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Gas Turbine Compressor Washing Economics and Optimisation using Genetic Algorithm

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Abstract

Studies have shown that online compressor washing of gas turbine engines slows down the rate of fouling deterioration during operation. However, for most operators, there is a balancing between the performance improvements obtained and the investment (capital and recurring cost). Washing the engine more frequently to keep the capacity high is a consideration. However, this needs to be addressed with expenditure over the life of the washing equipment rather than a simple cost-benefit analysis. The work presented here is a viability study of online compressor washing for 17 gas turbine engines ranging from 5.3 to 307MW. It considers the nonlinear cost of the washing equipment related to size categories, as well as nonlinear washing liquid consumption related to the variations in engine mass flows. Importantly, the respective electricity break-even selling price of the respective engines was considered. The results show that for the largest engine, the return of investment is 520% and the dynamic payback time of 0.19 years when washing every 72 hours. When this is less frequent at a 480-hour interval, the investment return and payback are 462% and 0.22 years. The optimisation study using a multi-objective genetic algorithm shows that the optimal washing is rather a 95-hour interval. For the smallest engine, the investment was the least viable for this type of application.

1. Introduction

Compressor fouling is the deposition and accretion of airborne particles on compressor blades as shown in **Figure 1**. The impact of compressor fouling on the engine performance includes a reduction in the power output and thermal efficiency (constant turbine entry operation) **[1,2]**. The impact of compressor fouling is usually incremental, with time, and the severity depends on the type of location (e.g., industrial, motorway, countryside, desert etc.), the environment (e.g. tropical or artic), the seasonal changes, as well as the arrangement of the inlet air filters. Air filters are usually installed for most gas turbine operations, however evidence from stripped engines shows that particles in many cases still gain access to the engine. The degree of this depends on the staging and class of air filters used.

Online compressor washing is to be considered as mitigation to significant drops in power output or performances, to allow for an extended period of operations without a shut-down. Igie et al. **[3]** show an experimental study involving accelerated fouling and subsequent online wash. The work shows that the recovery after a wash is not 100 per cent cleaned; hence washing should be applied proactively at engine commissioning or immediately after overhaul. Also, Boyce and Gonzalez **[4]** state that "*it is imprudent to let foulants buildup before commencing a water wash regime, since the foulants will be washed down stream causing blockages in the last stages.*" A similar type of redeposition is shown in the accelerated fouling and washing experimental work by Syverud and Bakken **[5]** which shows that this is possible. This means a preventative approach, rather than a reactive one. It is also important to note that the gains in improvement with online washing are generally smaller compared to offline washing that requires a shut-down as shown in Igie et al. **[6]**. However, the accumulative effect of several online washes ensures that the performance deterioration can be controlled pending when there is an opportunity to shut down for an offline wash. **Figure 2** is a depiction of online washing effects also evident in Stalder **[7]** and Schneider et al. **[8]**. This figure shows that excessive power losses can be lessened before the offline wash, and in addition, a more frequent wash is more beneficial.

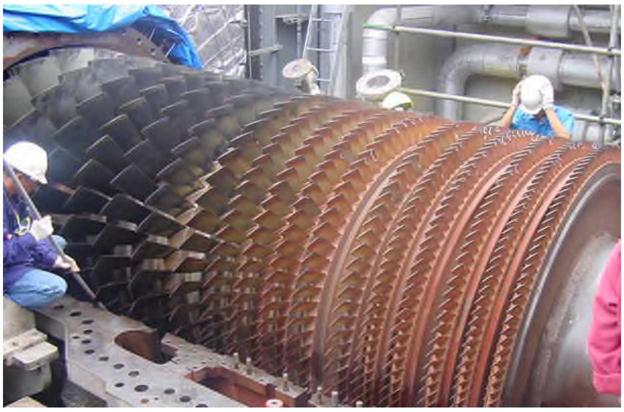


Figure 1 Front stage fouling of a multi-stage compressor [9]

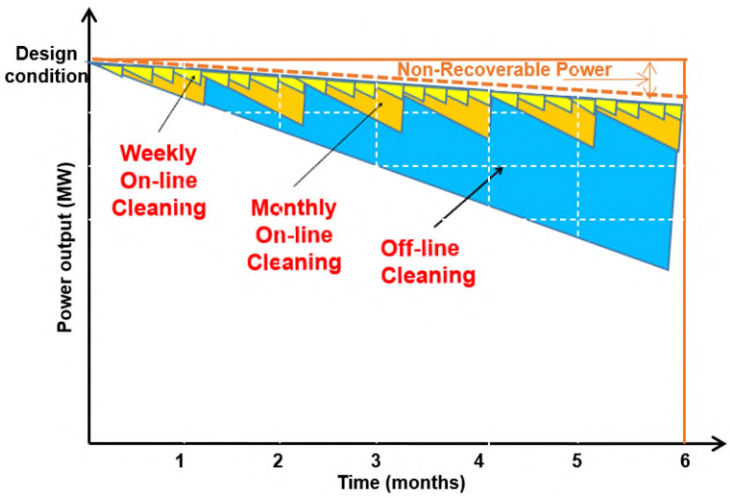


Figure 2 Depiction of online washing effects

Online compressor washing involves the installation of nozzles on the bellmouth or plenum of a gas turbine, in front of the engine as shown in **Figure 3**. These washing nozzles are usually installed around the centre line of the engine pointing towards the direction of airflow. The number of nozzles is dependent on the engine mass flow and the physical design of the machine. The nozzles are connected to a pipe network that leads to the washing skid delivery system which may be manual or automated. Hence the capital cost of the equipment includes the washing delivery system, piping connection with the nozzle bracket or setup plus overall installation. The recurring cost is that of demineralised water and/or washing detergents, for which the quantity will be determined by the washing interval.

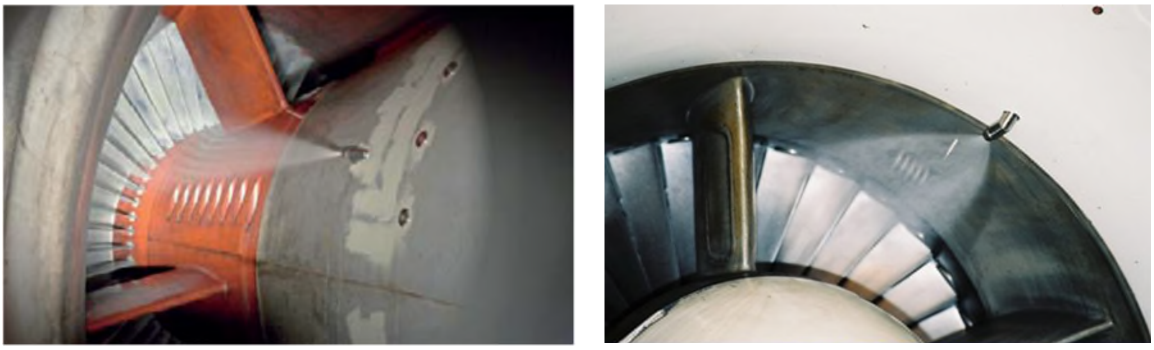


Figure 3 Online compressor washing arrangements – Left: nozzle on the bellmouth [10] and Right: nozzle on the plenum [11]

Refs **[6,8,12,13]** show the operational experience of adopting online compressor washing, pointing to performance benefits. This is typically a slowdown in the rate of degradation shown in Igie et al. **[6]** that compares the degradation trend for a wash and unwashed engine in the same power station. Schneider et al. **[8]** present the before and after washing effect of online washing, concluding that a daily wash is more effective than a weekly one, by a factor of two. However, adding that a weekly wash with detergent provided better performance outcomes than a daily water wash. There is a consensus that frequent washing is beneficial as demonstrated, however very few studies have considered the mathematical optimisation of the wash interval as shown in Aretakis et al. **[14].** The referred study on a 40MW engine operation uses the Simplex Downhill Method in Multi-dimensions to identify the optimal washing using the specific profit and specific energy cost as the criteria against the number of offline washings. Several studies have been carried out on electricity generation using different technologies and their impact on the environment. A study by Di Lorenzo et al. **[15]** has proposed a model using a Monte-Carlo simulation technique to select the best technology for the financial investments related to the electricity market. The model assesses the trade-offs between expected returns and the key risks imposed on decision-makers. Another study by Di Lorenzo et al. **[16]** has also proposed a model for reducing carbon-dioxide emissions from the power-generation sector using the concept of

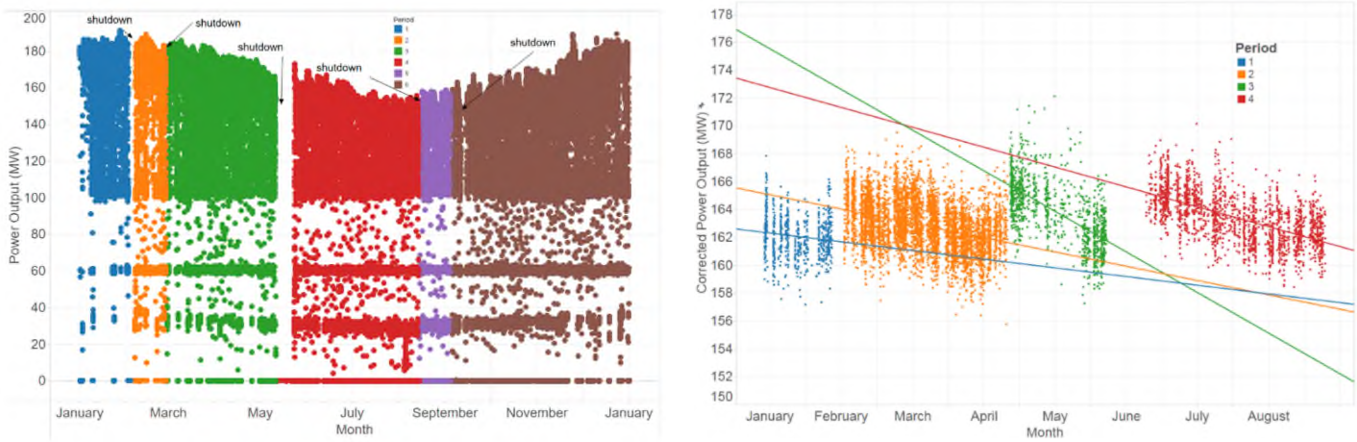
Techno-Economic, Environmental and Risk Analysis (TERA). The model performs screening over multiple options using modelling and assessment of several metrics. The present study here takes this a lot further for online washing, considering a viability analysis rather than a cost-benefit study. Here the work has considered the Break-Even Selling Price (BESP) of electricity for various engine conditions (clean, unwashed and washed compressor) of various engines. Also, a more detailed breakdown cost of washing investment is accounted for that has been related to the Return of Investment (RoI) and the Dynamic Pay Back (DPB) as a function of washing intervals. Published work on the economics of compressor washing **[17,18]** typically focus on cost-benefit and usually relates the gains to the life of the equipment and the overall returns or wider economics of the plant. The broader plant economics are considered here, also using Genetic Algorithm in the optimisation of washing interval, all benchmarked to the overall plant operation. For the first time, this study addresses the following:

- What is the BESP for different engine capacities in clean, unwashed and washed conditions?
- Also, what are the equipment RoI and DPB, for the corresponding BESP and conditions?
- What is an optimum online washing interval for different engine sizes, also concerning different levels of degradation?
- What is the influence of gas turbine engine size and number of engines on the viability for the same operation?

2. Performance and Economics – Methodology

The engine performance data used for the investigation is that of a GE Frame 7FA in a power station. The first year of the engine operation and data are used for this analysis and presented in **Figure 4**, by Igie et al. **[6]**. The engine operated with a combination of offline washing during shutdowns and online washing that occurred at an average of 55-hr intervals. In the case considered, the interval of washing consists of a liquid mixture ratio of 1:4, of concentrates to demineralised water. The referred study shows marked improvements in the engine performance after an offline washing as shown on the right-hand side of **Figure 4**. The left of the figure shows the raw data with the variation of the power output of the machine for the whole year. It also indicates the shutdowns in between the periods (described as continuous hours of operation). The authors estimate the degradation trend of the engine presented on the right of the figure, following the treatment of the data on the left-hand side. This data treatment involved correcting the parameters to ISO conditions, as well as comparing only periods with similar heat input, through a small range of fuel flows. As a result, less of the original raw data is used for the analysis. The degradation trend shown here is utilised for the analysis of the present work.

The degradation trend line used in the present study is the average obtained from the trend lines shown, for the first year, about 8640 hours of operation. For a comparative analysis of washed and unwashed effects, a second neighbouring engine without washing was considered. The average trend lines of these engines with washing and the unwashed engine, is presented in **Figure 5**. This figure shows a power reduction from an idealised clean engine condition. At the 8640th hour, there is a 7.2% reduction for the unwashed engine evaluated in Ref **[19]**, as opposed to 4% in the washed case.



Engine power output variation – year one Degradation trends of the engine

Figure 4 Reference heavy-duty engine operation [6]

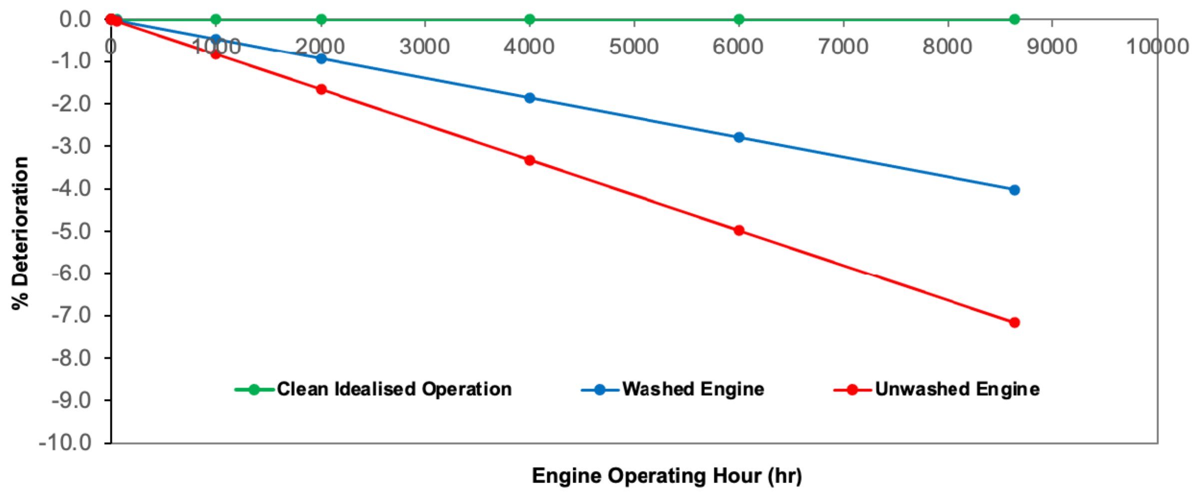


Figure 5 Power deterioration - washed and unwashed engine

The effectiveness of washing also termed recovery of lost power ($R_{p.lost}$) can be calculated based on **Equation (1)** for the 55-hour washed engine.

$$R_{P.lost} = \left[1 - \frac{P_{clean} - P_{washed}}{P_{clean} - P_{unwashed}}\right] \times 100 \quad \textbf{(1)}$$

Where P_{clean} is the clean idealised engine power output (assuming no degradation and perfect stable condition) at the nth hour, P_{washed} is the washed engine power output in the same hour, and $P_{unwashed}$ is that of the unwashed engine. As a result, the recovery of lost power with a 55-hour washing interval is 43.95 % at the 8640th as shown in **Figure 14** of the **Appendix**. To investigate the effect of other wash intervals not conducted in the actual engine operation, the trend line in **Figure 5** of the washed case (55-hour interval) was used. The approach was to establish the relationship between washed EOH with % deterioration (and hence power output). Subsequently, using the time-based power output (washed) in equation **Equation (1)** with the corresponding values for unwashed and clean engine to calculate *Rp.lost*. As such, relating every EOH to a *Rp.lost* shown in **Figure 14**. The mathematical relationship was then used to modify the fouled or unwashed condition to attain the washed operation in **Section 3.** The implication of this is that *Rp.lost* becomes smaller with time, therefore indicating that washing effectiveness is not constant. The additional wash intervals include: every 72, 120, 240 and 480-hour. For the individual cases, the power reductions in the final hour of operation amounts to 4.05%, 4.07%, 4.11% and 4.20% respectively. Their corresponding final recovery of lost power is 43.6%, 43.3%, 42.7% and 41.5%.

2.1 Liquid Quantity Utilised for Washing and Costs

The amount of liquid for washing is considered here; this is based on the water-to-air ratio by mass flow for the respective engine sizes from 5.3 to 307MW. In this study, 0.2% of liquid-to-air ratio is assumed, similar to Refs **[3,5]** that is a relatively small amount, applicable to the high-pressure online washing. In addition, the liquid composition consists of detergent concentrate and demineralized water in a ratio of 1:4. This is applied accordingly in all the cases investigated, with a washing duration of 10 minutes. Based on the publicly available data on individual engine mass flow **[20 - 22]**, it is convenient to calculate the quantity of liquid used; this is presented in **Table 1** as shown.

The associated capital, maintenance, and salvage cost of the washing equipment for small to large engines have been provided by R-MC Power Recovery Ltd and is shown in Table **2**. This table shows that the larger engines have the higher capital and maintenance cost, and the increase is not proportional to the engine size. The capital cost is higher for larger engines because of a larger storage tank, the requirement for more nozzles and piping, as well as a larger pump. The maintenance and salvage value costs are higher for these engines, given their size. However, the $/MW capital cost is lower for the larger engine in comparison to the smaller engine towards the left of the table.

The operational cost of 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 (UK price) respectively. Nevertheless, these values may vary in different locations, associated with the cost of transportation. **Table 3** shows the cost of washing for the largest and smallest engine, using 72 hours wash interval. As the concentrate to water ratio is 1:4, the liquid quantity constitutes only one-fifth, amounting to $677 per wash for the largest engine. The corresponding cost for the demineralised water is $45. As such the cost of each washing is $722 for the large engine. This amounts to $86,679 annually, given that washing every 72 hours is 120 instances of washing in a year. A similar calculation for the smallest engine is also shown in the table.

Table 1 Total washing liquid utilised for the respective engines

Manufacturer	Engine	Capacity (MW)	Engine Mass Flow (kg/s)	Volume/Wash (10 minutes) (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	403.7	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**	5.3	20.32	24

Table 2 Capital and maintenance cost of wash equipment for different engine sizes [23]

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

Table 3 First year cost of washing for the largest and smallest 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/ wash (10 minutes)	$722	$20
Cost of fluid (72hr/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**

When more than one engine is present, a single wash skid can be used for all engines, depending on the proximity. **Table 4** shows the breakdown cost for four engines, indicating that the increased cost is 1.9 and 1.3 times for the largest and smallest engine respectively. This appears to be more cost-effective, for the respective power generation. Also, the cost related to additional nozzles, a larger tank and piping connection and increased maintenance cost is marginally increased. However, the cost of washing liquid increases proportionally. **Figure 6** shows the total cost of washing for single and four-engine operations, at a wash interval of 72hrs. The variability for the respective cases is a result of variation in air mass flow for the engines.

Table 4 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**

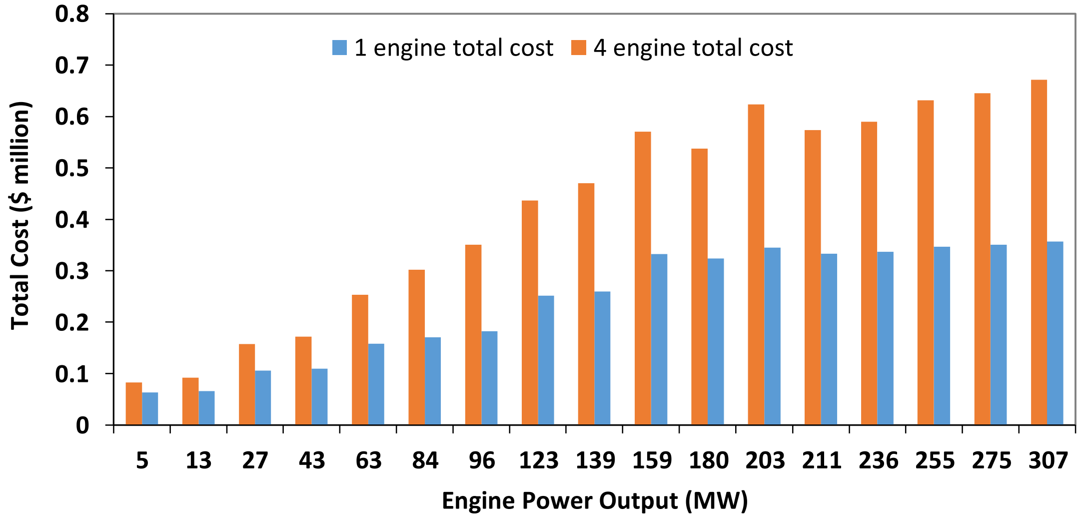


Figure 6 Total cost of washing for single and four engines

2.2 Cost of Electricity for Different Engines

The Break-Even Selling Price of Electricity (BSPE) generally varies based on the size of the engine and how the power is generated. Additionally, for viable operations, the cost of online washing that varies also as a function of the engine size can be factored in when working out the viability of operations. The BESP is calculated to estimate the price of electricity to be sold for different engine sizes and separate conditions (clean, unwashed and washed engine). Subsequently, a dynamic analysis to identify if the performance benefits of washing outweigh its capital investment and recurring cost.

To estimate the BESP, the duration of the project, that is the life of the engine, was considered. Also, the electricity and fuel price, fixed and variable O&M cost, discount and income tax rate, plant availability, construction time, investment cost, depreciation and escalation rate for fuel and electricity. The BESP is calculated according to the following equation:

$$BESP = \frac{\sum_{t=1}^{n}[(I_t + M_t + F_t) \times (1+i)^{-t}]}{\sum_{t=1}^{n}[E_t \times (1+i)^{-t}]} \quad \textbf{(2)}$$

Other calculations were made to estimate the annual net cash flow (ANCF), annual operation profits (AOP), annual loan replacement (ALR), annual tax (AT), plant depreciation, net present value (NPV) and the internal rate of return (IRR). These were based on input data such as engine power output, fuel burn and the energy produced per annum. The following **Equations (3)** to **(8)** were used.

$$ANCF = AOP - ALR - AT \quad \textbf{(3)}$$

$$AOP = ES - fuel\ cost - O\&M\ cost \quad \textbf{(4)}$$

$$AT = TR * TI + ETR * E \quad \textbf{(5)}$$

The economic parameters for NPV and IRR are calculated using the following equations:

$$NPV = \sum_{t=1}^{n} CF_t * (1+i)^{-t} - I \quad \textbf{(6)}$$

$$IRR = i^* \ni' NPV(i^*) \quad \textbf{(7)}$$

$$\underset{[0,n]}{min}\{n'\} \ \ni' \ \sum_{t=1}^{n'} CF_t \times (1+i)^{-t} \geq 0 \quad \textbf{(8)}$$

For the calculations, the pay-back period (PBP) must satisfy **Equation (8)**. The ANCF, AOP and AT are calculated according to Ref **[24]**. For the 307MW engine, the estimated prices adopted in this study are from the Gas Turbine World **[25]** and are made on standard gas-only (natural gas) single cycle plant. The plant prices cover only the equipment. 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 for the 307 MW engine is $245/kW and up to $730/kW for the smaller engine of 5.3 MW machine according to the equations for the equipment cost in Ref **[25]**. The economic input data for the 307MW engine is shown in **Table 5.** To run the model, there is a need to initially guess the electricity price. A value of $0.065/kWh is the cost of electricity at which the NPV is zero. The method adopted for the economic module calculation is the discounted cash flow technique (DCF).

Table 5 Economic input model data for 307MW engine – clean condition

Parameter	Value
Engine power output (kW)	307,000
Fuel burn (kg/year)	555,508,170
Energy produced (kWh)	2,652,480,000
Availability (%)	98.6
Power plant lifespan (year)	25
Operating hour (h)	8640
Interest rate (%)	10
Electricity price ($/kWh)	0.065
Fuel price of natural gas ($/kg)	0.2445
Time period for depreciation (year)	20
Construction time (year)	3
Specific and variable O&M cost ($/kW)	17.83
Actual fuel price escalation rate (%)	2
Actual electricity price escalation rate (%)	2.5
Actual O&M escalation rate (%)	2

2.3 Compressor Washing Economics

To investigate the economics of compressor washing, the cost of degradation without washing (where possible), needs to be calculated. This can be made in comparison with the associated cost of washing alongside the quantified and resulting performance improvements. The aim here is to establish if the performance benefit outweighs the capital investment and recurring cost. To achieve these, the Annual Savings (AS), dynamic PBP, Return on Investment (RoI), and NPV are to be calculated and mathematically described from **Equations (9)** to **(15).**

$$AS = \left(R_w - C_{fw} - C_{om}\right) - \left(R_f - C_{ff}\right) \tag{9}$$

For this dynamic analysis that considers an interest rate (i) of 8%, the following formulas are used for the analysis:

$$NPV = -C + SV_0 + \sum_{i=1}^{N} \frac{AS_t}{(1+i)^t} \tag{10}$$

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

$$PWF = \sum_{i=1}^{N} \frac{1}{(1+i)^t} = \frac{(1+i)^N - 1}{i(1+i)^N} \tag{11}$$

Where PWF is the present worth factor. **Equation (10)** can be written as

$$NPV = -C + SV_0 + AS \times PWF \tag{12}$$

The DPB is the smallest value of N that makes the net present value non-zero:

$$NPV = -C + SV_0 + \sum_{t=1}^{N_{min}=DPB} \frac{AS}{(1+i)} \geq 0 \tag{13}$$

$$DPB = \frac{-ln\left[1 - \frac{i(C - SV_0)}{AS}\right]}{ln(1+i)} \quad \textbf{(14)}$$

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

$$NPV = -C + SV_0 + \sum_{t=1}^{N} \frac{AS}{(1 + RoI)^t} = 0 \quad \textbf{(15)}$$

In this 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 (13 years). The sum of these present values and the salvage 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.

3. Economic Analysis of Different GT Engines

The **Figure 7** shows the power factor (ratio of actual power to maximum power output), applicable to the different engines under investigation. This approach has been subsequently applied non-dimensionally, to different engine sizes ranging from 5.3 to 307MW. The figure shows an idealised clean engine case, the unwashed and the washed case (480 hours of operation before a wash) obtained from the analysis in **Section 2**. The figure also shows that recovery of lost power or effectiveness is higher in the first 2000 hours of operation. It is consistent with the understanding that washing effectiveness decreases with extended time in operation. As the power output reduces for a given combustor temperature, so does the heat rate increase. This is given that the reduced power is generated at relatively higher fuel flow in comparison to the same clean engine part-load power. It is important to note that the absolute amount of fuel used is less but in relation to the latter, it is more. The effect of this heat rate increase was accounted for in the analysis.

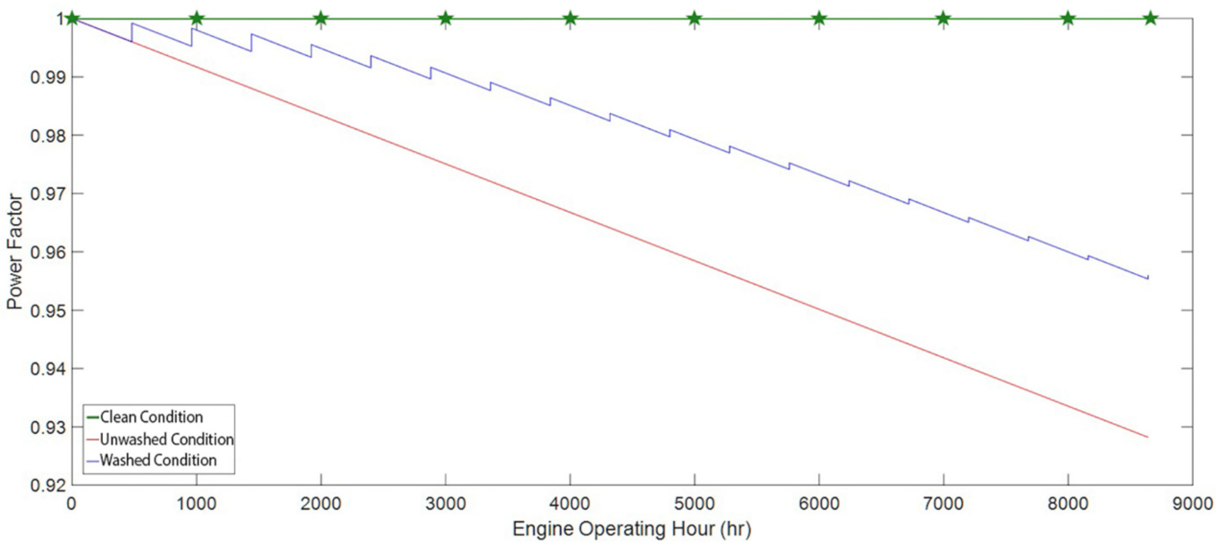


Figure 7 Clean, unwashed and washed operation with 480-hr wash interval

The use of **Equations (9) to (15)** is presented here to evaluate the viability of online compressor washing for different engines and varied wash intervals. **Figure 7** which consists of non-dimensional trends of operations (clean, unwashed and washed conditions) applies to all the engines. From the figure, the estimated energy produced per year, applicable to the 307MW engine is 2,652,480 MWh for clean idealised operation. Based on the degradation trend (unwashed), the energy produced is 2,557,292 MWh and that of washed condition at 480 hours wash interval is 2,606,195 MWh. These values have simply been calculated by finding the area under the curve. Those of other wash intervals are presented in **Table 6**, indicating that the more frequent washing (e.g., 72 hours) amounts to higher energy production, compared to the less frequent interval, however it is important to note that narrower interval brings about greater washing cost. The trends in energy production shown apply to all the engines, and the smallest engine is also provided in the table.

Table 6 Energy produced by largest and smallest engine (different conditions)

Description	**307 MW engine** (MWh)	**5.3 MW engine** (MWh)
Clean idealised operation	2,652,480	45,377
Unwashed condition	2,557,292	43,749
Washed condition – 72-hour interval	2,613,639	44,713
Δ (Washed – Unwashed)	**56,347**	**964**
Washed condition – 120-hour interval	2,611,645	44,679
Δ (Washed – Unwashed)	**54,353**	**930**
Washed condition – 240-hour interval	2,609,274	44,638
Δ (Washed – Unwashed)	**51,983**	**889**
Washed condition – 480-hour interval	2,606,195	44,585
Δ (Washed – Unwashed)	**48,904**	**837**

From **Equation (2)**, it can be observed that the BESP plus the profit margin for the 307 MW in clean condition is $66.6/MWh shown in **Table 7.** The table also shows that for the 5.3MW engine, it is $96.0/MWh, as well as the engine sizes in between. It can be noticed that the BESP for the heavy-duty engine is lower than the light-duty engine: this is due to the higher cost of production for the smaller engine. Small engines cost significantly more $ per kW than the larger ones. A profit margin has been applied for the cost of electricity production of all the engine capacity. The table also shows the corresponding BESP for unwashed and washed (72-hour interval) conditions. From the table, it is shown that the electricity price for break-even is greater in the unwashed condition and $0.3/MWh above the price for the washed case.

Table 7 BESP for different engine capacities at clean, unwashed and washed conditions

Engine power (MW)	BESP($/MWh) **(Clean)**	BESP ($/MWh) **(Unwashed)**	BESP ($/MWh) **(Washed 72-hr interval)**
307	66.6	67.7	67.4
275	64.6	65.7	65.3
255	69.1	70.3	69.9
236	68.7	69.9	69.5
211	69.4	70.6	70.2
203	70.2	71.4	71.0
180	74.4	75.7	75.3
159	77.6	78.9	78.5
139	72.1	73.3	72.9
123	78.7	80.1	79.7
96	83.0	84.4	84.0
84	82.2	83.6	83.1
63	77.8	79.2	78.7
43	75.0	76.4	75.9
27	77.3	78.7	78.3
13	82.6	84.2	83.7
5	96.0	97.8	97.2

The total cost of the unwashed engine degradation in relation to the idealised clean engine operation is shown in **Table 8,** for the respective engines. The cost of less energy production is the difference between the energy produced in the clean and unwashed case. However, it is important to note that the lower power generated in the unwashed degraded operation is at a lower thermal efficiency compared to a clean part-load operation for the same output. Hence, there is an excess fuel cost that accrues, though in relative terms, but not an absolute value. The average cost of fuel is $1,758/kWh ($6/MMBTU) and the clean engine heat rate of 9002kJ/kWh increases by 1.6% in the final hour of operation. For the 307MW engine, the clean engine cost of fuel is $135.8M, that of the unwashed and washed engines are $133M and $135.4M respectively. Hence, the cost of power loss due to fouling and additional fuel cost due to an increase in heat rate is $6.3M and $2.1M respectively. These are high values that need to be considered in the context of the scale of operation. The same method is applied for other engines, down to the 5.3MW rated engine shown in **Table 8**. This also indicates that the cost of degradation increases with an increase in engine capacity for the same level of degradation.

Table 8 Cost of degradation (unwashed engine) for gas turbine engines

Engine Capacity (MW)	**Cost of Less Energy ($)**	**Cost of Excess Fuel ($)**	**Total degradation 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

The **Equations (9)** to **(15)** are subsequently applied to calculate the AS, NPV, DPB and RoI. **Table 9** indicates the parameters used for the estimation. It shows the capital and operation cost of the washing equipment, also in relation to fuel cost at different engine conditions, as well as their respective incomes. These have been provided for the largest and smallest engine, for cases with one machine or four machines in the same power station. The main increased cost with four engines is due to the more liquid utilised with respect to the size of the engine, as one wash equipment serves all machines. The calculation of the RoI amounts to the values shown in **Figure 8** for the different engines; this is for the most frequent (72-hour interval) and least frequent washing (480-hour). It generally shows that the RoI is better at a more frequent wash at 72-hour intervals than 480-hour. This means that the additional washing cost for the 72-hour interval is relatively small in comparison to its bigger gains due to higher energy production. It also shows that though the RoI generally increases with engine size (for this application in power generation), it is not linear. This is attributed to the nonlinear cost of the washing equipment. This figure indicates the maximum and minimum RoI of 520% and 462% for the 307MW engine. The maximum value for the 5.3MW engine is 59%, while it has a minimum value of 52%. See **Figure 15** and **Figure 16** of the **Appendix** for the corresponding DPB and NPV.

Table 9 Costs for the largest and smallest engine (case of one and four engines) at 72 hr wash interval

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

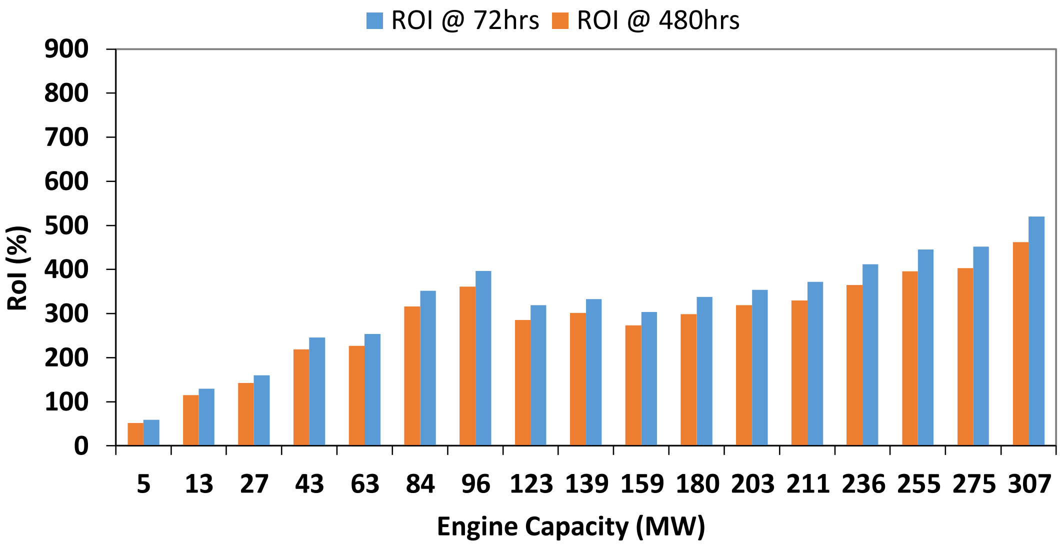


Figure 8 RoI of washing for at 72 and 480hrs-intervals for different engines

It is important to highlight as in **Table 10,** that achieving a total of approximately 255MW using more than one engine (e.g., four units of 63MW) provides better economic viability than with one engine at 255MW. This emphasises the benefit of large scale when the capital cost is a lot less. The four-engine case increases the RoI by 1.9 times with an increased annual savings of about $179,700. However, when comparing an engine of the same type, an increase from one to four engines increases the RoI by 3.4 times on average. This is shown in **Figure 9**.

Table 10 Influence of number of engines on economic performance at 72hrs interval

Size (MW)	AS ($)	NPV ($)	DPB (yrs.)	ROI (%)
255	1,091,773	8,395,126	0.22	445
63 (4)	**1,271,432**	**9,908,716**	**0.12**	**867**

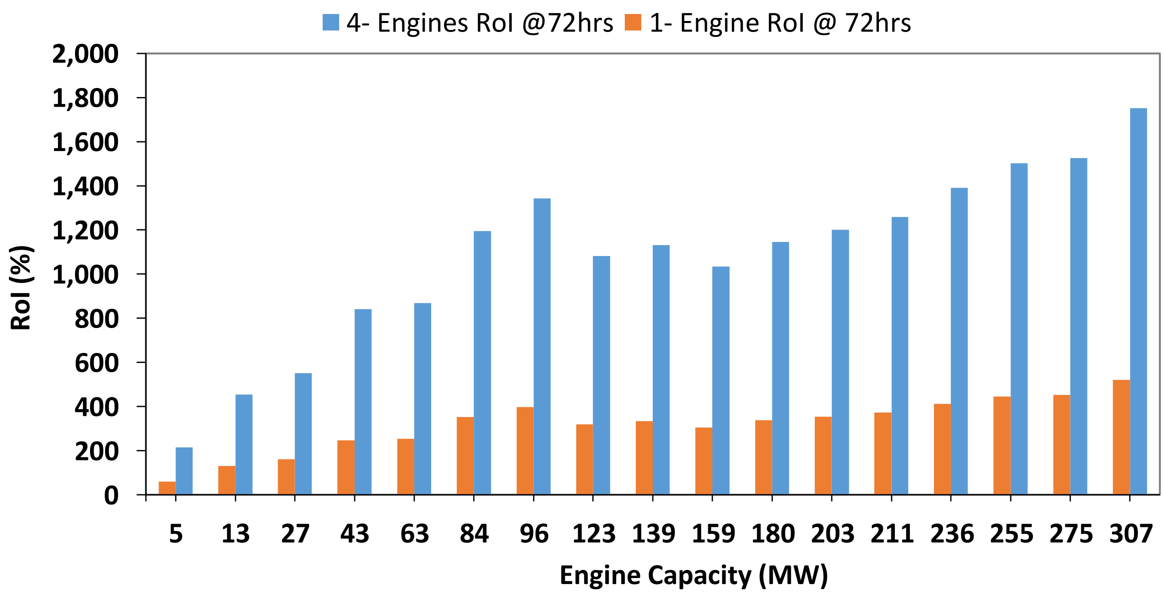


Figure 9 RoI of one and four engines at 72-hour wash intervals

Further to the investigation described, the degradation rate is subsequently reduced by half, and a quarter, to examine the economic viability of compressor washing. This amounts to 3.6% and 1.8% reductions in the power output in the 8640th hour. The RoI of these is compared to the initial case with a final power reduction of 7.2% in **Table 11.** This shows that for the same interval of washing for any given engine, the RoI reduces when the amount of degradation is less. This means that when the level of deterioration is lower and more frequent washing has been applied, it becomes expensive to the operator.

Table 11 RoI for different degradation rates with best & worst wash interval

	RoI (%) (72hrs interval)			RoI (%) (480hrs interval)		
Size (MW)	**Default**	***0.5**	***0.25**	**Default**	***0.5**	***0.25**
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

4. Mathematical Optimisation of Online Washing

A mathematical optimisation model for online compressor washing that accounts for the performance and economic aspects was developed using Multi-Objective Genetic Algorithm (MOGA). The model estimates an optimum washing interval for all the engines discussed, at the same level of time-based degradation. The Non-dominated Sorting Genetic Algorithms II (NSGA II) is the optimisation method selected to find an optimum interval of washing. This method was selected based on its simplicity, robustness and ease of implementation for optimal solutions. It has the advantage of maximising and minimising an individual criterion within a problem. Two objective functions have been identified for the current multi-objective problem. These are Net Profit After Deducting the Washing Cost (NPADWC) which is to be maximum and secondly, the operation & maintenance cost of the washing equipment (O&MCWE) that needs to be minimised. The input parameters to the algorithm input include engine capacity, engine operating hours, cost of electricity, cost of natural gas, heat rate and per cent heat rate increase and degradation rate as shown in **Figure 10**.

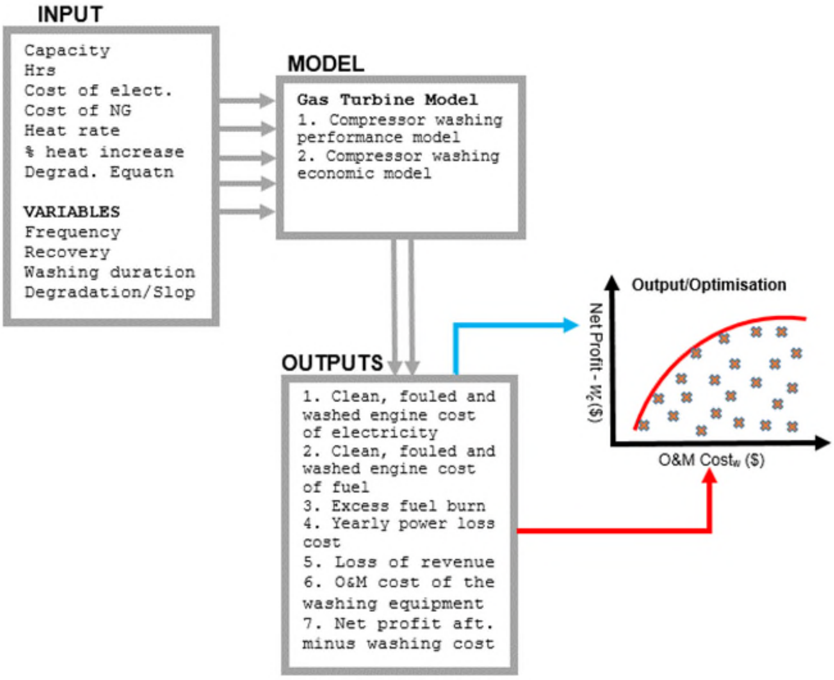


Figure 10 Flow chart of multi-objective GA procedure

The model consists of two layers for the calculation; layer one is for compressor washing performance and layer two is for compressor washing economics as shown in **Figure 10**. The combination of the two models is then used for optimisation. Four design variable parameters were identified and selected for optimisation with two variables such as degradation and effectiveness/recovery run on a real-time base. The other design variable parameters are the interval of washing **with a** lower limit of **72-hr** and upper limit of **480-hr**, washing duration with an upper limit of 10mins and a lower limit of 9mins. The output results from the two models calculated are energy sold and cost of fuel (clean, unwashed and washed conditions), excess fuel burn, the yearly cost of energy loss, the loss of revenue due to degradation and net profit after deducting washing cost as shown in **Figure 10**. Two fitness functions have been selected from the output results to run for optimisation and they are used to find an optimum solution. The online washing analysis has 2 dimensions of the fitness functions selected and these are the O&M cost of the washing equipment and net profit after deducting washing cost as previously stated. The fitness functions evaluate the fitness at each iteration and produce a desired solution. The fitness function equations selected for the optimisation are stated using **Equations (16)** and **(17) [23].**

$$C_{OM} = W_{fl} \times C_{fl} \times \left({EOH}/{Pd} \right) + C_m \quad \textbf{(16)}$$

$$NP_{after\ deduction} = AP_w - C_w \quad \textbf{(17)}$$

$Where;$

$$AP_w = NP_{we} - NP_{fe} \quad \textbf{(18)}$$

$$NP_{we} = COE_w - COF_w \quad \textbf{(19)}$$

$$NP_{fe} = COE_f - COF_f \quad \textbf{(20)}$$

$$C_w = C_{OM} + C_{pw} \quad \textbf{(21)}$$

For initialisation, a population size of (PopSize = 400), generation (gen = 300), number of variables (nVars = 2), number of objective function (nCriteria = 2) has been applied. Also, decision variables with upper and lower values and a function have been used to evaluate each objective.

The structure of the NSGA II **[26]** is shown in **Figure 11**. The populations of chromosomes are evaluated on two criteria mentioned O&MCWE and NPADWC. The population is generated between the upper and lower values of each decision variable. It processes and returns the solution of the fitness function by sorting it in a chromosomes vector. The next step involves sorting the populations, ranking or grading using the non-domination-sorting method. The ranking of the population implemented for the analysis is based on the Goldberg **[26-29]**. The selection process is performed based on two criteria. One is the location of the solutions assigned, and a rank is assigned to it; also, a lower rank is selected. Two is to compare when the rank of two individuals is equal, then a crowding distance has to be compared. For this, individuals with a higher crowding distance are selected. Lastly, 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 P_c = 0.9 and a mutation probability of P_m = 1/n.

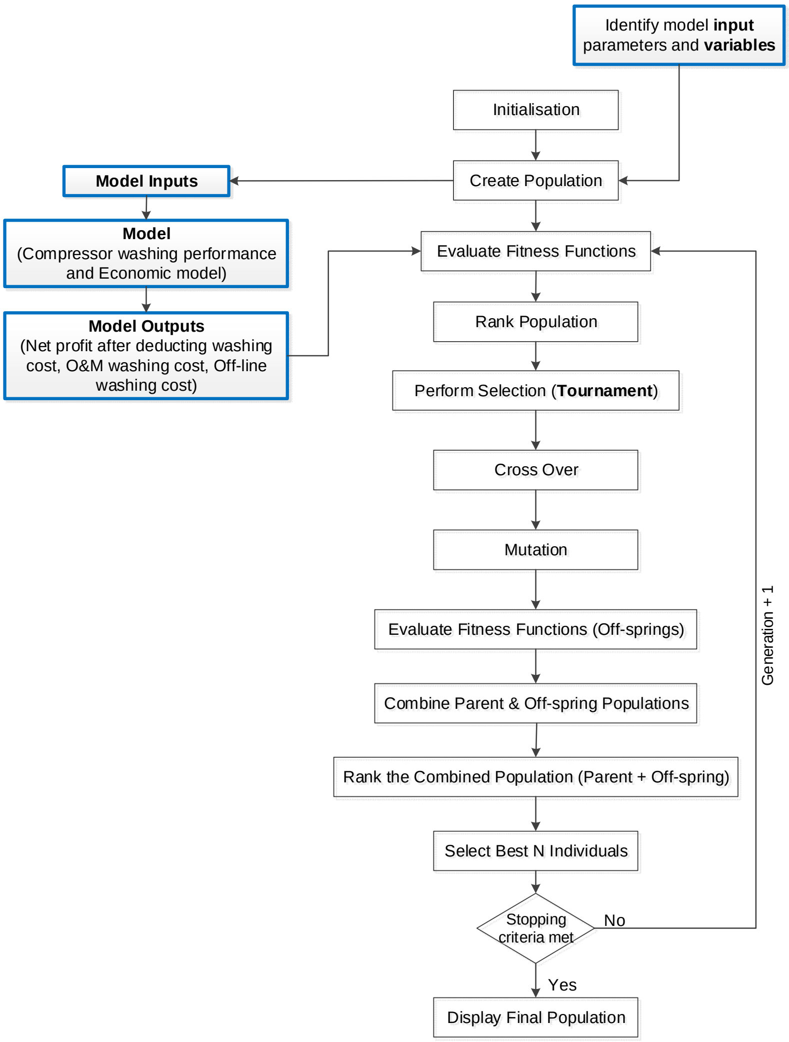


Figure 11 Structure of the NSGA II

4.1 Optimisation Case Study

The MOGA optimisation results have been analysed for the first year of operation. The total O&MCWE for the 307MW engine is higher at the narrow interval of washing and this decreases with a wider wash interval as shown on the left of **Figure 12.** The optimised maximum and minimum costs were found to be $70,000 and $23,000 respectively. The corresponding NPADWC for the same engine is shown on the right of **Figure 12**, indicating maximum and minimum profits of $1.36 million and 1.17 million respectively. It indicates that by widening the interval of compressor washing, the profit reduces. The combination of the two objectives O&MCWE (minimised) and NPADWC (maximised) amounts to the details shown in **Figure 13**. The Pareto surface shows that the rise in NPADWC is also related to an increase in the O&MCWE. The increase in profit is significant up to approximately $1.36 million which coincides with a cost of approximately $65,000 and corresponds to 95hrs intervals of washing. **Table 12** shows the analysis for the other engines, indicating that under similar circumstances, the optimum wash interval differs based on the engine size. This ranges from 90hrs to 110hrs for the same level of degradation and application. It can be observed that the light-duty 5.3MW engine has a negative net profit – not viable. For this engine, the NPADWC minimum and maximum are -$17,800 and -$23,200 respectively. The loss has been influenced by the relatively higher equipment cost.

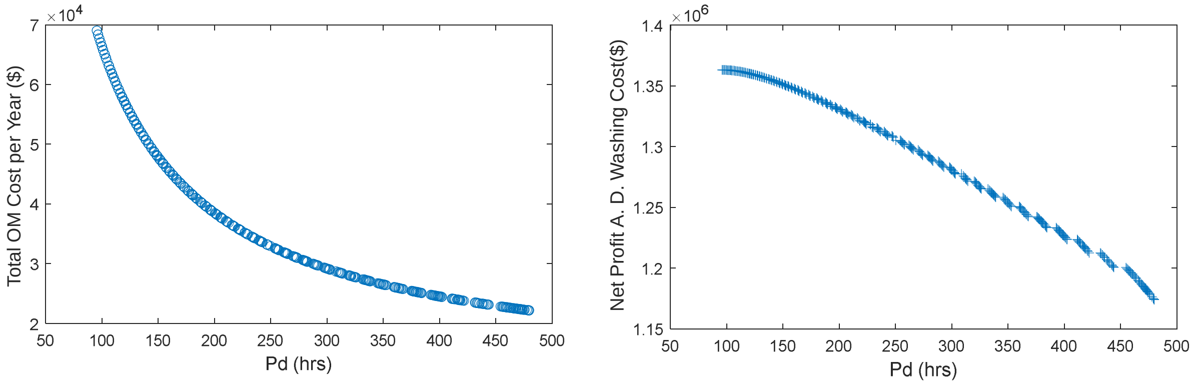


Figure 12 O&MCWE and NPADWC for 307MW engine

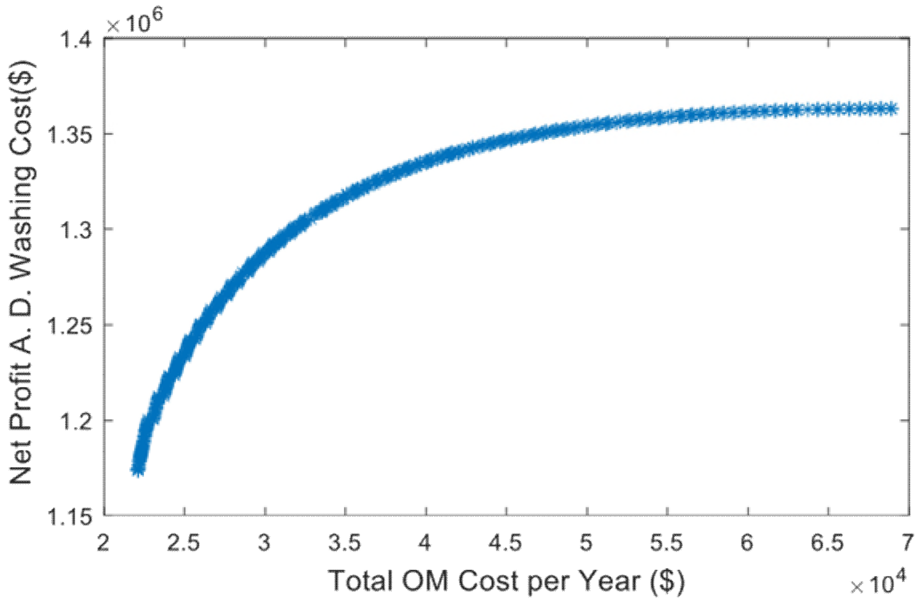


Figure 13 NPADWC versus O&MCWE for 307MW engine

Table 12 Optimum interval of washing for online 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
5.3	-1.78×10^4	3.8×10^3	-

The influence of degradation rate and optimum wash interval was also investigated. This included an increase in the degradation rate by a quarter and cases of reductions by a quarter and by half as indicated in **Table 13.** This shows that for increased degradation rate, the optimal wash interval became narrower (i.e., more frequent). The opposite is the case for lower degradation rates, where the interval is reduced. The table shows that increasing or decreasing the degradation rate did not make the 5.3MW operation viable.

Table 13 Degradation rates and corresponding optimised wash interval

Degradation Rates	*1.5	Default	*0.5	*0.25
Optimum interval (**307MW**)	80hrs	95hrs	110hrs	115hrs
General comments	Most frequent			Less frequent
Optimum interval (**5.3MW**)	-	-	-	-
General comments	Not viable	Not viable	Not viable	Not viable

5. Conclusions

The study has presented the economic viability of online compressor washing for different engine sizes, at different washing intervals. It was found that:

- the increase in BESP can be up to $1.1/MWh when comparing the clean and unwashed conditions. There can be up to a $0.3/MWh decrease in between the washed and unwashed condition.
- for the largest engine, the cost of degradation in a year is up to $8M, while for the smallest, it is about $200K.
- an increase in the washing frequency by 6.7 times, increased the RoI by 1.13 times.
- the RoI is nonlinear with an increase in engine size, though larger engines generally are more promising. This is influenced by the non-proportional rise in washing equipment cost; i.e the $/MW capital cost of the equipment is higher for smaller engines. In addition to the fact that the specific mass flow (hence washing liquid quantity) of individual engines is nonlinear.
- increasing the number of engines by 4 of the same type in a power station using the same washing system can increase the RoI by 3.4 times on average. Where smaller engines are used to make up for one engine, the increase in RoI can be 1.9 times as shown in the case of four 63MW against one 255MW engine.

- the RoI is less promising with reduced degradation. When the degradation rate is reduced by half and also a quarter, the RoI decreased to 353% and 269% respectively, for the 72-hour wash interval in the case of the largest engine.
- the smallest engine considered proved to be the least economically viable with compressor washing for this type of baseload application

The mathematical optimisation study that focused on the first year of operation identifies the optimum wash interval using GA. It shows that:

- washing more frequently is generally better, however, when satisfying the objective function for maximum net profit and minimum cost, the minimum possible wash interval is not the optimal solution.
- the optimal wash interval is also influenced by the degradation rate, as well as the engine size. The smallest engine considered did not show any optimal wash interval in the first year of operation. This is due to the negative net profit in the first year.

The study has shown the use of actual gas turbine degradation trends to estimate the viability of online compressor washing. This study can be extended to gas turbine operators wanting to invest or those already implementing compressor washing. For the smaller engines used predominantly in the oil and gas sector, the value of the energy production is so significantly high, that viability of online washing is expected to be far more optimistic.

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Nomenclature

AP_w	Additional profit due to washing
C_{ff}	fuel cost per annum for unwashed engine ($)
C_{fl}	Cost of fluid
CF_t	net cash flow at year t
C_{fuel}	cost of fuel per annum ($/MMBTU)
C_{fw}	fuel cost per annum for washed engine ($)
C_m	Maintenance cost of washing
COE_f	Cost of electricity unwashed engine
COE_w	Cost of electricity washed engine
COF_f	Cost of fuel unwashed engine

COF_w	Cost of fuel washed engine
C_{om}	yearly maintenance/operational cost ($)
C_{pw}	Capital cost Washing
C_w	Total cost of washing
E_t	electricity generation at year t
F_t	fuel expenditures at year t
i	interest rate (%)
I_t	investment expenditures at year t
L	litre
M_t	operation & maintenance expenditures at year t
nCriteria	number of criteria
NP_{ad}	Net profit after deducting washing cost
NP_{fe}	Net profit unwashed engine
NP_{we}	Net profit washed engine
nVars	number of decision variables
P_{clean}	clean power (MW)
Pd	Interval
$P_{unwashed}$	unwashed power (MW)
P_m	mutation probability
P_{washed}	washed power (MW)
R_f	income from selling electricity by unwashed engine ($)
$R_{P.lost}$	recovery of power loss (%)
R_w	income from selling electricity by washed engine ($)
SV_0	salvage value ($)
W_{fl}	Washed fluid
Δ	change in energy (MWh)
$	dollar

Acronyms

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 ($)
BESP	break-even selling price ($/MWh)
C	capital cost of equipment ($)
DPB	dynamic payback (yrs)
E	emission
EOH	engine operating hours (hrs)
ES	electricity sold ($)
ETR	emission tax rate
gen	generation
GT	gas turbine
I	initial cost of the investment
IRR	internal rate of return (%)
MOGA	multi objective genetic algorithm
MW	megawatt
MWh	megawatt hour
N	life expectancy of the equipment (yrs)

n	lifetime of the investment (yrs)
NPADWC	net profit after deducting washing cost
NPV	net present value ($)
NSGA II	non-dominated sorting genetic algorithms ii
O&M	operation and maintenance cost
O&MCWE	operation and maintenance cost of washing equipment
PopSize	population size
PWF	present worth factor
RoI	return on investment (%)
TERA	Techno-Economic, Environmental and Risk Analysis
TI	taxable income ($)
TR	tax rate

Appendix

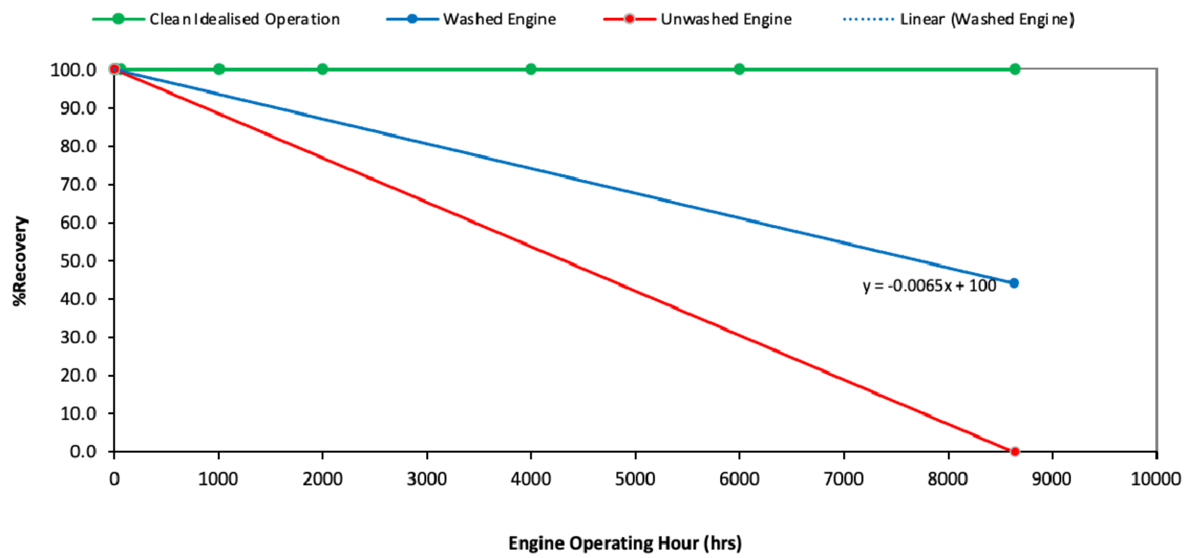

Figure 14 % Recovery of lost power washed engine

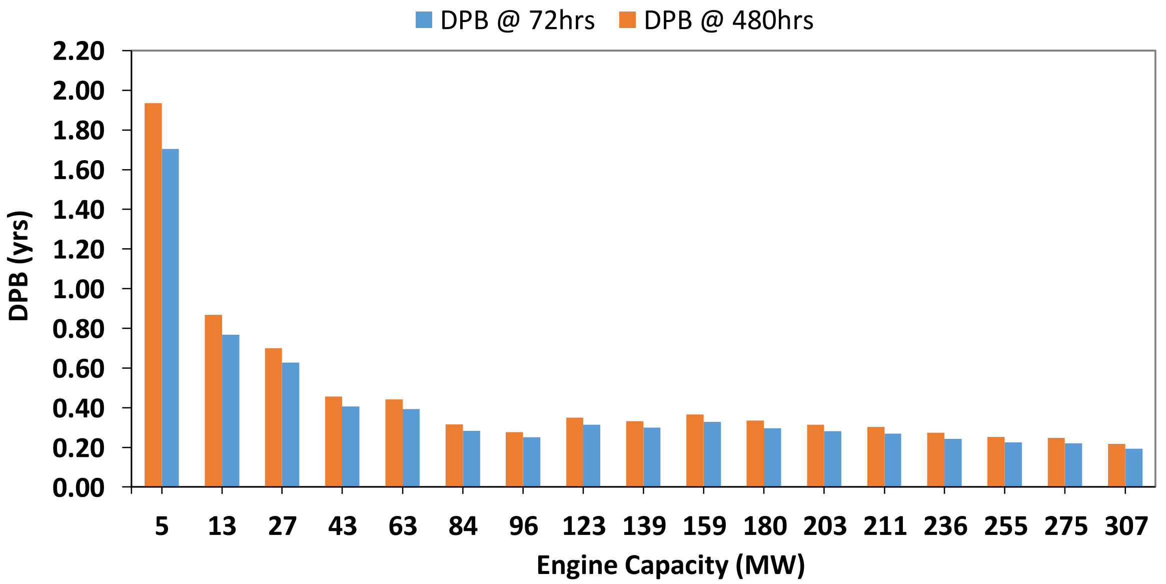

Figure 15 DPB of washing for at 72 and 480-hr intervals for different engines

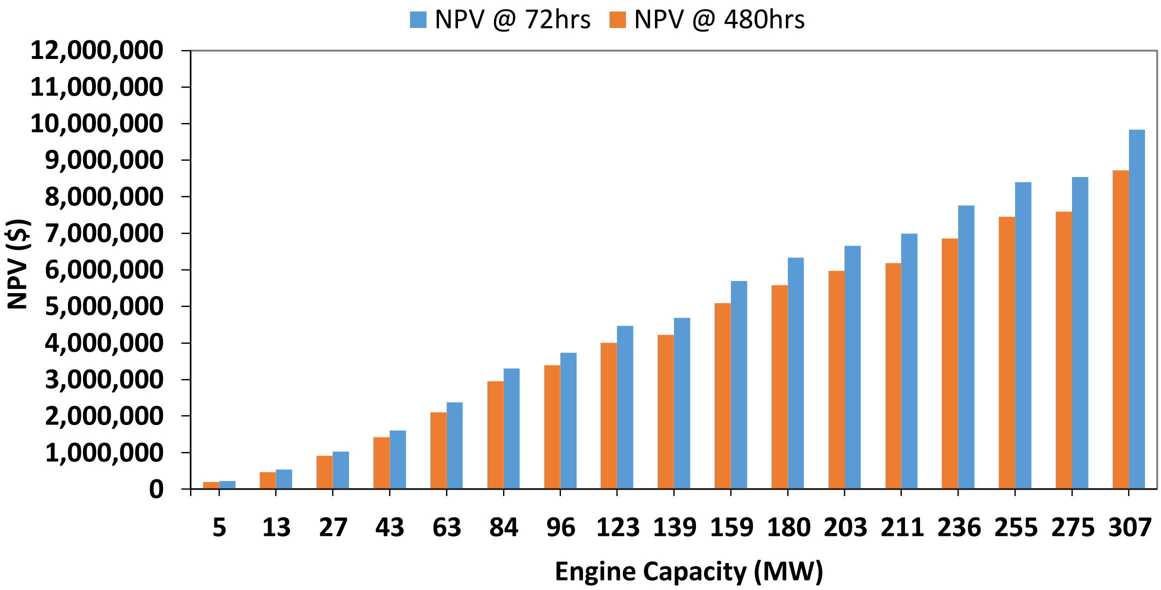

Figure 16 NPV of washing for at 72 and 480-hr intervals for different engines

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