washing interval. However, the total benefit due to washing for heavy and light-duty engine are $4,649,005 and $114,642 respectively.

Table 5-6 Economic benefit for different engine capacity

Capacity (MW)	Total Benefit (720hrs) ($)	Total Benefit (4320hrs) ($)
307	4,649,005	2,535,821
275	4,039,360	2,203,287
255	4,006,503	2,185,366
236	3,683,078	2,008,952
211	3,329,579	1,816,134
203	3,235,476	1,764,805
180	3,045,037	1,660,930
159	2,805,474	1,530,258
139	2,284,492	1,246,086
123	2,192,088	1,195,685
96	1,811,744	988,224
84	1,576,723	860,031
63	1,114,468	607,891
43	733,291	399,978
27	478,251	260,864
13	242,505	132,276
5	114,642	62,532

5.4.3 Financial Benefit of Washing

To analyze the economic benefit for the plant, four key aspects are estimated for the plant profit/loss and these are net profit after deducting washing cost (NPADWC), specific cost of energy produced (SCEP), total cost for off-line washing and benefit due to power recovery. To analyze the plant performance in terms of washing, two case studies has been chosen and the case 1 is for more frequent off-line washing of 720hrs and case 2 is for less frequent off-line washing of 4320hrs with 12 and 2 intervals of washing in 8640th hour respectively.

The total cost for off-line washing for case 1 (more frequent washing) with respect to large engine of 307MW is $285,433 while for case 2 (less frequent washing) is $272,906 respectively. The cost of washing for case 1 has higher losses due to fouling and higher benefit due to off-line washing operation and this is influenced by a higher number of washing (more frequent). However, the cost of washing for case 2 has higher losses and lower benefit, this is due to the influence of a smaller number of washing (2 off-line washing per annum only) which brings lower benefit to the operator and higher losses due to fouling. The total costs for off-line washing for smaller engine (5.3MW capacity) for the case 1 and case 2 are $61,262 and $60,910 respectively, this shows that less frequent washing has higher losses and lower benefit, and this is due to smaller number of washing and less energy been recovered compared to more frequent washing. The total washing costs for off-line washing increases with an increase of engine capacity for the 720hrs and 4320hrs off-line washing shown in Table 5-7.

To investigate the economic benefit in terms of power recovery, two case studies has been chosen and analyzed and the case 1 is at 720hrs while case 2 is at 4320hrs with 12 and 2 washing intervals respectively. The benefit due to power recovery for case 1 with respect to large engine of 307MW is $4,649,005 while for case 2 is $2,535,821. The benefit of power recovery for case 1 is higher than case 2 by $2,113,184 this is due to higher energy recovered due to higher number of off-line washing or higher effectiveness of washing. However, the benefit due to washing for smaller engine of 5.3MW for the case 1 and case 2 are $114,642 and $62,532 respectively, this also shows that case 1 is higher than case 2 by $52,110 due to higher energy, number of off-line washing and higher effectiveness of washing. This indicates that benefit in terms of power recovery increases with an increase of engine capacity for the same level of degradation and application.

The same case study has been chosen in order to evaluate and estimate the SCEP and measure the profitability of a project, case 1 is at 720hrs and case 2 is at 4320hrs with 12 and 2 intervals of washing respectively. The SCEP for case 1 and case 2 with respect to large engine of 307MW are $56.52/MWh and $58.02/MWh respectively. The SCEP with more frequent washing is lower than for less frequent washing, this means more frequent washing is less expensive by $1.50/MWh and this gives more revenue to the operator for case 1. However, for less frequent washing the SCEP is higher compared to case 1, this is due to accumulation of deposits due to fouling that burns more fuel and gives higher loss of revenue to the operator. The specific cost of energy production for smaller engine of 5.3MW for the case 1 and case 2 are $76.56/MWh and $78.67/MWh respectively. The specific cost of energy for case 2 is more expensive and higher than the case 1 by $2.11/MWh, this is influenced by the accumulation of deposits and gives higher loss of revenue to the operator. The SCEP generally decreases with an increase of engine capacity in most cases and increases in others with an increase of engine capacity, the decrease is influenced by the washed energy delivered and the total cost associated with washing.

To investigate whether the performance benefit due to washing increases the plant operational profit, two case studies as previously used have been chosen and studied and these are the most frequent off-line washing of 720hrs and less frequent off-line washing of 4320hrs for case 1 and 2 with 12 and 2 intervals of washing respectively. The net profit after deducting washing cost (NPADWC) for case 1 with respect to large engine of 307MW is $2,454,370 and for case 2 is $1,983,207. The NPADWC for case 1 is higher than case 2 by $471,163 and this is influenced by higher number of washing (more frequent) that gives more energy due to washing and higher cost associated with off-line washing and is promising. However, the net profit for case 2 has lower washed energy delivered and lower cost associated with off-line washing compared to case 1, this is due to the influence of a smaller number of washing that brings lower benefit to the operator and higher losses due to fouling. The NPADWC for smaller engine (5.3MW capacity) for the case 1 and case 2 are $10,493 and $-4,662 respectively, this shows that less frequent washing has negative and lower NPADWC by a difference of $15,155, this is due to less energy been recovered and lower cost associated with off-line washing compared to more frequent washing. The NPADWC increases with an increase of engine capacity for the 720hrs and 4320hrs of intervals for off-line washing shown in Table 5-7. The increased performance benefit promised by off-line washing mostly outweighs the financial cost with higher net profit/operational profit for more frequent washing and lower net profit/operational profit for less frequent washing.

Table 5-7 Net profit after deducting washing cost for different GT capacity at 720hrs and 4320hrs frequency

Size (MW)	Net Profit 720hrs Add. Profit Washing ($)	Specific Cost Energy ($/MWh)	Net Profit A. D. ($)	Net Profit 4320hrs Add. Profit Washing ($)	Specific Cost Energy ($/MWh)	Net Profit A. D. ($)
307	2,739,803	56.52	2,454,370	2,256,113	58.02	1,983,207
275	2,387,693	54.74	2,103,372	1,961,310	56.19	1,688,590
255	2,359,163	58.64	2,075,455	1,944,022	60.20	1,671,404
236	2,171,761	58.25	1,889,862	1,787,536	59.79	1,515,220
211	1,965,101	58.75	1,684,097	1,616,231	60.31	1,344,064
203	1,908,716	59.45	1,625,346	1,570,428	61.02	1,297,867
180	1,791,419	63.09	1,511,782	1,477,269	64.76	1,205,329
159	1,648,855	65.77	1,367,786	1,360,808	67.52	1,088,630
139	1,351,055	60.85	1,138,398	1,109,333	62.46	904,890
123	1,290,269	66.60	1,079,080	1,063,564	68.37	859,366
96	1,072,473	69.69	929,083	879,917	71.55	743,352
84	936,006	68.78	794,746	766,163	70.62	629,953
63	667,665	64.73	528,516	542,433	66.47	406,574
43	444,159	61.69	347,003	357,618	63.36	262,559
27	292,077	63.17	195,533	233,589	64.88	138,631
13	150,104	66.26	88,449	118,738	68.07	57,763
5	71,755	76.56	10,493	56,249	78.67	-4,662

5.5 The Case Study and Consideration (Off-Line & On-Line Washing)

The engine operational data for fouling degradation in use is of Engine-1 in which the performance was monitored during its operation with off-line washing only. The average trend line used for this analysis is demonstrated in previous chapter using extended correction method.

5.5.1 Duration and Quantity of Liquid Consumed per Washing

The estimates on the amount of liquid utilised for washing is based on the water-to-air ratio by mass flow as previously used with 0.2% [27,45] of water-air-ratio is adopted by on-line washing and 0.1% adopted by off-line washing. With publicly available data on individual engine mass flow [109–111], it is suitable to calculate the quantity of liquid in use as previously estimated. The duration considered and used for on-line washing is approximately 10 minutes with engine operating at base load while for off-line washing is approximately 25 - 30 minutes, applying a mixture of detergent and demineralized water. The duration considered for the rinse cycle is approximately 25 minutes and this depends on the nozzle system installed. In this study, 2 rinse cycles with demineralized water has been assumed. Table 5-8 indicates the wide-ranging engines with the amount of liquid used per on-line and off-line washing taken into account in the study, from 5.3 to 307MW.

Table 5-8 Amount of liquid consumed/wash/engine on-line and off-line washing

Capacity (MW)	Mass Flow (kg/s)	On-line Washing Cycle(s) (l)	Off-line Washing Cycle(s) (l)	Rinse Cycle(s) (l)
307	723.48	868	1,302	2,605
275	669.96	804	1,206	2,412
255	640.47	769	1,153	2,306
236	553.38	664	996	1,992
211	510.31	624	919	1,837
203	624.14	749	1,123	2,247
180	444.52	533	800	1,600
159	513.47	616	924	1,848
139	474.37	569	854	1,708
123	403.7	484	727	1,453
96	394.17	473	710	1,419
84	291.66	350	525	1,050
63	190.06	228	342	684
43	121.11	145	218	436
27	91.63	110	165	330
13	39.19	47	71	141
5	20.32	24	37	73

5.5.2 Power Recovery and Frequency (Off-line and On-line Washing)

On-line and Off-line compressor washing combination plays a vital role in recovering of GT power loss during operation due to fouling. In order to combine and perform on-line and off-line washing operation in a plant there is need for higher degradation as every washing becomes more expensive. To estimate the recoveries for on-line and off-line washing, a modified recoveries for on-line washing has been adopted and implemented here as previously discussed. However, to estimate the improvement in performance for off-line washing, as previously discussed an 80% recovery of lost power has been estimated and adopted in the analysis by using non-recoverable performance degradation percentage according to Leusden et al. [12]. Varied frequencies of off-line washing interval such as, every 720hrs, 1440hrs, 2880hrs and 4320hrs are implemented. However, the frequency for on-line washing interval implemented in the analysis are 72hrs, 120hrs, 240hrs and 480hrs respectively.

5.5.3 Capital and Operational Cost for Off-line and On-line Washing

The related capital, maintenance and salvage cost of the washing equipment from small to large engines has been provided by **R-MC** and the table is shown in chapter three. The operational cost of the liquid that includes the washing liquid has also been accounted for R-MC Power Guard concentrate mixture with demineralized water in the ratio of 1:4 assuming the same quantity and cost of concentrates and demineralized water used for on-line and off-line washing. Table 5-9 shows the total cost of washing for on-line and off-line washing from large engine of 307MW down to 5.3MW at 72hrs on-line and 720hrs off-line. The on-line washing cost includes the capital cost, operation and maintenance cost while the off-line washing cost include only the operation and maintenance cost as the same equipment is used for both on-line and off-line washing.

Table 5-9 Total cost of on-line & off-line washing + maintenance cost

	1- Engine			4- Engine		
Capacity (MW)	**On-line ($)**	**Off-line ($)**	**Total Cost ($)**	**On-line ($)**	**Off-line ($)**	**Total Cost ($)**
307	357,079	25,433	382,512	671,196	72,613	743,809
275	350,666	24,321	374,987	645,545	68,165	713,710
255	347,133	23,708	370,841	631,412	65,714	697,126
236	336,700	21,899	358,599	589,679	58,475	648,154
211	332,700	21,004	353,704	573,681	54,895	628,576
203	345,177	23,369	368,546	623,589	64,357	687,946
180	323,657	19,637	343,294	537,507	49,427	586,934
159	331,917	21,069	352,986	570,550	55,158	625,708
139	259,633	17,657	277,290	470,692	48,788	519,480
123	251,166	16,189	267,355	436,826	42,914	479,740
96	182,424	13,391	195,815	351,137	39,002	390,139
84	170,143	11,260	181,403	302,012	30,482	332,494
63	157,971	9,149	167,120	253,322	22,037	275,359
43	109,150	6,157	115,307	171,607	14,434	186,041
27	105,618	5,544	111,162	157,482	11,984	169,466
13	65,535	3,154	68,689	91,790	6,065	97,855
5	63,274	2,762	66,036	82,744	4,497	87,241

The total cost/expenditure for the first year for 307MW and 5.3MW engine that includes the capital cost are $382,512 and $66,036 respectively. These values are not 4 times the cost when 4 units of engines are applied to the respective engines. Table 5-9 highlights this, indicating that the increased cost is 1.95times and 1.32times for the heavy and light duty engine respectively. The reduced cost is mainly attributed to the fact that one washing equipment can serves more than one engine within proximity, making it more cost effective.

5.6 Economic Analysis of Off-Line and On-Line Washing

The trend lines for clean, fouled and washed engine for 307MW were generated for case 1 (most frequent) at 72hrs on-line and 720hrs off-line washing interval and also for case 2 (less frequent) at 480hrs on-line and 4320hrs off-line washing interval. The ideal clean engine power delivered is 307MW and it’s usually not the case due to natural wear and tear, the estimated energy produced per year for the idealised clean engine is 2,652,480 MWh shown in Table 5-10 and Table 5-11 respectively. Based on the degradation trend, the energy produced for the fouled condition is 2,557,292 MWh for case 1 and 2. The trend for on-line compressor washing has been obtained by applying the results for the effectiveness of washing obtained previously for on-line at 72hrs, 120hrs, 240hrs and 480hrs interval. However, an 80% recovery/improvement of lost power has been applied at every 720hrs, 1440hrs, 2880 and 4320hrs interval for off-line washing respectively. The total energy produced for case 1 (best case in terms of energy production) at 720hrs off-line and 72hrs on-line and for case 2 at 4320hrs off-line and 480hrs on-line (worst case in terms of energy production) are 2,641,032 MWh and 2,622,018 MWh respectively. It can be observed case 1 has higher energy production compared to case 2 by a difference of 19,013 MWh. This high value is due to the influence of higher number of off-line and on-line washing combination (more frequent). Figure 5-7 and Figure 5-8 shows the trend lines for clean, fouled and washed engine of 307MW for the best and worst case combination in terms of net profit after deducting washing cost respectively. It have been observed that 1st two off-line washing for the best combination at 720hrs is not useful/beneficial as the percentage recoveries are very small and shutdown for the 2-off-line washing (20hrs for cooling and washing) reduces the total benefit, using the first off-line washing at the 3rd of 720hrs intervals of off-line washing adds more profit/benefit and is realistic and that shows it has reduced the number of off-line washing due to on-line washing that took place.

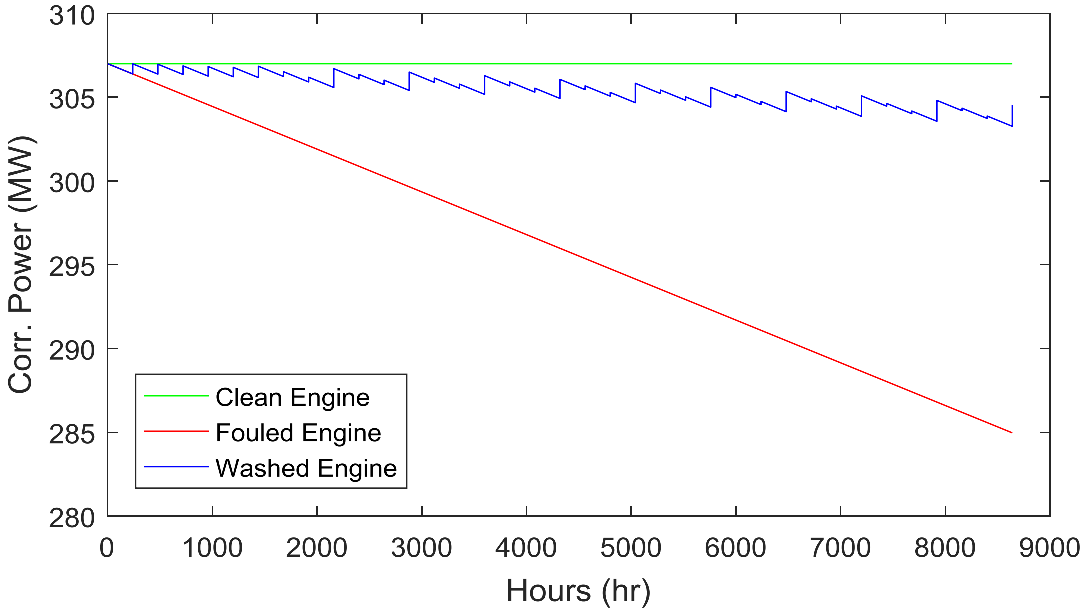


Figure 5-7 Trend lines for on-line and off-line washing of 307MW engine at 240hrs on-line and 720hrs off-line

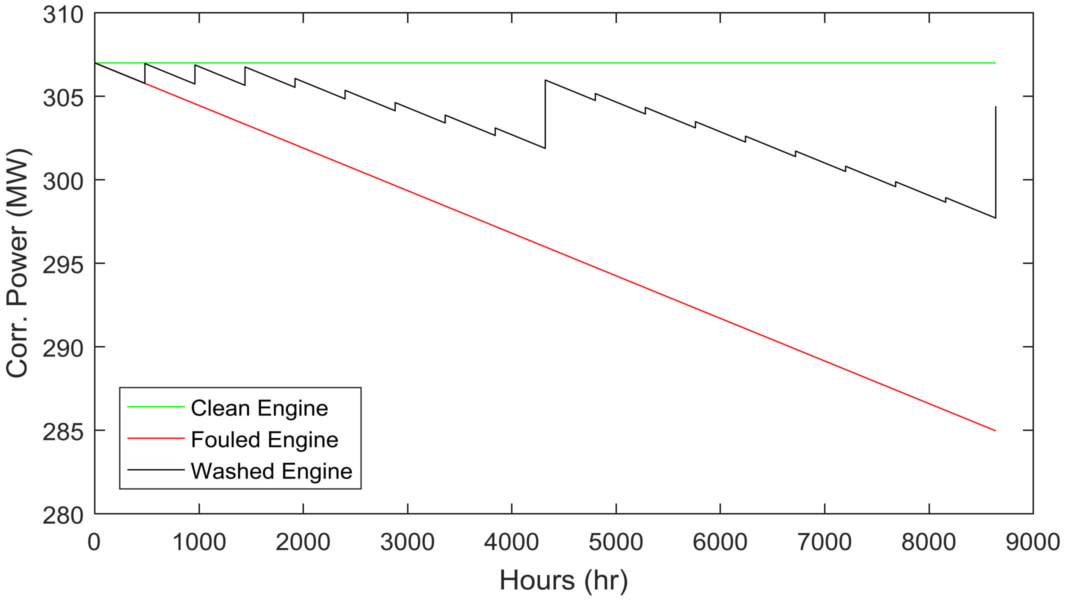


Figure 5-8 Trend lines for on-line and off-line washing of 307MW engine at 480hrs on-line and 4320hrs off-line

It is more beneficial to combine 240hrs on-line with 720hrs off-line that gives highest net profit after deducting washing cost, lower cost of washing combination of $321,837. However, the energy generated is not highest with the value of 2,638,965MWh. This shows that it is a good practice to combine more frequent off-line washing with less frequent on-line washing. At a rated output of 307MW, 8 cases have been investigated. These are 70% and 80% recovery of lost power, with 72hrs, 120hrs, 240hrs and 480hrs intervals of wash at 720hrs, 1440hrs, 2880hrs and 4320hrs off-line washing respectively. Table 5-10 and Table 5-11 indicate the resulting energy produced for these cases, as well as that of a significantly smaller engine with the same rate of degradation and washing schemes. Figure 5-9 and Figure 5-10 indicate the resulting trend line for clean, washed and degraded for smaller engine of 5.3MW with the same rate of degradation and washing schemes.

Table 5-10 Heavy & light-duty engine of 307MW & 5.3MW 720hr washing interval

Description	**Interval**	**Frequency**	**307MW**		**5.3MW**	
	(hrs)	(hrs)	70%	80%	70%	80%
Clean (MWh)	**720**	**72**	**2,652,480**	**2,652,480**	**45,377**	**45,377**
Fouled (MWh)			**2,557,292**	**2,557,292**	**43,749**	**43,749**
Washed (MWh)			2,637,518	2,641,032	45,121	45,181
$\Delta E\ (MWh)$			**80,227**	**83,740**	**1,372**	**1,432**
Washed (MWh)	**720**	**120**	2,636,517	2,640,234	45,104	45,168
$\Delta E\ (MWh)$			**79,225**	**82,942**	**1,355**	**1,419**
Washed (MWh)	**720**	**240**	2,634,978	2,638,965	45,078	45,146
$\Delta E\ (MWh)$			**77,686**	**81,674**	**1,329**	**1,397**
Washed (MWh)	**720**	**480**	2,633,761	2,637,944	45,057	45,129
ΔE (MWh)			**76,470**	**80,652**	**1,308**	**1,380**

Table 5-11 Heavy & light-duty engine of 307MW & 5.3MW 4320hr washing interval

Description	**Interval**	**Frequency**	**307MW**		**5.3MW**	
	(hrs)	(hrs)	70%	80%	70%	80%
Clean (MWh)	**4320**	**72**	**2,652,480**	**2,652,480**	**45,377**	**45,377**
Fouled (MWh)			**2,557,292**	**2,557,292**	**43,749**	**43,749**
Washed (MWh)			2,625,720	2,627,494	44,920	44,950
$\Delta E\ (MWh)$			**68,428**	**70,202**	**1,171**	**1,201**
Washed (MWh)	**4320**	**120**	2,624,305	2,626,189	44,895	44,928
$\Delta E\ (MWh)$			**67,014**	**68,898**	**1,146**	**1,179**
Washed (MWh)	**4320**	**240**	2,622,440	2,624,463	44,863	44,898
$\Delta E\ (MWh)$			**65,149**	**67,171**	**1,114**	**1,149**
Washed (MWh)	**4320**	**480**	2,619,807	2,622,018	44,818	44,856
ΔE (MWh)			**62,515**	**64,727**	**1,069**	**1,107**

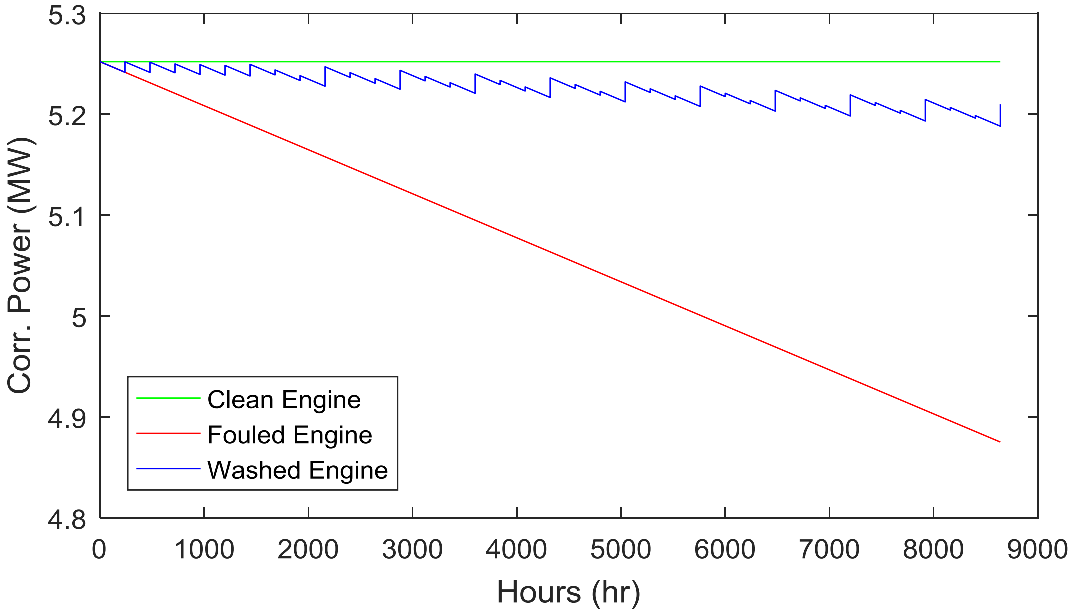


Figure 5-9 Trend lines for on-line and off-line washing of 5.3MW engine at 720hrs on-line and 240hrs off-line

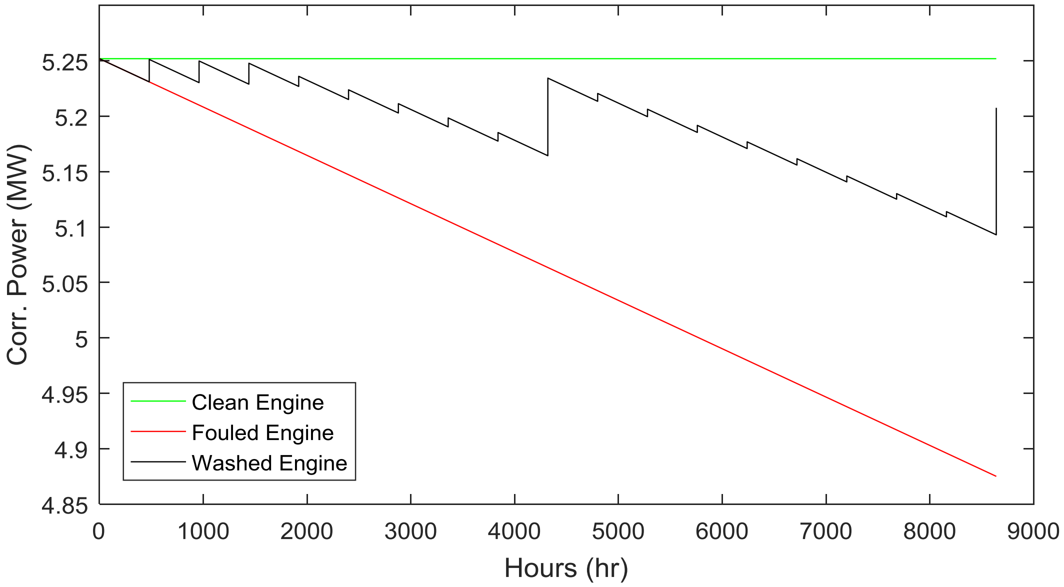


Figure 5-10 Trend lines for on-line and off-line washing of 5.3MW engine at 480hrs on-line and 4320hrs off-line

As would be observed from Table 5-10 and Table 5-11 increasing the number of intervals of washing or recovery of lost power would increase the energy produced. However, it is important to note that the energy produced with changes in frequencies of washing is small. This also shows that it is more economical and beneficial to use more frequent off-line washing with less frequent on-line washing (considering net profit after deducting washing cost). These calculations have been made for all the rated capacities, amounting to 136 cases for the 17 engines.

5.6.1 Economic Losses (Off-line and On-line Washing)

The economic losses comprises those associated with the on-line and off-line washing process and it consists of the following:

- Cost of on-line washing
- Cost of off-line washing

The total cost of washing comprises capital, operation and maintenance cost of the washing equipment for the on-line washing. The other cost contains the operation and maintenance cost of the liquid used by off-line washing. The total cost of washing calculated at 72hrs - 720hrs are shown in Table 5-12.

Table 5-12 Economic losses for different engine capacity (On-line and Off-line)

Capacity (MW)	Total Washing Cost ($)	Loss of Revenue ($)	Total Losses ($)
307	382,512	8,434,158	8,816,670
275	374,987	7,320,279	7,695,266
255	370,841	7,270,729	7,641,570
236	358,599	6,680,463	7,039,062
211	353,704	6,037,318	6,391,022
203	368,546	5,867,616	6,236,162
180	343,294	5,527,683	5,870,977
159	352,986	5,094,585	5,447,571
139	277,290	4,139,301	4,416,591
123	267,355	3,978,608	4,245,963
96	195,815	3,281,621	3,477,436
84	181,403	2,853,016	3,034,419
63	167,120	2,009,921	2,177,041
43	115,307	1,317,153	1,432,460
27	111,162	856,414	967,576
13	68,689	432,063	500,752
5	66,036	203,381	269,417

** Loss of revenue due to fouling is the same with the previous chapter

The total shutdown duration of washing used for heavy-duty engine is assumed to be between 8 to 10 hours [113]. However the washing period is assumed to be 2 hours for heavy and light-duty engines. The downtime required for light and aero-derivative engines may cool down within 1.5 to 3 hours due to lower metal mass [113]. The total economic losses for on-line and off-line washing for different engine capacity is shown in Table 5-12. The shutdown cost and the benefit due to fuel saved as a result of off-line washing has been removed from the calculation, as off-line washing was considered as an opportunity.

5.6.2 Economic Benefit (Off-line and On-line Washing)

The economic benefit for combining off-line and on-line washing that are associated with the recovery of loss performance due to off-line and on-line washing includes the following:

- Benefit due to power recovery (on-line and off-line washing)

The total benefit for washing comprises the cost of power recovered due to washing (on-line and off-line washing). The total benefit due to washing for the case 1 and case 2 are shown in Table 5-13. The on-line and off-line washing time is assumed to be 10 minutes and 2 hours respectively for all the engines capacities as previously discussed.

Table 5-13 Economic benefit for different engine capacity (On-line and Off-line)

Capacity (MW)	Total Benefit (720 – 72hrs) ($)	Total Benefit (4320 - 480hrs) ($)
307	5,577,096	4,310,811
275	4,845,747	3,745,515
255	4,806,332	3,715,049
236	4,418,341	3,415,152
211	3,994,270	3,087,367
203	3,881,382	3,000,110
180	3,652,927	2,823,526
159	3,365,537	2,601,388
139	2,740,550	2,118,305
123	2,629,701	2,032,625
96	2,173,426	1,679,947
84	1,891,489	1,462,025
63	1,336,952	1,033,395
43	879,681	679,949
27	573,725	182,472
13	290,917	224,864
5	137,528	106,302

The benefit due to power recovery here (washing) is obtained by deducting the fouled energy from the washed energy (on-line and off-line washing combination) and multiplying with the cost of electricity that gives the benefit for the washing.

The benefit due to fuel saved (shutdown) is achieved by calculating the total fuel that has been saved during the cooling process (unused fuel) multiplied by shutdown duration and the fuel cost and has removed from the calculation as previously stated, the benefit due to washing is highlighted in Table 5-13. As would be observed from the table, for 307MW engine it has a total cost benefit due to washing of approximately $5,577,096 while for the smaller engine of 5.3MW it has a total cost benefit due to washing of approximately $137,528.

5.6.3 Financial Benefit of Washing

To investigate the economic benefit of the plant, four key features are assessed for the plant profit, these includes specific cost of energy produced (SCEP), net profit after deducting washing cost (NPADWC), total cost for off-line and on-line washing and benefit due to power recovery. To examine the plant performance in terms of off-line and on-line washing combination, two case studies have been analyzed and case 1 (best case) is for more frequent washing combination of 720hrs - 240hrs off-line and on-line washing and case 2 (worst case) is for less frequent off-line and on-line washing of 4320hrs - 480hrs respectively.

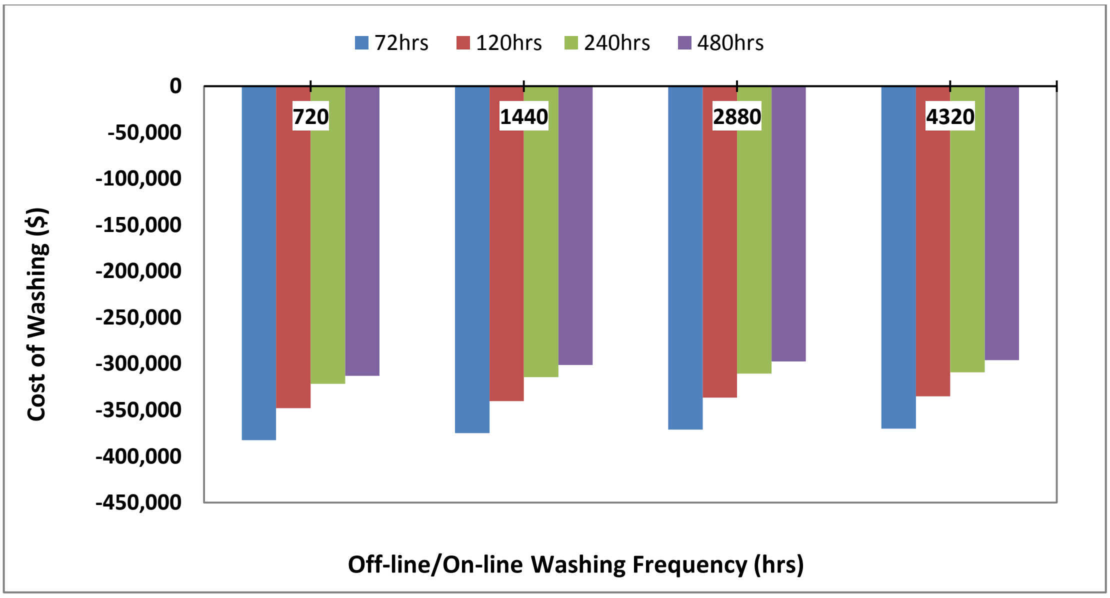


Figure 5-11 Comparison of cost related with washing of 307MW at different off-line and on-line washing combination

The total costs for off-line and on-line washing combination for case 1 and case 2 with respect to large engine of 307MW are $321,837 and $296,307 respectively shown in Figure 5-11. The total cost of washing for case 1 has higher losses and higher benefit due to off-line and on-line washing operation and this is influenced by higher number of off-line and on-line washing (12 off-line and 36 on-line washing per annum). However, the cost of washing for case 2 has higher losses and lower benefit and it is influenced by smaller number of washing and more deposit built up (2 off-line and 18 on-line washing per annum) which totally brings lower benefit to the operator and higher losses. The total cost of washing (off-line & on-line) for smaller engine of 5.3MW capacity (Figure 5-12) for case 1 and case 2 are $64,333 and $63,616 respectively, the result shows that less frequent washing has lower cost of washing and this is due to smaller number of washing and less energy being recovered compared to more frequent washing. The total washing cost that are connected with off-line and on-line washing combination increases with an increase of engine capacity for the combination of 720hrs - 240hrs and 4320hrs - 480hrs respectively.

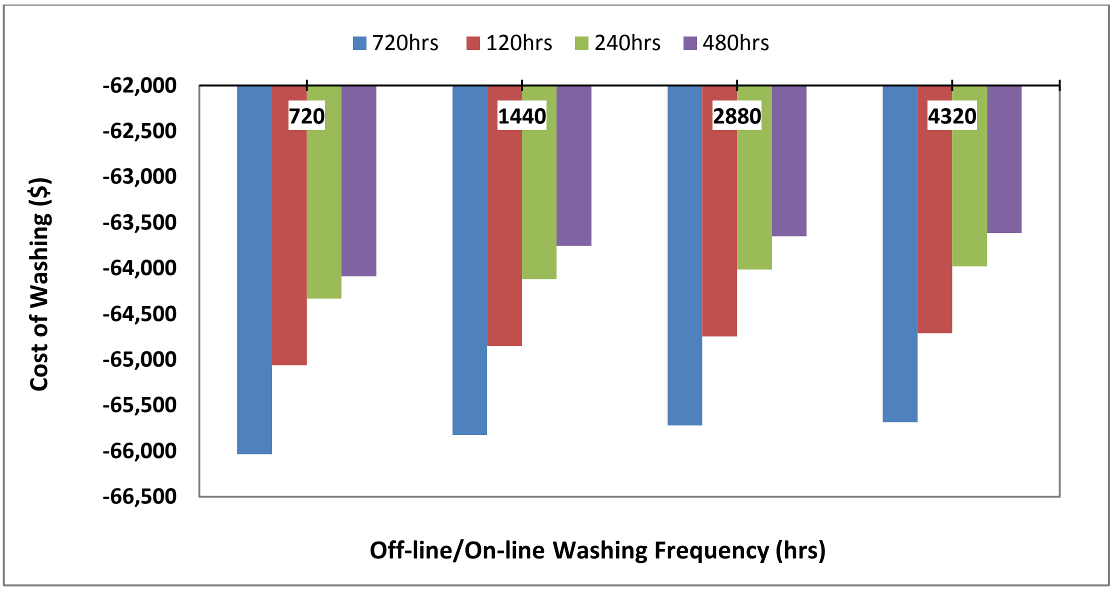


Figure 5-12 Comparison of cost related with washing of 5.3MW at different off-line and on-line washing combination

To investigate the economic benefit due to power recovery, two case studies has been analyzed and these are most frequent (720hrs – 240hrs) and less frequent (4320hrs – 480hrs) washing for case 1 and case 2 as previously discussed. The benefit due to power recovery for case 1 with respect to large engine of 307MW is $5,439,458 and for case 2 is $4,310,812. The benefit due to power recovery for case 1 is greater than case 2 by $1,128,646 this is influenced by higher energy recovered due to higher number of off-line and on-line washing or higher effectiveness of washing. However, the benefit due to washing for smaller engine of 5.3MW for the case 1 and case 2 are $134,134 and $106,302 respectively, this also shows that case 1 is higher than case 2 by $27,832 due to higher energy for the case 1 and higher effectiveness of washing. This also shows that benefit due to power recovery increases with an increase of engine capacity for the same level of degradation and application.

The same case study has been examined in order to evaluate the SCEP and measure the profitability of a project, a case 1 is at 720hrs - 240hrs and case 2 is at 4320hrs - 480hrs respectively. The SCEP for case 1 and case 2 with respect to large engine of 307MW are $55.98/MWh and $56.76/MWh while for smaller engine of 5.3MW is at $75.86/MWh and $76.95/MWh respectively. The SCEP for large and small engine with more frequent washing is lower than for less frequent washing by $0.78/MWh and $1.09/MWh respectively. This translates to more profit for the operator for case 1 compared to case 2 as the cost of producing the energy is lower and cheaper. However, for less frequent washing the SCEP is higher and expensive compared to case 1, this is due to accumulation of deposits due to fouling which burns more fuel and gives higher loss of revenue to the operator. The SCEP generally decreases with an increase of engine capacity in most cases and increases in others with an increase of engine capacity, the decrease is influenced by the washed energy delivered and the total cost connected with off-line washing.

To investigate whether the performance benefit due to off-line and on-line washing outweigh the plant operational profit, two case studies as previously used has been analyzed and these are the most frequent off-line/on-line washing of 720hrs – 240hrs and less frequent off-line/on-line washing of 4320hrs – 480hrs for case 1 and 2 respectively. The net profit after deducting washing cost (NPADWC) for case 1 and 2 with respect to large engine of 307MW is $2,598,894 and $2,366,086 respectively shown in Figure 5-13. The NPADWC for case 1 is higher than case 2 by $232,808 and is influenced by higher number of washing that gives more energy and higher cost associated with the off-line/on-line washing. However, the net profit for case 2 have lower washed energy delivered and lower cost associated with off-line/on-line washing compared to case 1, this is due to the influenced of smaller number of washing that brings lower benefit to the operator and higher losses due to fouling. The NPADWC for smaller engine of 5.3MW capacity (Figure 5-14) for case 1 and case 2 are $13,223 and $5,658 respectively, this highlighted that less frequent washing has lower NPADWC by a difference of $7,565, this is influenced by lower energy recovered and lower cost associated with off-line/on-line washing compared with more frequent washing. The NPADWC increases with an increase of engine capacity for the 720hrs – 240hrs and 4320hrs – 480hrs of off-line and on-line washing shown in Table 5-14. The increase performance benefit promised by off-line and on-line washing outweighs the financial cost with higher net profit for more frequent washing combination and lower net profit for less frequent washing combination.

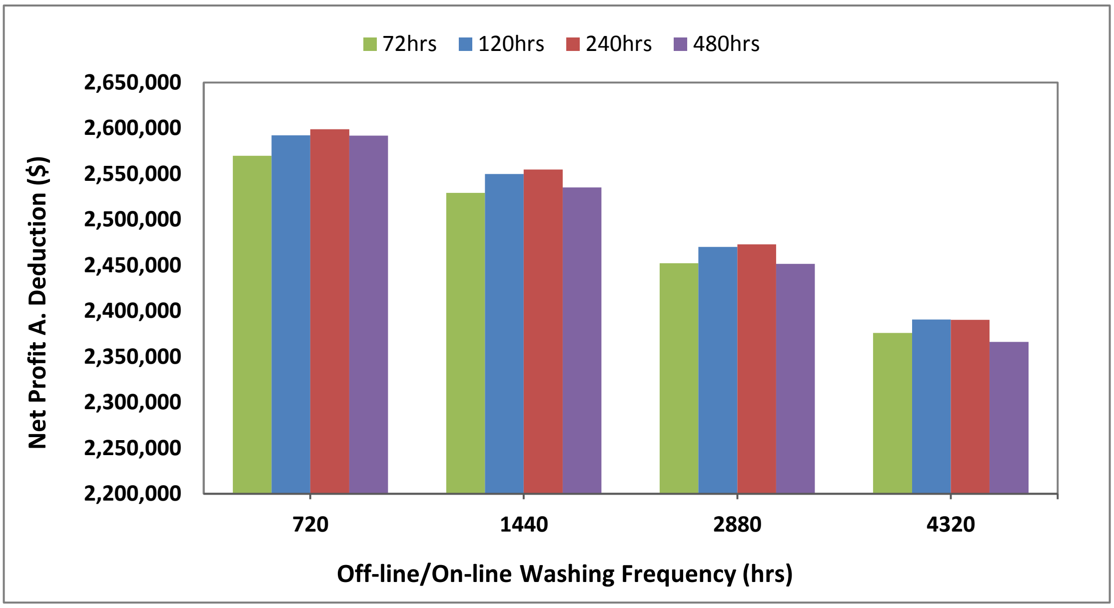


Figure 5-13 Comparison of net profit after deducting washing cost of 307MW GT at different off-line washing with on-line washing combination

Off-line and on-line washing operational practice in a plant is proportional to the rate of degradation, as degradation rate increases and becomes worst, the combination of off-line and on-line washing intervals is shorter (more frequent). However, when the degradation rate is less, combination of off-line and on-line washing intervals is longer (less frequent). Example, the engine operational data for fouling used is of heavy-duty engine in which the performance was monitored during its operation with 7.2% reduction in the power output at the end of the year using extended method. It can be noticed combining off-line and on-line at 720hrs - 240hrs is promising and yields highest profit.

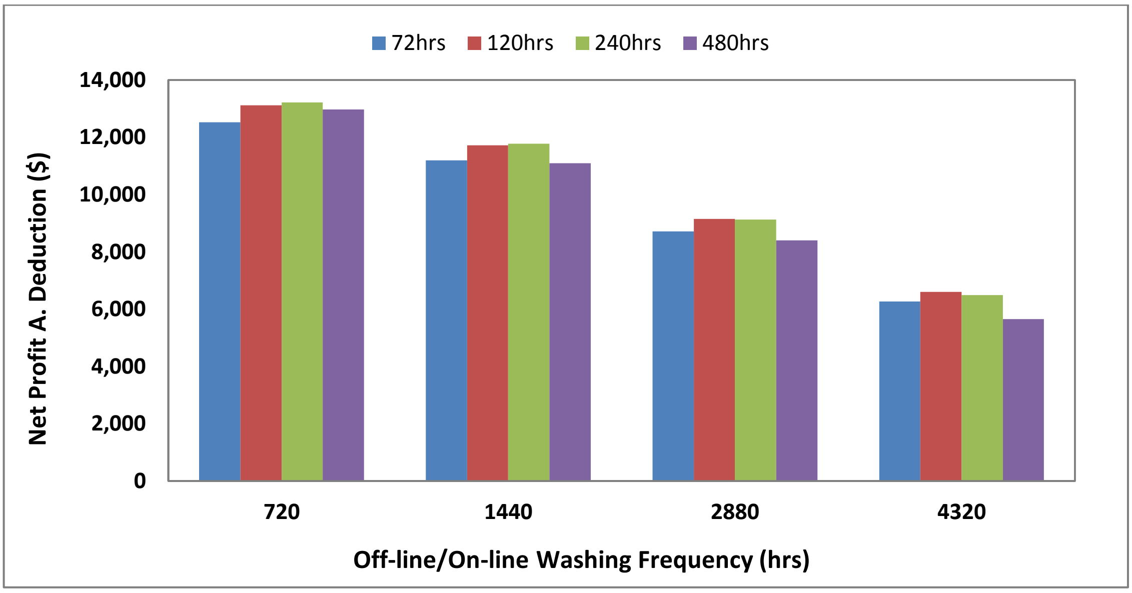


Figure 5-14 Comparison of net profit after deducting washing cost of 5.3MW GT at different off-line washing with on-line washing combination

However, it was observed the 1st two-off-line washing at 720hrs becomes idle or non-useful as there was very little improvement or impact of washing at that EOH and the degradation rate was very low. Reducing the number of off-line washing to 10 is promising and the 1st off-line washing intervals becomes longer at 2160th hour. However, using 720hrs – 240hrs combination is more realistic and profitable compared to other washing combination. Using the most frequent off-line washing of 720hrs has decreased the number of on-line washing to 240hrs intervals. It is beneficial to combine 720hrs – 240hrs that gives highest net profit after deducting washing cost of $2,598,894, low cost of washing combination of $321,837. However, the energy generated is not highest with the value of 2,638,965MWh. This shows that it is a good practice to combine more frequent off-line washing with less frequent on-line washing.

5.6.4 Influence of Changes in Degradation Rate

To investigate the financial effect of washing benefit on changes in degradation rate, the rate of fouling has been estimated and discussed previously, the performance was monitored during its operation with 7.2% reduction of power output at 8640th hour using extended method. Further to the investigation on degradation level, when the degradation rate is subsequently halved, in order to investigate the financial effect of washing.

Table 5-14 Net profit after deducting washing cost for different GT at 720hrs - 240hrs and 4320hrs - 480hrs frequency (7.2% drop)

	Net Profit 720hrs - 240hrs			**Net Profit 4320hrs – 480hrs**		
Size (MW)	**Specific Cost Energy ($/MWh)**	**Add. Profit Washing ($)**	**Net Profit A. D. ($)**	**Specific Cost Energy ($/MWh)**	**Add. Profit Washing ($)**	**Net Profit A. D. ($)**
307	55.98	2,920,731	2,598,894	56.76	2,662,393	2,366,086
275	54.22	2,547,186	2,228,384	54.97	2,319,455	2,024,295
255	58.08	2,514,450	2,197,322	58.89	2,292,724	1,998,196
236	57.69	2,315,483	2,003,295	58.50	2,110,270	1,817,608
211	58.19	2,095,598	1,785,853	59.00	1,909,268	1,617,530
203	58.88	2,035,255	1,719,053	59.70	1,854,576	1,560,398
180	62.49	1,908,930	1,602,916	63.36	1,741,143	1,450,815
159	65.15	1,756,602	1,446,677	66.06	1,602,756	1,310,950
139	60.27	1,441,473	1,203,966	61.11	1,312,370	1,091,602
123	65.97	1,375,070	1,141,571	66.89	1,253,987	1,034,734
96	69.02	1,144,500	981,742	69.99	1,041,656	892,808
84	68.13	999,538	842,594	69.08	908,825	762,173
63	64.12	714,509	563,329	65.02	647,623	503,149
43	61.10	476,531	371,381	61.97	430,309	329,433
27	62.56	313,955	210,478	63.45	282,716	182,472
13	65.62	161,836	161,836	66.57	145,084	81,064
5	75.86	77,556	13,223	76.95	69,274	5,658

This amounts to a 3.6% reduction in the power output at the end of 8640th hour. To examine the plant performance at a stated percentage power reduction in terms of off-line and on-line washing combination from large to small engine shown in Table 5-15, two case studies have been analyzed and case 1 is for more frequent washing combination of 720hrs - 240hrs and case 2 is for less frequent washing of 4320hrs - 480hrs respectively. At a lower degradation rate of 3.6% power drop, the total cost that are connected with off-line and on-line washing combination for cases 1 and 2 decrease with the same degradation rate, and constant in the case of lower degradation rate, this is influenced by the number of washing. The economic benefit due to power recovery from large to small GT engine for cases 1 and 2 decrease with a decrease in degradation rate, this is influenced by higher energy recovered due to fouling and a higher number of off-line and on-line washings for the case 1 and that give higher effectiveness of washing.

Table 5-15 A Net profit after deducting washing cost for different GT at 720hrs - 240hrs and 4320hrs - 480hrs frequency at halved degradation (3.6% drop)

Size (MW)	Net Profit 720hrs - 240hrs			Net Profit 4320hrs – 480hrs		
	Specific Cost Energy ($/MWh)	Add. Profit Washing ($)	Net Profit A. D. ($)	Specific Cost Energy ($/MWh)	Add. Profit Washing ($)	Net Profit A. D. ($)
307	55.68	2,329,395	2,007,558	56.07	2,200,226	1,903,918
275	53.93	2,025,397	1,706,596	54.30	1,911,532	1,616,372
255	57.77	2,007,060	1,689,932	58.17	1,896,197	1,601,669
236	57.38	1,845,662	1,533,474	57.78	1,743,056	1,450,394
211	57.88	1,668,881	1,359,136	58.27	1,575,716	1,283,978
203	58.57	1,621,541	1,305,339	58.97	1,531,202	1,237,024
180	62.15	1,525,086	1,219,073	62.58	1,441,193	1,150,865
159	64.80	1,404,770	1,094,845	65.25	1,327,847	1,036,041
139	59.95	1,145,618	908,110	60.36	1,081,066	860,298
123	65.62	1,098,025	864,526	66.07	1,037,483	818,230
96	68.65	908,751	745,993	69.12	857,329	708,480
84	67.76	791,410	634,467	68.23	746,054	599,402
63	63.77	560,630	409,449	64.21	527,187	382,713
43	60.77	369,873	264,723	61.19	346,762	245,886
27	62.22	241,720	138,242	62.66	226,101	125,857
13	65.26	122,977	57,574	65.72	114,601	50,581
5	75.44	58,299	-6,034	75.97	54,158	-9,458

The specific cost of energy produced for cases 1 and 2 from small to large GT engine decreases with an increase in GT capacity while cases 1 and 2 decrease in terms of degradation rate, this makes the energy production cost for large GT engines cheaper. The net profit after deducting washing cost for cases 1 and 2 increases from small to large GT engine and decreases with a decrease of degradation rate.

Example, the net profit after deducting washing cost for case 1 at 7.2% and 3.6% power drop are $2,598,894 and $2,007,558 for large GT engines and $13,223 and -$6,034 for smaller GT engines respectively. The net profit after deducting washing cost is lower and negative at a lower deterioration rate of 3.6% drop. This is influence by lower degradation rate and higher number of washings that supplies less washed energy and higher costs related with the off-line and on-line washings. This confirmed that the rate of degradation is directly proportional to the number of washings, as the degradation rate increases the number of washings increased. A further reduction in the level of degradation by another half, amounting to 1.8% reduction in power output at the 8640th hour shows that washing is viable except the smaller GT engine. Consistent with previous cases the more frequent washing at lower degradation rate amounts to relatively lower net profit, higher costs that are connected with off-line washing and lower specific cost of energy produced shown in Table 5-16.

Table 5-16 Net profit after deducting washing cost for different GT at 720hrs - 240hrs and 4320hrs - 480hrs frequency at halved degradation (1.8% drop)

	Net Profit 720hrs - 240hrs			**Net Profit 4320hrs – 480hrs**		
Size (MW)	**Specific Cost Energy ($/MWh)**	**Add. Profit Washing ($)**	**Net Profit A. D. ($)**	**Specific Cost Energy ($/MWh)**	**Add. Profit Washing ($)**	**Net Profit A. D. ($)**
307	55.54	2,033,726	1,711,889	55.72	1,969,142	1,672,834
275	53.78	1,764,503	1,445,702	53.96	1,707,570	1,412,410
255	57.62	1,753,366	1,436,237	57.81	1,697,934	1,403,406
236	57.23	1,610,752	1,298,563	57.42	1,559,449	1,266,787
211	57.72	1,455,523	1,145,777	57.91	1,408,940	1,117,202
203	58.41	1,414,685	1,098,482	58.60	1,369,515	1,075,337
180	61.99	1,333,165	1,027,151	62.20	1,291,218	1,000,890
159	64.63	1,228,854	918,929	64.84	1,190,392	898,586
139	59.79	997,690	760,183	59.98	965,414	744,646
123	65.44	959,502	726,004	65.66	929,232	709,978
96	68.47	790,876	628,118	68.70	765,165	616,316
84	67.58	687,347	530,403	67.80	664,668	518,017
63	63.60	483,690	332,510	63.81	466,969	322,495
43	60.60	316,544	211,394	60.81	304,988	204,112
27	62.05	205,602	102,125	62.26	197,793	97,549
13	65.08	103,548	38,145	65.30	99,360	35,340
5	75.23	48,671	-15,662	75.49	46,600	-17,016

5.7 Summary

In summary, the study has presented a cost benefit analysis focusing on the costs that are related with washing (off-line and on-line washing combination), specific cost of energy produced and net profit after deducting washing cost for different engines, related to their rated capacities. This is of the assumption that all engines have similar existing levels of deterioration and percentage heat rate increase. The following are the findings;

- The degradation rate has a great noticeable effect on the total plant profits, and extra care has to be taken to avoid higher degradation rate and regular on-line and off-line washing has to be conducted to reduce the level of deterioration rate for GT engine.
- The increase performance benefit or higher power output promised by combination of off-line and on-line washing outweighs the increased financial cost with higher operational profit (higher net profit after deducting washing cost) for more frequent washing combination and lower operational profit (lower net profit after deducting washing cost) for less frequent washing combination.
- The total washing cost related with washing (off-line and on-line washing), net profit after deducting washing cost and benefit due to power recovery increases with an increase of engine sizes for the same level of degradation and application.
- With high level of losses off-line or on-line washing are directly proportional to deposition or rate of degradation, as the degradation rate increases, off-line or on-line washing is more frequent. When the degradation rate decreases, off-line and on-line washing is less frequent.
- The cost of off-line washing equipment is not proportional to the size of the equipment. The economics is more favourable for larger engines due to economy of scale. This is due to a higher value of power production and significantly more penalty per MW of electricity generated for the same percentage losses. This can be overcome by implementing more than one single small engines unit.
- When off-line and on-line washing at different combination are incorporated, using the most frequent off-line washing of 720hrs combine with 240hrs on-line washing provides higher net profit after deducting washing cost compared to other washing combinations and this has reduces the number of on-line washing to 36 times in a year.

- Off-line washing is part of the plant maintenance procedures while on-line washing is part of the plant operation procedures. Implementing these two methods together improves the plant profitability and reducing the cost of energy production.
- Using the first off-line washing for the 720hrs at the 3rd intervals of washing increases the total profit and that shows it has reduced the number of off-line washing due to the usefulness of on-line washing at 240hrs frequency which decelerate the rate of degradation as time progress.
- The additional profit with respect to washing from the total profit of the plant shows that profits at 720hrs frequency are $2,739,803 and $71,755 while at 4320hrs are $2,256,113 and $56,249 for large and small GT engine of 307MW and 5.3MW respectively. This highlights the benefit for the washing and consistent with previous cases the more frequent washing amounts to relatively higher profits. The additional profit for the washed engine at 720hrs frequency is relatively higher than that of 4320hrs by a difference of $483,690 and $15,506 respectively.
- The net profits after deducting the washing cost at 720hrs frequency are $2,454,370 and $1,983,207 while at 4320hrs frequency are $10,493 and -$4,662 for the large and small GT engine respectively. It can be noticed from the output results that net profits after deduction of washing cost and equipment for a small GT engine is negative at 4320hrs, however at 720hrs frequency is positive with a lower value and this is due to washing benefit. This also indicates that the viability of washing for small GT engine at 720hrs is lower while at 4320hrs is found to be not viable.

6 COMPRESSOR WASHING OPTIMIZATION USING NON-DOMINATED SORTING GENETIC ALGORITHM

This work provides an optimization method for evaluating on-line and off-line compressor washing performance and economics for different engine capacities, using the non-dominated sorting genetic algorithm approach, in order to find an optimum washing frequency.

6.1 Introduction

Genetic Algorithm (GA) is a set of search and optimization methods suited to solve complex problems [114]. GA is one of the types of optimization algorithms used to find the maximum or minimum of a function. Optimization is the method of search for a better solution which is used in many engineering aspects to improve performance of a system within specified limits and constraints [95]. GA is one of the most common optimization solvers in Matlab, regularly used for scientific research to solve complex optimization problems in many areas such as engineering, management and science [115–119]. To minimize or maximize the performance of a solvers certain parameters need to be chosen such as population size, generation, fitness scaling, selection, mutation, crossover, migration, stopping criteria and plot functions etc. Many of the solvers lack robustness and cannot be used for multi-objective criteria problems. GAs depend on a single fitness measure. Unfortunately many cases are not suitable for single criterion and the design process cannot be expressed in relations to a single value. Such cases are best expressed in terms of multiple criteria. Each criterion represents different measurement and can have complex interactions with each other. The multi-objective problems have, more than one criterion and each criterion may represent different measures with complex interactions between each other. The Non-dominated Sorting Genetic Algorithm (NSGA II) method has been chosen due to its robustness, ease of implementation and promising optimal solutions. The NSGA II has an advantage of maximising and minimising an individual criterion within a problem. NSGA II uses probabilistic transition rules, together with fitness function information and works with coding of the parameter set, and it searches from population of points. The aim of this study is to determine an optimum frequency of on-line and off-line washing using non-dominated sorting genetic algorithm.

6.2 Simple Genetic Algorithm

The basic steps that made up a simple GA involves starting population, fitness function, selection, crossover, mutation and repeat process (generation). The flow chart for simple genetic algorithm is shown in Figure 6-1.

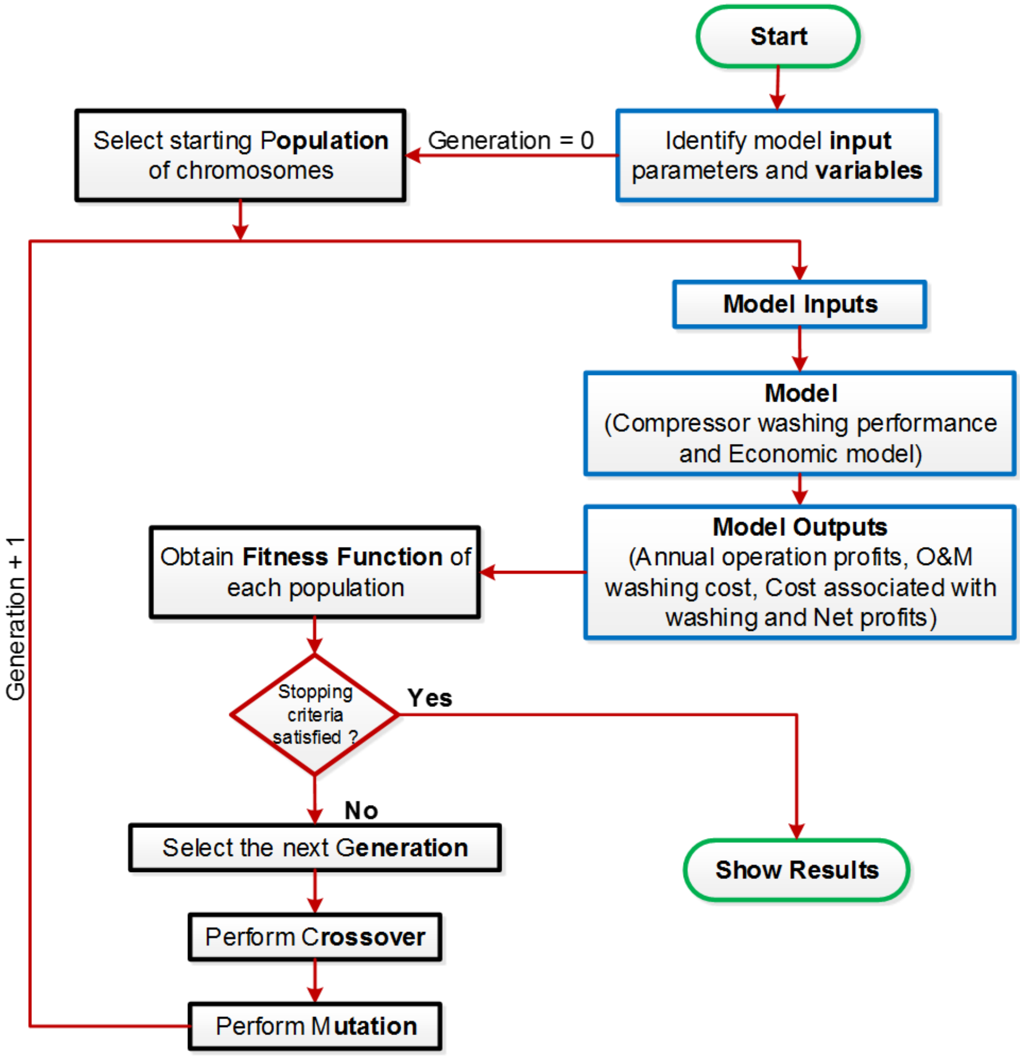


Figure 6-1 Simple genetic algorithm

6.3 Non-Dominated Sorting Genetic Algorithm II

NSGA II is a search algorithm for finding Pareto front or non-dominated solutions of multi-objective optimization problems [96]. NSGA II consists of three key features that are non-dominated sorting in which the individual population are sorted according to the level of non-domination, elitism which has the ability of storing all non-dominated solutions, and crowding distance which has the ability to maintain the diversity and spread of the solutions [96]. NSGA II is a non-domination based genetic algorithm for solving multi-objective optimization problems. It is very effective and efficient and has better sorting algorithm, integrates elitism with no sharing parameter needed to be selected [96,97]. The NSGA II have been implemented in Matlab using the Deb code [96] shown diagrammatically in Figure 6-2.

6.1 On-line Washing Coding Design

Multi objective optimization is used for a wide range of problems to find an optimum solutions. Typical optimum solutions are Pareto front solutions or non-dominated solutions, and these could be convex front or non-convex (concave) front and depending on the direction of optimal solution. It is likely to have problems that require two or more objective functions for most industrial applications. Multi objectives optimization designs are generally used to solve most real-world optimization problems, it can be categorized into 3 different scenarios: minimizing all the fitness functions, maximizing all the fitness functions, and combining the two functions together by maximizing some functions and minimizing others. One of the most important steps to implement when optimizing a problem is to identify an objective function. Two objective functions have been identified and these are net profit after deducting washing cost to be maximum, operation & maintenance (O&M) cost of the washing equipment to be minimum. To design multi-objective GA code that minimises the O&M cost for the washing equipment while maximizing the net profit after deducting washing cost at an optimum frequency certain parameters need to be used or selected as the model input such as engine capacity, operating hours, cost of electricity, cost of natural gas, heat rate and percent heat rate increase and degradation rate and so on.

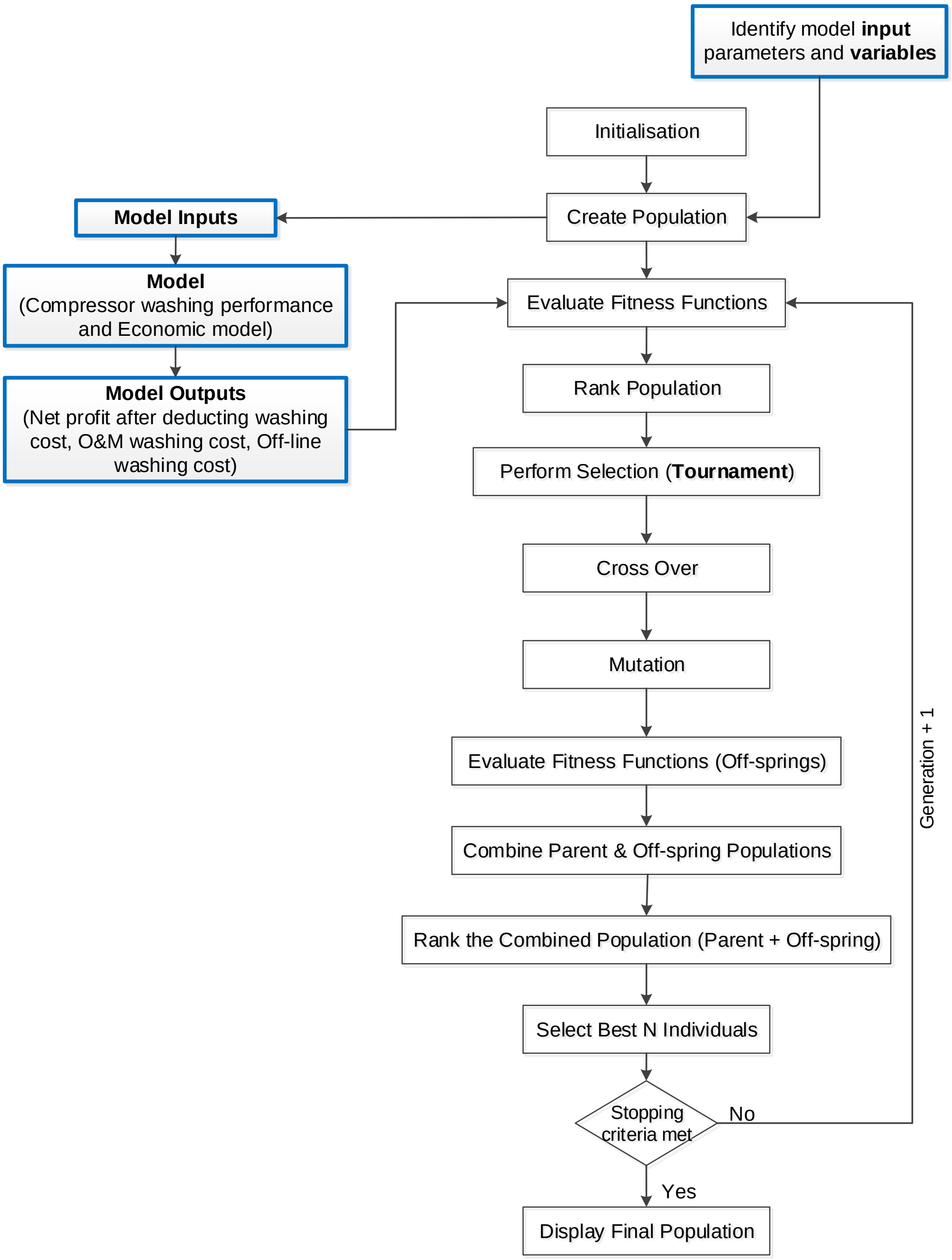


Figure 6-2 NSGA II structure

The model consists of two layers for the calculation; layer one is for compressor washing performance and layer two is for compressor washing economics. The variable parameters selected are the frequency of washing, total washing duration per minutes, degradation level and the effectiveness of washing fluid.

The output from the model are the clean, fouled and washed electricity sold, clean, fouled and washed cost of fuel, excess fuel burn, yearly power loss cost and loss of revenue due to fouling and net profit after deducting the washing cost as shown in Figure 6-3.

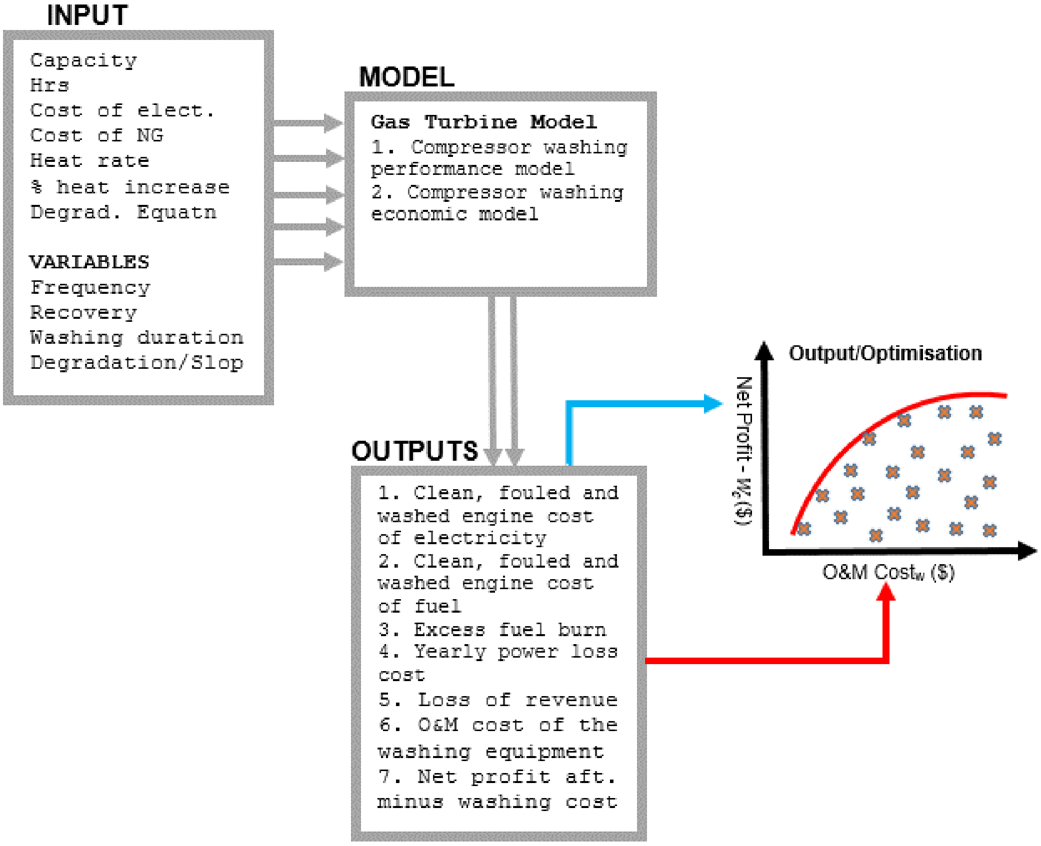


Figure 6-3 Multi-objective GA procedure flowchart (On-line)

Two fitness functions have been selected from the output model results to run for optimization and equations (3-57) to (3-62) are used in the optimization model. The fitness functions evaluate the fitness at each iteration lying in the design space X and produces a desired solution in the objective space Y.

6.2 On-line Washing Model Implementation

The NSGA II code structure is an extension of a simple genetic algorithm. The code consists of Matlab functions, for loops, data and constant. Matlab function are files that accept input arguments and yield output arguments, but the file name and function name must have the same name.

6.2.1 Objective and Variable Description Function

The on-line washing analysis problem has 2 dimensions of the fitness functions selected and these are O&M cost of the washing equipment and net profit after deduction of the washing cost. Four design variables are identified with two variables built-in and these are time based degradation and varying effectiveness or recovery due to washing from an upper limit to a lower limit of each frequency are estimated for each run, and the other design variable parameters are frequency of washing with an upper limit of 480hrs and a lower limit of 72hrs, and total washing duration per minutes with an upper limit of 10mins and a lower limit of 9mins.

6.2.2 Initialization

Random values within the stated range of population are initialized. The decision variables are been initialized based on lower and upper likely values. A function has been used to evaluate each objective and taking one chromosome after another by passing the decision variable to the function, processing it and returning the value for the fitness functions. The values are stored on the workspace at the end of the chromosome vector itself. The input values are inserted by the user and then stored and displayed on the workspace after running the program. The values inserted by the user are PopSize = 400, gen = 300, nVars = 2, nCriteria = 2. A random initial chromosome has now been created for criteria 1 and 2 that represents the total number of populations.

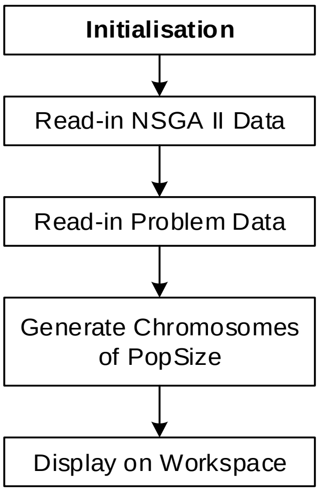


Figure 6-4 Initialisation

6.2.3 Evaluation of Objective Function

The populations of chromosomes are evaluated into model inputs on the two criteria, O&M cost of the washing equipment (O&MCWE) and net profit after deduction of the washing cost (NPADWC), and the population has been generated between the upper and lower values of each decision variables, processing and returning the solution of the fitness function and storing it in a chromosomes vector in a workspace.

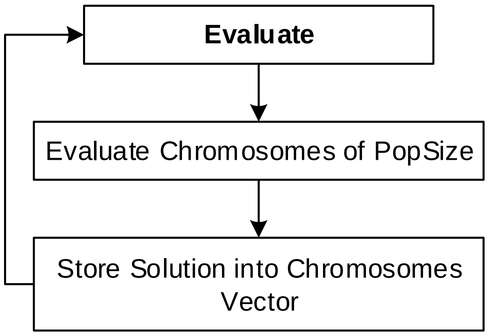


Figure 6-5 Evaluation of all criteria

6.2.4 Sort the Initialized Population

This is the section where current populations are sorted, ranked or graded by means of non-domination-sorting method. The ranking of the population implemented in this analysis is based on Goldberg [90,91,96,97]. This determine for each individual population the rank and the crowding distance equivalent to the position in the front they belong.

6.2.5 Selection Method

The selection process for the best individual is applied in order to choose best individuals for mating and the best solution can be selected based on rank and the crowding distance. The selection process is performed on the basis of two criteria. First is the location of the solutions assigned and a rank is assigned to it and usually a lower rank is selected. Second is to compare when the rank of two individuals are equal, then a crowding distance has to be compared, and individuals with the higher crowding distance is selected.

6.2.6 Genetic Operators (Crossover and Mutation Operator)

Parent chromosomes are utilized to produce off-springs with the help of genetic operators. A Simulated Binary Crossover (SBX) and polynomial mutation have been applied in the analysis with a crossover probability of 0.9 ($P_c = 0.9$) and a mutation probability of $1/decision\ variables$ ($P_m = 1/n$). A real coded GA has been implemented for this analysis with a distribution index of crossover and mutation as $mu = 20$ and $mum = 20$ respectively [102]. Also, it is one chromosome that can be replace based on rank and the crowding distance, the front are added one by one until the complete front is reached which is higher than the population size. The chromosomes in the front are added consequently to the population based on the crowding distance.

6.2.7 Discussion of the Result

The genetic algorithm optimization results for the analysis are saved in ASCII text format and consist of a set of decision variables generated, objective function value, ranking of the population value, and the crowding distance value and all added together to form chromosomes vector.

The two objective function values in the chromosomes vector are total operation and maintenance costs of the washing equipment (TO&MCWE) and net profit after deducting washing cost (NPADWC). The total O&MCWE for the 307MW capacity decreases with an increase in the washing frequency (less frequent washing with lower number of washing interval) to when it start to reach a stable state at about one year of operation. The optimized maximum and minimum O&M cost for 307MW estimated were found to be $\$7.0 \times 10^4$ and $\$2.3 \times 10^4$ respectively. The optimized O&M cost trend curve has experienced discontinuity especially at the end of the curve shown in Figure 6-6. The total O&MCWE function has been used for minimisation of the fitness function. Considering the NPADWC for the same engine (307MW) and with the same frequency of washing intervals (O&M cost) decreases with an increase in the number of frequency with the maximum and minimum profits of optimized compressor at $\$1.36 \times 10^6$ and $\$1.17 \times 10^6$ respectively. The optimize period for the frequency covered experienced discontinuity of the frequency from 200hrs to the end of the year (Figure 6-7). The NPADWC function has been used for maximisation of the fitness function in order to estimate profit at optimized frequency.

When optimizing the two criteria for the 307MW engine capacity (NPADWC and O&MCWE), the decision variables were chosen, and the input algorithm parameters were also chosen as mentioned previously. The result shows a convex Pareto surface with the direction of the optimal search starting from the middle of the surface. The optimized minimum solutions for the objective one and two are $\$2.3 \times 10^4$ and $\$1.17 \times 10^6$ while the optimized maximum solutions for the objective one and two are $\$7.0 \times 10^4$ and $\$1.36 \times 10^6$ respectively. The Pareto surface shows that as the net profit increases after deducting the washing cost the total O&M cost of the washing also increases until it reaches a stable zone at approximately $\$6.5 \times 10^4$ and that corresponds to a net profit of approximately $\$1.36 \times 10^6$. The optimized frequency of washing that corresponds to O&M cost and net profit is approximately 95hrs intervals of washing. The total savings from an optimized washing frequency compared to most frequent washing (72hrs frequency of washing) found is to be $346,000.

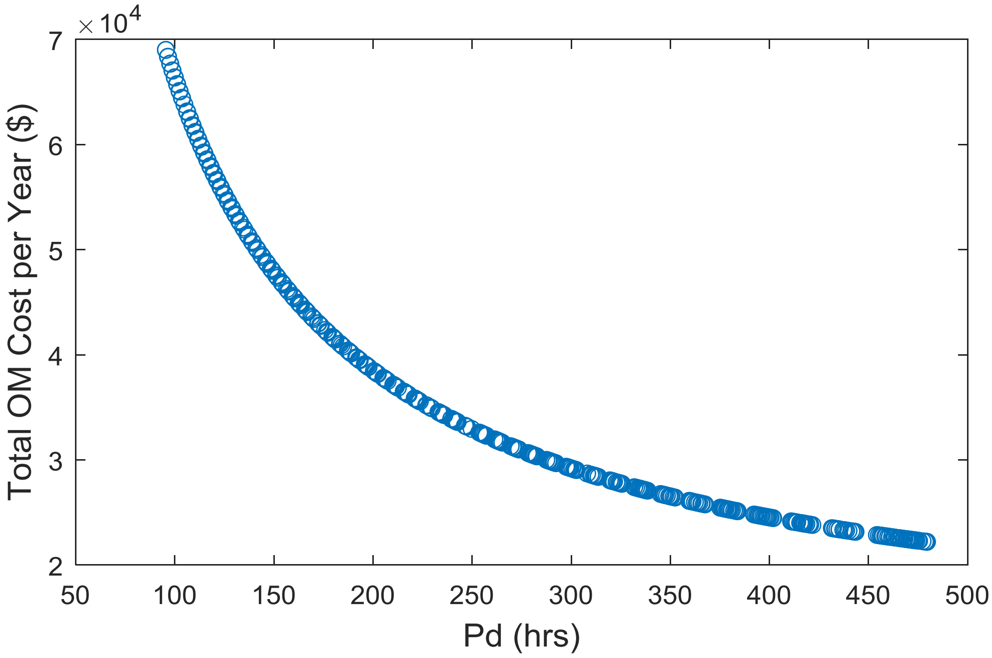


Figure 6-6 Optimized total O&M cost per year for 307MW

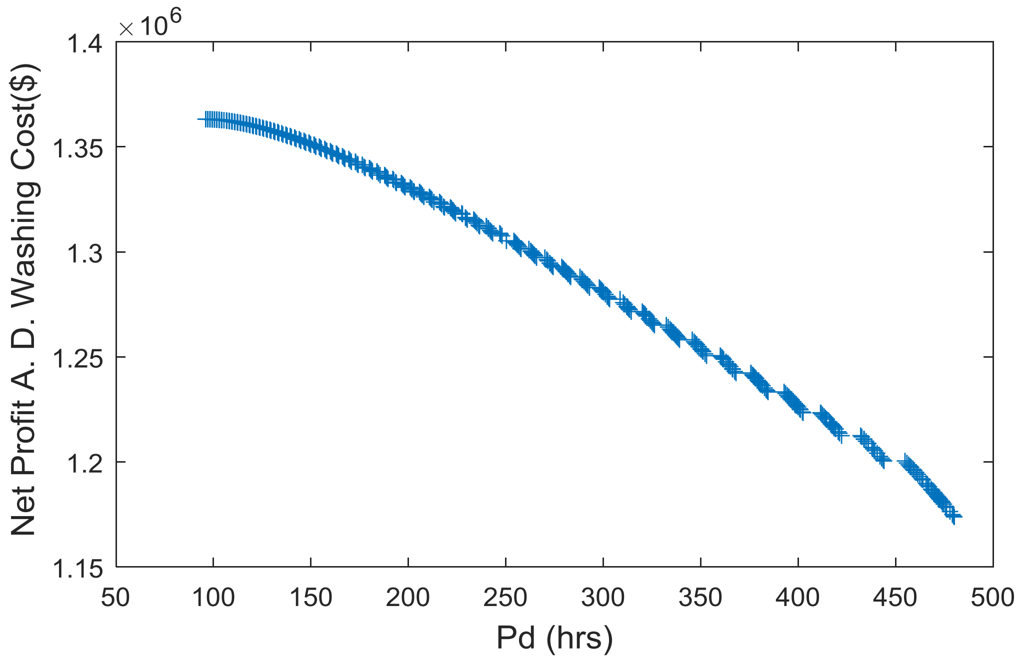


Figure 6-7 Optimized net profit per annum for 307MW

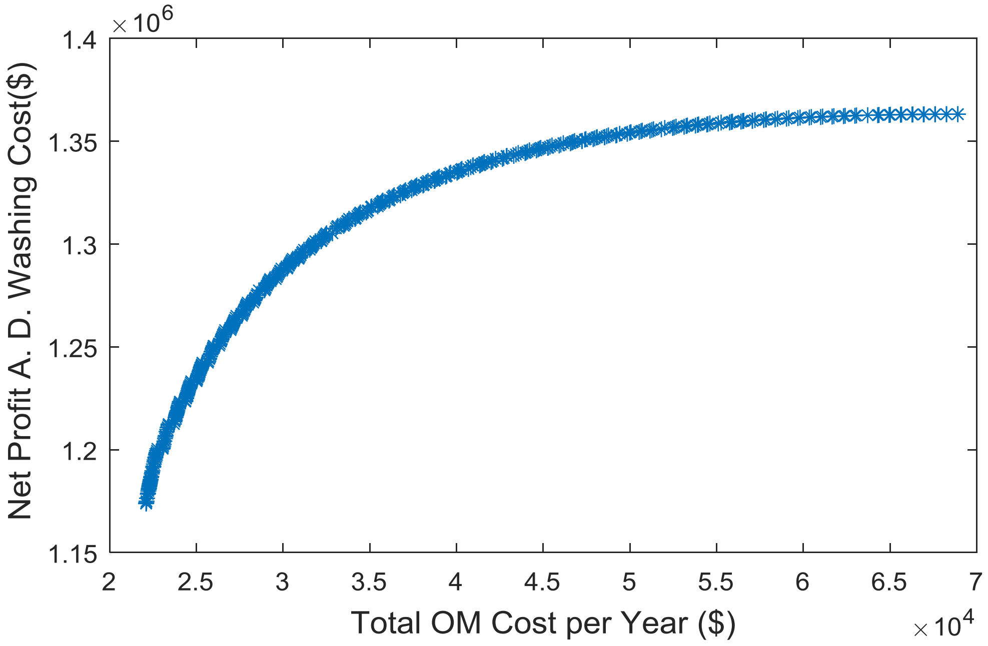


Figure 6-8 Optimized net profit and total O&M cost per annum for 307MW

The total O&MCWE for the light-duty engine of 5.3MW capacity decreases with an increase of washing frequency (decrease in the number of washing intervals) that experienced a state of discontinuity. The optimised maximum and minimum O&M costs for 5.3MW estimated were found to be $3,960 and $2,680 respectively. The total O&MCWE function has been used for minimisation of the fitness function. However, the NPADWC of the light-duty engine of 5.3MW and with the same frequency of washing intervals decreases with an increase of washing frequency with negative net profit for the minimum and maximum losses at $-\$1.78 \times 10^4$ and $-\$2.32 \times 10^4$ respectively. The loss has been influenced due to higher equipment cost which didn't outweigh the economic cost for the light GT, this also shows that the economics is more favourable for the larger engines due to economy of scale.

When optimizing the two fitness functions for the smaller engine of 5.3MW, the decision variables were chosen and the input algorithm parameters were also chosen and applied. The result shows a negative solution (losses) for the NPADWC as stated previously (Figure 6-9) indicating a loss for the investment at one year of operation. This loss has been incurred due to higher cost of equipment which didn't outweigh the economic cost, this also highlighted that the economics are more favourable for the larger engines. Table 6-1 shows that as the engine size or capacity increases the optimized net profit after deducting the washing cost increases and the optimized O&M cost for the washing equipment also increases giving an optimized washing frequency for different engine sizes.

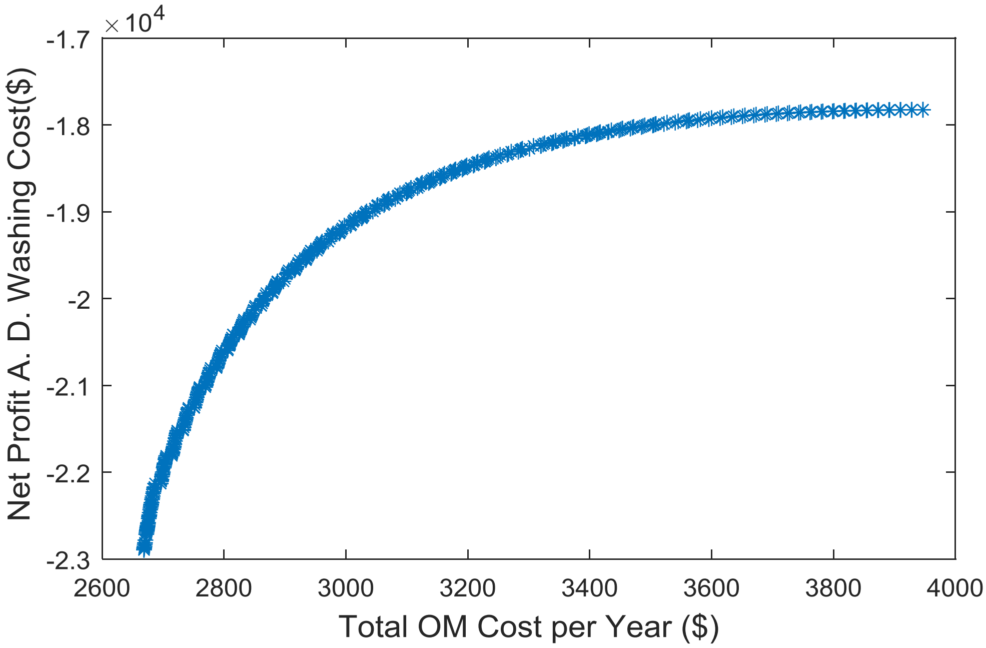


Figure 6-9 Optimized net profit and total O&M cost per annum for 5.3MW

The optimized washing frequency for the heavy-duty engine of 307MW is 95hrs which has lower numbers of washing and cost savings compared to the most frequent washing of 72hrs. The optimized washing frequency for the light-duty engine of 5.3MW was found to be negative and hence not viable. The optimum washing frequency for GT engine ranges from 90hrs to 110hrs.

Table 6-1 Optimum frequency of washing for on-line washing

Capacity (MW)	Net Profit W_c ($)	O&M Cost ($)	Optimum point (hrs)
307	1.36×10^6	6.5×10^4	95
275	1.15×10^6	6.0×10^4	97
255	1.14×10^6	5.8×10^4	92
236	1.03×10^6	5.3×10^4	90
211	9.03×10^5	4.8×10^4	90
203	8.60×10^5	5.4×10^4	105
180	8.00×10^5	4.5×10^4	90
159	7.05×10^5	4.6×10^4	105
139	5.95×10^5	4.0×10^4	110
123	5.62×10^5	3.5×10^4	105
96	4.98×10^5	3.1×10^4	108
84	4.20×10^5	2.6×10^4	105
63	2.63×10^5	1.9×10^4	100
43	1.71×10^5	1.3×10^4	97
27	7.90×10^4	1.03×10^4	103
13	2.94×10^4	5.4×10^3	92
5	-1.78×10^4	3.8×10^3	-

6.2.8 Influence of Changes in Population Size and MaxGeneration

The population size determines the solutions available for a design problem and the larger the population size the longer the time to converge in order to find the optimal solutions. Increasing the number of generations can provide better solutions. A larger population requires a fewer number of generations and takes longer time to move from one generation to another while a lower population requires a larger number of generations. To observe the changes in the population size and the number of generation the NSGA input parameters are changed/modified. The new input parameter values are PopSize = 800, number of gen = 500, nVars = 2, nCriteria = 2. A random initial chromosome has now been created for criteria 1 and 2 that represent the total number of populations. It was observed as the population size and number of generations increases it takes longer time to move from one generation to another (converge) in order to terminate the program, but it provides better and more concentrated solutions (Figure 6-10).

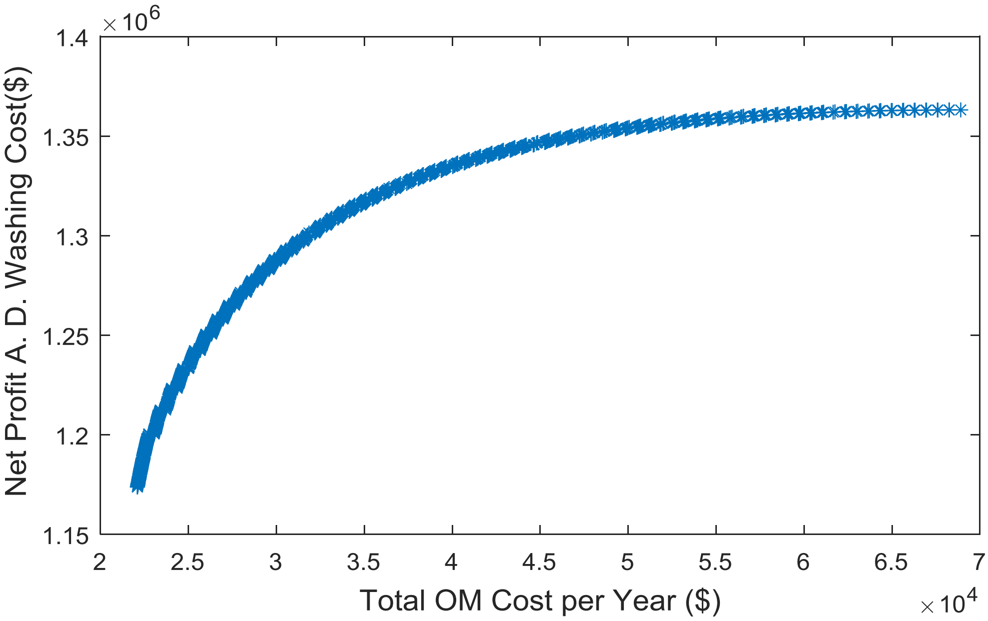


Figure 6-10 Effect of changes in population size and generation

6.2.9 Influence of Changes in Degradation Rate

This investigates the effect of changes in degradation rate on the benefit of washing frequency using the NSGA II method. Firstly, the performance was optimized at 7.2% reduction of power output at 8640th hour as previously discussed. Example, when optimizing the two criteria at 7.2% power drop (NPADWC and O&MCWE) for the 307MW engine, the decision variables were chosen and the input algorithm parameters were also chosen and using the previous information for input performance, input economics. The Pareto surface shows that as the NPADWC increases the total O&MCWE also increases until it reaches a stable zone at approximately $\$6.5 \times 10^4$ and that corresponds to a net profit of approximately $\$1.36 \times 10^6$. The optimized frequency that corresponds to O&M cost and net profit is approximately 95hrs intervals of washing. Using an optimized washing frequency of 95hrs instead of the most frequent washing (72hrs washing) has saved $346,000 at 8640th hour.

Secondly, when a reduction in the level of degradation applied by half, amounting to 3.6% reduction in power output at the 8640th hour in order to investigate the effect of changes in degradation rate on the benefit of washing frequency. When optimizing the two criteria at the stated power drop (NPADWC and O&MCWE) for the 307MW engine, the decision variables and the input algorithm parameters were applied using the previous information. The result shows a convex Pareto surface with the direction of the optimal search start from the middle of the surface. The optimized minimum and maximum solutions for the objective one and two are $\$2.2 \times 10^4$ and $\$9.1 \times 10^5$ and also $\$6.2 \times 10^4$ and $\$1.04 \times 10^6$ (Figure 6-11) respectively.

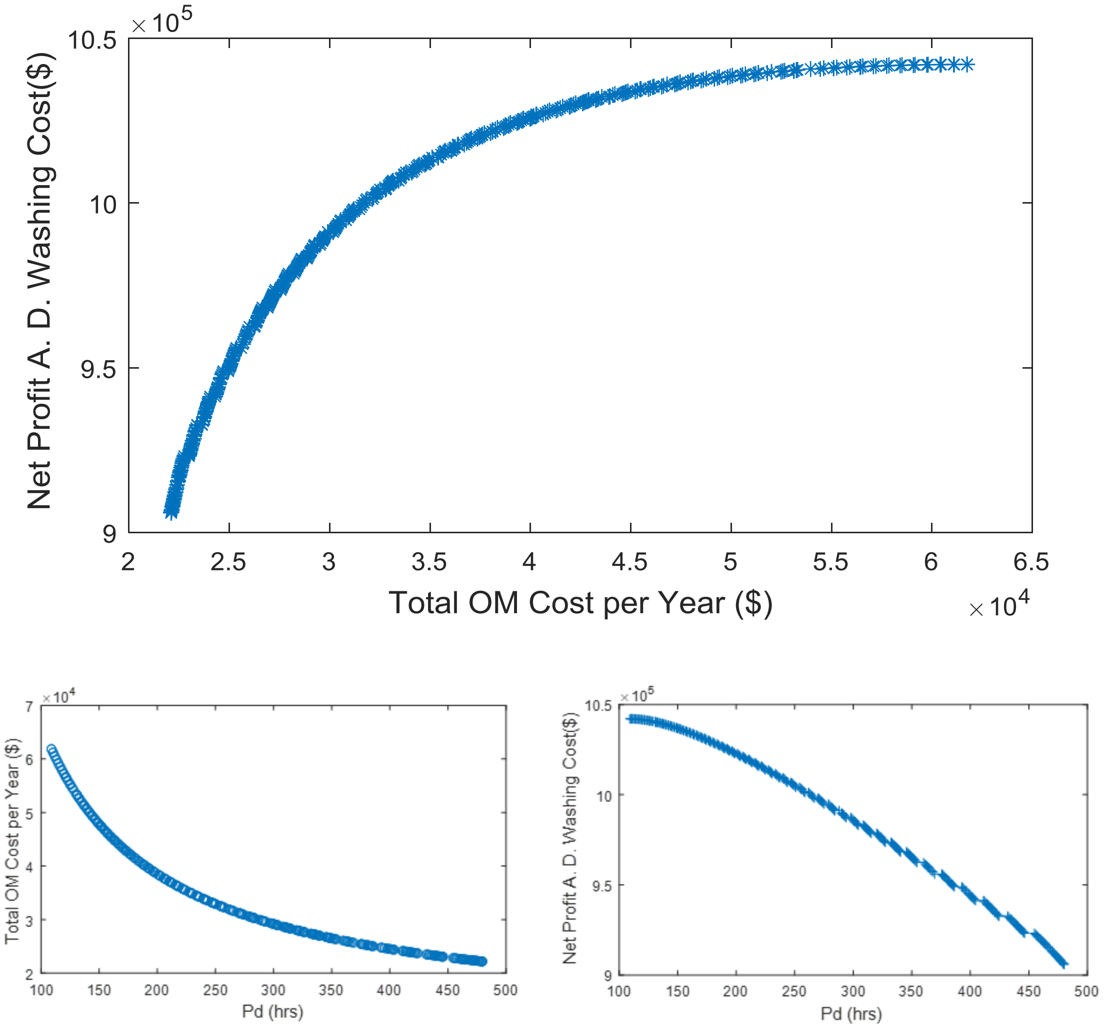


Figure 6-11 Optimized operational changes due to degradation rate at 3.6% power drop

The Pareto surface shows that as the NPADWC increases the total O&MCWE also increases until it reaches a stable zone at approximately $\$5.9 \times 10^4$ and that corresponds to a net profit of approximately $\$1.04 \times 10^6$. The optimized frequency of washing that corresponds to O&M cost and net profit is approximately 110hrs intervals of washing. This shows that as the deterioration level becomes lower (3.6% power drop) the frequency of washing is lower, NPADWC has lower and the O&MCWE is also less. This is consistent with previous cases for more frequent washing with lower degradation amounts to relatively lower RoI while for more frequent washing with highest degradation amounts to relatively higher RoI.

A further reduction in the level of degradation by another half, amounting to 1.8% power drop in the 8640th hour shows an optimized frequency of 115hrs and that corresponds to an optimized NPADWC of $\$8.84 \times 10^5$ and O&MCWE of $\$5.5 \times 10^4$. It can be noticed the net profit after deducting the washing cost and O&M cost of the washing are lower and the optimized frequency is higher compared to 3.6% power drop. This is also consistent with the previous cases for more frequent washing with lower degradation amounting to relatively lower RoI.

Further to the investigation on degradation level, when the degradation rate is subsequently 1.5times the original degradation (1.5 *7.2% power drop), in order to investigate the effect of changes in degradation rate on the benefit of washing frequency. This amounts to a 10.8% reduction in the power output at the end of 8640th hour. When optimizing the two criteria that are NPADWC and O&MCWE for the 307MW engine, the decision variables and the input algorithm parameters were also chosen using previous information. The optimized minimum and maximum solutions for the objective one and two are $\$2.2 \times 10^4$ and $\$1.44 \times 10^6$ and also $\$7.5 \times 10^4$ and $\$1.69 \times 10^6$ respectively. The Pareto surface shows that as the NPADWC increases the total O&MCWE also increases until it reaches a stable zone at approximately $\$7.0 \times 10^4$ and that correspond to a net profit of approximately $\$1.69 \times 10^6$. The optimized frequency of washing that corresponds to O&M cost and net profit is approximately 80hrs intervals of washing. It can be noticed the optimized frequency of washing (most frequent) at highest deterioration rates is lower compared to all other deterioration rate (Table 6-2), this is due to higher NPADWC and that amounts to higher O&M of the washing cost, and this also consistent with more frequent washing with higher degradation amounts to relatively higher RoI. This also highlighted that as the degradation level increases for a certain operations, the optimized frequency of washing increases (more frequent washing) while the frequency of washing decreases (less frequent washing) with a decrease in the degradation rate. This shows that degradation rate (fouling) is directly proportional to the frequency of washing (Table 6-2).

Table 6-2 shows the influence of optimized on-line washing on different degradation rate for the 307MW and 5.3MW engine capacity. For the 307MW engine the optimum frequency of washing increases from 80hrs to 115hrs with a decrease in deterioration rate. For the small engine of 5.3MW, the table indicated that washing is not viable for all the stated degradation rate.

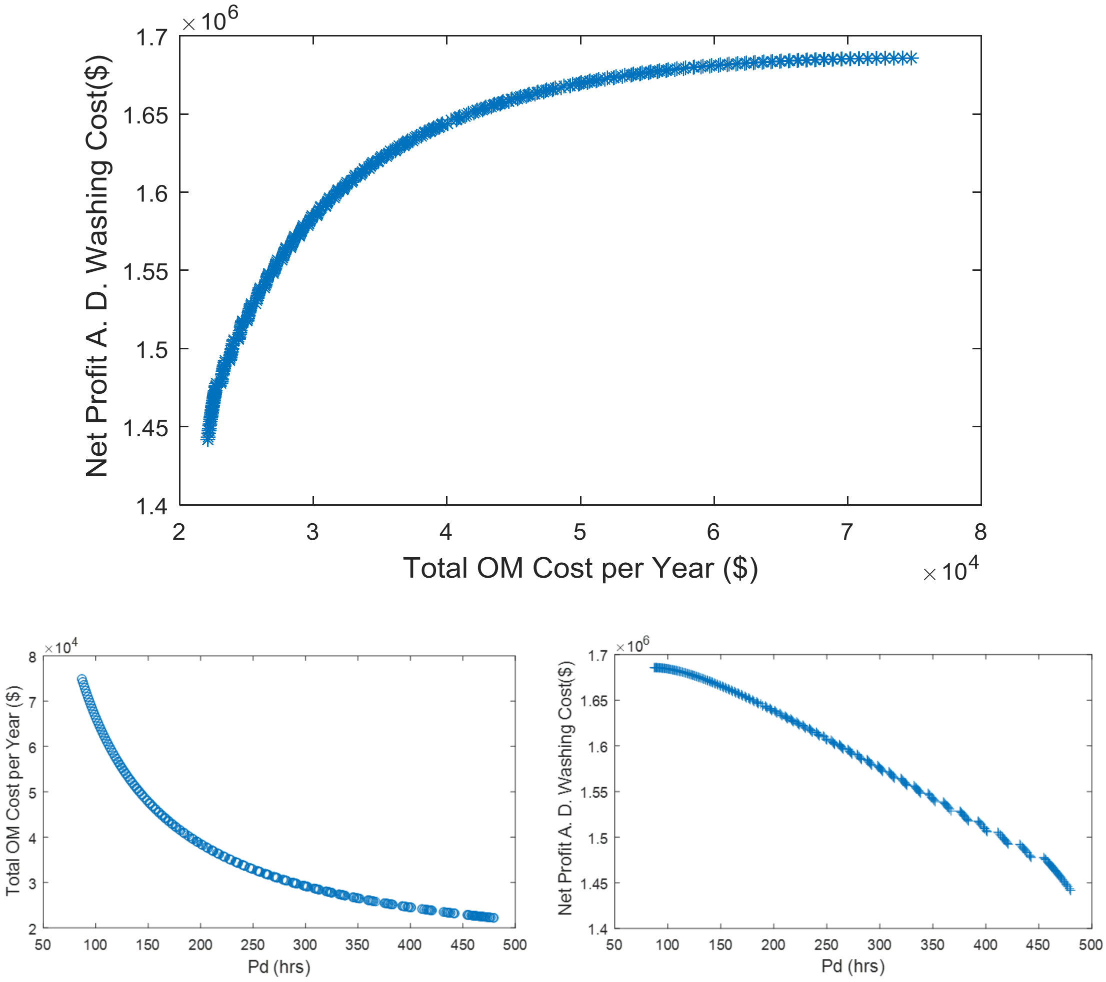


Figure 6-12 Optimized operational changes in degradation rate at 10.8% power drop

Table 6-2 Influence of on-line washing on different degradation rate

Degradation Rates	10.8%	7.2%	3.6%	1.8%
Optimum frequency (307MW)	80hrs	95hrs	110hrs	115hrs
General comments	Most frequent			Less frequent
Optimum frequency (5.3MW)	-	-	-	-
General comments	Not viable	Not viable	Not viable	Not viable

6.3 Off-line Washing Coding Design

Two objective functions have been identified for the off-line washing and these are net profit after deducting washing cost (NPADWC) to maximize, and off-line washing cost (OWC) to minimize. To design multi-objective GA code that minimized the OWC while maximized the NPADWC at an optimum frequency certain parameters need to be used or selected as the model input such as engine capacity, operating hours, fixed O&M cost, variable O&M cost, mixture ratio of the concentrates, lower heating value, cost of electricity, cost of natural gas, heat rate, and degradation rate and so on. The model comprises of two layers for the calculation, layer one is for compressor washing performance (off-line) and layer two is for compressor washing economics. The decision variable parameters selected in the study are the frequency of washing, total washing duration per minutes, slope/degradation and the effectiveness of washing fluid. The output from the model are total economic benefits, total financial loss, total cost related with off-line washing, personnel cost, specific cost of energy produced, clean, fouled and washed electricity sold, clean, fouled and washed cost of fuel, and NPADWC for the plant as shown in Figure 6-13.

The two fitness functions selected from the output model to run for optimization are highlighted from equations (3-50) to (3-52). The fitness functions evaluates the fitness at each iteration lying in the design space X and produces a desired solution in the objective space Y.

6.4 Off-line Washing Model Implementation

The NSGA II code structure is like on-line washing and consist of an initialization and creation, evaluation, sort the initialized population, evolutionary process, selection method using tournament, genetic operators, replace chromosomes and finally a display of the output results.

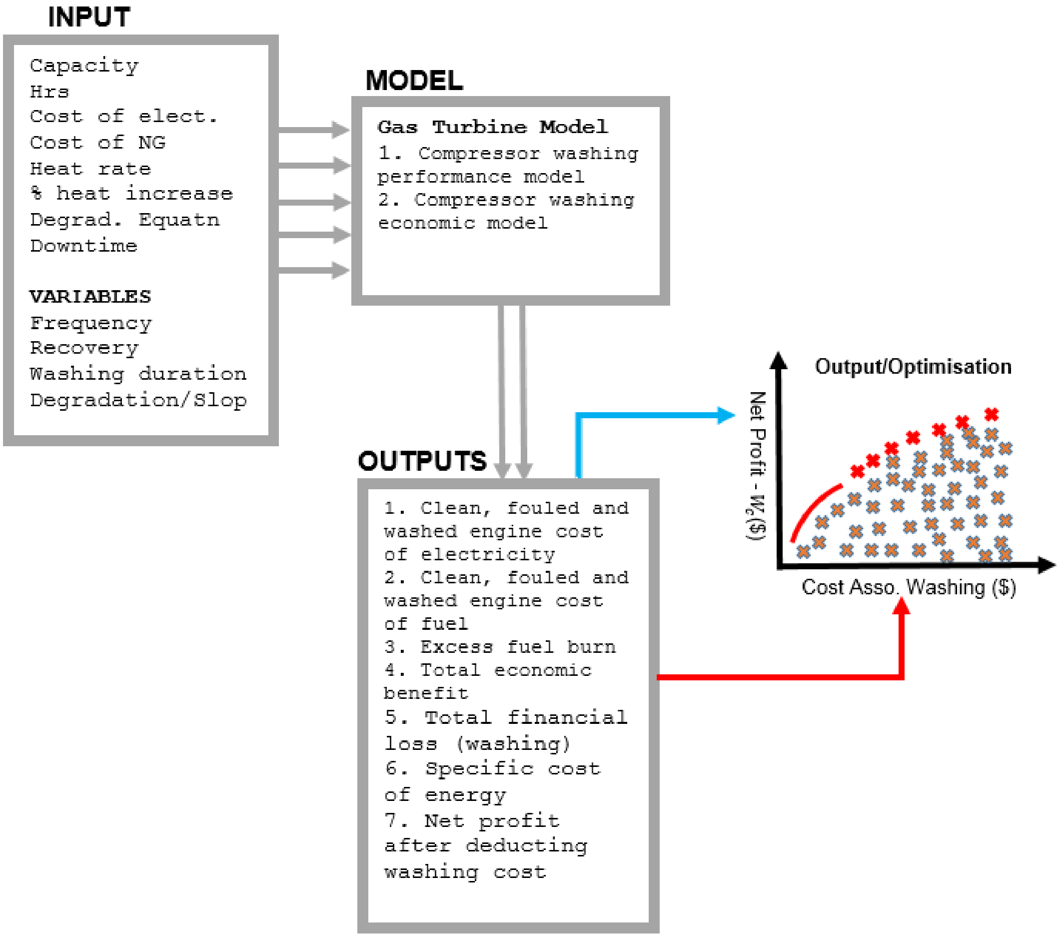


Figure 6-13 Multi-objective GA flowchart (Off-line)

6.4.1 Objective and Variable Description Function

The off-line washing analysis problem has two dimensions of the fitness functions selected and these are total cost related with off-line washing and net profit after deducting washing cost for the plant. Four dimension of design variables are identified with two variables built-in (degradation and recovery of washing), and these design variables parameter are frequency of washing (off-line) with an upper limit of 4320hrs and a lower limit of 720hrs, effectiveness or recovery due to washing from an upper limit of 80% to a lower limit of 70%, total washing duration per minutes with an upper limit of 30mins and a lower limit of 25mins and a time based degradation.

6.4.2 Initialization and Evaluation

Random values within the stated range of population are initialized. The decision variables are also been initialized based on lower and upper likely values stated. The input values are inserted by the user and the program displayed input values on the workspace. The input values are PopSize = 400, gen = 300, nVars = 2, nCriteria = 2, maximum and minimum variable for criteria 1, 2 are frequency of washing, effectiveness of washing fluid, degradation and total washing duration. A random number has been generated between the maximum and minimum possible values for each of the decision variable in the loop. A random initial chromosome has now been created for criteria 1 and 2 that represent the total number of populations.

A fitness function is now used to evaluate the function of each chromosomes passing the decision variable to the function, process it and return the solution of the fitness function and then store it in a chromosomes vector in a workspace.

6.4.3 Sort the Initialized Population

This is the section where current populations are sorted, ranked or graded by non-dominated-sorting method. The ranking of the population implemented in the off-line washing analysis is based on Goldberg [90,91,96,97]. This determines for each individual population the rank and the crowding distance equivalent to the position in the front they belong.

6.4.4 Selection Method and Genetic Operators

The selection process is performed on the basis of two criteria. First is the location of the solutions belong with a rank assigned, a lower rank is being selected. Second is to compare when the ranks of two individuals are equal, then a crowding distance has been compared, and individuals with higher crowding distance is selected.

6.4.5 Genetic Operators (Crossover and Mutation Operator)

The genetic operators comprise of crossover and mutation that are utilized to produce off-springs from parent chromosomes. Genetic operation is performed on the basis of the first decision variables elements in the chromosomes vector.

Evaluation of the fitness function of each off-spring has been performed and concatenate the off-springs chromosomes with fitness value.

A chromosome is replaced base on rank and the crowding distance, the front are added one by one until the complete front is reached which is higher than the population size. The chromosomes in the front is added consequently to the population based on the crowding distance.

6.4.6 Discussion of the Result

The genetic algorithm optimization results of the analysis are saved in ASCII text format and consist of a set of decision variables generated, objective function value, ranking of the population value, and the crowding distance and added together for each chromosome in order to form chromosomes vector.

The two objective function values in the chromosomes vector are off-line washing cost (OWC) and net profit after deducting washing cost (NPADWC). The OWC for 307MW capacity decreases with an increase in the washing frequency that experiences single value results at the beginning of operation to when it reached 2900hrs. The optimised minimum and maximum OWC for 307MW estimated found to be $\$2.75 \times 10^5$ and $\$2.98 \times 10^5$ (Figure 6-14) respectively. The OWC function has been used for minimisation of the fitness function. However, the NPADWC for the same engine (307MW) and with the same frequency of washing intervals decreases with an increase in the frequency with the minimum and maximum profits of optimised compressor of $\$1.70 \times 10^6$ and $\$2.52 \times 10^6$ (Figure 6-15) respectively. The NPADWC function has been used for maximisation of the fitness function in order to obtain an optimized profit.

When optimizing the two fitness functions for the 307MW engine, (OWC and NPADWC), the decision variables and input algorithm parameters were chosen with input performance and economics. The result shows a convex Pareto surface with the direction of the optimal search at the end of the surface. The minimum solutions for the objective one and two are $\$2.75 \times 10^5$ and $\$1.70 \times 10^6$ while the maximum solutions for objective one and two are $\$2.98 \times 10^5$ and $\$2.52 \times 10^6$ respectively. The Pareto surface shows that as the NPADWC increases the OWC increases with a curve and single value results. The optimized frequency of washing that corresponds to net profit of $\$2.52 \times 10^6$ and the total cost related with washing of $\$2.98 \times 10^5$ is approximately 796hrs intervals of washing (Figure 6-16). The OWC for the light-duty engine of 5.3MW capacity decreases with an increase in the number of washing intervals (washing frequency).

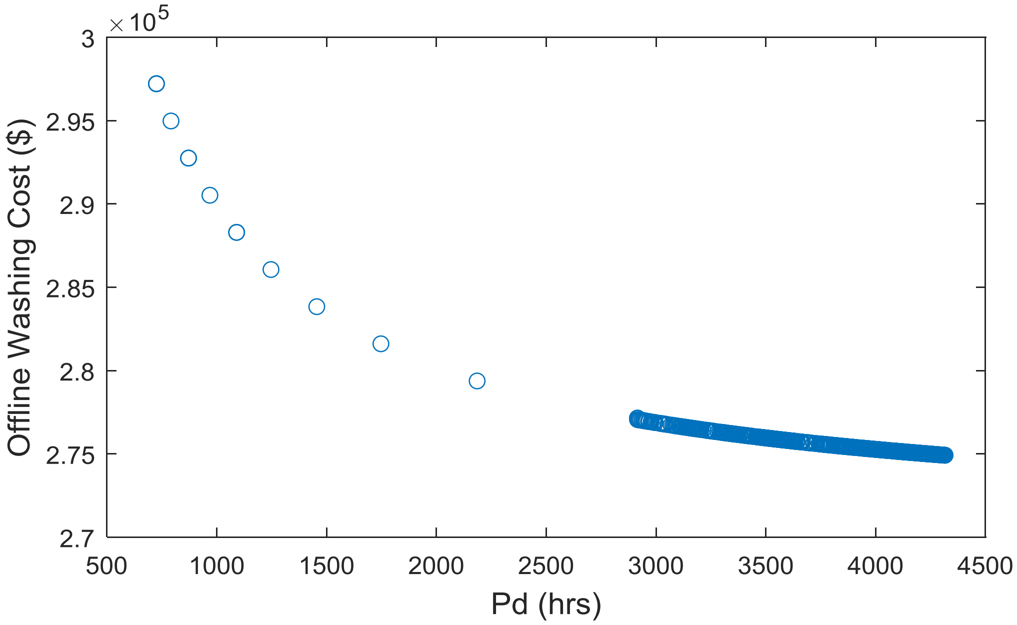


Figure 6-14 Optimized total cost related with washing per year for 307MW

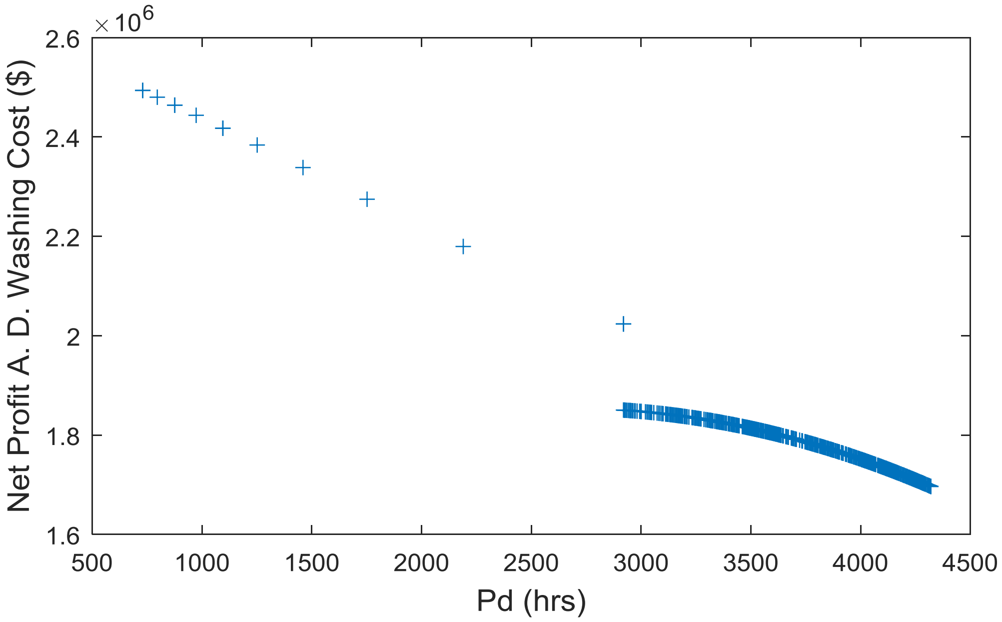


Figure 6-15 Optimized net profit per year for 307MW

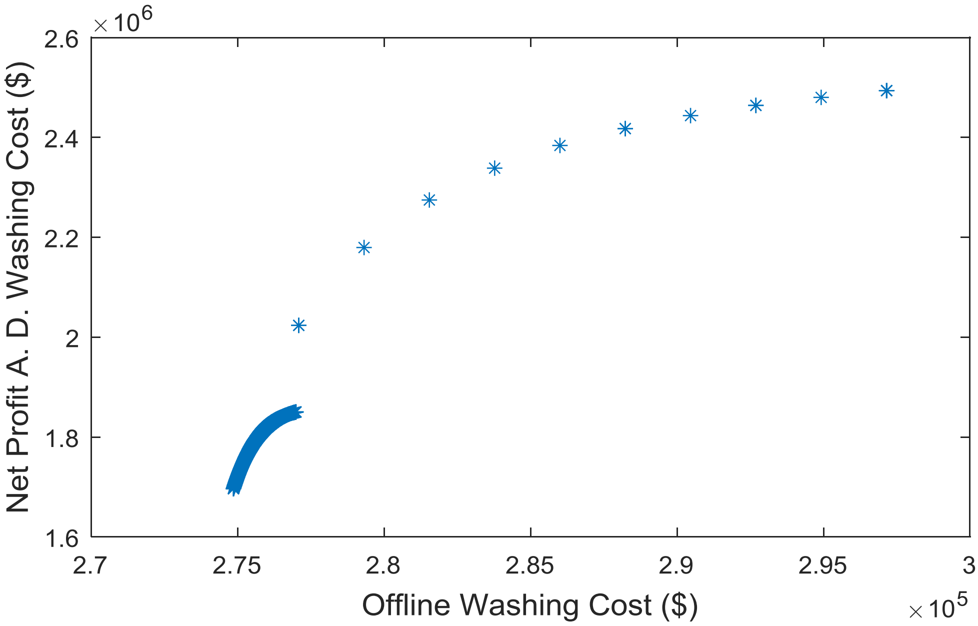


Figure 6-16 Optimized net profit and total cost related with washing per annum for 307MW

The optimised minimum and maximum OWC found to be $\$6.096 \times 10^4$ and $\$6.16 \times 10^4$ (Figure 6-17) respectively. However, the NPADWC of the light-duty engine of 5.3MW and with the same frequency of washing intervals decreases with an increase in the washing frequency with the minimum and maximum NPADWC at $-\$1.2 \times 10^4$ and $\$1.3 \times 10^4$ (Figure 6-18) respectively.

When optimizing the two criteria for the 5.3MW engine, the decision variables and the input algorithm parameters were chosen and applied. The result shows a convex Pareto surface with the direction of the optimal search toward the end of the surface. The OWC is used to minimize the function while the NPADWC is used to maximize the function. The average minimum solutions for the objectives one and two are $\$6.096 \times 10^4$ and $-\$1.2 \times 10^4$ while the average maximum solutions for objectives one and two are $\$6.16 \times 10^4$ and $\$1.3 \times 10^4$ respectively. The Pareto surface shows that as the NPADWC increases the OWC increases. The optimized frequency of washing for the light-duty engine of 5.3MW corresponds to NPADWC of $\$1.3 \times 10^4$ and OWC of $\$6.16 \times 10^4$ and is approximately 796hrs intervals of washing (Figure 6-19).

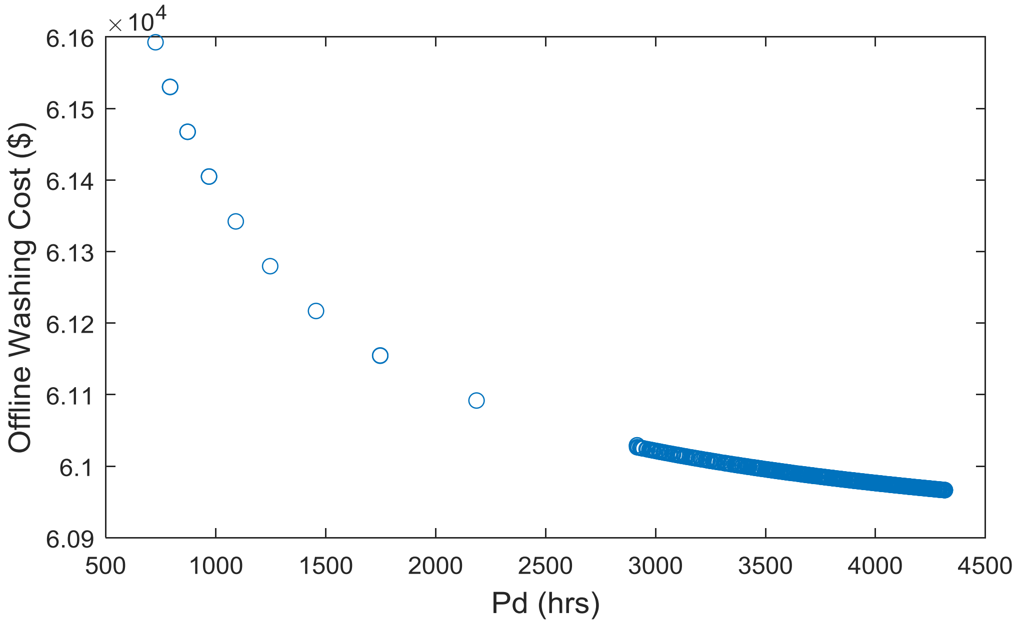


Figure 6-17 Optimized total cost related with washing per year for 5.3MW

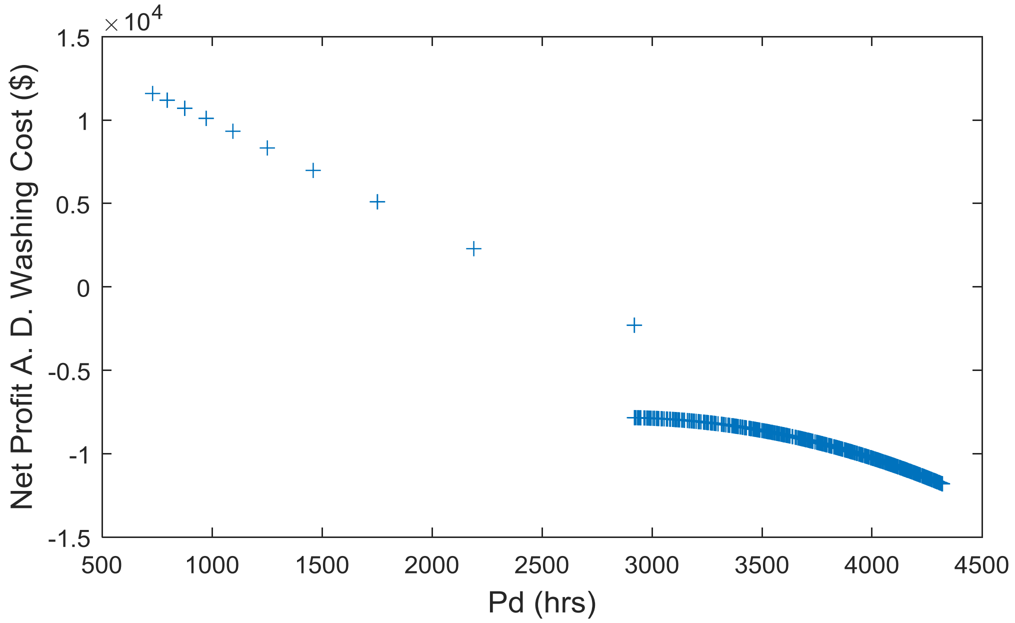


Figure 6-18 Optimized net profit per year for 5.3MW

Table 6-3 shows that as the engine size or capacity increases the optimized net profit and total cost of off-line washing increases that gives an optimized washing frequency for different engine sizes. The optimized washing frequency for the large engine of 307MW is 796hrs which has 11 off-line washing and cost savings compared to the most frequent washing of 720hrs (12 off-line washing).

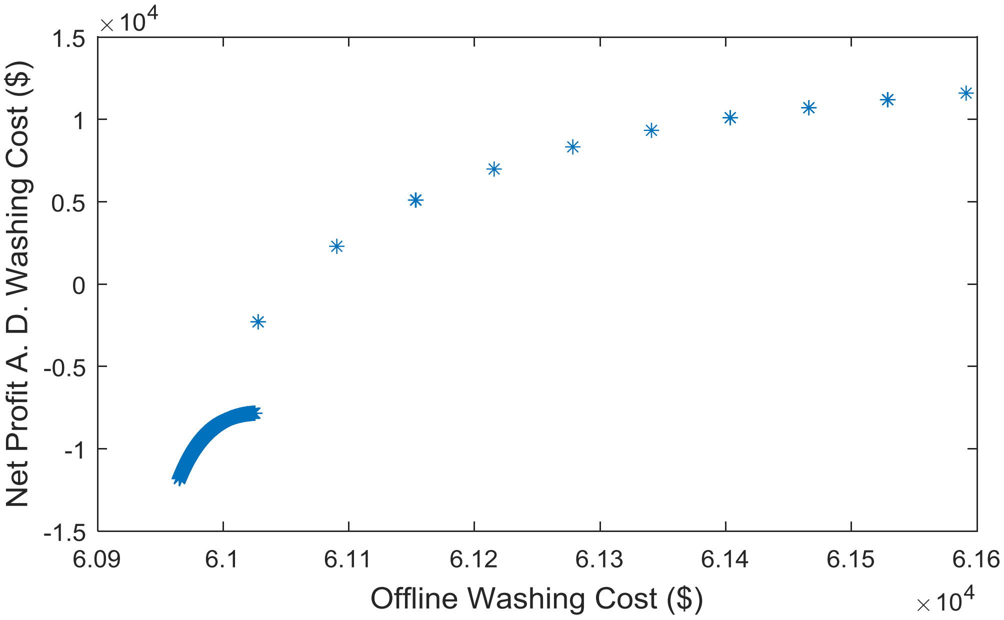


Figure 6-19 Optimized net profit and total cost related with washing per annum for 5.3MW

Table 6-3 Optimum frequency of washing for off-line washing

Capacity (MW)	NPADWC **($)**	OWC **($)**	**Optimum point (hrs)**
307	2.52×10^6	2.97×10^5	796
275	2.14×10^6	2.96×10^5	730
255	2.12×10^6	2.94×10^5	796
236	1.93×10^6	2.91×10^5	796
211	1.71×10^6	2.90×10^5	730
203	1.64×10^6	2.91×10^5	796
180	1.54×10^6	2.87×10^5	730
159	1.39×10^6	2.89×10^5	730
139	11.6×10^5	2.21×10^5	796
123	11.0×10^5	2.18×10^5	796
96	9.45×10^5	1.49×10^5	730
84	8.1×10^5	1.46×10^5	730
63	5.4×10^5	1.425×10^5	730
43	3.54×10^5	9.92×10^4	796
27	2.0×10^5	9.81×10^4	796
13	9.1×10^4	6.23×10^4	730
5	6.16×10^4	1.3×10^4	796

The optimized washing frequency for the light-duty engine of 5.3MW is also 796hrs which also has 11 off-line washing compared to the most frequent washing. The optimum washing frequency (off-line washing) ranges from 730hrs to 796hrs.

6.4.7 Influence of Changes in Degradation Rate

This is to examine the effect of changes in degradation rate on the benefit of washing frequency using NSGA II method. Example, when optimizing the two criteria at 7.2% power drop (NPADWC and OWC) for the 307MW engine, the decision variables and the input algorithm parameters were chosen using the previous information for input performance and input economics. The Pareto surface shows that as the NPADWC increases the OWC increases. The optimized frequency of washing that corresponds to NPADWC of $\$2.52 \times 10^6$ and OWC of $\$2.97 \times 10^5$ is approximately 796hrs intervals of washing.

When a reduction in the level of degradation applied by half, amounting to 3.6% power drop at 8640th hour in order to examine the effect of changes in degradation rates on the benefit of washing frequency.

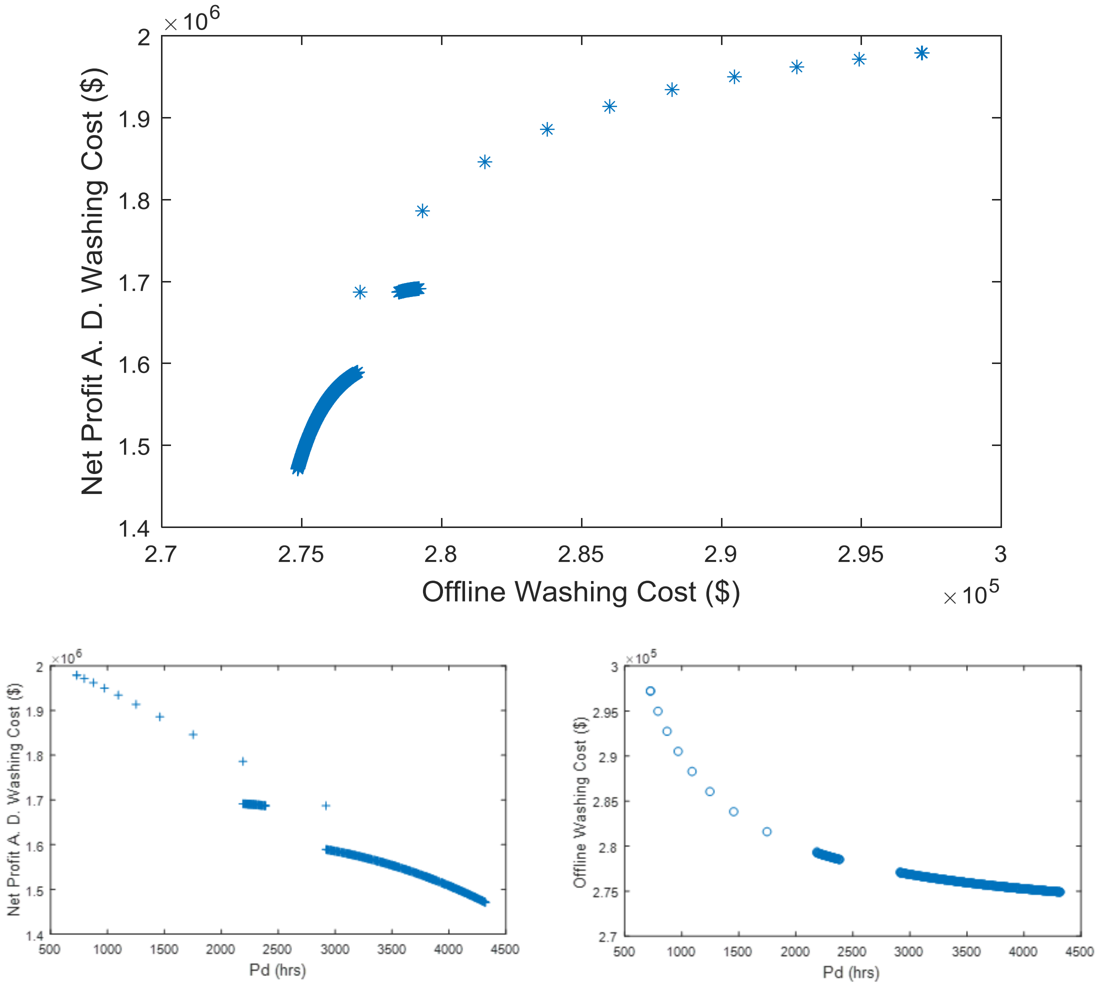


Figure 6-20 Optimized operational changes due to degradation rate at 3.6% power drop (off-line washing)

When optimizing the two objective functions at the stated power drop (NPADWC and OWC) for a large engine of 307MW, the decision variables and the input algorithm parameters were applied using the previous information. The Pareto surface shows that as NPADWC increases the OWC also increases. The optimized frequency of washing that corresponds to NPADWC of $\$1.98 \times 10^6$ and the OWC of $\$2.97 \times 10^5$ is approximately 730hrs of washing (Figure 6-20). This shows that as the deterioration level becomes lower (3.6% power drop) the frequency of washing is 730hrs, net profit after deducting washing cost is lower and the total cost related with the off-line washing are the same compared to (7.2% power drop case).

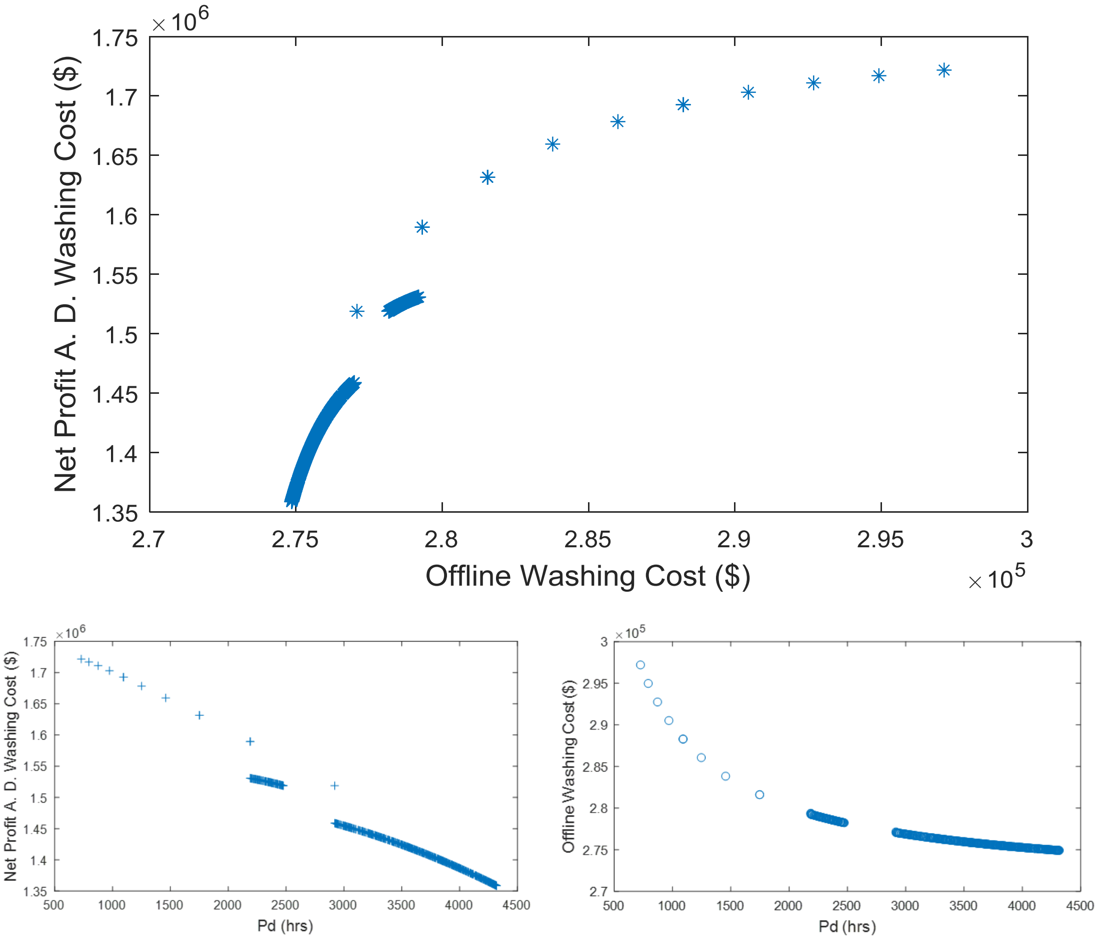


Figure 6-21 Optimized operational changes due to degradation rate at 1.8% power drop (offline washing)

A further reduction in the level of degradation by another half, amounting to 1.8% power drop in the 8640th hour shows an optimized frequency of 730hrs and that corresponds to an optimized NPADWC of $\$1.73 \times 10^6$ and OWC of $\$2.97 \times 10^5$ (Figure 6-21). It can be noticed the net profit after deducting washing cost is lower and total cost related with the off-line washing is the same and the optimized frequency is the same compared to 3.6% power drop.

Further to the investigation on degradation level, when the degradation rate is subsequently 1.5times the original degradation (1.5 *7.2% power drop), in order to examine the effect of changes in degradation rate on the benefit of washing frequency. This amounts to a 10.8% reduction in the power output at the end of 8640th hour.

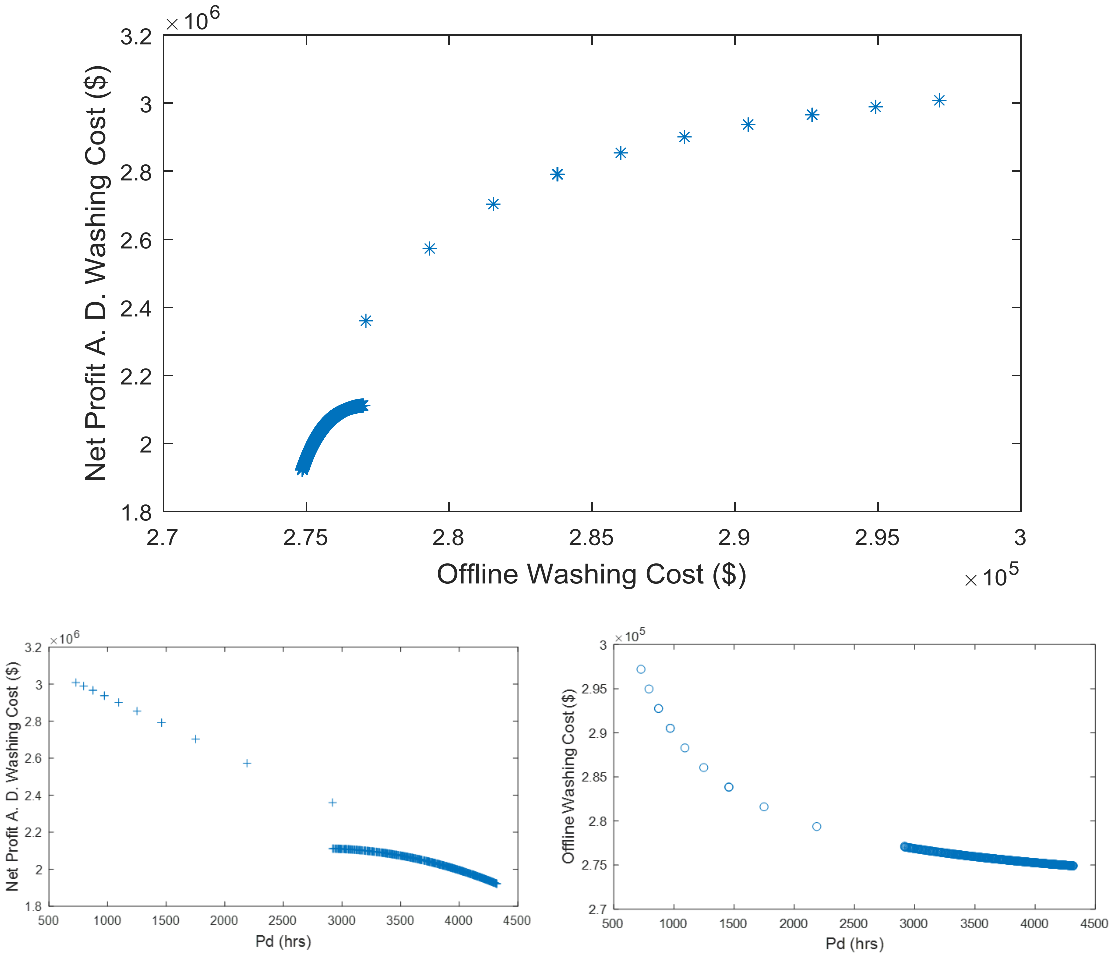


Figure 6-22 Optimized operational changes due to degradation rate at 10.8% power drop (off-line washing)

When optimizing the two criteria that is NPADWC and OWC for the 307MW engine, the decision variables and the input algorithm parameters were chosen using previous information. The Pareto surface shows that as the

NPADWC increases the OWC also increases with an optimized washing frequency of 730hrs and that corresponds to an optimized NPADWC of $\$3.0 \times 10^6$ and OWC of $\$2.97 \times 10^5$. It can be noticed the optimized frequency of washing (most frequent) at highest deterioration rate is 730hrs, this is due to the highest NPADWC and the total cost related with the off-line washing is the same for all the cases.

Table 6-4 shows the effect of optimized off-line washing on different degradation rate for the large and small engine of 307MW and 5.3MW engine capacities. For the 307MW engine the optimum frequency of washing ranges from 730hrs to 796hrs with a decrease in deterioration rate. For the small engine of 5.3MW, the optimum frequency of washing also ranges from 730hrs to 796hrs with a decrease in deterioration rate. The optimum washing frequency for the small engine at 3.6% and 1.8% deterioration are not viable. From the optimized results obtained it shows that washing 11× *per annum* is more profitable and cost savings compared to most frequent washing at 720hrs of washing.

Table 6-4 Influence of off-line washing on different degradation rate

Degradation Rates	10.8%	7.2%	3.6%	1.8%
Optimum frequency (307MW)	730	796	730	730
Optimum frequency (5.3MW)	796	730	Not viable	Not viable

6.5 Summary

The study has presented an optimization method capable for evaluating compressor washing performance and economics for different engine capacities using non-dominated sorting genetic algorithm approach/method, in order to find an optimum washing frequency with the least cost. The algorithm for on-line washing is capable of estimating the operation and maintenance cost of the washing equipment and the net profit after deducting washing cost at an optimum frequency. The algorithm for off-line washing also estimate the net profit after deducting the washing cost and the total cost related with off-line washing at an optimum frequency. The following are the key findings for optimized on-line and off-line washing:

- The optimum on-line washing frequency ranges from 90hrs to 110hrs for all the engine capacity for the same level of degradation (7.2% power drop) and application, except the light-duty engine of 5.3MW that was found to be negative, due to loss in net profit after deduction of the washing cost and washing equipment, and it’s not viable.
- The total cost savings for the large engine of 307MW from an optimized on-line washing frequency compared to frequent washing (base line case of 72hrs washing frequency) found to be \$346,000 at 8640th hour.
- When a degradation level increases for certain operations from the baseline degradation, the optimized frequency of washing increases (more frequent washing) while the optimized frequency of washing decreases (less frequent washing) with a decrease in the degradation rate. This shows that degradation rate is proportional to an optimized frequency of washing.
- When the deterioration level becomes lower for an optimized on-line washing operation (3.6% power drop), the optimized frequency of washing is lower, net profit after deducting washing cost is lower and the O&M cost of washing is also less. It has been observed at 1.8% power drop the net profit and O&M cost of the washing are lower and the optimized frequency is higher compared to 3.6% power drop. This is consistent with the previous case for more frequent washing with lower degradation amounts to relatively lower RoI. When the highest deterioration rate is applied (10.8% power drop) the optimized frequency of washing (most frequent) are lower compared to all other deterioration rate, this is due to higher net profit and that amounts to higher O&M of the washing cost, and this also consistent with more frequent washing with higher degradation amounts to relatively higher RoI.
- The optimal solutions for off-line washing shows convex Pareto surface as the net profit after deducting washing cost increases the total cost related with washing increases for all the degradation rates and the solutions tend toward more frequent washing.

- A significant benefit to the operator has been observed when an optimized washing frequency is applied. Using an optimized washing strategy with different site specific data will reduce significant losses for the operator.

7 CONCLUSION AND RECOMMENDATION

7.1 Conclusions

In summary, the research work presented in this thesis involves engine performance evaluation and economic analysis of GT on-line compressor washing. The cost-benefit analysis of the GT off-line compressor washing and a combination of the two methods and compressor washing optimization has been discussed.

The major contributions of this study include:

- The viability of applying compressor washing for different engine capacity has been identified. This takes into account the respective BESP for individual capacity.
- Able to relate the effectiveness of washing as a function of frequency using real data obtained from the actual machine.
- A method for finding an optimal frequency of on-line and off-line washing using a non-dominated sorting genetic algorithm for different engine sizes has been identified.
- The best combination of crank soak and on-line compressor washing cycles that offered the maximum economic benefit (net profit) has been identified.

The result shows that a fouling degradation trend obtained from the actual machine operation was implemented and applying extrapolated degradation trend for the four years of operation by extended method amounts to an average of 7.2% drop in the power output and 1.6% heat rate increase at 8640th hour of operation. The cost of fouling for the 17 engine investigated by implementing the same level of degradation and application, related to their rated capacities ranging from a 5MW single machine to a 300MW unit vary significantly, from $203,000 for light engine to $8,434,000 for heavy-duty engine in one year of operation depending on the level of deterioration. However, applying the extrapolated degradation trend for the standard method shows higher power drop and increase in heat rate compared to the extended method. This is due to taking only inlet temperature and pressure into account in correcting the data. Using an extended correction method gives more accurate estimates for the percentage degradation.

The cost-benefit analysis for on-line washing from 72hrs to 480hrs frequency was investigated, focusing on the viability of compressor washing for various gas turbine engines. The application of different washing frequencies with recoveries of lost power shows a significantly higher return on investment for the larger engines in comparison to the smaller engines. This is partly because the cost of on-line washing equipment is not proportional to the size of the equipment. The economics is more favourable for larger engines due to the economy of scale. This is due to a higher value of power production and a significantly more penalty per MW of electricity generated for the same percentage losses. This can be overcome by implementing more than one single small engine unit. When the number of engines increases to 4 for given operations, the return on investment increases by a factor of 3.4. This is possible one wash unit can be applied to more than one engine within proximity. Higher return on investment is achieved when more than one relatively small engine is used to obtain a higher total power output. This is about 1.9 times higher for four 63MW engines versus one 255MW, as relatively cheaper washing equipment is implemented for the same total operational capacity. This increases the annual savings to about $180,000. The study also shows that on-line washing is viable for electric power generation. It was observed that for smaller light-duty engines, the return on investment is very low especially in situations where the level of fouling is relatively lower. On-line compressor washing is a lot more viable when the expected level of degradation is high.

The result of the LCOE analysis for different engine sizes shows that for a heavy-duty engine of 307MW at clean condition is $66.6/MWhr while for the light-duty engines of 5MW is $96/MWhr. It was observed that the LCOE for the light engine is higher compared to the heavy-duty engine, this is due to higher genset price in $/kW of GT and the capital cost of washing equipment compared to the heavy-duty engine. This analysis concludes that the LCOE of a GT engine decreases with an increase of engine capacity for the same level of deterioration and application.

Implementing on-line washing as above shows an additional profit as the washing frequency increases. Thus, for the 72hrs frequency of wash, both large and small engines yielded \$1,371,000 and \$39,000 respectively, while at a 480hrs frequency a profit of \$1,157,000 and \$33,100 was obtained for the large and small engines respectively. However, the profit at 72hrs frequency seems to be higher when compared to that of 480hrs frequency. This is due to higher effectiveness of washing and fewer deposits are built-up. This highlights the benefit of frequent and consistent washing which amounts to relatively higher profits. The increased performance benefit or higher power outputs promised by on-line washing typically outweighs the increased financial cost.

A cost-benefit analysis of GT off-line washing has also been investigated from 720hrs to the 4320hrs frequency and a combination of the two methods (on-line and off-line). The result shows that the degradation rate has a great effect on the plant profits, but extra care must be taken to avoid higher degradation rate. When off-line and on-line washing at different combination is incorporated, it shows that adopting the most frequent on-line washing at the 72hrs combine with the most frequent off-line washing does not give higher benefit, as the on-line washing is effective and greatly could decrease the number of off-line washing. Combining the most frequent off-line washing with a fair amount of on-line washing case of 36 times a year provides higher net profit compared to other washing combinations. The total washing cost that is related to washing, net profit after deducting washing cost and benefit due to power recovery increases with an increase in engine sizes for the same level of degradation and application.

An optimization method capable of evaluating compressor washing performance and economics using non-dominated sorting genetic algorithms approach has been applied. The result shows an optimum on-line washing frequency ranges from 90hrs to 110hrs for all engine capacities except light-duty engine of 5MW of the same level of degradation (7.2% power drop) and application. The optimized washing frequency for the light-duty engine was found to be negative and it’s not viable, this is due to the negative net profit. A significant benefit to the operator was observed when an optimized washing frequency is applied. A computer programme was developed that includes the compressor washing performance and economics and the compressor washing optimization for on-line and off-line compressor washing.

Finally, the engine performance evaluation and economic analysis of GT compressor washing for different rated capacities have been achieved. The study highlighted that applying on-line compressor washing decelerates the rate of degradation due to fouling, this might eliminate the rate of degradation as the case for off-line washing. The study also highlighted that applying optimum washing frequency increases the net profit and of course the total profit.

7.2 Recommendations and Future Work

The recommendations and future work consist of the following:

I. Effort should be made to explore the optimal combination of compressor washing and filtration systems to propose filter arrangements and compressor washing scheme that an optimum balance of techniques. As the use of a high-efficiency filter system may require minimal washing and vice versa.
II. Investigate the economic impact of compressor fouling and compressor washing on the aero engines.
III. The model does not support quadratic and polynomial equations for the degraded engine trend line for on-line and off-line washing. The model is limited to the linear equation only for the degraded engine trend line for on-line and off-line washing analysis, which serves as input to the economic analysis. The performance model for washing can be modified to accommodate a polynomial degradation equation trend line curve.
IV. Filtration system model should be included in the software programme for compressor washing performance and economics and compressor washing optimization in order to estimates an optimum balance between filtration system and compressor washing. This includes the optimum compressor washing and with the minimum filter replacement.

V. A creep life and emission model should be incorporated/integrated into the compressor washing model to observe the benefit of washing on blade life and emission reduction.

VI. The number of start due to off-line washing can be included in the off-line washing analysis as it has a noticeable effect on the plant total profit and additional profit due to washing.

VII. The interval of washing is the ratio of equivalent operating hours to frequency. When the denominator (frequency) is not divisible by equivalent operating hours for the optimization. It cut some of the hours of operation in the model since the ratio of the operational hours to frequency is a decimal. In this case, an extra operating hour is added to the equivalent operating hours with an inequality not to exceed 8760hrs in 1 year of operation. Adjusting the model to suit and accommodate the actual operating hours for each frequency of washing improves the accuracy of the result for the optimum frequency of washing for the optimization.

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APPENDICES

Comprises of five sections; appendix A, appendix B, appendix C, appendix D and appendix E

Appendix A

SOFTWARE PROGRAMME FOR COMPRESSOR WASHING ECONOMICS

This section presents a software programme for the compressor washing performance and economics and the compressor washing optimization for on-line and off-line compressor washing for different engine sizes.

Introduction

The use of computer program on different engineering application has become very common process or practice by developing a user-friendly application that process the actual engine data and generate the compressor washing (performance and economics) output cost automatically. The monitoring tool for the compressor washing calculates the on-line/off-line washing performance and economics and gives an output result for the operational profit for the on-line/offline compressor washing. The evaluation procedures for the performance and economic analysis were previously done manually which requires significant amount of time especially when different GT's are used in one plant that experienced different degradation rate. The development of this software program has greatly reduced the time required for the data processing and analysis of the compressor washing performance and economics. The most essential goal of using graphical user interface (GUI's) is to make it easier for the end-users of the program. The software program can handle different engine capacities from light-duty to heavy-duty, it can also handle different design and configurations. It has been proven simple, reliable, accurate, and robust, ease of implementation and produces a promising solution.

This study unlike others explores the cost-benefit analysis using a computer program, focusing on the viability of compressor washing for various gas turbines or rated capacities. The study also presents a computer program for optimization capable of estimating an optimum washing frequency for a time based degradation.

User Interface of the Model

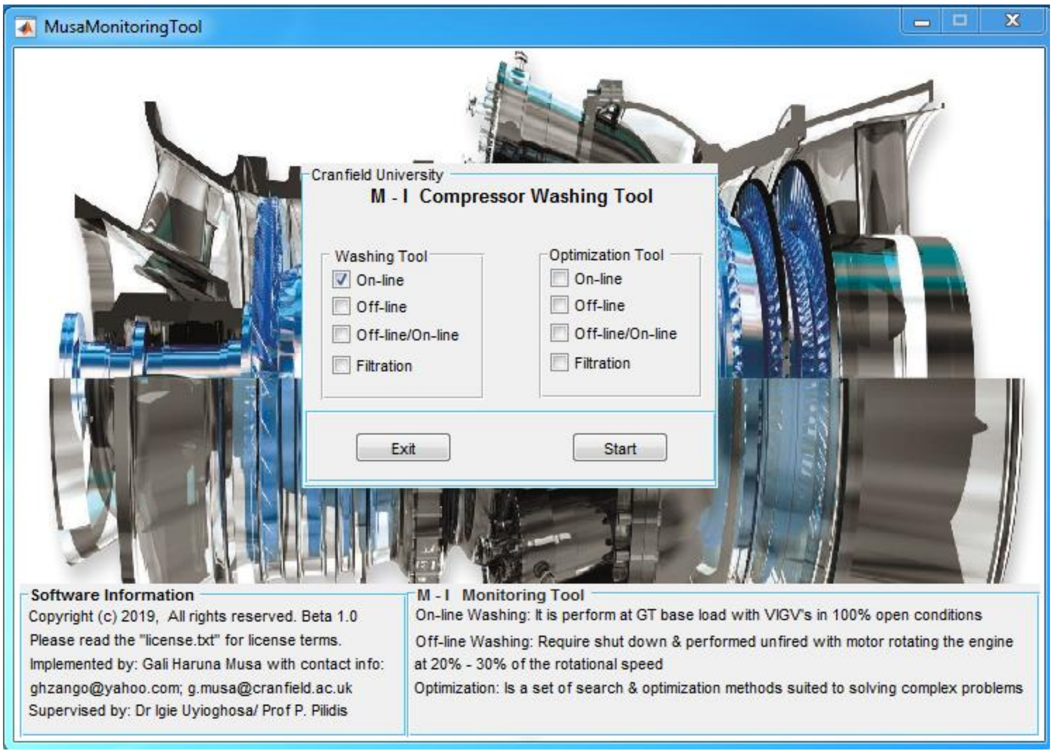
A user interface (UI) is a graphical representation of one or more windows that controls components which enable a user to carry out interactive tasks. The UI tools carry out computation, read data files, connect with other UI’s, and show data results in tabular or graphical format.

The monitoring tool for the compressor washing performance and economics can be categorized into three main area namely;

- Compressor washing monitoring tool interface
- Performance model (on-line and off-line washing or combination) interface
- Economics model (on-line and off-line washing or combination) interface

Compressor Washing Monitoring Tool Interface

This is a home user interface (UI) of the program where the user can select the type of program to analyse for the performance and economics calculations (Figure_Apx A-1). Once the program have been chosen the next step is to click the start button to switch into the main program for the performance calculations.



Software Information
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Supervised by: Dr Igie Uyioghosa/ Prof P. Pilidis

M - I Monitoring Tool
On-line Washing: It is perform at GT base load with VIGV's in 100% open conditions
Off-line Washing: Require shut down & performed unfired with motor rotating the engine at 20% - 30% of the rotational speed
Optimization: Is a set of search & optimization methods suited to solving complex problems

Figure_Apx A-1 Model program interface

Performance Model Interface

This is the performance model UI where the user is able to define all the performance input parameters based on engine operational data for on-line and off-line or a combination of the two method. The program can generate and estimate an output results in a tabular format and a standard graph.

Economics Model Interface

This is the economics model UI where the user is able to define all the economics input parameters based on engine operational data for on-line and off-line and or a combination of the two methods. The program is able to compute and generate an output results in a tabular format and a standard graph. The economics result compares the simple and the dynamic analysis.

Program Structure

The structure of the program is divided into 2 section; that is washing and the optimization tool. The washing tool consists of 2 layers, which includes performance and economics. The washing tool (performance and economics) is divided into on-line, off-line, combination of the two methods, while the optimization tool comprises of on-line and off-line. The general procedure for running the program can be summarized using the following steps:

- Select and click the type of program to run using a checkbox
- Click a start pushbutton to switch into the main program
- Click a sample pushbutton of the input performance to generate the default data, the user being able to edit the data to suit the engine type in use
- Select the run button key to start the program and generate results in graphical & tabular format
- Export button key is used to export data into excel for more statistical analysis
- Reset button is used to reset the data in order to generate another set of data
- The home button key is used to return back to the main program
- Economics pushbutton is used to pop up to the economics sections
- A performance pushbutton is used to pop up back to performance sections

- An exit button is used for exiting the program in order to select another layer i.e. off-line washing, off-line and on-line washing combination.

Input Data for On-line Washing

The user is required to input the parameters available on the program interface. The input parameters are used to estimate the performance for the on-line washing. A sample of input data are used as a default input parameters. The available data for the input parameters used for the analysis are as follows:

- Engine capacity is the power rating of the GT engine
- Pd is the frequency/intervals of washing
- hrs is the equivalent operating hours per annum
- Cost of electricity which depends on the technology and the size of GT engine
- Cost of natural gas for the particular year
- Heat rate and heat rate increase due to degradation and are usually in percentage
- Recovery/increase is representing the effectiveness of washing and usually in percentage (time based recovery rate)
- Slope representing the engine degradation and assuming a linear degradation per annum obtained

Sample and reset button key are used to set up the analysis. Sample default data is generated by the program and used as an example. The reset button is used to reset the data to zero after a series of analysis.

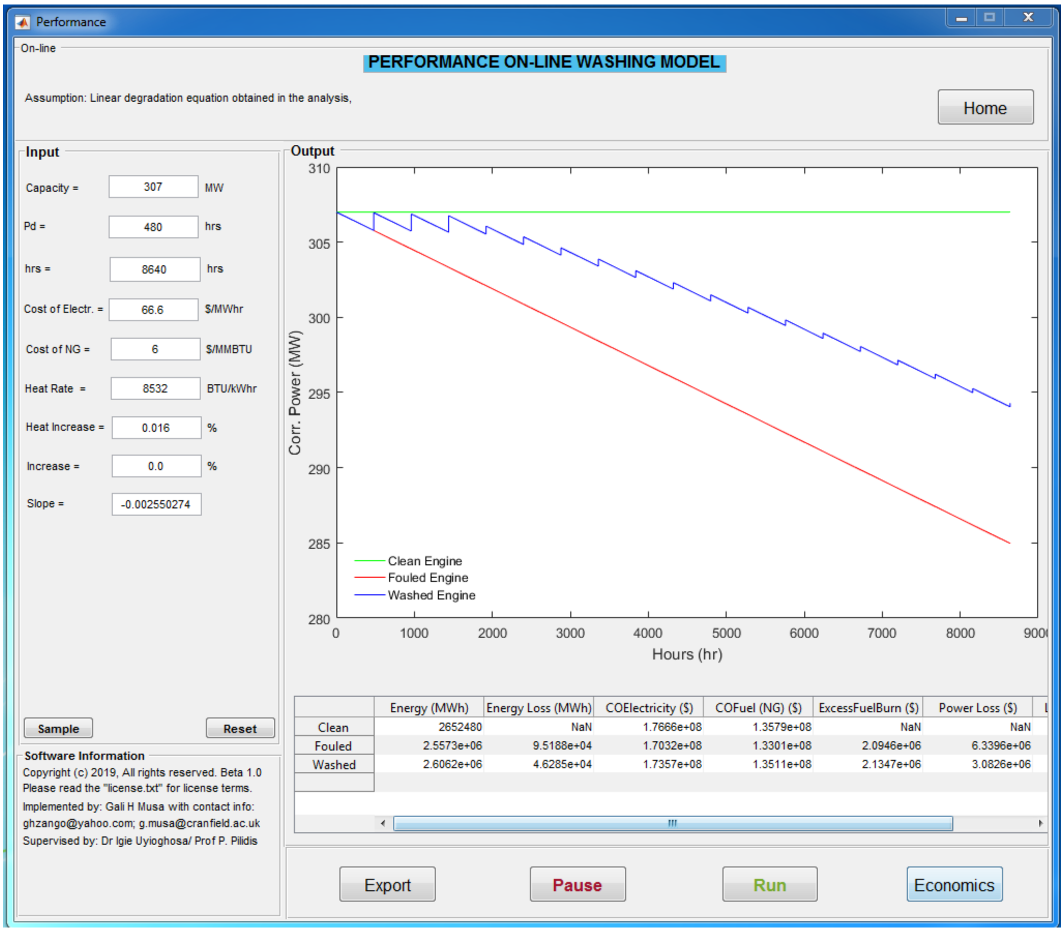
Output Data for On-line Washing

The program generates output results after a series of calculations and computations, the results are in graphical and tabular format that show the clean, fouled and washed engine data. Some important buttons are used to generate the results for all the output cases, as follows:

- Run
- Export
- Economics

- Home

The summary of the results have been highlighted in the table for the generated energy, loss of energy per annum due to fouling and washing, cost of electricity generated, fuel cost, excess fuel burn due to fouling, power loss due to degradation, and loss of revenue for the fouled and washed case (Figure_Apx A-2).



Assumption: Linear degradation equation obtained in the analysis,

Capacity = 307 MW
Pd = 480 hrs
hrs = 8640 hrs
Cost of Electr. = 66.6 $/MWhr
Cost of NG = 6 $/MMBTU
Heat Rate = 8532 BTU/kWhr
Heat Increase = 0.016 %
Increase = 0.0 %
Slope = -0.002550274

	Energy (MWh)	Energy Loss (MWh)	COElectricity ($)	COFuel (NG) ($)	ExcessFuelBurn ($)	Power Loss ($)
Clean	2652480	NaN	1.7666e+08	1.3579e+08	NaN	NaN
Fouled	2.5573e+06	9.5188e+04	1.7032e+08	1.3301e+08	2.0946e+06	6.3396e+06
Washed	2.6062e+06	4.6285e+04	1.7357e+08	1.3511e+08	2.1347e+06	3.0826e+06

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Figure_Apx A-2 Performance for on-line washing model interface

Input Data for Economics

The economics button is used which switched the program into economic model section, the user is required to input the parameters available on the program interface. The input parameters are used to estimate the economics output parameters for the compressor washing. The available data for the input used for the analysis are as follows:

- Capital cost of the washing equipment depending on the size of GT
- Pd is the frequency of washing and same as input
- hrs is the equivalent operating hours per annum and same as input
- Engine mass flow which depends on the size of GT engine and manufacturer
- Cost of concentrates guard for washing
- Cost of demineralized water
- Life of the equipment which depends on the usage of the equipment and the number of engines
- Interest rate and the number of engines
- Fuel flow of the engine
- Mixture ratio
- Duration of the washing

Output Data for Economics

The program generates an output after a series of computations, the result shows an annual savings, NPV, RoI and Payback for simple and dynamic analysis, cost of fluid per annum and total cost of washing showing in Figure_Apx A-3. It also includes net profits for clean, fouled and washed engine, additional profit due to washing cost and net profit after deducting washing cost. Some important buttons are used to generate the results for the output and these are run, export, and exit which is used to exit the program, while the performance button is used to return back (switch) to performance window.

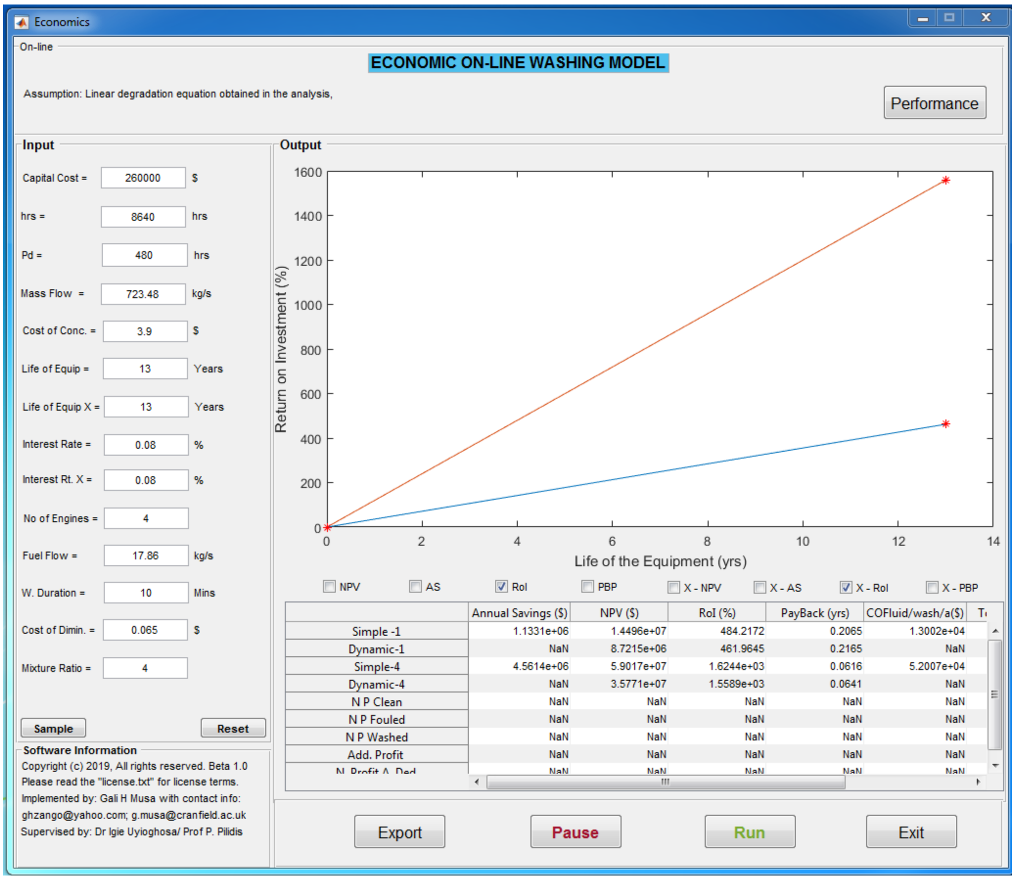
Input Data for Off-line Washing

The user is required to input the parameters available on the program interface. The input parameters are used to estimate the performance for the off-line washing. The available data for the input used for the analysis are similar to the on-line washing plus the following:

- Downtime is the time required for engine cool down plus the duration for washing
- Pd is much higher than for on-line and it represents the frequency of washing

- Recovery/Increase which represents the effectiveness of washing and is higher than on-line

The other program is a combination of on-line and off-line washing, the program also requires input parameters for the computation and is similar to on-line and off-line input data previously discussed.



Assumption: Linear degradation equation obtained in the analysis,

Capital Cost = 260000 $
hrs = 8640 hrs
Pd = 480 hrs
Mass Flow = 723.48 kg/s
Cost of Conc. = 3.9 $
Life of Equip = 13 Years
Life of Equip X = 13 Years
Interest Rate = 0.08 %
Interest Rt. X = 0.08 %
No of Engines = 4
Fuel Flow = 17.86 kg/s
W. Duration = 10 Mins
Cost of Dimin. = 0.065 $
Mixture Ratio = 4

	Annual Savings ($)	NPV ($)	RoI (%)	PayBack (yrs)	COFluid/wash/a($)
Simple -1	1.1331e+06	1.4496e+07	484.2172	0.2065	1.3002e+04
Dynamic-1	NaN	8.7215e+06	461.9645	0.2165	NaN
Simple-4	4.5614e+06	5.9017e+07	1.6244e+03	0.0616	5.2007e+04
Dynamic-4	NaN	3.5771e+07	1.5589e+03	0.0641	NaN
N P Clean	NaN	NaN	NaN	NaN	NaN
N P Fouled	NaN	NaN	NaN	NaN	NaN
N P Washed	NaN	NaN	NaN	NaN	NaN
Add. Profit	NaN	NaN	NaN	NaN	NaN
N Profit A Ded	NaN	NaN	NaN	NaN	NaN

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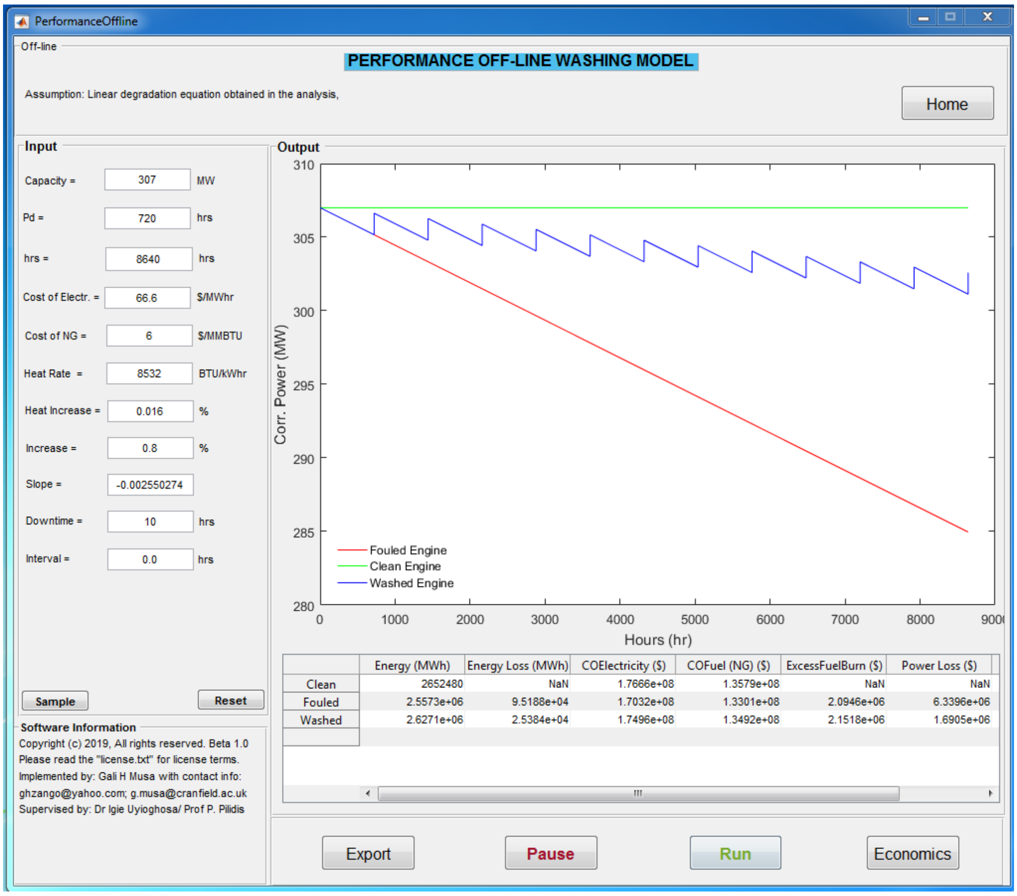
Figure_Apx A-3 Economics for on-line washing model interface

Output Data for Off-line Washing

The program generates the output after a series of calculations, the summary of the results for the graph shows the clean, fouled and washed engine data. Some important buttons are used to generate results as discussed previously and these are run, export, economics, and home button to return back to the main program. In the table summary of the results (Figure_Apx A-4) shows the energy generated,



Assumption: Linear degradation equation obtained in the analysis,

Capacity = 307 MW
Pd = 720 hrs
hrs = 8640 hrs
Cost of Electr. = 66.6 $/MWhr
Cost of NG = 6 $/MMBTU
Heat Rate = 8532 BTU/kWhr
Heat Increase = 0.016 %
Increase = 0.8 %
Slope = -0.002550274
Downtime = 10 hrs
Interval = 0.0 hrs

	Energy (MWh)	Energy Loss (MWh)	COElectricity ($)	COFuel (NG) ($)	ExcessFuelBurn ($)	Power Loss ($)
Clean	2652480	NaN	1.7666e+08	1.3579e+08	NaN	NaN
Fouled	2.5573e+06	9.5188e+04	1.7032e+08	1.3301e+08	2.0946e+06	6.3396e+06
Washed	2.6271e+06	2.5384e+04	1.7496e+08	1.3492e+08	2.1518e+06	1.6905e+06

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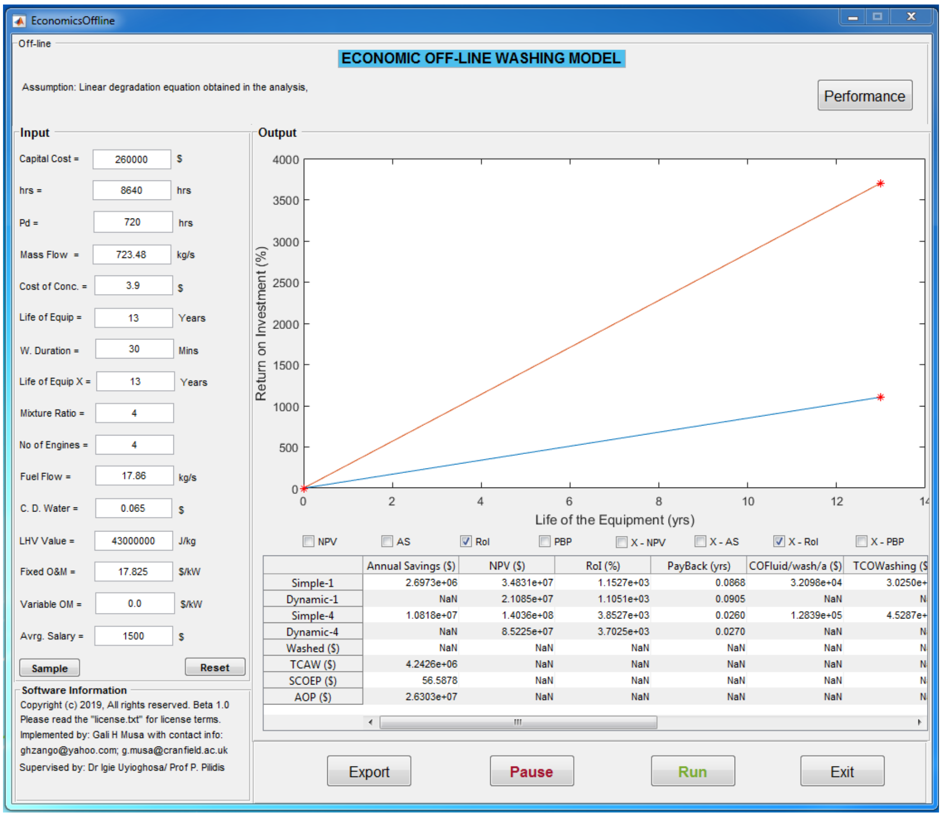
Figure_Apx A-4 Performance for off-line washing model interface

loss of energy for the year due to fouling and with regard to washing, cost of electricity generated, fuel costs, excess fuel burn due to fouling, power loss cost due to degradation, and loss of revenue for fouled and with washed engine. When combined the on-line and off-line washing, the program generates output results after a series of computations. In the program it is possible to analyse the on-line, off-line and a combination of the two methods using the same graph.

Input and Output Data for Economics

The user is required to input the parameters available on the program interface. The input parameters are used to estimate the economics for the off-line compressor washing. The available data for the input parameters used for the analysis are similar, to the on-line washing plus the following (Figure_Apx A-5): washing duration, fixed O&M cost, variable O&M cost, average salary and lower heating value (LHV). The program generates the output results after a series of computations, the results showing annual savings, NPV, RoI, Payback, cost of fluid per annum, total cost for washing, downtime cost, benefit due to fuel saved, benefit due to power recovery and annual operation profits. It is also possible to combine the on-line and off-line washing economics and generate there output results. But the program requires input parameters similar to on-line and off-line input data. Moreover, the results for the on-line, off-line and a combination of the two can be shown diagrammatically in one graph (Figure_Apx B-6).



Assumption: Linear degradation equation obtained in the analysis,

Capital Cost = 260000 $
hrs = 8640 hrs
Pd = 720 hrs
Mass Flow = 723.48 kg/s
Cost of Conc. = 3.9 $
Life of Equip = 13 Years
W. Duration = 30 Mins
Life of Equip X = 13 Years
Mixture Ratio = 4
No of Engines = 4
Fuel Flow = 17.86 kg/s
C. D. Water = 0.065 $
LHV Value = 43000000 J/kg
Fixed O&M = 17.825 $/kW
Variable OM = 0.0 $/kW
Avrg. Salary = 1500 $

☐ NPV ☐ AS ☑ RoI ☐ PBP ☐ X - NPV ☐ X - AS ☑ X - RoI ☐ X - PBP

	Annual Savings ($)	NPV ($)	RoI (%)	PayBack (yrs)	COFluid/wash/a ($)	TCOWashing ($
Simple-1	2.6973e+06	3.4831e+07	1.1527e+03	0.0868	3.2098e+04	3.0250e+
Dynamic-1	NaN	2.1085e+07	1.1051e+03	0.0905	NaN	N
Simple-4	1.0818e+07	1.4036e+08	3.8527e+03	0.0260	1.2839e+05	4.5287e+
Dynamic-4	NaN	8.5225e+07	3.7025e+03	0.0270	NaN	N
Washed ($)	NaN	NaN	NaN	NaN	NaN	N
TCAW ($)	4.2426e+06	NaN	NaN	NaN	NaN	N
SCOEP ($)	56.5878	NaN	NaN	NaN	NaN	N
AOP ($)	2.6303e+07	NaN	NaN	NaN	NaN	N

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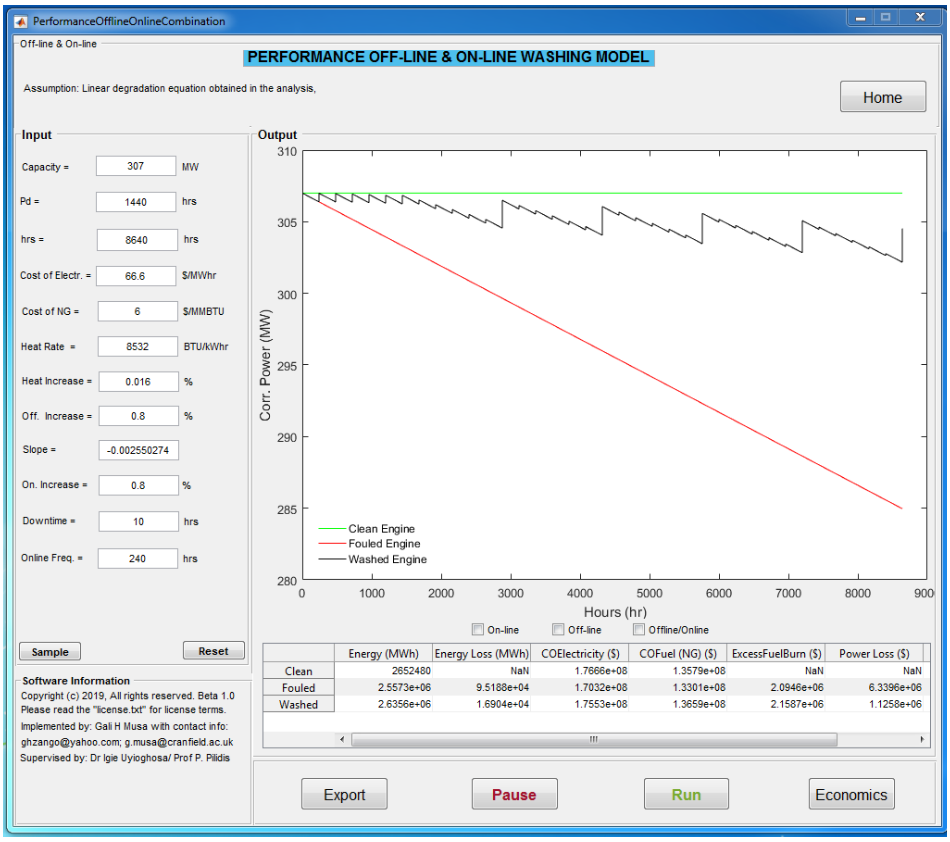
Figure_Apx A-5 Economics for off-line washing model interface

Program Structure

The optimization tool program has been designed using NSGA II together with compressor washing model and it is developed using graphical user interface which carry out computation, read data files, connect with other UI’s, and show data results in a graphical form. The monitoring tool for the compressor washing optimization can be categorized into three namely;

- Compressor washing optimization tools interface



Assumption: Linear degradation equation obtained in the analysis,

Capacity = 307 MW
Pd = 1440 hrs
hrs = 8640 hrs
Cost of Electr. = 66.6 $/MWhr
Cost of NG = 6 $/MMBTU
Heat Rate = 8532 BTU/kWhr
Heat Increase = 0.016 %
Off. Increase = 0.8 %
Slope = -0.002550274
On. Increase = 0.8 %
Downtime = 10 hrs
Online Freq. = 240 hrs

☐ On-line ☐ Off-line ☐ Offline/Online

	Energy (MWh)	Energy Loss (MWh)	COElectricity ($)	COFuel (NG) ($)	ExcessFuelBurn ($)	Power Loss ($)
Clean	2652480	NaN	1.7666e+08	1.3579e+08	NaN	NaN
Fouled	2.5573e+06	9.5188e+04	1.7032e+08	1.3301e+08	2.0946e+06	6.3396e+06
Washed	2.6356e+06	1.6904e+04	1.7553e+08	1.3659e+08	2.1587e+06	1.1258e+06

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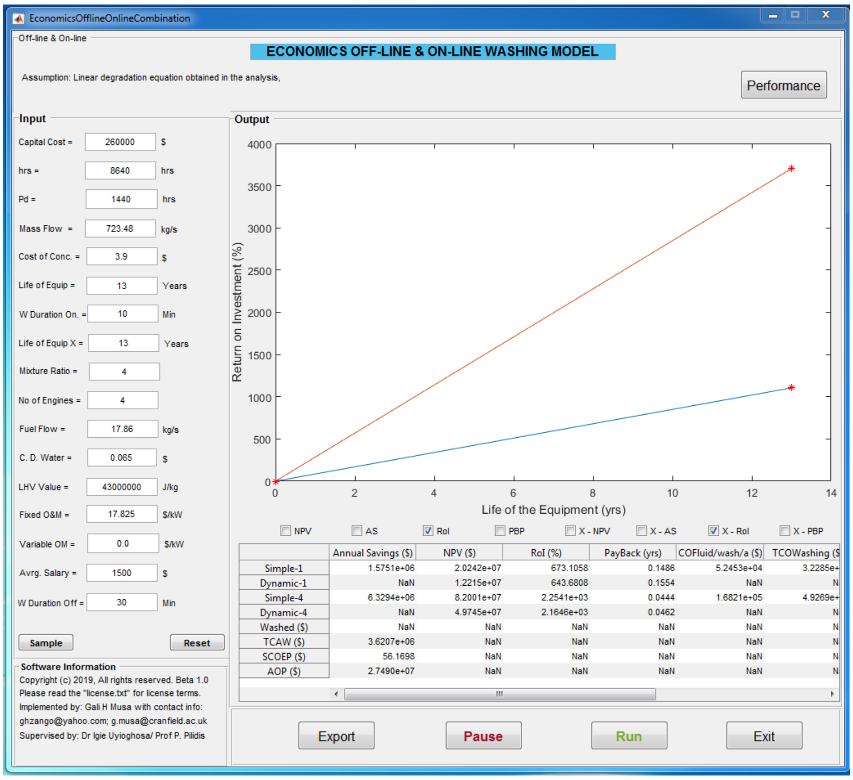
Figure_Apx A-6 Performance for on-line and off-line washing model interface



Assumption: Linear degradation equation obtained in the analysis,

Capital Cost = 260000 $
hrs = 8640 hrs
Pd = 1440 hrs
Mass Flow = 723.48 kg/s
Cost of Conc. = 3.9 $
Life of Equip = 13 Years
W Duration On. = 10 Min
Life of Equip X = 13 Years
Mixture Ratio = 4
No of Engines = 4
Fuel Flow = 17.86 kg/s
C. D. Water = 0.065 $
LHV Value = 43000000 J/kg
Fixed O&M = 17.825 $/kW
Variable OM = 0.0 $/kW
Avrg. Salary = 1500 $
W Duration Off = 30 Min

☐ NPV ☐ AS ☑ RoI ☐ PBP ☐ X - NPV ☐ X - AS ☑ X - RoI ☐ X - PBP

	Annual Savings ($)	NPV ($)	RoI (%)	PayBack (yrs)	COFluid/wash/a ($)	TCOWashing ($
Simple-1	1.5751e+06	2.0242e+07	673.1058	0.1486	5.2453e+04	3.2285e+
Dynamic-1	NaN	1.2215e+07	643.6808	0.1554	NaN	N
Simple-4	6.3294e+06	8.2001e+07	2.2541e+03	0.0444	1.6821e+05	4.9269e+
Dynamic-4	NaN	4.9745e+07	2.1646e+03	0.0462	NaN	N
Washed ($)	NaN	NaN	NaN	NaN	NaN	N
TCAW ($)	3.6207e+06	NaN	NaN	NaN	NaN	N
SCOEP ($)	56.1698	NaN	NaN	NaN	NaN	N
AOP ($)	2.7490e+07	NaN	NaN	NaN	NaN	N

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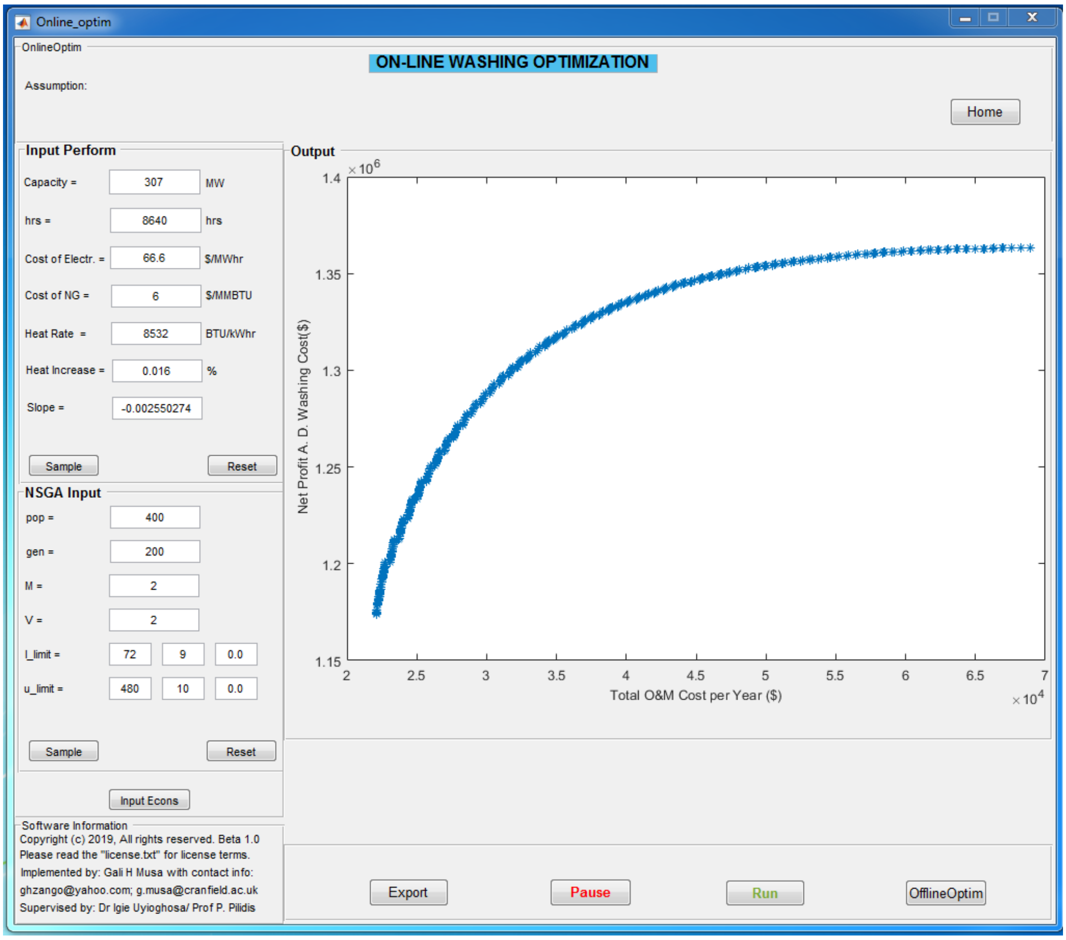
Figure_Apx A-7 Economics for on-line and off-line washing model interface

- On-line washing (performance and economics) optimization interface
- Off-line washing (performance and economics) optimization interface

The structure of the optimization tool consists of 3 layers that include performance, economics and optimization. The optimization tools are divided into on-line and off-line washing optimization. User is required to input the parameters for the program. The data for the input performance and economics for on-line and off-line washing parameters are similar to the previous ones plus the NSGA II input parameters and that include the following:

- Population size
- Number of generations
- Number of objective function
- Number of decision variable
- Upper and lower limits


Online_optim

OnlineOptim

ON-LINE WASHING OPTIMIZATION

Assumption:

Input Perform

Capacity = 307 MW
hrs = 8640 hrs
Cost of Electr. = 66.6 $/MWhr
Cost of NG = 6 $/MMBTU
Heat Rate = 8532 BTU/kWhr
Heat Increase = 0.016 %
Slope = -0.002550274

NSGA Input

pop = 400
gen = 200
M = 2
V = 2
l_limit = 72 9 0.0
u_limit = 480 10 0.0

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Figure_Apx A-8 On-line washing optimization interface

The program generates an output results after a series of computations, the results are in graphical format that shows the optimized Pareto front for the on-line and off-line washing that estimates the optimum washing frequency.

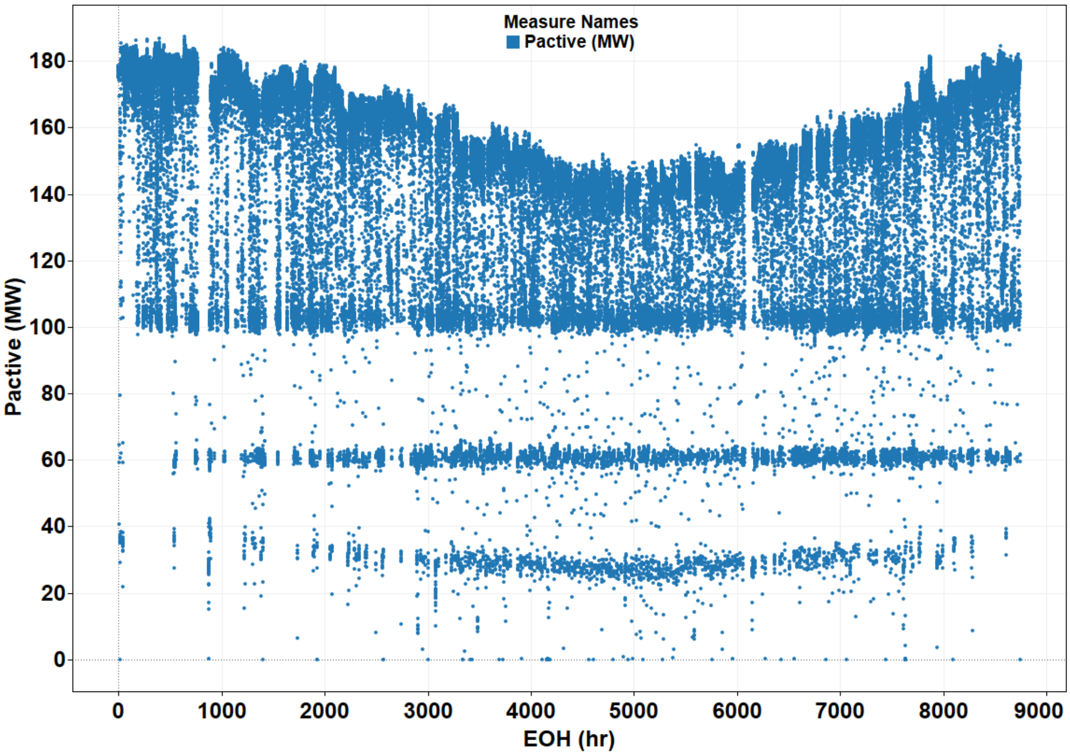
Summary

The study has presented a computer program for the performance and economics analysis for compressor washing for different engine sizes or capacities. The performance section estimates the energies, loss area, cost of electricity generated, fuel cost and fouling cost. However, the economic section of the application evaluates the operation and maintenance cost of the washing equipment, annual savings, total cost associated with washing, payback period, return on investment, and net present value of the equipment and net profit after deducting washing cost of either on-line or off-line washing or a combination of the two methods. The study also presented a computer program for the optimization for on-line and offline compressor washing for different engine sizes or capacities. The optimization of the compressor washing methods have been applied using NSGA II to estimates the optimum washing frequency for different engine capacities. For the online washing, two objective functions have been applied and these are net profit after deducting washing cost to be maximized, and the operation and maintenance cost of the washing equipment to be minimized. However, the two objective functions applied for off-line washing are net profit after deducting washing cost to be maximized, and total off-line washing cost meant to be minimized. The following are the key achievements:

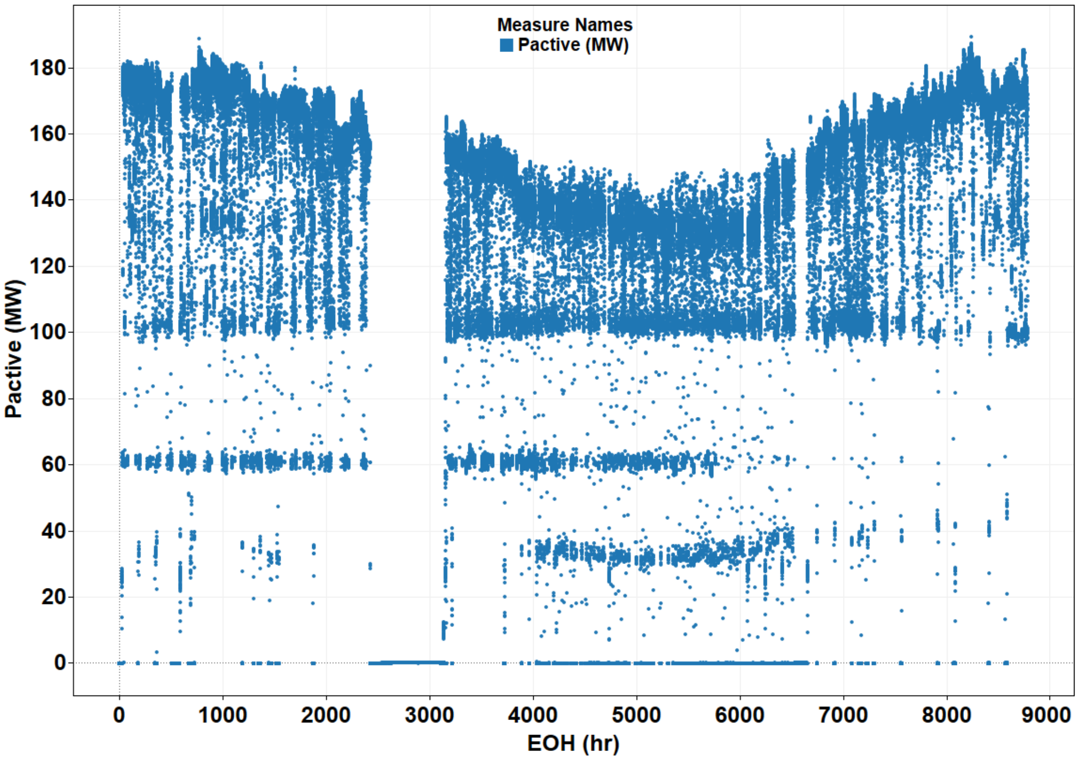
- Development of a computer program for on-line/ off-line washing performance that estimates the yearly power loss cost, excess fuel burn and loss of revenue due to fouling.
- Development of a computer program for on-line/ off-line washing economics that estimates the net profit after deducting washing cost and O&M cost of the washing equipment for on-line washing, total off-line washing cost and net profit after deducting washing cost for off-line washing.

- Development of a computer program for the combination of the two methods that is on-line/ off-line washing for the performance and economics analysis.
- Development of a computer program for on-line and off-line washing optimization that estimates the optimum washing frequency.

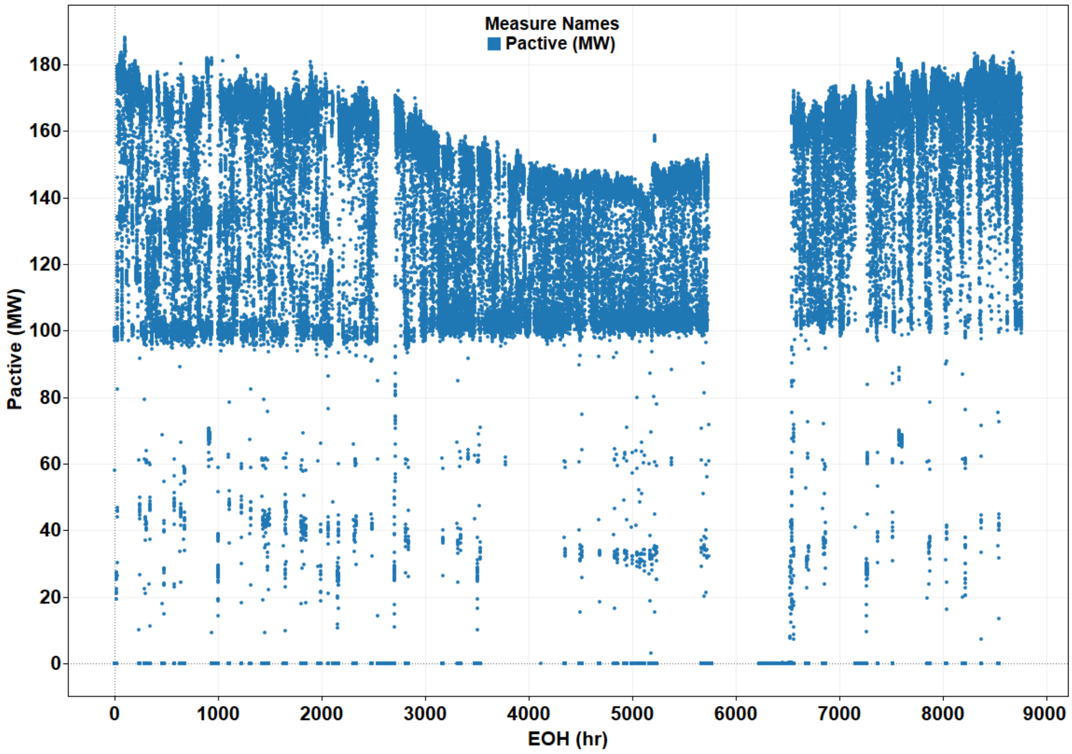
Appendix B (Engine Data Evaluation)



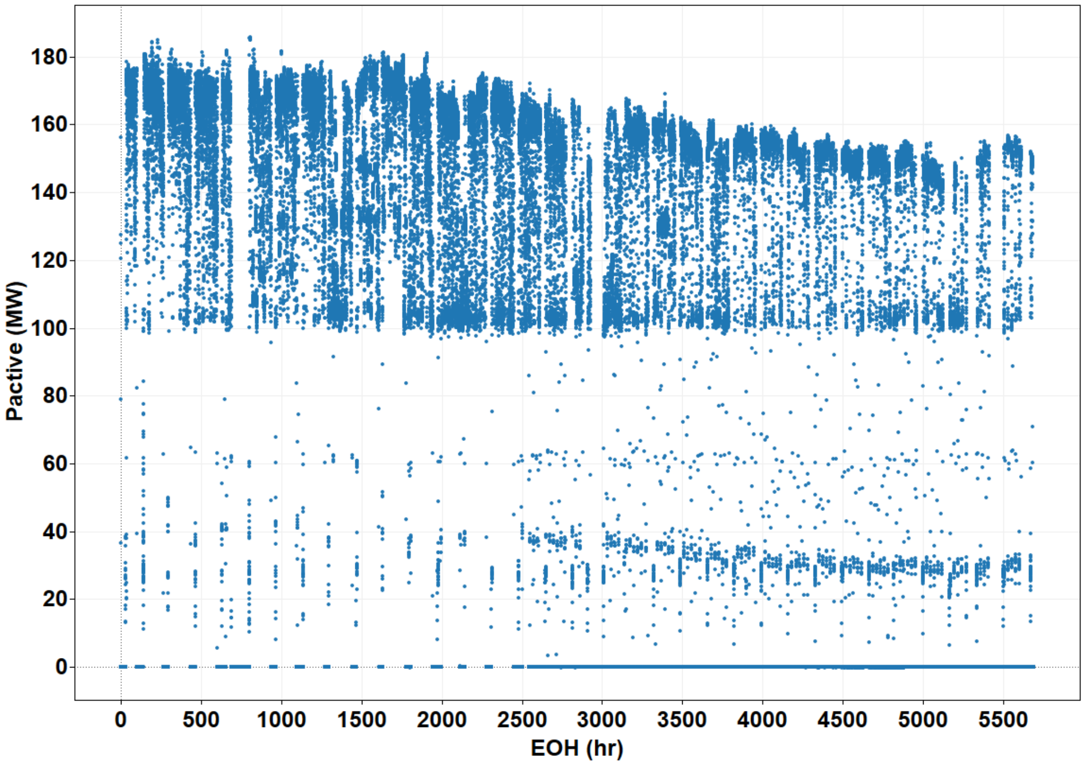
Figure_Apx B-1 Actual engine power for year 1



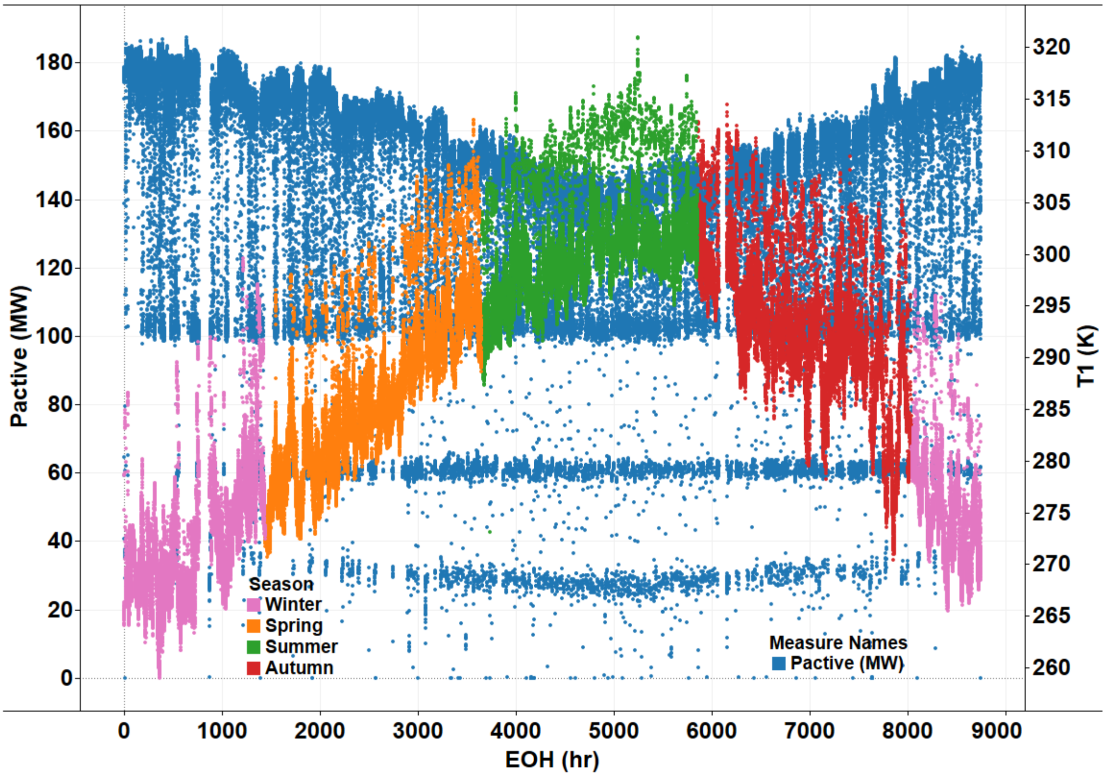
Figure_Apx B-2 Actual engine power for year 2



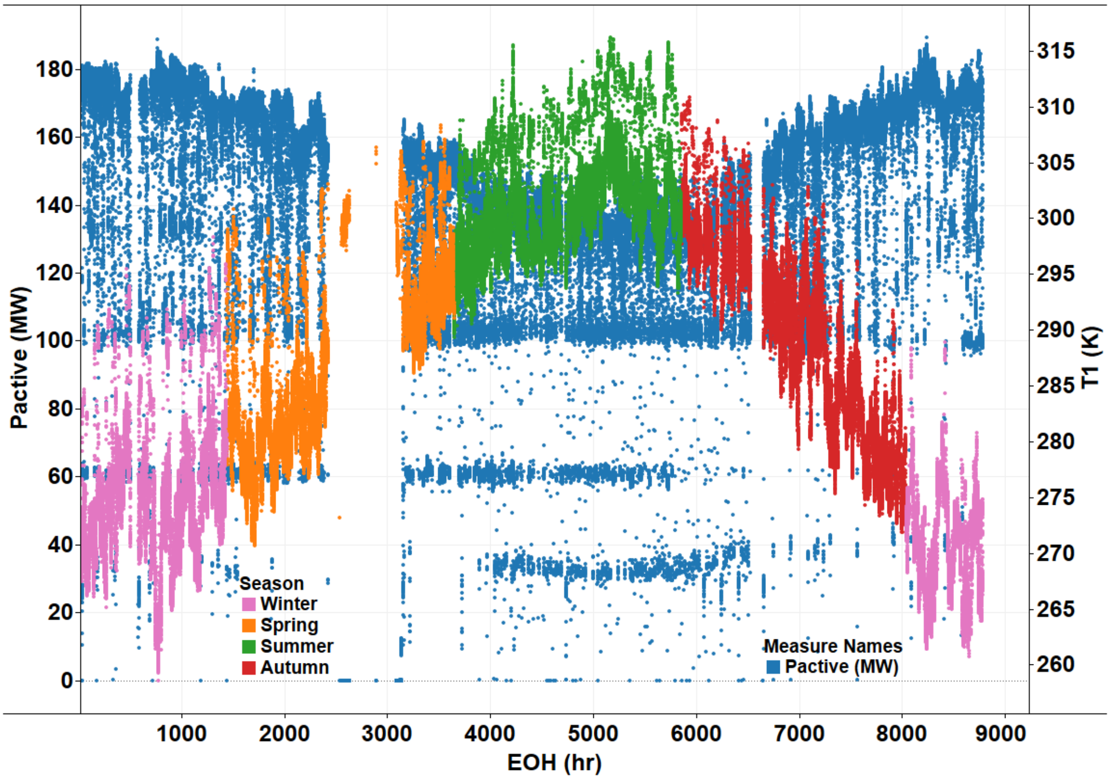
Figure_Apx B-3 Actual engine power for year 3



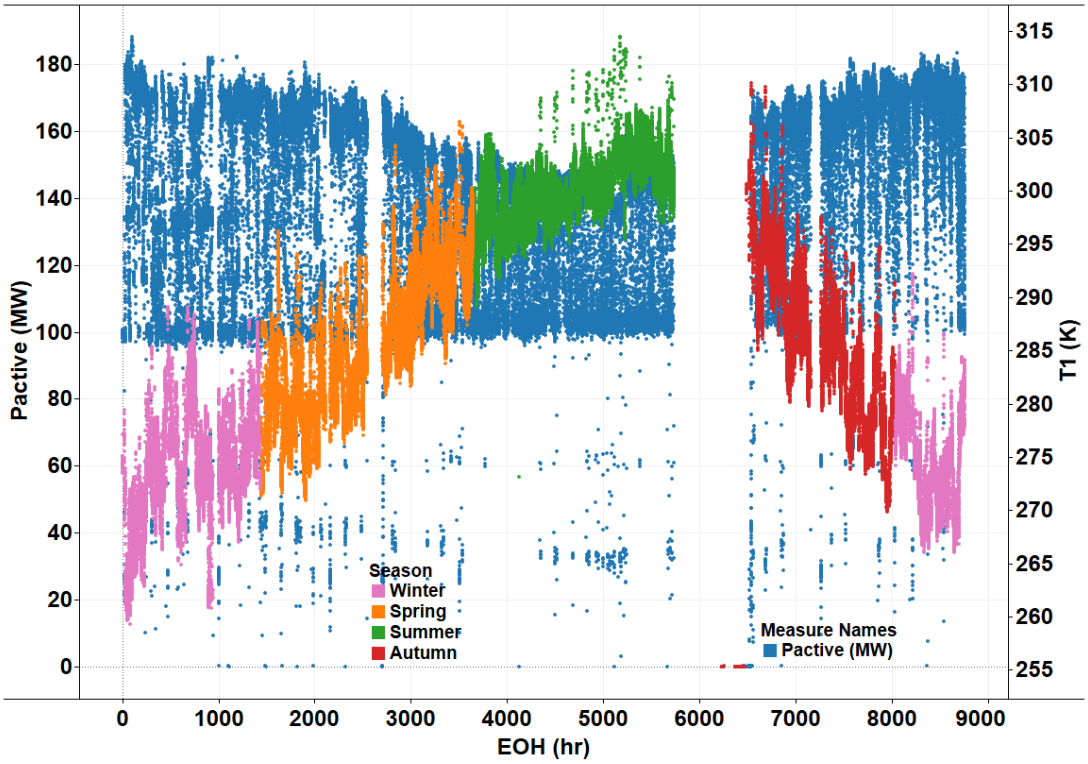
Figure_Apx B-4 Actual engine power for year 4



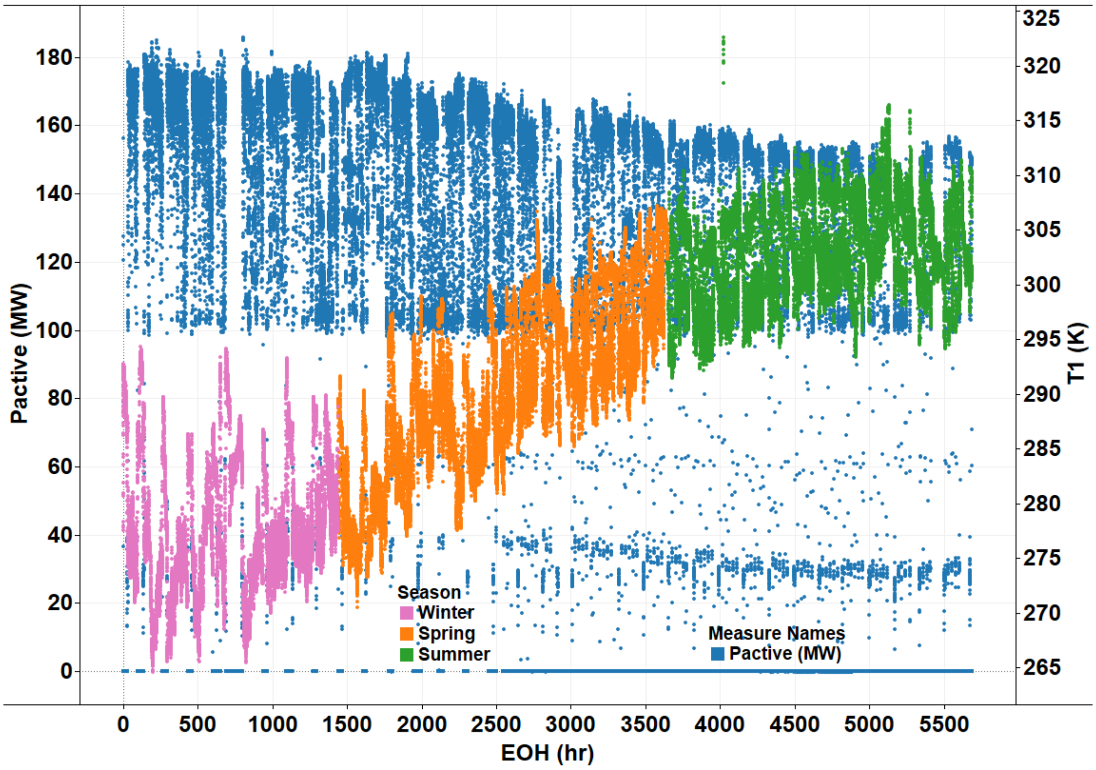
Figure_Apx B-5 Active power and T1 against time (seasons) for year 1



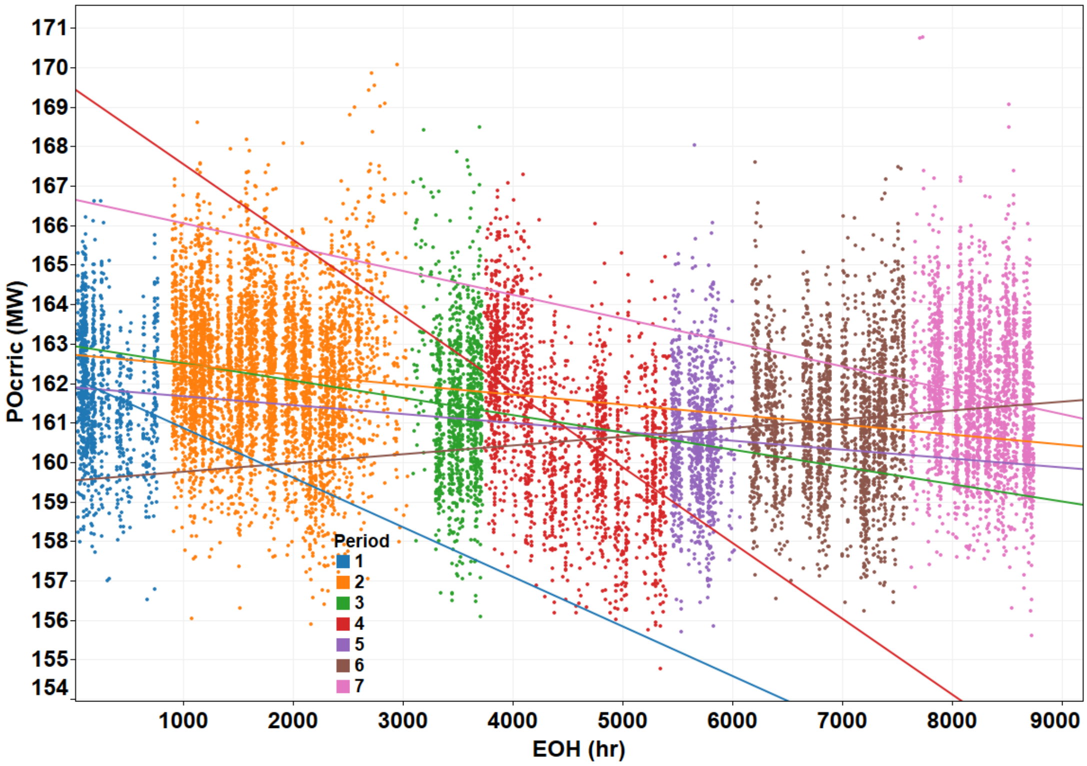
Figure_Apx B-6 Active power and T1 against time (seasons) for year 2



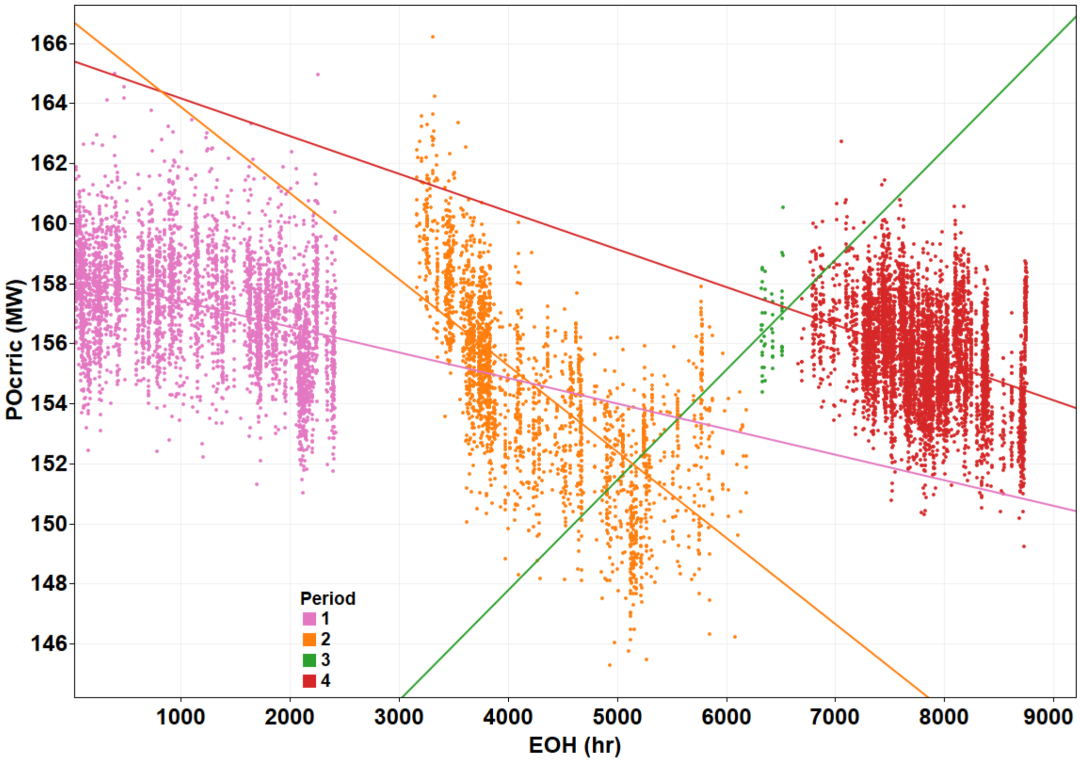
Figure_Apx B-7 Active power and T1 against time (seasons) for year 3



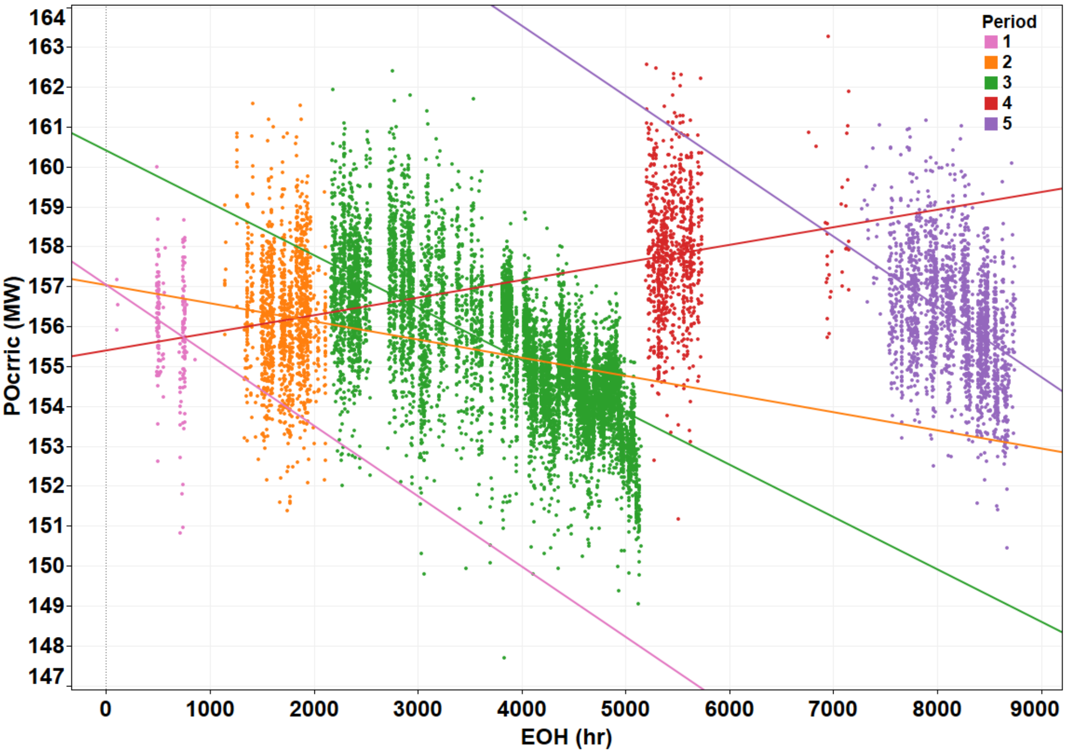
Figure_Apx B-8 Active power and T1 against time (seasons) for year 4



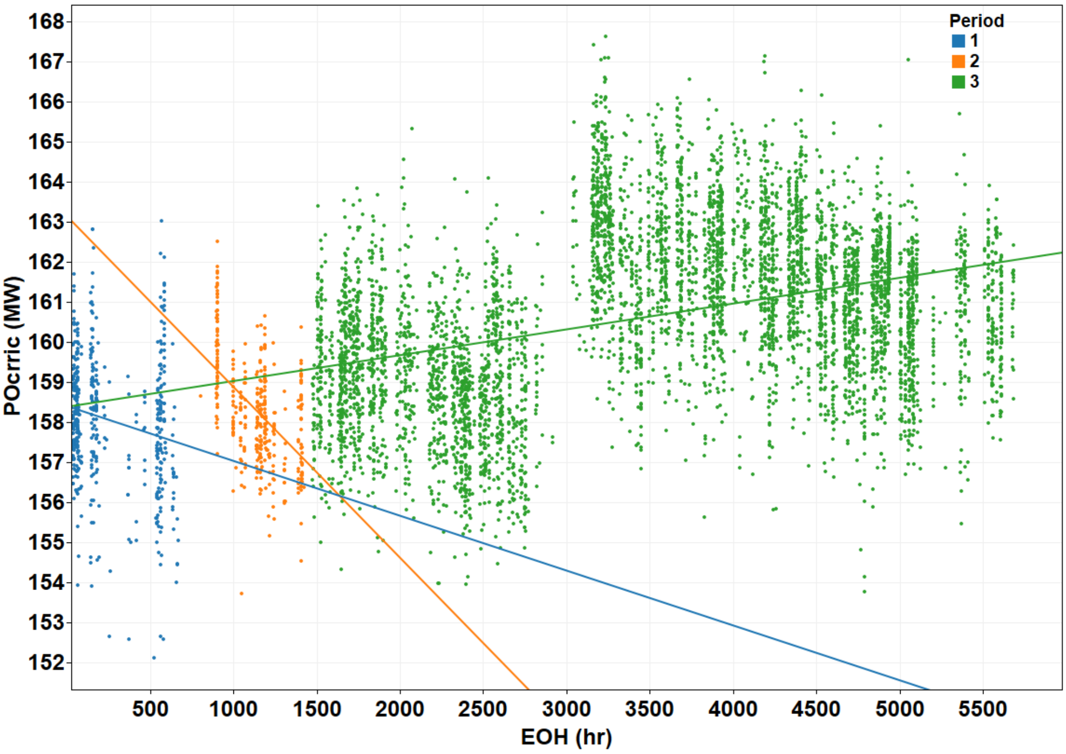
Figure_Apx B-9 Trend lines for corrected power along the EOT for year 1 (VIGV 80 – 84%, FF_{corr} 8.9 – 9.1kg/s)



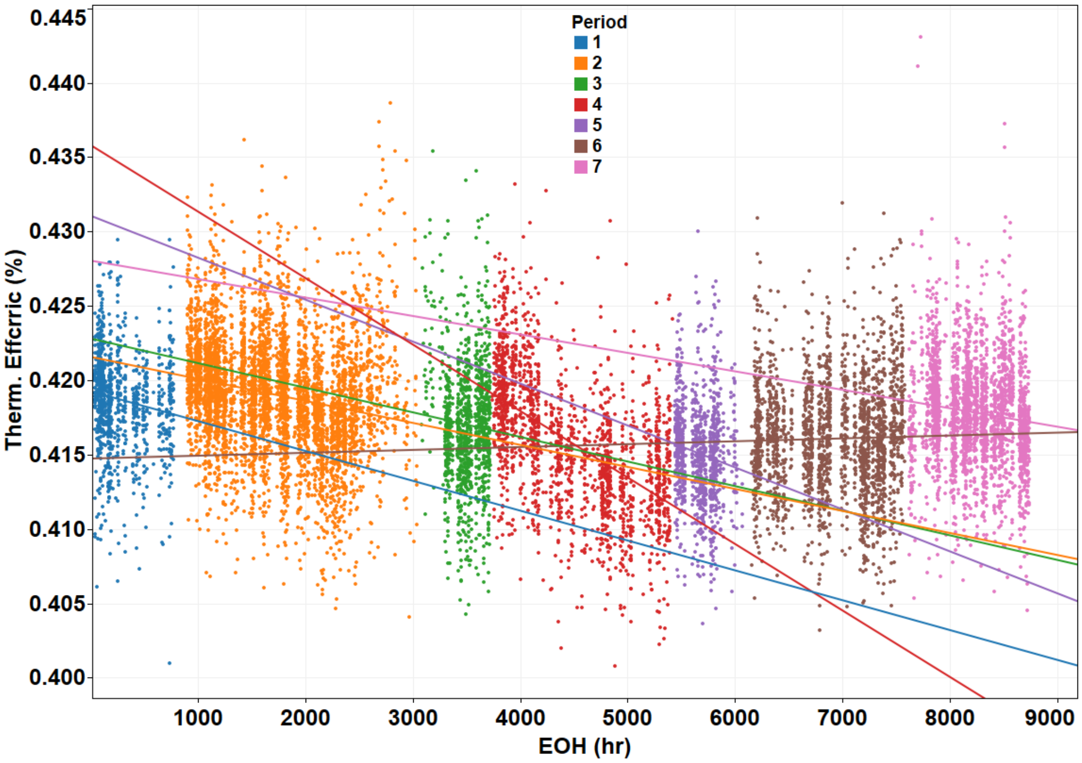
Figure_Apx B-10 Trend lines for corrected power along the EOT for year 2 (VIGV 80 – 84%, FF_{corr} 8.7 – 8.9kg/s)



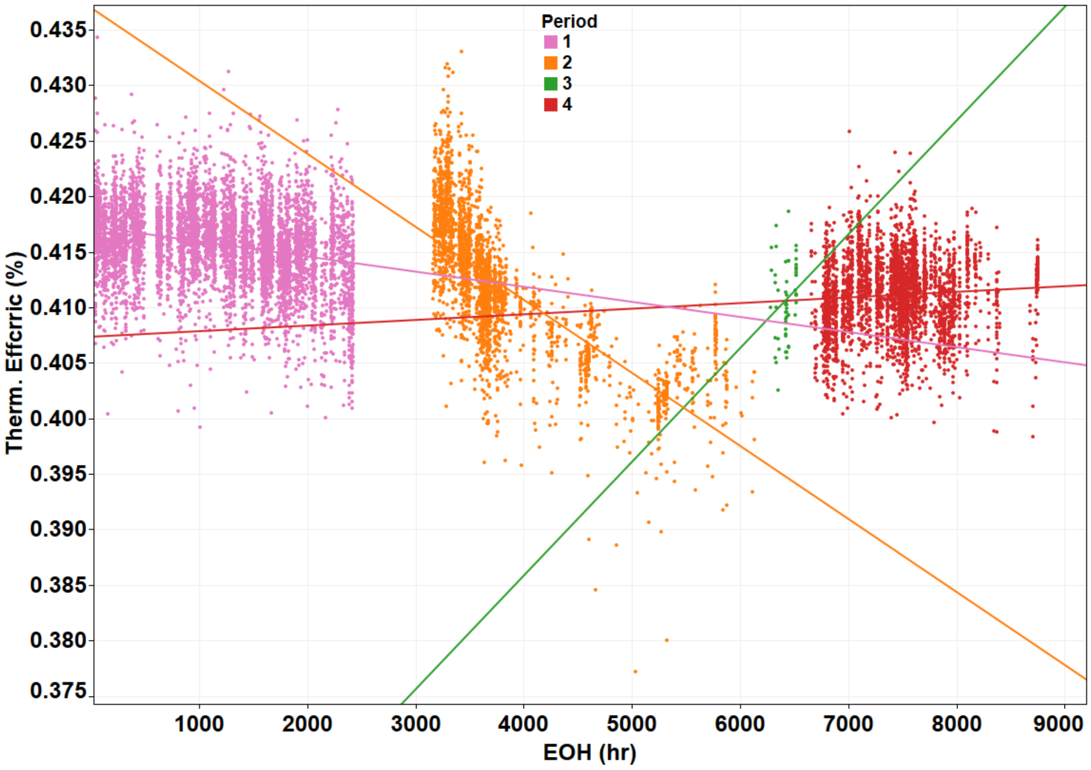
Figure_Apx B-11 Trend lines for corrected power along the EOT for year 3 (VIGV 80 – 84%, FF_{corr} 8.85 – 9.0kg/s)



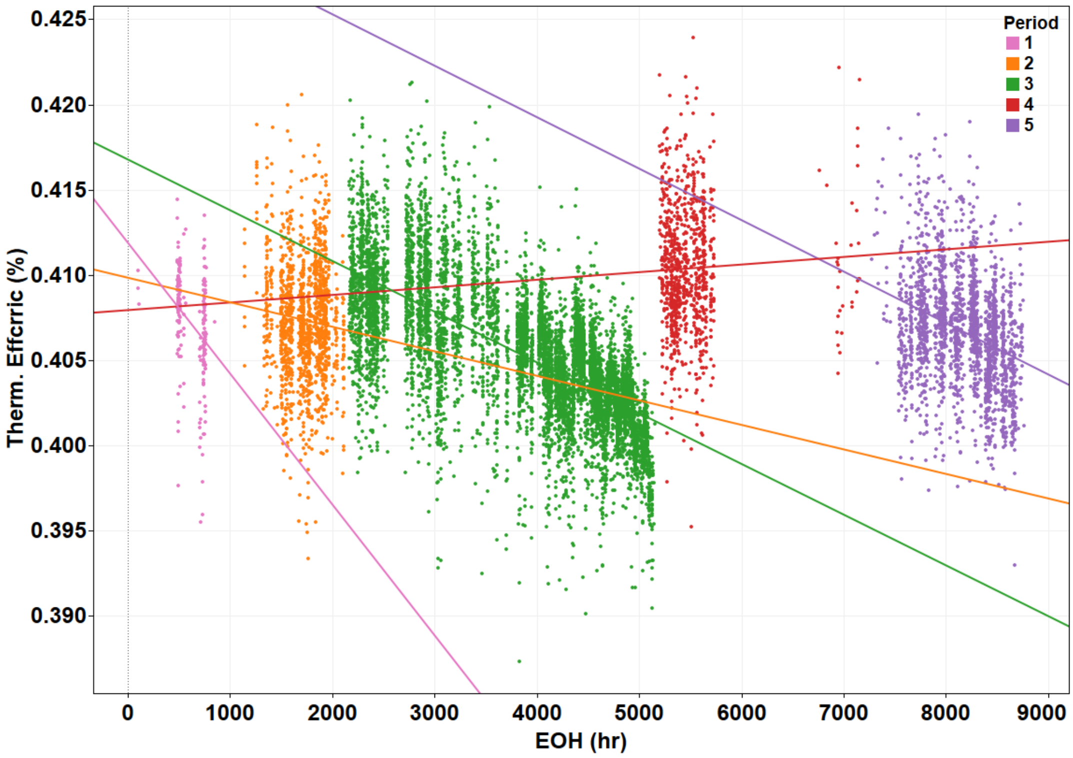
Figure_Apx B-12 Trend lines for corrected power along the EOT for year 4 (VIGV 80 – 84%, FF_{corr} 9.0 – 9.2kg/s)



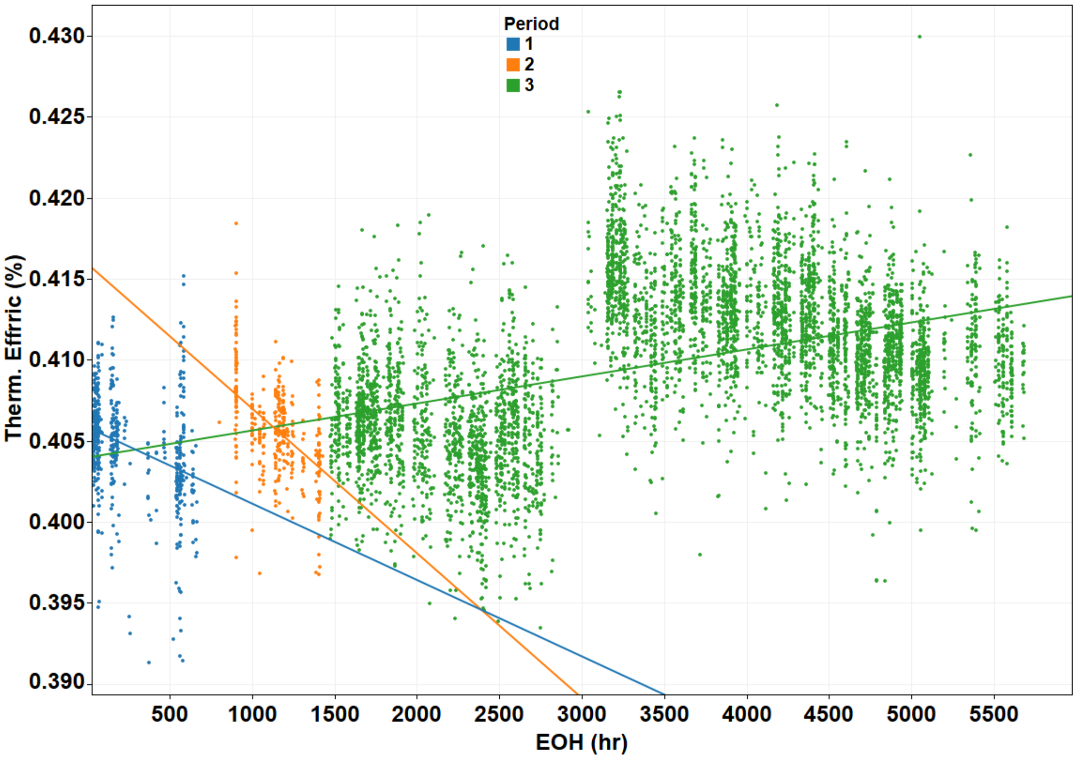
Figure_Apx B-13 Trend lines for thermal efficiency along the EOT for year 1 (VIGV 80 – 84%, FF_{corr} 8.9 – 9.1kg/s)



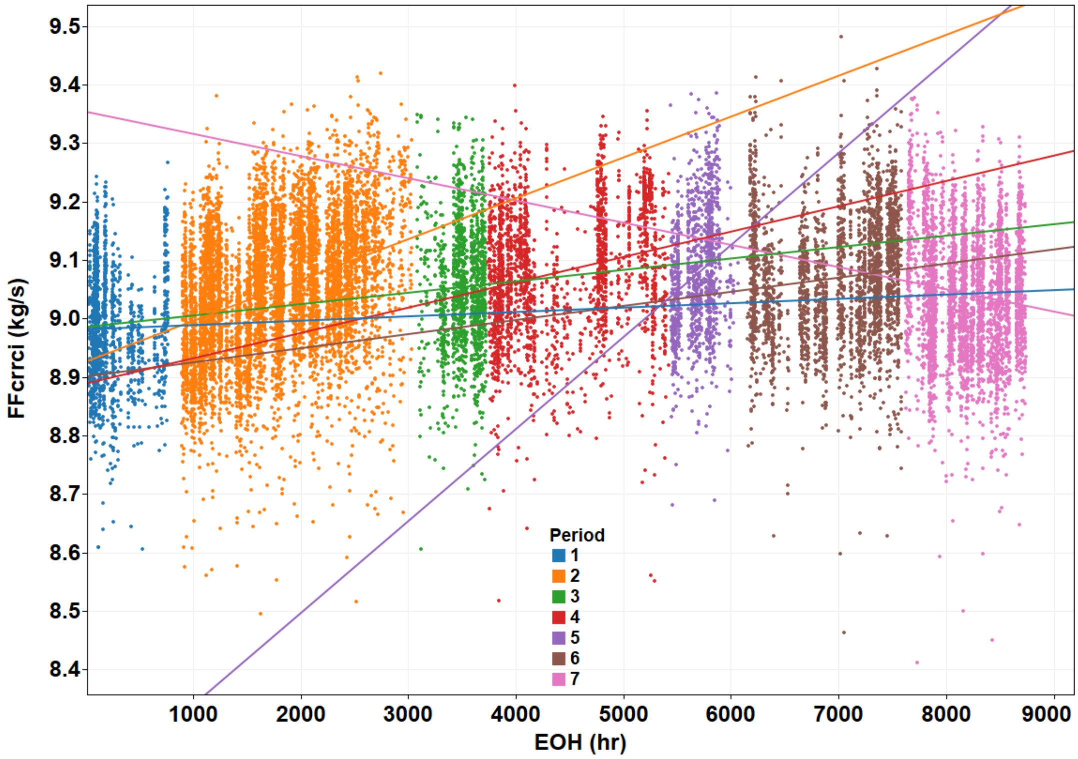
Figure_Apx B-14 Trend lines for thermal efficiency along the EOT for year 2 (VIGV 80 – 84%, FF_{corr} 8.9 – 9.1kg/s)



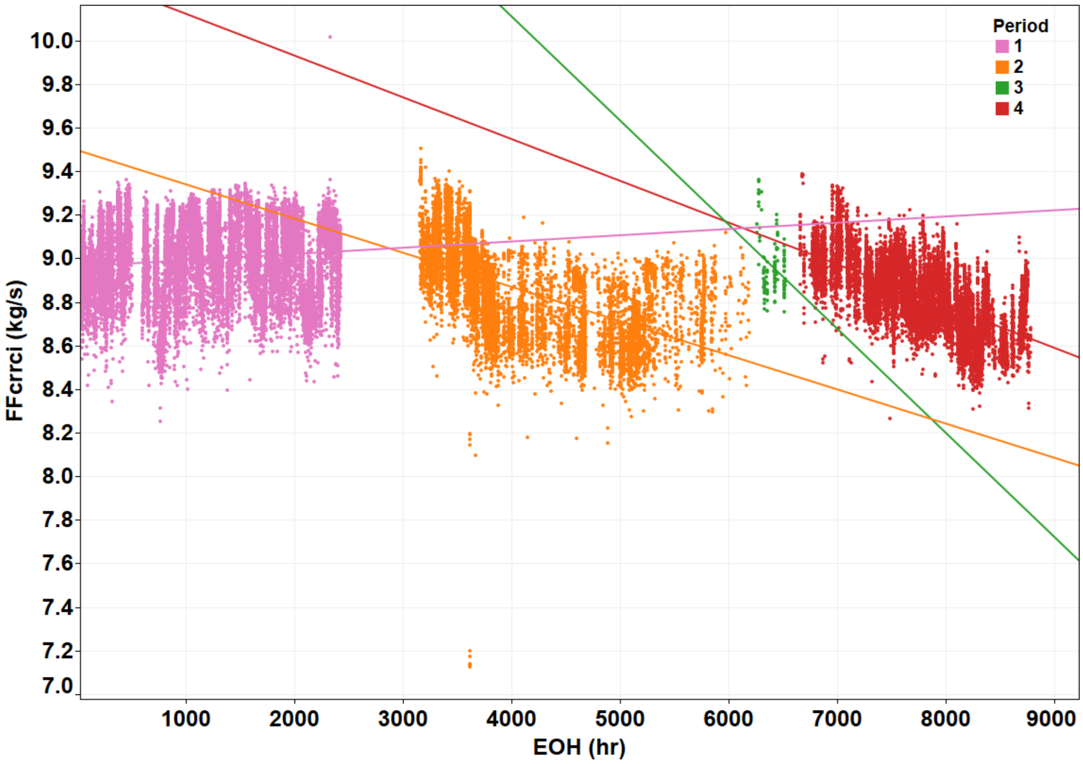
Figure_Apx B-15 Trend lines for thermal efficiency along the EOT for year 3 (VIGV 80 – 84%, FF_{corr} 8.85 – 9.0kg/s)



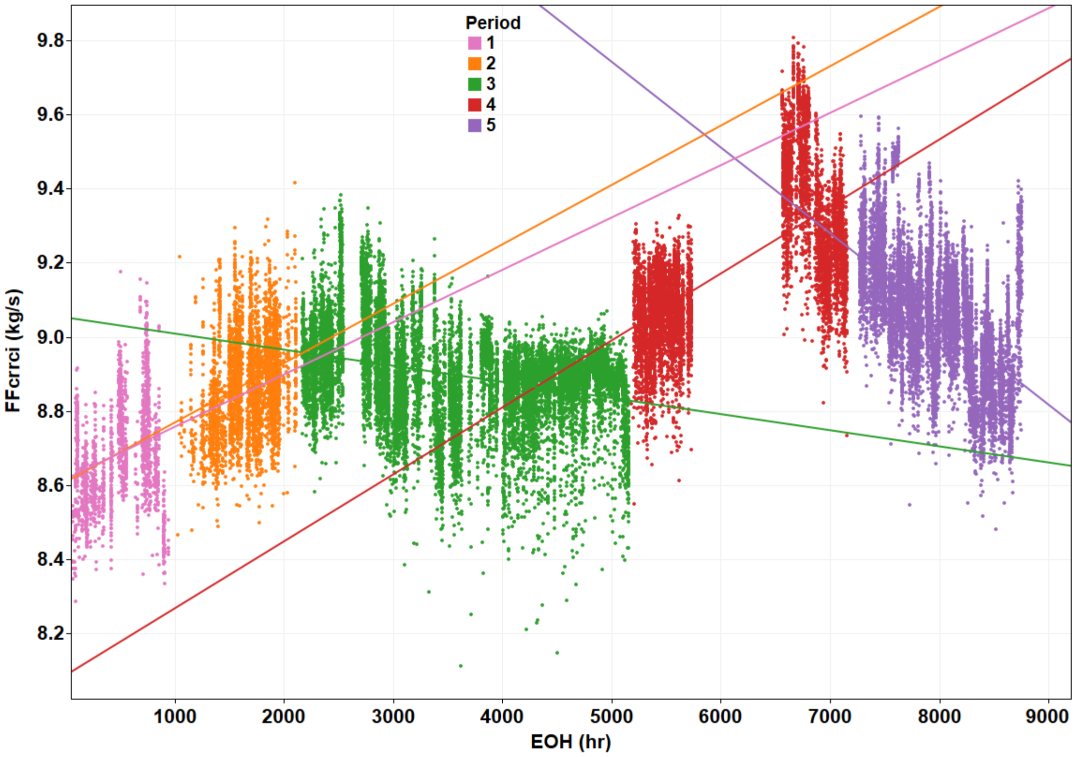
Figure_Apx B-16 Trend lines for thermal efficiency along the EOT for year 4 (VIGV 80 – 84%, FF_{corr} 9.0 – 9.2kg/s)



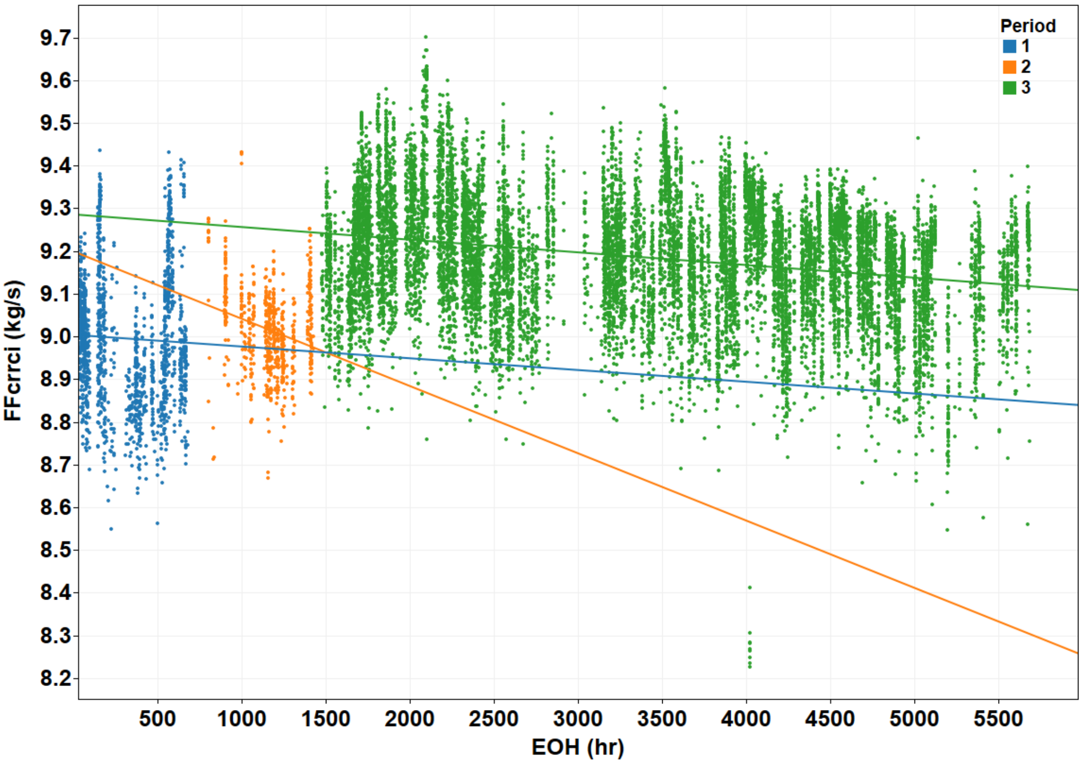
Figure_Apx B-17 Trend lines for corrected fuel flow along the EOT for year 1 (VIGV 80 – 84%, P_{crcit} 160 – 166MW)



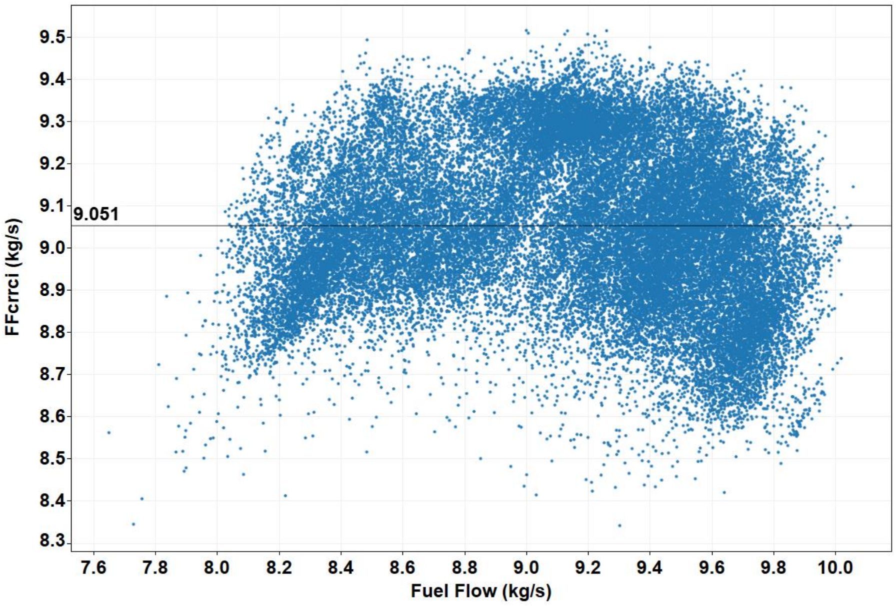
Figure_Apx B-18 Trend lines for corrected fuel flow along the EOT for year 2 (VIGV 80 – 84%, P_{crcit} 100 – 166MW)



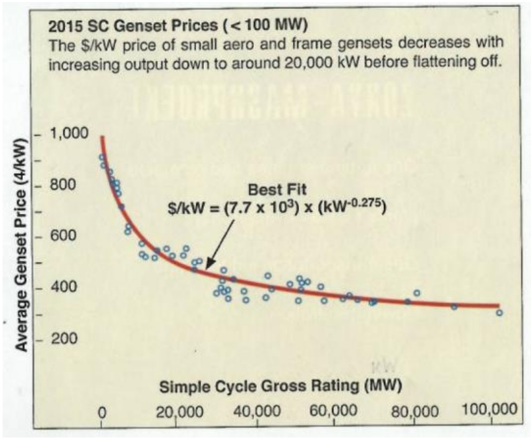
Figure_Apx B-19 Trend lines for corrected fuel flow along the EOT for year 3 (VIGV 80 – 84%, P_{crcit} 100 – 166MW)



Figure_Apx B-20 Trend lines for corrected fuel flow along the EOT for year 4 (VIGV 80 – 84%, P_{crcit} 100 – 166MW)



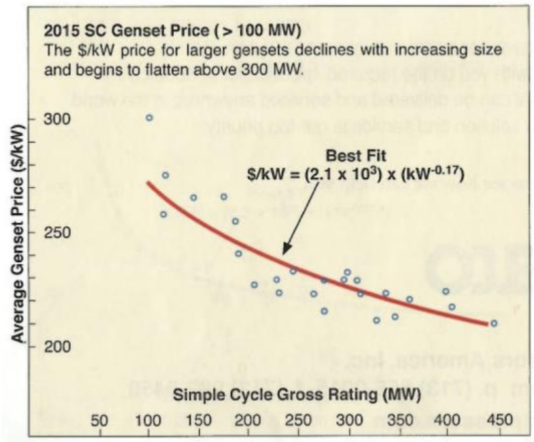
Figure_Apx B-21 Corrected fuel flow against fuel flow per year 1



2015 SC Genset Prices (< 100 MW)

The $/kW price of small aero and frame gensets decreases with increasing output down to around 20,000 kW before flattening off.

Figure_Apx B-22 Simple cycle genset price < 100 MW [120]



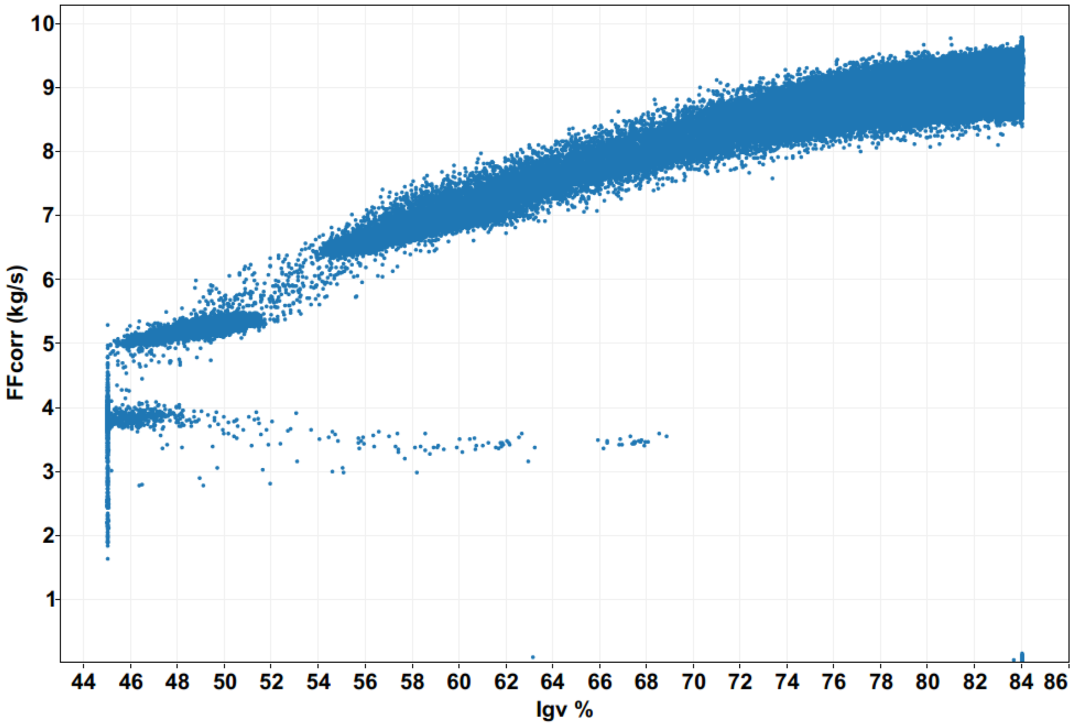
2015 SC Genset Price (> 100 MW)

The $/kW price for larger gensets declines with increasing size and begins to flatten above 300 MW.

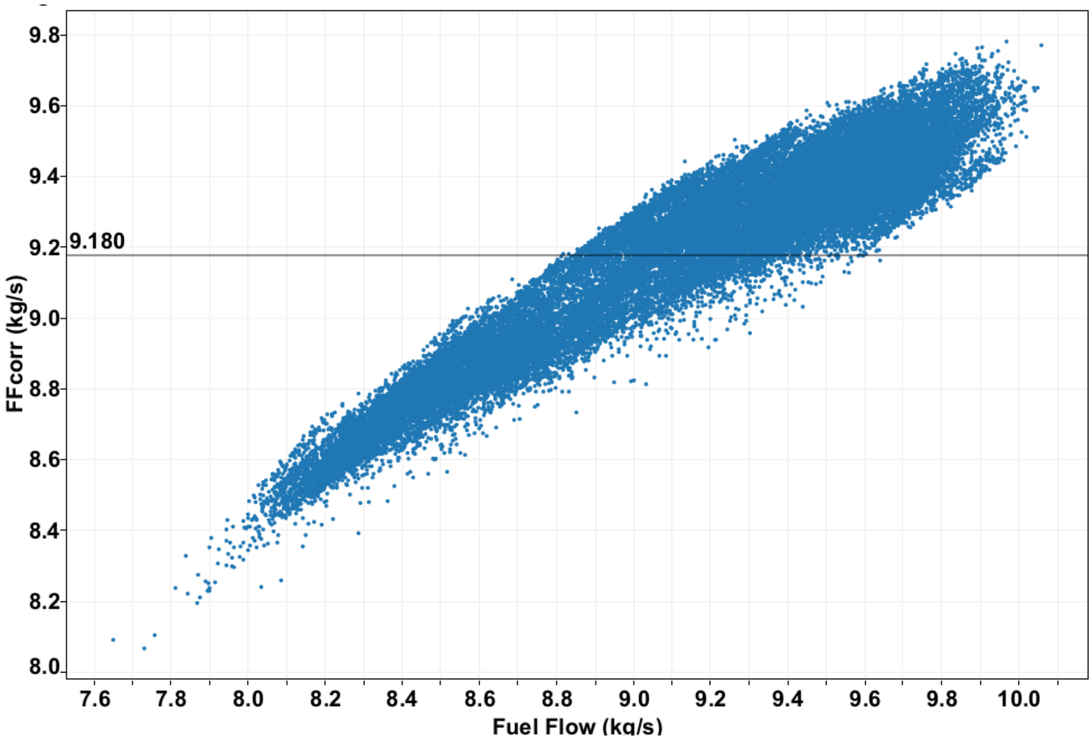
Figure_Apx B-23 Simple cycle genset price > 100 MW [120]

Appendix C (Engine Data Evaluation Standard Method)

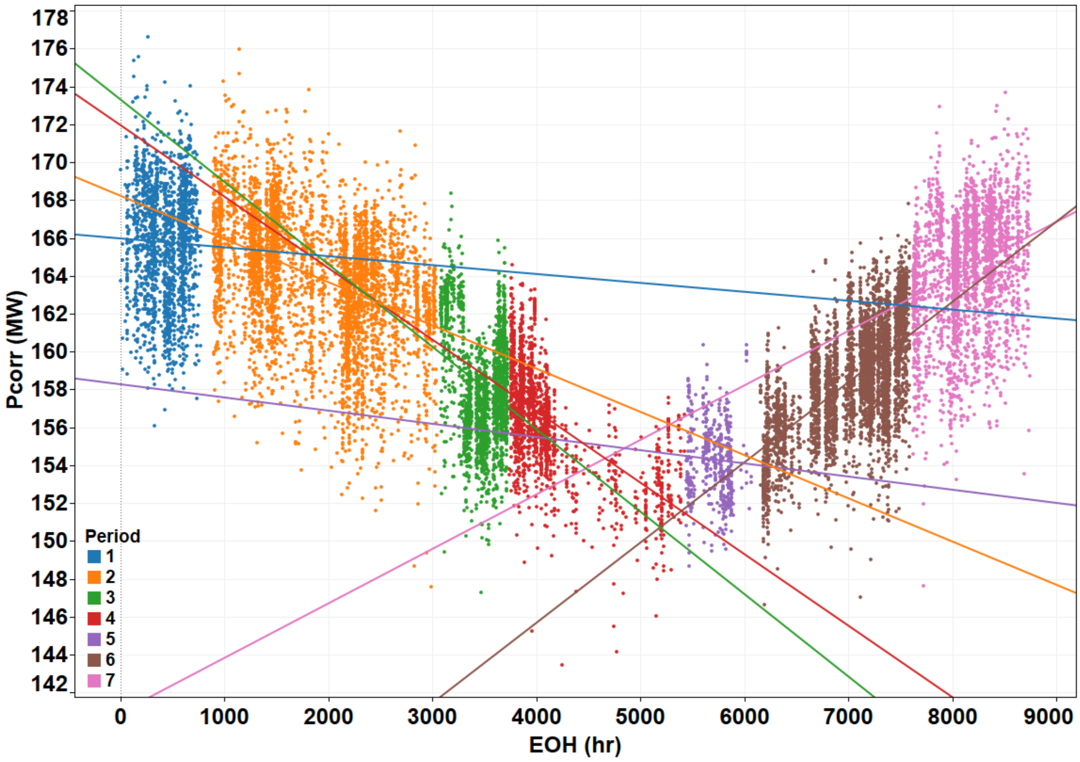
Applying this extrapolated degradation trend for the standard method amounts to 11.35% reduction in the power output at 8640th hour shown in Figure_Apx C-9. The reductions in power output with respect to time implemented (standard method) is a result of the extensive analysis that accounts for the effects of ambient conditions (inlet temperature and pressure only) and bias effect of power setting (load variation). The same method similar to extended correction method for the heat rate has been applied, an average percentage heat increase of 2.40% rise has been obtained and adopted to all power capacity/engines. The results for the standard method shows higher power drop and heat rate increase compared to the extended method, this is due to taken only the effect of inlet pressure and temperature into account in correcting the data as the environment experience higher relative humidity, this gives less accurate estimates for the percentage degradation. The same method has been applied to the degraded trend line for the standard method in order to analyse the economic analysis of different GT capacity. The results shows higher cost of fouling for the standard method, this is due to higher percentage of power output reduction.



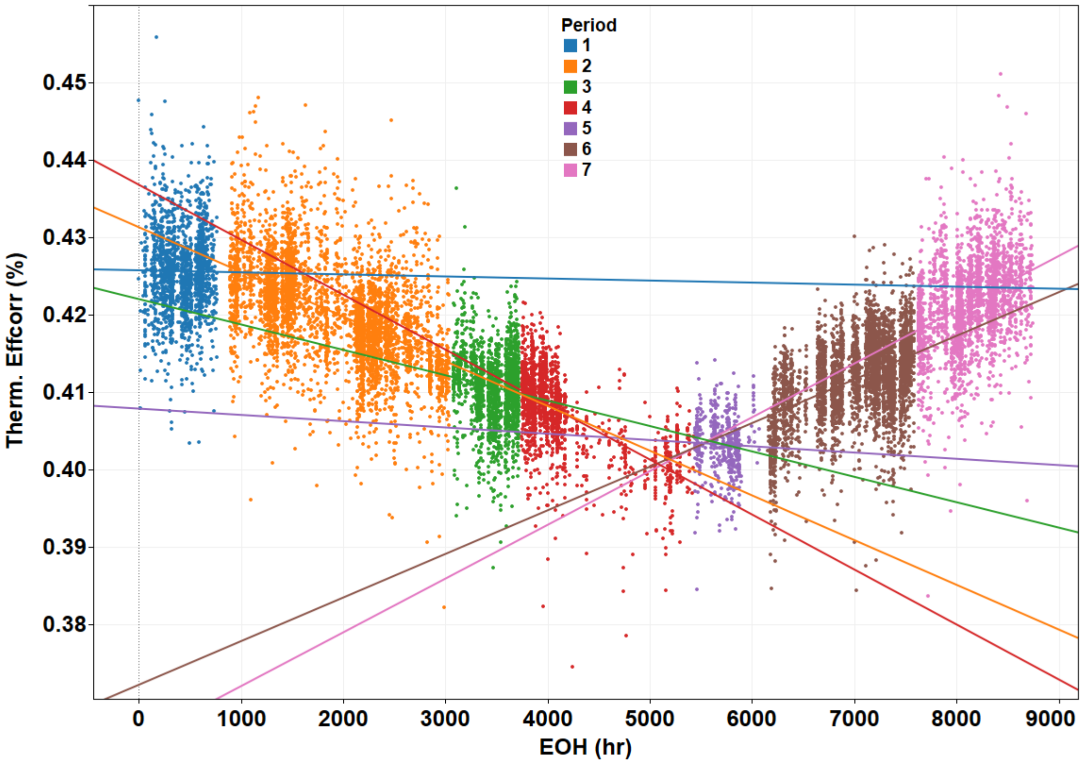
Figure_Apx C-1 Corrected fuel flow against IGV per year



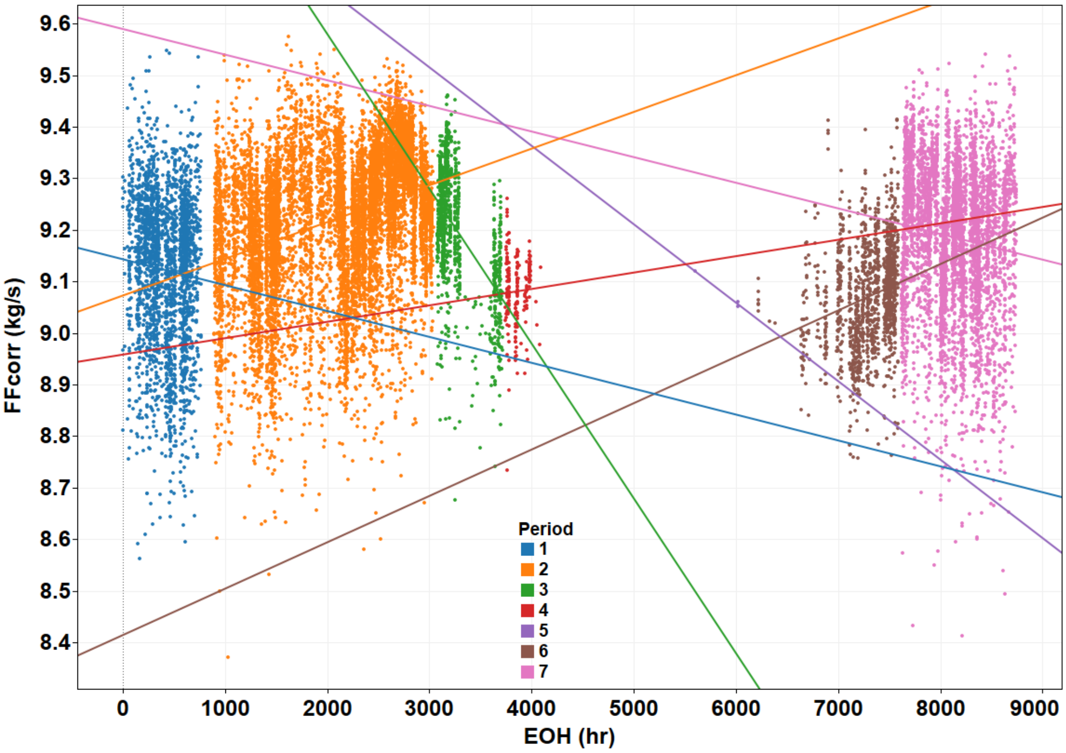
Figure_Apx C-2 Corrected fuel flow against fuel flow per year



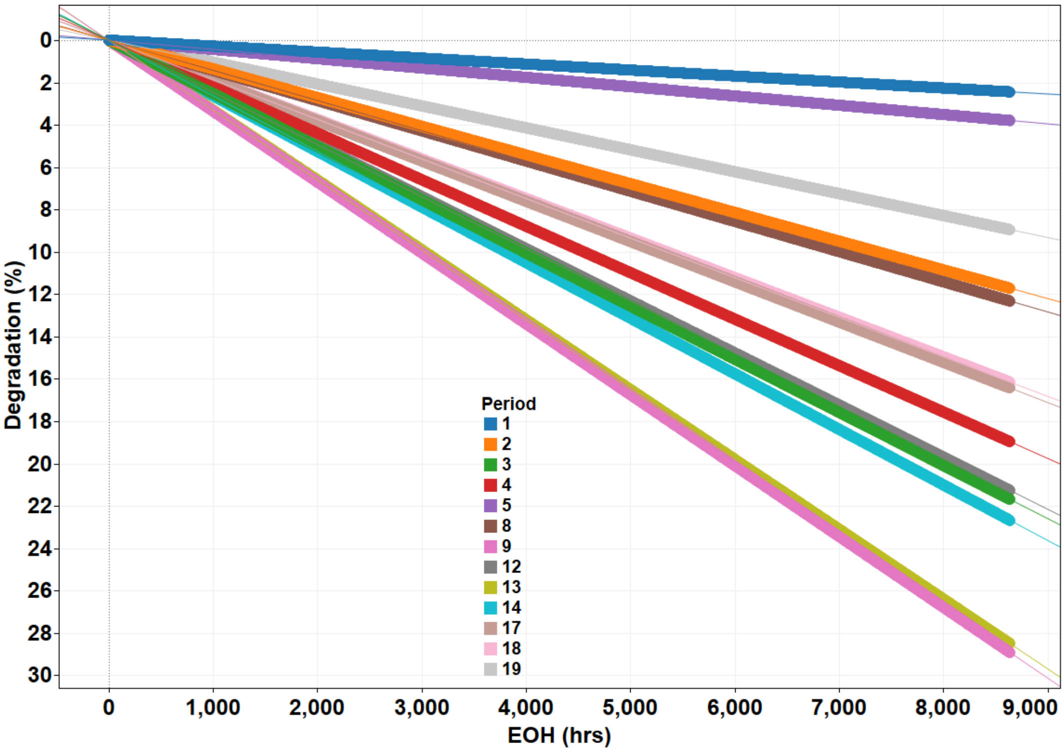
Figure_Apx C-3 Trend lines for corrected power along the EOT for year 1 (VIGV 73 – 84%, FF_{corr} 8.8 – 9.2kg/s)



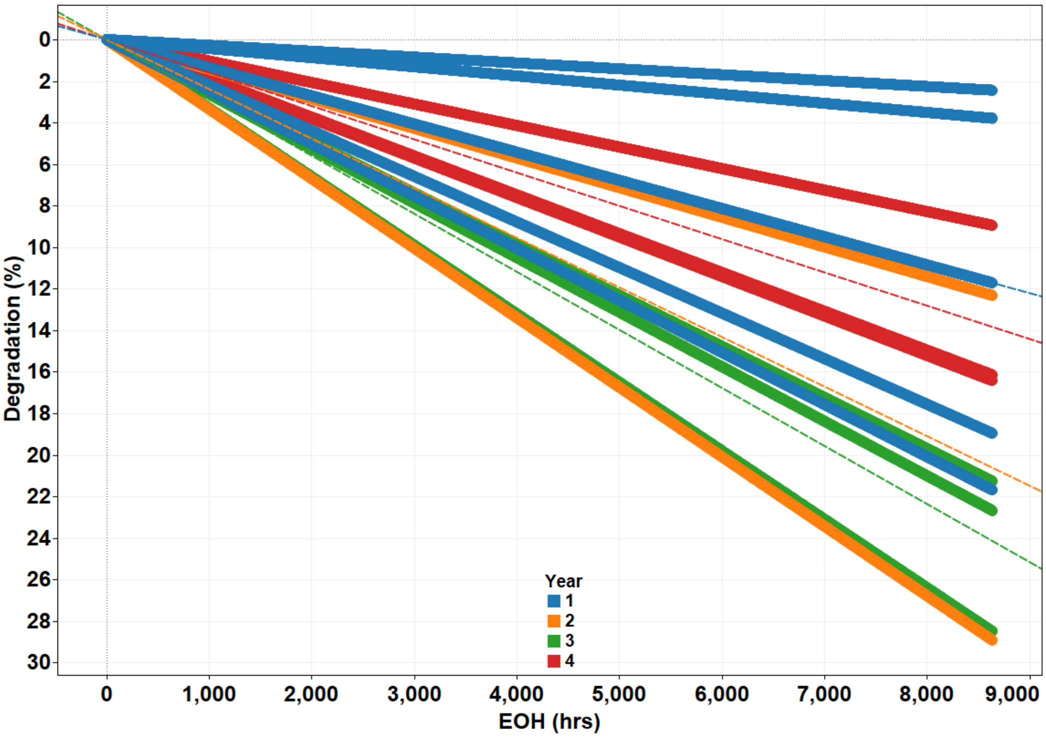
Figure_Apx C-4 Trend lines for thermal efficiency along the EOT for year 1 (VIGV 73 – 84%, FF_{corr} 8.8 – 9.2kg/s)



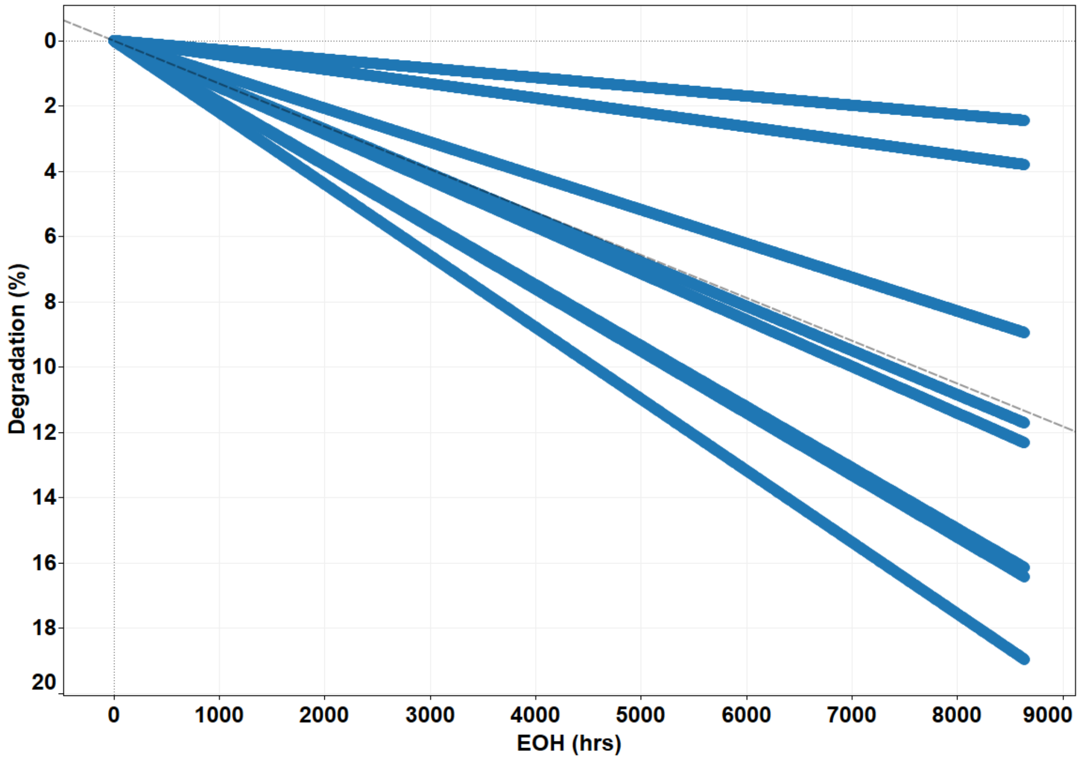
Figure_Apx C-5 Trend lines of corrected fuel flow per year for year 1 (VIGV 73 – 84%, P_{corr} 160 – 170MW)



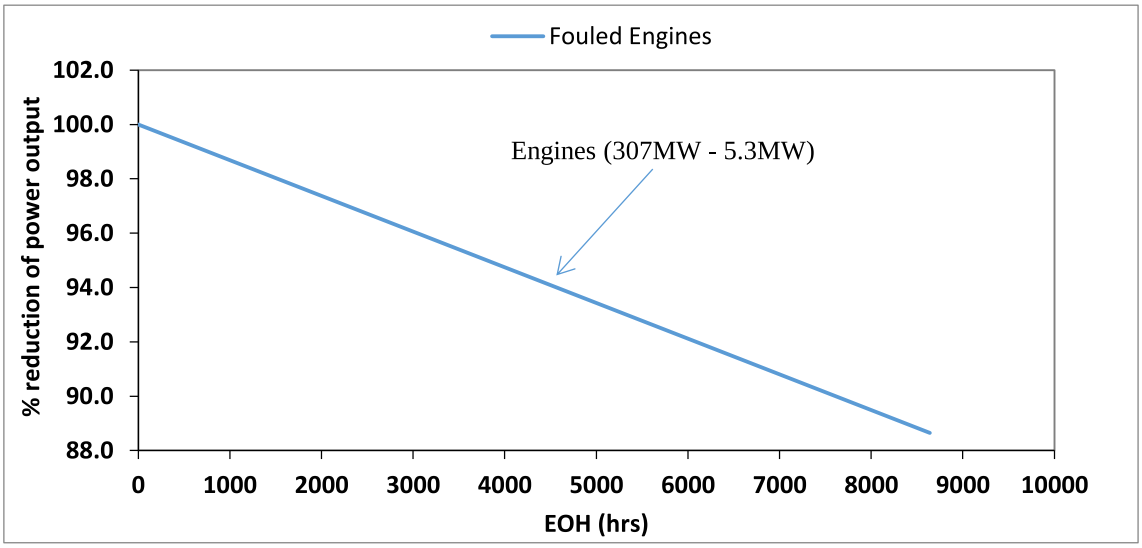
Figure_Apx C-6 Degradation trends for all period for 4 years of operation



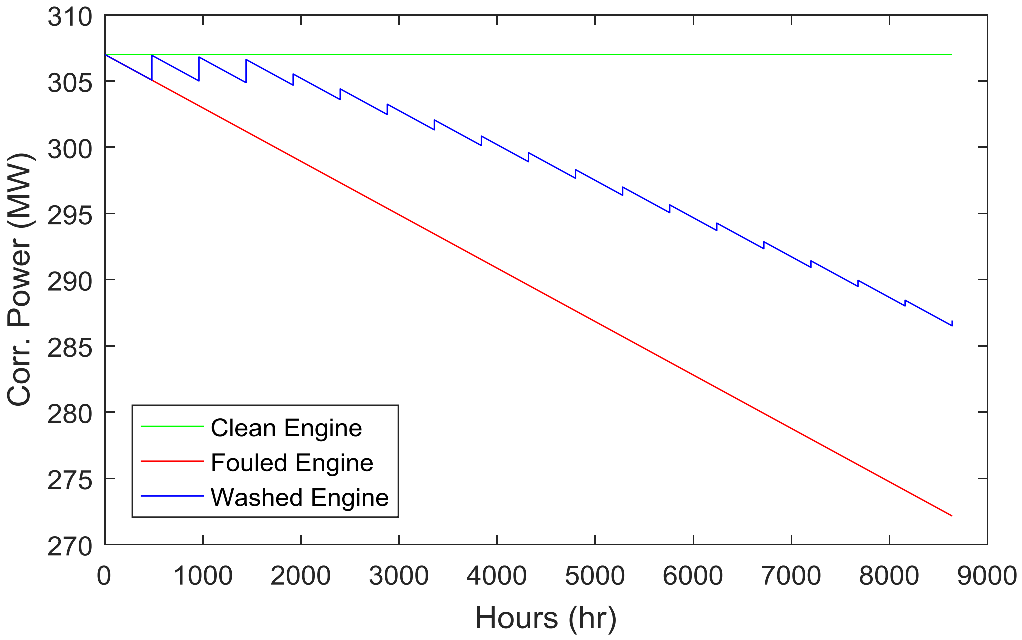
Figure_Apx C-7 Average degradation trends for every year of operation



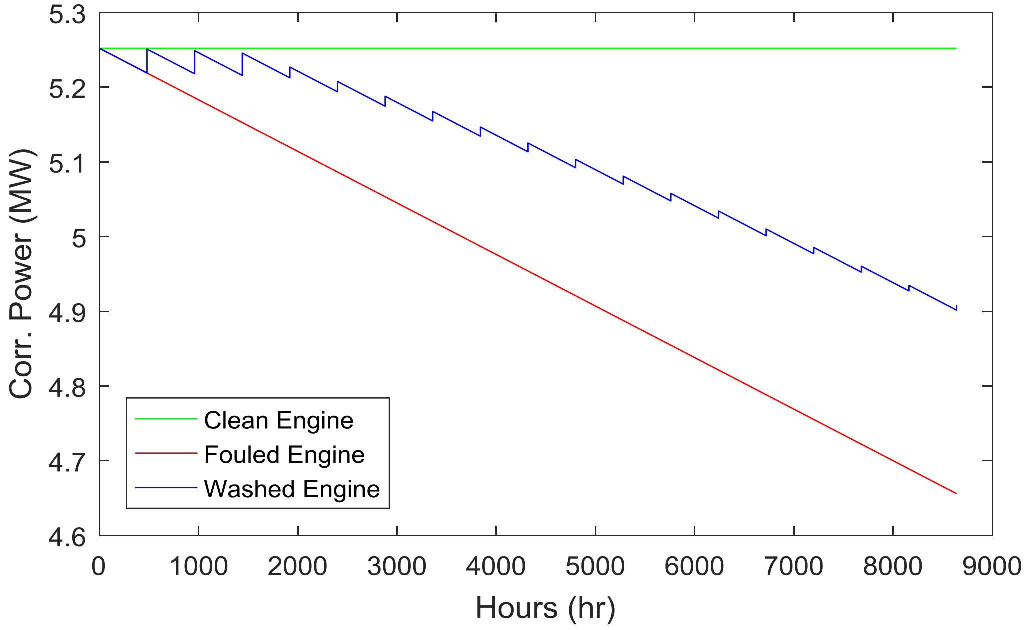
Figure_Apx C-8 Average degradation trends of 4 years of operation



Figure_Apx C-9 Percentage reduction of power (degradation) applicable to all engines (Standard)



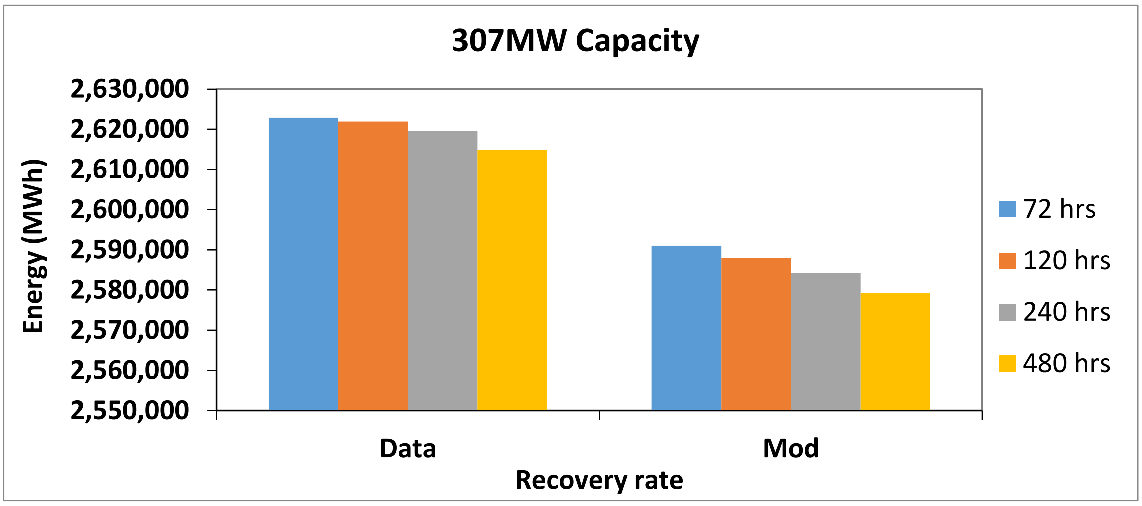
Figure_Apx C-10 Trend lines for clean, fouled and washed engine of 307MW at 480hrs interval



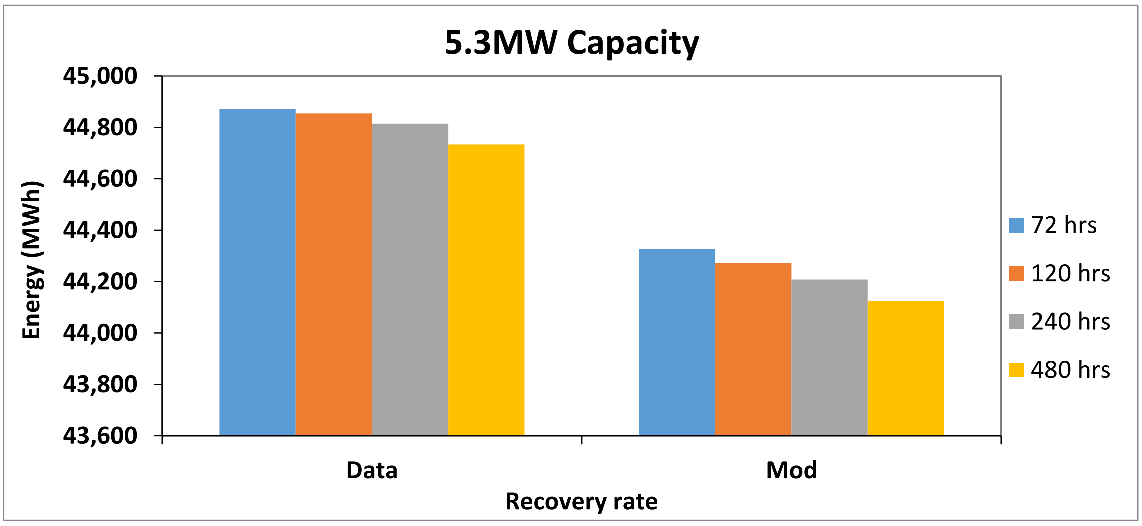
Figure_Apx C-11 Trend lines for clean, fouled and washed engine of 5.3MW at 480hrs interval

Table_Apx C-1 Heavy and light-duty engines of 307MW and 5.3MW capacity

Description	**Frequency** (hrs)	**307MW** **Experiment**	**Modified**	**5.3MW** **Experiment**	**Modified**
Clean (MWh)	**72**	2,652,480	2,652,480	45,377	45,377
Fouled (MWh)		2,501,948	2,501,948	42,802	42,802
Washed (MWh)		2,622,918	2,591,056	44,872	44,326
$\Delta E\ (MWh)$		120,970	89,108	2,070	1,524
Washed (MWh)	**120**	2,621,964	2,587,902	44,855	44,273
$\Delta E\ (MWh)$		120,016	85,954	2,053	1,471
Washed (MWh)	**240**	2,619,582	2,584,154	44,814	44,208
$\Delta E\ (MWh)$		117,634	82,206	2,012	1,406
Washed (MWh)	**480**	2,614,858	2,579,285	44,734	44,125
$\Delta E\ (MWh)$		112,910	77,337	1,932	1,323



Figure_Apx C-12 Energy delivered due to washing against recovery rate of washing

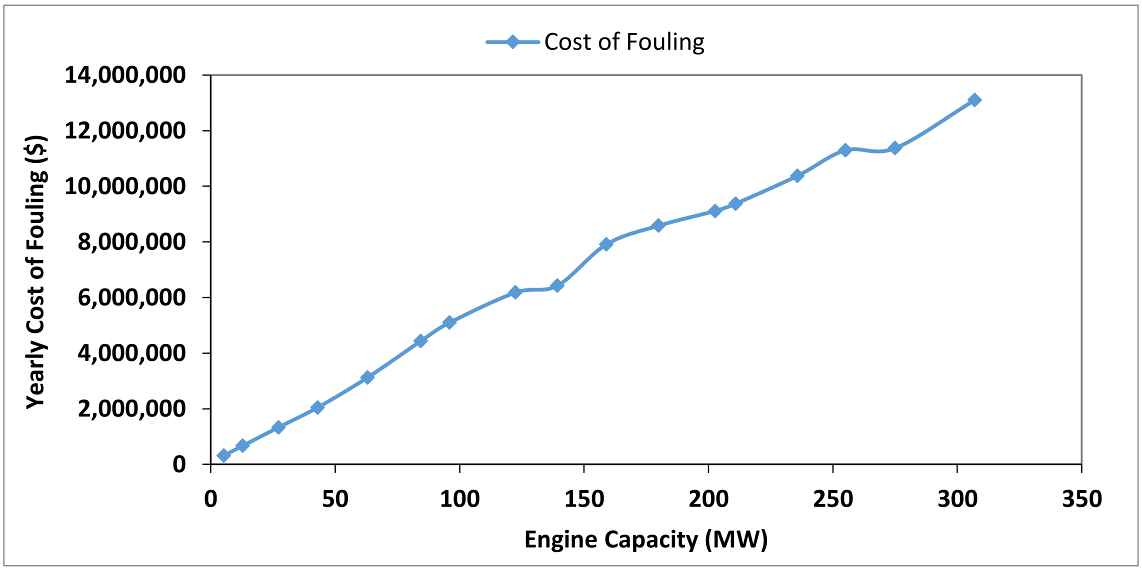


Figure_Apx C-13 Energy delivered due to washing against recovery rate of washing

Table_Apx C-2 Sample calculation for the cost of fouling of 307MW engine

Energy delivered in a year at 72hrs interval		
1.	Clean engine energy delivered [MWh]	2,652,480
2.	Fouled engine energy delivered [MWh]	2,501,948
3.	Washed engine energy delivered [MWh]	2,591,056
Average power delivered per 8640 hours		
4.	Average power delivered for clean engine [MW]	307.00
5.	Average power delivered for fouled engine [MW]	289.58
6.	Average power delivered for washed engine [MW]	299.89
Selling value of electricity generated		
7.	Average cost of electricity [$/MWh]	66.6
8.	Clean engine cost of electricity ($)	176,655,168
9.	Fouled engine cost of electricity ($)	166,629,739
10.	Washed engine cost of electricity ($)	172,564,353
Cost of fuel ($)		
11.	Average cost of fuel (natural gas) [$/MMBTU]	6
12.	Heat rate of 307MW engine [BTU/kWh]	8,532
13.	Average heat rate increase [%]	1.6
14.	Clean engine cost of fuel ($)	135,785,756
15.	Fouled engine cost of fuel ($) (inclusive of excess fuel due to higher rate)**	131,153,637
16.	Washed engine cost of fuel ($)	135,008,662
Cost of power loss and heat rate increase ($)		
17	Yearly power loss cost ($)	10,025,429
18.	Yearly excess fuel cost ($)	3,073,913
19	**Loss of revenue due to fouling ($)**	**13,099,342**

** Related to higher heat rate, inclusive of excess fuel - **$** 3,073,913



Figure_Apx C-14 Yearly cost of fouling from 5.3MW to 307MW GT

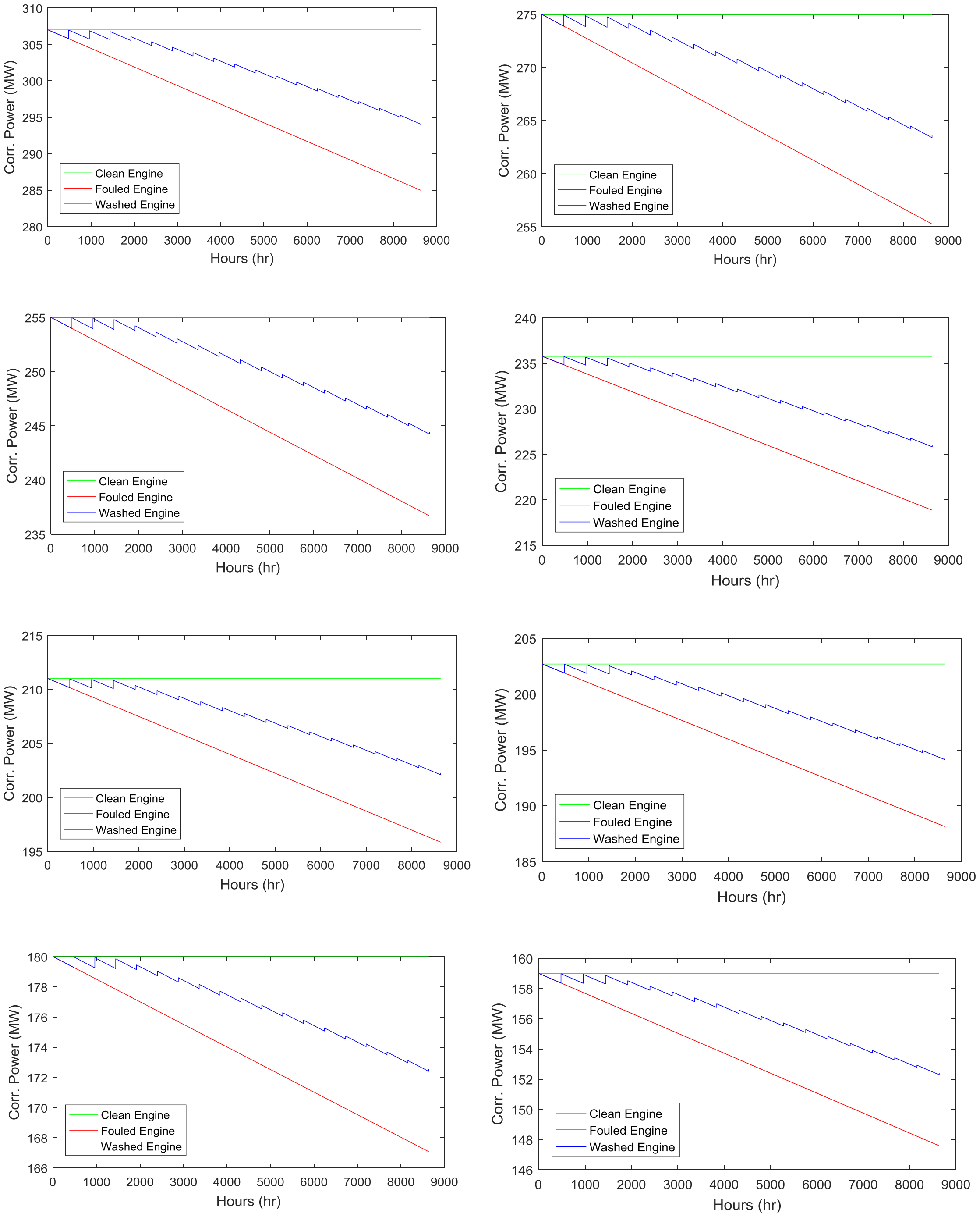
Table_Apx C-3 Cost of fouling for gas turbine engines

Engine Capacity (MW)	Cost of Less Energy ($)	Cost of Excess Fuel ($)	Total Fouling Cost ($)
307	10,025,429	3,073,913	13,099,342
275	8,710,750	2,659,269	11,370,019
255	8,639,897	2,652,304	11,292,201
235.78	7,942,442	2,433,301	10,375,743
211	7,180,130	2,196,880	9,377,011
202.7	6,977,202	2,136,154	9,113,356
180	6,566,528	2,018,392	8,584,921
159	6,049,914	1,862,216	7,912,130
139.35	4,926,433	1,502,882	6,429,315
122.5	4,727,169	1,451,977	6,179,147
96	3,906,965	1,190,264	5,097,229
84.36	3,400,156	1,031,589	4,431,745
63	2,403,315	719,376	3,122,691
43	1,581,322	465,519	2,046,841
27.21	1,031,332	299,749	1,331,081
12.912	522,956	148,771	671,727
5.252	247,222	69,050	316,271

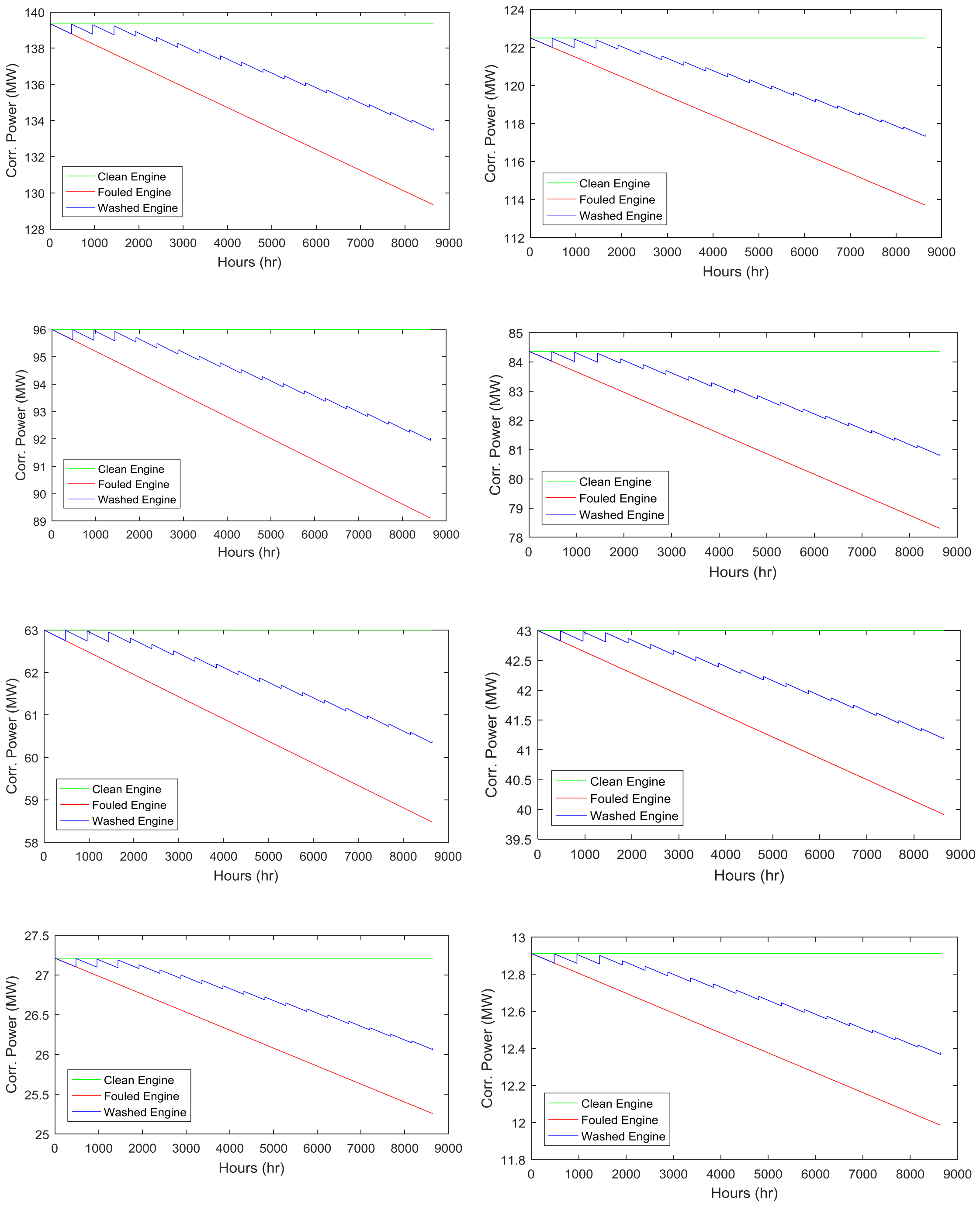
Table_Apx C-4 Parameters for 1 and 4-heavy-duty engines of 307MW and 5.3MW capacity at 72hrs frequency

Description	1-Heavy-duty 307MW	4-Heavy-duty 307MW	1-Light-duty 5.3MW	4-Light-duty 5.3MW
Capital cost of equipment/ installation - **C**	$260,000	$312,000	$58,500	$70,200
Yearly maintenance/operational cost of equipment- C_{om}	$97,079	$359,196	$4,774	$12,544
Fuel cost per annum for fouled engine - C_{ff}	$131,153,637	$524,614,548	$2,946,118	$11,784,472
Fuel cost per annum for washed engine - C_{fw}	$135,008,662	$540,034,648	$3,032,714	$12,130,856
Income from selling electricity by fouled engine - R_f	$166,629,739	$666,518,956	$4,108,997	$16,435,988
Income from selling electricity by washed engine - R_w	$172,564,353	$690,257,412	$4,255,342	$17,021,368
Salvage value of equipment - SV_0	$26,000	$31,200	$5850	$7,020
Life expectancy of the equipment - ***N***	13	13	13	13
Interest rate - ***i***	8%	8%	8%	8%

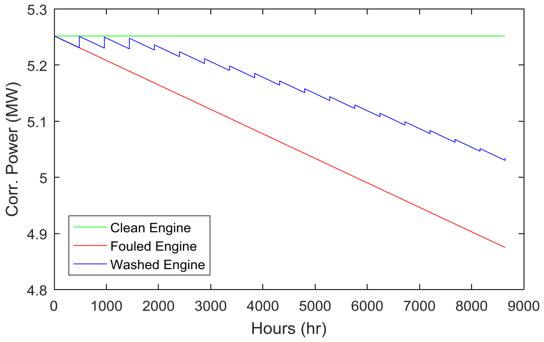
Appendix D (On-line / Off-line Washing and Combination)



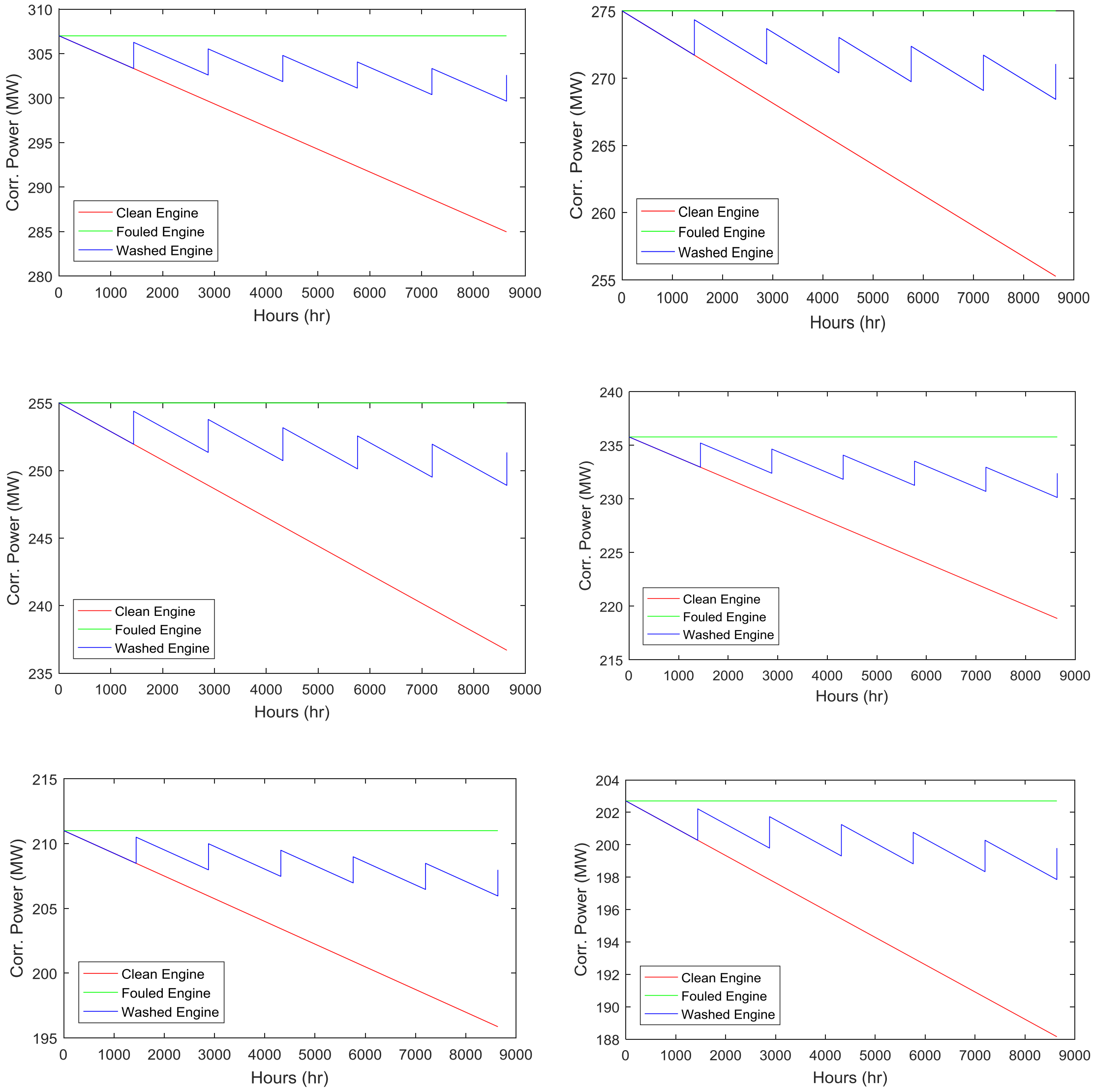
Figure_Apx D-1 Trend lines for clean, fouled and washed engine of 307MW – 159MW at 480hrs interval



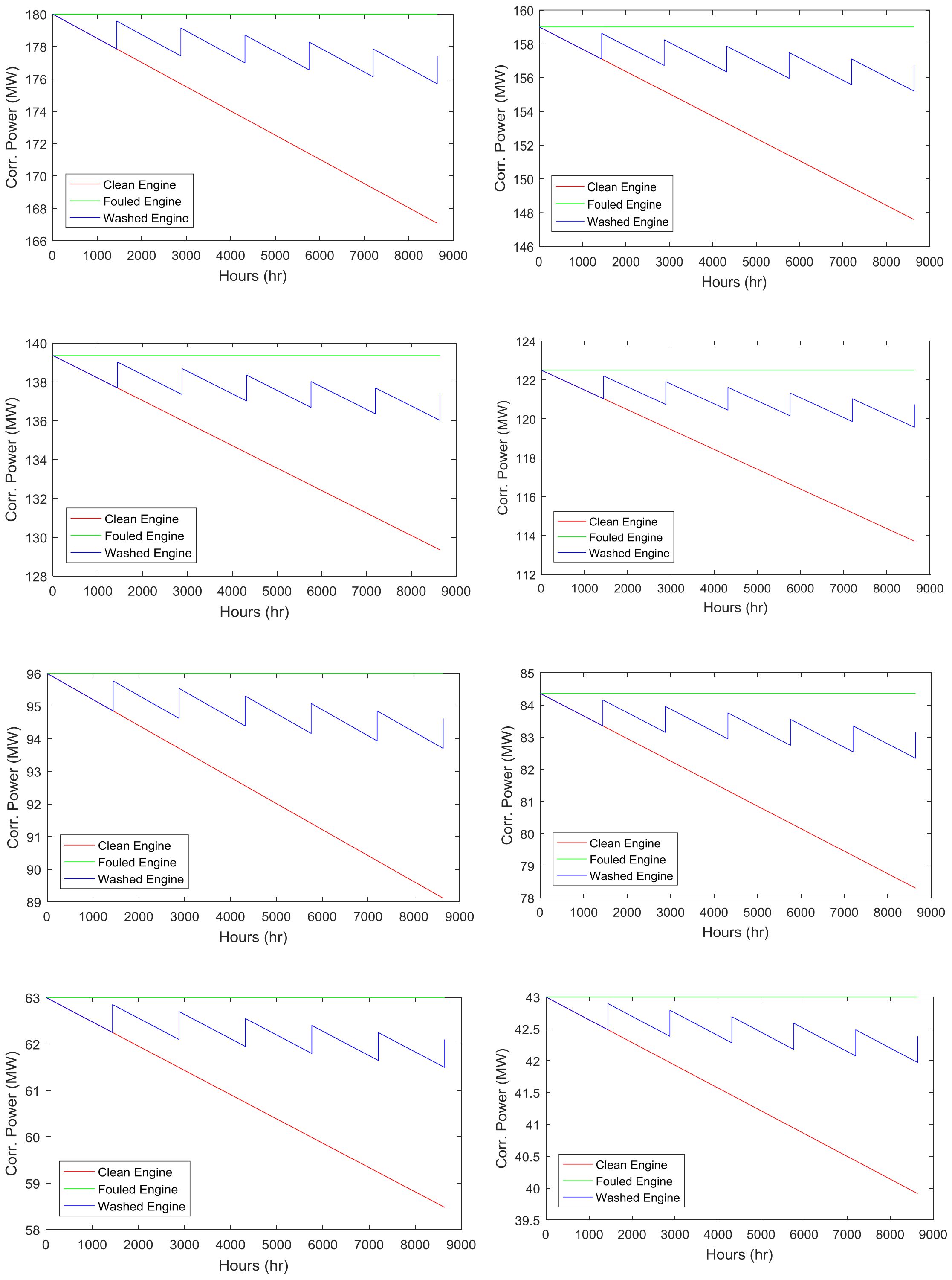
Figure_Apx D-2 Trend lines for clean, fouled and washed engine of 139MW – 13MW at 480hrs interval



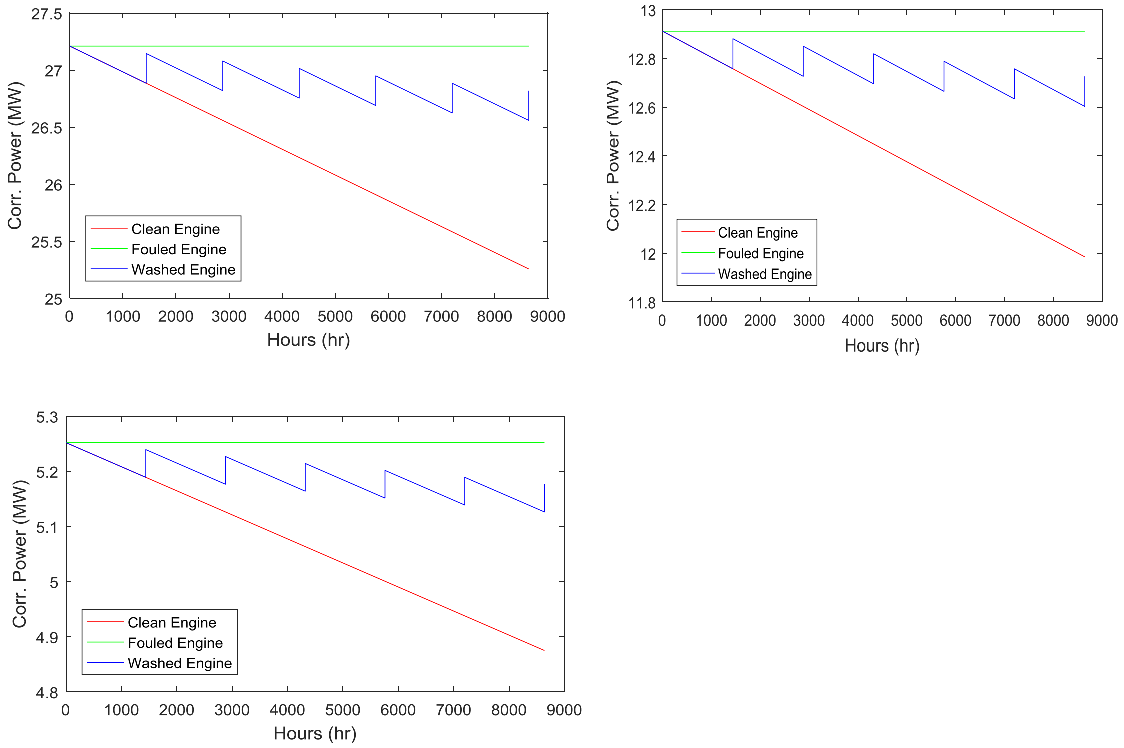
Figure_Apx D-3 Trend lines for clean, fouled and washed engine of 5MW at 480hrs interval



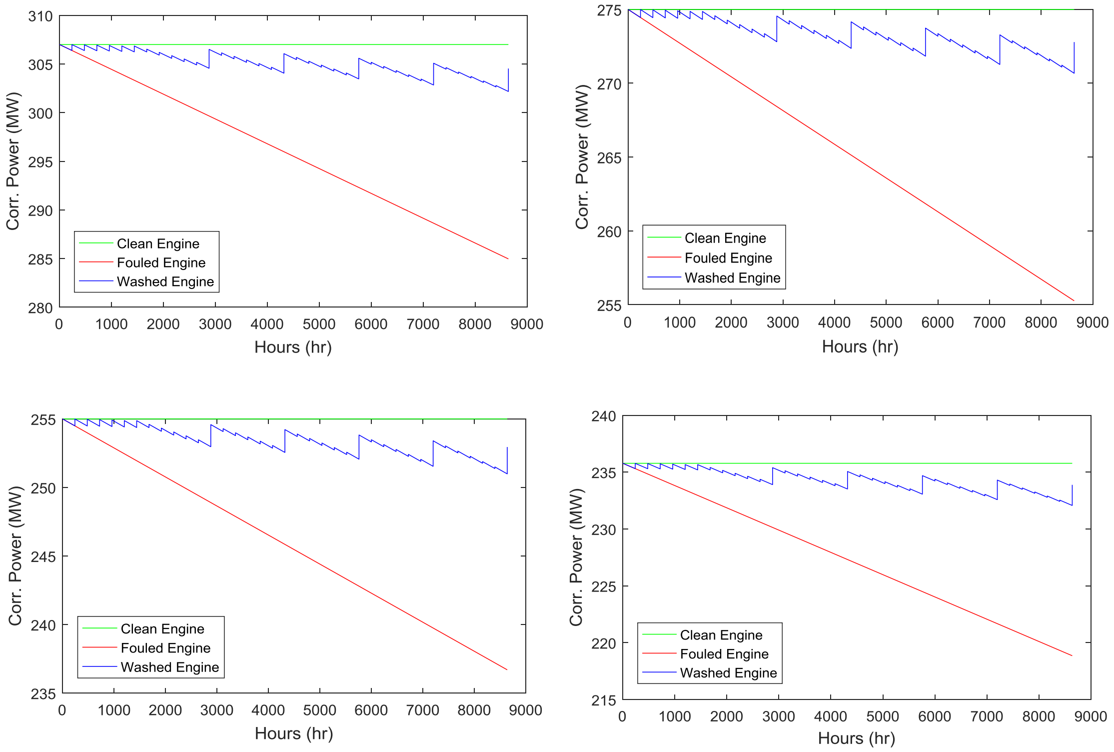
Figure_Apx D-4 Trend lines for clean, fouled and washed engine of 307MW - 203MW at 1440hrs interval 80% recovery



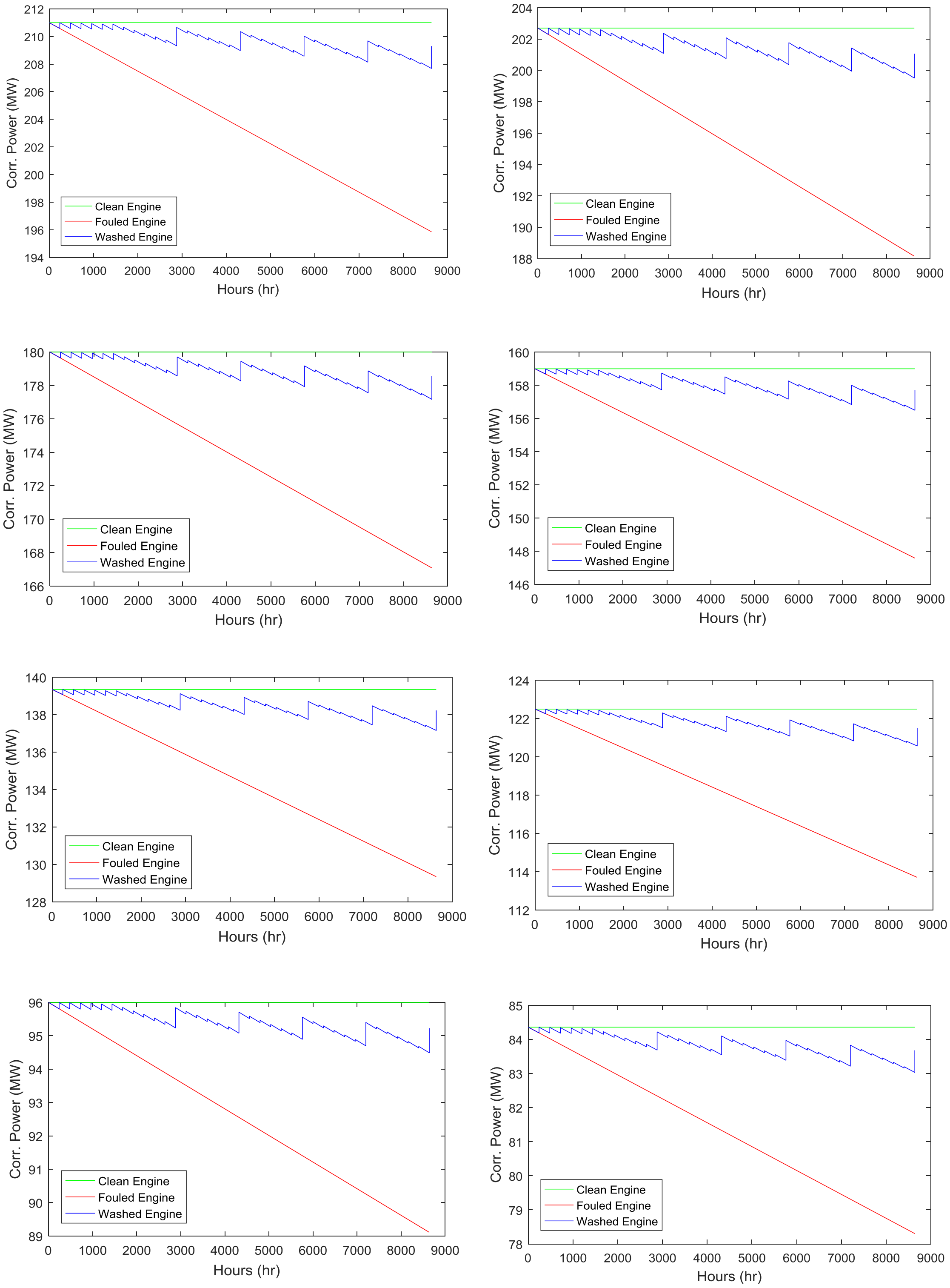
Figure_Apx D-5 Trend lines for clean, fouled and washed engine of 180MW - 43MW at 1440hrs interval 80% recovery



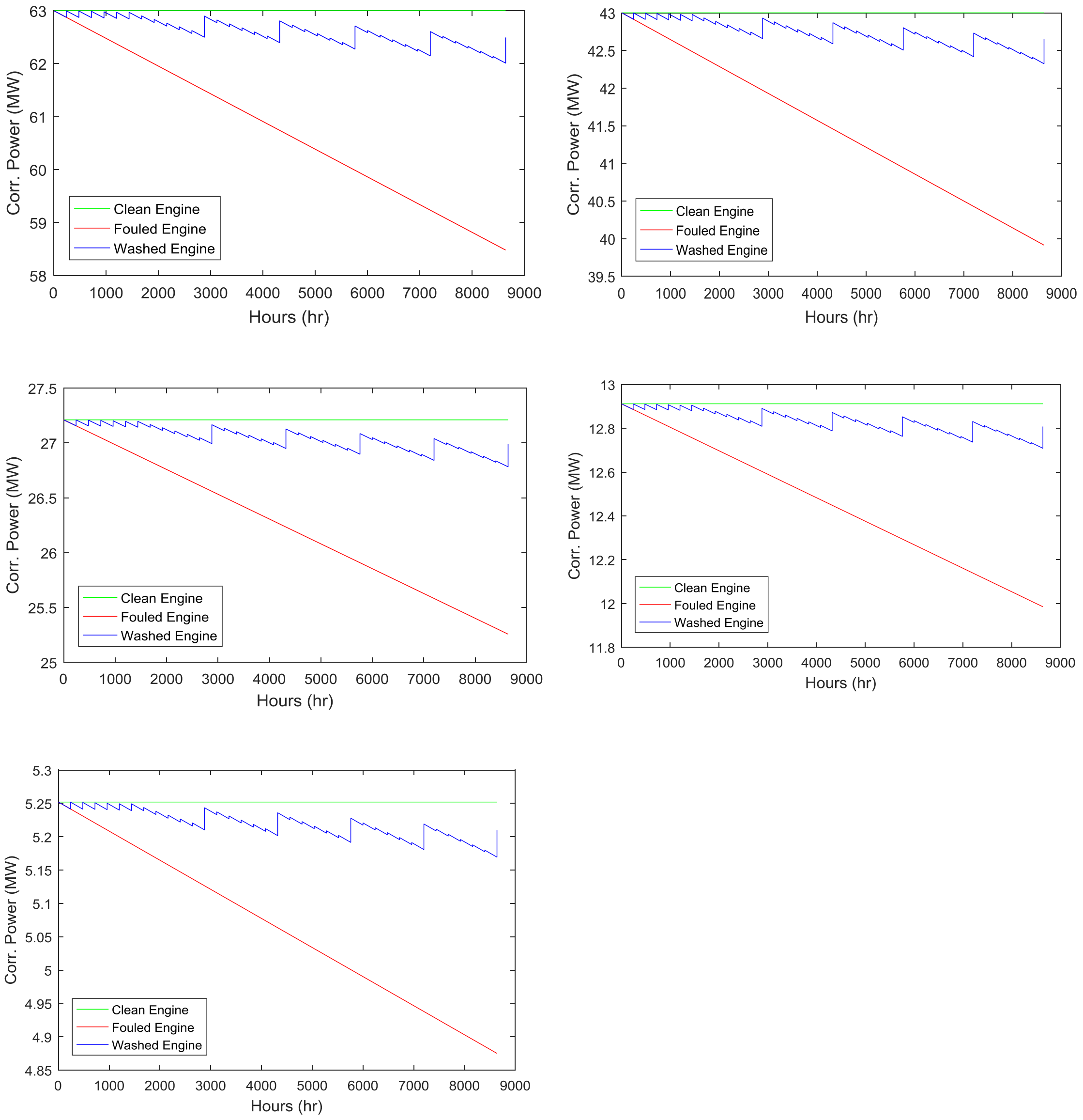
Figure_Apx D-6 Trend lines for clean, fouled and washed engine of 27MW - 5MW at 1440hrs interval 80% recovery



Figure_Apx D-7 Trend lines for clean, fouled and washed engine of 307MW - 236MW at 1440hrs interval 80% recovery

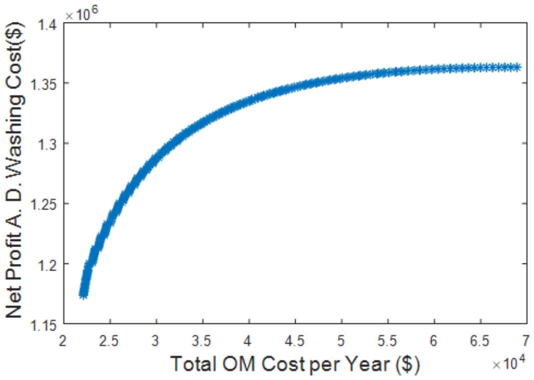


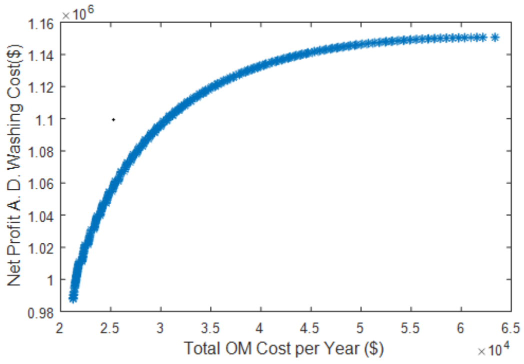
Figure_Apx D-8 Trend lines for on-line and off-line washing of 211MW – 84MW engine at 240hrs on-line and 1440hrs off-line

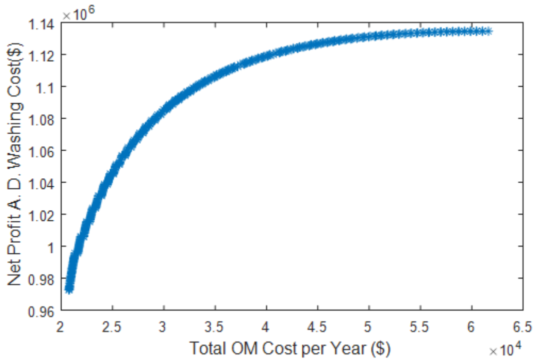


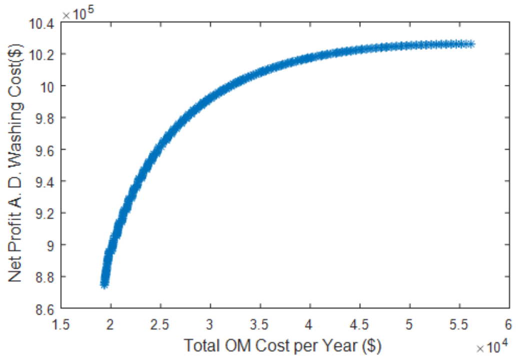
Figure_Apx D-9 Trend lines for on-line and off-line washing of 63MW – 5MW engine at 240hrs on-line and 1440hrs off-line

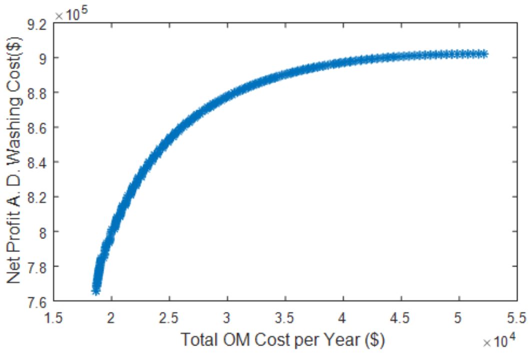
Appendix E (Optimization)

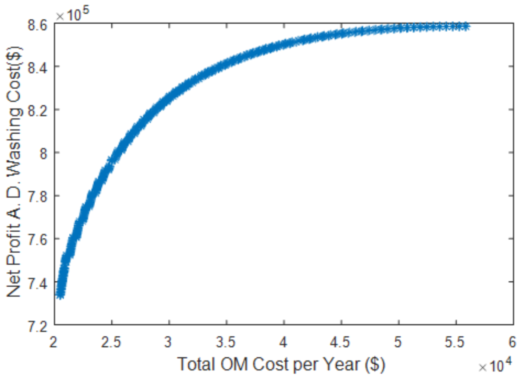


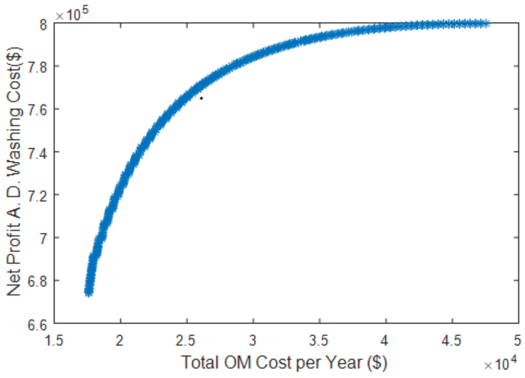


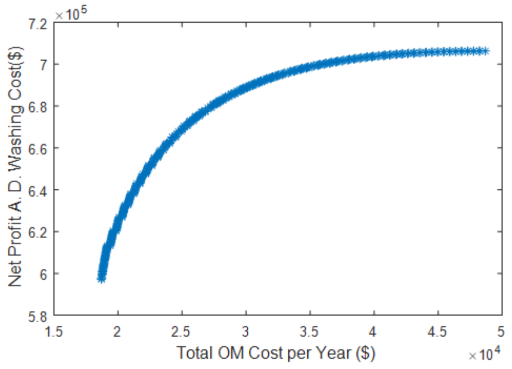


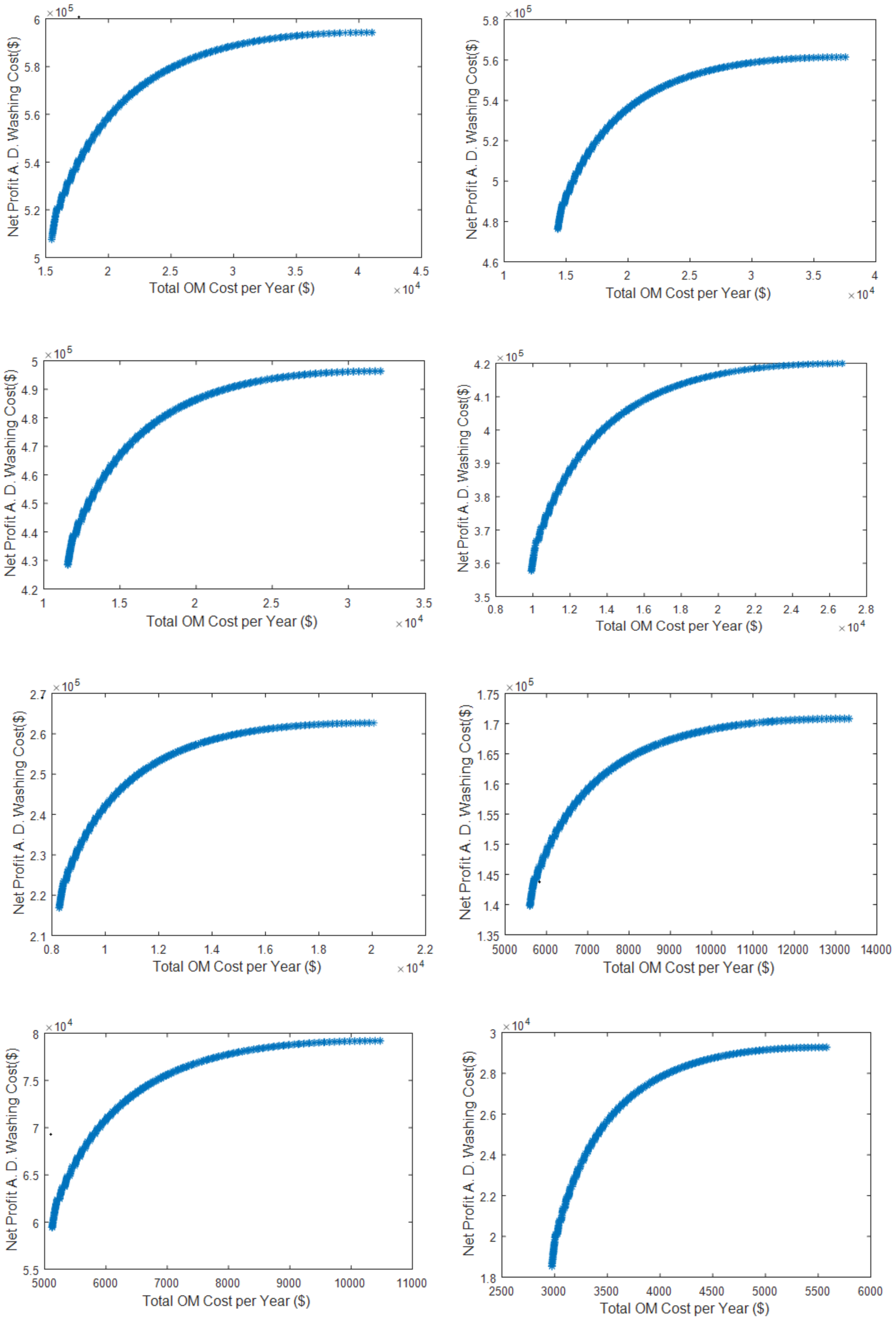




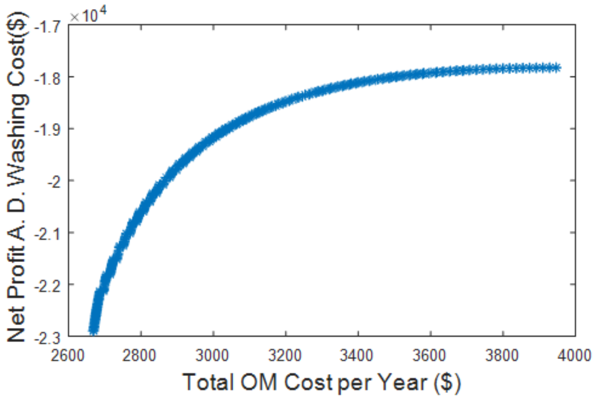








Figure_Apx E-1 Optimized net profit and total O&M cost per annum for 307MW



Figure_Apx E-2 Optimized net profit and total O&M cost per annum for 5MW