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EMPIRICAL APPROACH FOR GAS TURBINE EMISSIONS TAX EVALUATION

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ABSTRACT

Gas turbine engine are one of the major prime movers used in industry and aviation to produce energy and power. However, a major limitation of gas turbine engines, in relation to climate change, is that they are mostly powered by fossil fuels which when burnt, release emissions in varying amounts into the atmosphere. Growing evidence worldwide, suggests that emissions from fossil fuels could be a major contributor to global climate change. As a result, various emission policies and goals, aimed at mitigating the effect of climate change are on the increase. Current trends in emissions policies tend towards potential for future taxation of emissions by any system capable of generating emissions. Therefore, current technologies, systems and procedures must be ready for potential changes in future economic climate due to changing environmental policies.

In this study, an emissions model is developed which evaluates the emissions generated and any potential emissions tax payable on emissions generated by a gas turbine engine over an operating horizon. The developed approach applies gas turbine information on fuel type, considered emissions and adopted emissions control to estimate the amount of emissions generated by a gas turbine. As a validation to the estimating methodology, the developed emissions model is applied to evaluate the known emissions rate for some gas turbines. Comparison of emissions model estimates with recorded values from the U.S. department of energy and the California energy commission reveal a difference of less than 3%.

Keywords: Gas Turbine, Emissions model, Emission rate, Empirical modelling

NOMENCLATURE

E	Emissions
F	Factor
P	Air Pollution
CE	Cost Effectiveness
CO	Carbon monoxide
CI	Electricity Cost Impact
EU	European Union
kW	Kilowatt
MF	Matching Factor
MW	Megawatt
MW	Molar Weight
PM	Particulate Matter
UK	United Kingdom
US	United States
DLN	Dry Low NOx
EICO	Carbon Emissions Index
EINOx	NOx Emissions Index

EMR	Emission rate
EOH	Engine Operating Hours
EPA	Environmental Protection Agency
ESPR	El Segundo Power Redevelopment
ETax	Emissions Tax
ET_{rate}	Emissions Tax rate
EU ETS	EU Emissions Trading System
LAER	Lowest Achievable Emissions Rate
NOx	Nitrogen oxide
O2	Oxygen
P	Pollutant
PPMV	Parts Per Million by Volume
PSR	Perfectly Stirred Reactor Model
REM	Repurposed Engine model
REM_UC	Uncontrolled Repurposed Engine Model
REN21	Renewable Energy Policy Network for the 21st Century
VOC	Volatile Organic Compounds
w.r.t.	with respect to
Subscript	
Activity	
control	
d	dry
E	Estimated
Factor	
Rate	
conc.	Concentration

INTRODUCTION

In recent years, a great deal of awareness and consciousness has emerged globally in relation to emissions reduction. According to a 2014 report by the Renewable Energy Policy Network for the 21st Century (REN21), about 78% of worldwide energy comes from non-renewable sources and 22% from renewable sources. Non-renewable sources such as fossil fuels are one of the major sources of greenhouse gases identified as potential contributors to global climate change. Consequently, current environmental policies and economic trends are shifting towards reliance on clean renewable energy sources. Even though complete reliance on renewable energy sources is quite a while away, if at all possible, it is necessary for the survival of any organisation, particularly those operating equipment which rely on non-renewable energy sources, to build in sufficient flexibility into their systems and organisation procedures so as to accommodate the ever changing environmental and economic trends which increasingly favours clean renewable sources.

As an example, a fast approaching change in environmental policy which may affect numerous installations in the UK is the carbon emissions tax policy. This policy is expected to take effect from 1st April, 2019 in the event that the UK leaves the EU in March 2019 without a deal [1]. The carbon emissions tax is a measure that would introduce tax on carbon dioxide emissions (*and other greenhouse gas emissions on a carbon equivalent basis*) produced by stationary installations currently in the EU Emissions Trading System (EU ETS). This carbon emissions tax is expected to support the UK to meet its legally binding carbon reduction targets which will be unaffected by leaving the EU. Similar policies like this may potentially emerge in the future and organisations with the potential of being affected need to be ready and able to handle this changes.

Presented in this study is an approach for evaluating the emissions rate and any associated emissions tax for gas turbines over an operating period. The approach utilizes information on engine fuel type, considered emissions and implemented emissions control technology to evaluate gas turbine engine emissions rate and emission tax. The emissions model presented is a component of an overall economic model developed for gas turbine techno-economic analysis [2].

EMISSIONS MODELLING

Emissions modelling involves capturing all elements, characteristics and variables in a system which influences the emissions generated by the system, for the purpose of estimating or simulating the amount of pollutant released by the considered system. With very few exception, emissions are not measured directly but are estimated using a variety of models ranging in complexity from simple lookup tables to highly sophisticated and complex algorithms used to predict emissions [3].

Gas turbine emissions modelling usually entails a thorough understanding and investigation of the processes and phenomenon occurring in a gas turbine combustor. This often results in the development of highly complex numerical and computational simulation models which are usually only applicable to a specific set of considerations. Emissions perdition techniques fall into four general categories [4].

- Empirical models
- Semi empirical models
- Simple physics-based models
- High fidelity simulation models

For a gas turbine emissions modelling approach to be relevant in policy making and quick reaction studies (particularly for an organisation seeking to incorporate swift emissions estimating flexibility into its system), it is expected that the approach should:

- Adequately describe the physical relationships between operating conditions, combustor design parameters and pollutant emissions in a consistent way [4].
- Implement design and operating parameters that would be suitable for an analyst to employ in projecting future technology.
- Possess sufficient generality such that it can be applied to estimate pollutant emissions in combustor designs across engine manufacturers [4].
- Have clearly defined and well understood uncertainties and limitations.

Empirical and physics-based models possess the most characteristics to meet the outlined requirements.

Empirical models

Empirical models are models based on observation, experience and experiment as opposed to any clearly describable mathematical relationship for a considered system. Empirical and semi-empirical emission models possess characteristics that support consistent correlation across all combustors as opposed to different variants for every type of combustor. Equation (1) and Equation (2) describe a common industry empirical methodology for NOx and CO emissions evaluation [4].

$$\mathrm{EINO}_x = f_1\,(T_3) {P_3}^{0.4} \exp\,(19(\bar{h} - h)) \qquad (1)$$

$$\mathrm{EICO} = \frac{f_2\,(T_3)}{P_3} \qquad (2)$$

Physics-Based models

Physics-based models like the Perfectly Stirred Reactor Model (PSR) and the PLUG Flow Reactor (PLUG) use physics-based principles to approximate the behaviour and estimate emissions generated in considered combustion systems. Physics based models require more physical input and variables and are more complex than empirical methods [4].

In this study, an empirical approach to gas turbine emissions estimation is presented. The approach utilizes engine operating information to evaluate the amount of pollutant emissions generated by a gas turbine engine.

Applications of Emissions Modelling Techniques

Due to the variability, complexity, and intricacy associated with gas turbine combustor modelling and emissions evaluation, several techniques have been employed to evaluate the emissions generated by gas turbines. Presented below are studies which have implemented some of these techniques.

- Soroudi et al apply reactor network modelling approach to predict the NOx emissions generated by a stationary gas turbine. The reactor network is constructed based on a spatio temporal distribution mixture fraction, upstream of the combustor flame front and flow residence time within the flame volume. Results from the study reveal that the presented model accurately predicts NOx emissions in the considered dry low emissions combustor.

Further considerations in the study reveal that flame position and fuel consumption have the most significant effect on NOx emissions [5].

- Honegger in his study on gas turbine combustion modelling for a parametric emissions monitoring system, developed a gas turbine combustor model, based on a lean premixed combustor, to predict NOx and CO emissions formation in gas turbines. Comparison of predicted emissions results with those obtained from a turbine test cell, operating under similar conditions, revealed a highly accurate match for NOx emission estimates at any load. However, Honegger reported that due to high variations in CO formation at part load operation, model estimates only matched the CO test cell results at full load [6].
- Meloni performed 3D numerical combustion simulation to evaluate pollutant emissions and the temperature field in a case study gas turbine engine similar to the General Electric Frame 6001B. Combustion modelling and NOx emissions evaluation where respectively conducted using a flamelet model and Zeldovich's mechanism. For CO estimation, an innovative approach was applied to compute the Rizk and Mongia relationships through user defined functions. The author reported that in comparison to previously recorded experimental results, NOx predictions delivered the best results with slight overestimation in CO predictions [7].
- İlbaş and Karyeyen numerically investigated the combustion performance and emissions in a model gas turbine combustor. Numerical modelling of turbulent non-premixed diffusion flames was performed using the K-E model of turbulent flow, the PDF/mixture fraction model of non-premixed combustion and the P-1 radiation model. Results from the overall investigation concluded that coke oven gas, town gas I, town gas II and water gas were appropriate for usage as alternative fuel delivering suitable performance with lesser overall emissions in comparison to generator gas [8].

This study presents an approach for evaluating the emissions generated by gas turbines based on a unit's emissions activity, associated emissions factor and implemented emissions control technology. The approach is less complex than conventional techniques and also sufficiently generic for application in estimating the emissions rate and associated emissions tax for a variety of gas turbine emissions consideration.

METHODOLOGY

The emissions model presented in this study is a component of an overall economic model associated with estimating the emissions generated and any potential emissions tax payable on emissions generated by a gas turbine.

Emissions Model

The developed emissions model applies gas turbine information on fuel type, emissions type and adopted emissions control to estimate the emissions generated (emissions rate) by a gas turbine (Figure 1). Equation (3) through Equation (6) characterize the emissions estimating model.

The main pollutant emission considered in this study include Nitrogen oxides (NOx), Carbon monoxide (CO), Volatile Organic Compounds (VOC) and Particulate Matter (PM). Three categories of emissions control are considered. They include water/steam injection control, lean-premix combustor control and uncontrolled (referring to a system with no implemented emissions control). Fuel type consideration has also been assigned under four main categories. These include: Natural gas fired units, Distilled oil fired units, Landfill Gas fired units and Digester fired units.

Emissions Rate

The emissions rate of any system is characterized by the emissions activity, the emissions factor and the emissions control associated with the system. The **emissions activity** quantifies how active the system is. It is measured in "activity units" per period. The **emissions factor** relates the activity of the system to the type and amount of pollutant generated by the system and the **emissions control** quantifies the efficiency of the implemented pollutant control. Equation (3) describes the emissions rate.

$$EMR = E_{Activity} \times E_{Factor} \times E_{control} \qquad (3)$$

Where EMR is the Emissions rate per period, $E_{Activity}$ is the emissions activity per period, E_{Factor} is the emissions factor per activity and $E_{control}$ is the emissions control factor. In this study, **a control factor of 1 indicates that the emission control factor is built** into the considered system and no external control technology is implemented. A **control factor less than 1 quantifies the efficiency of emissions control** for an adopted external emissions control technology.

Emissions Factor

The emission factor in this study is evaluated from Equation (4) using data from the U.S. Environmental Protection Agency's emissions factor documentation (AP-42 data sheet) for gas turbines. In this documentation, pollutant concentrations provided are based on average values from multiple tests conducted on various turbines, and are categorized based on fuel type and control technology for all pollutants generated from gas turbines. A matching factor is used to map the evaluated emissions factor to a particular engine unit as described in Equation (4) and Equation (5).

$$E_{Factor} = \left(P_{conc.} \times 10^{-6} \times \left(\frac{1}{Molar\ Volume}\right) \times MW \times F_d \times \left(\frac{20.9}{20.9 - \%O_2}\right)\right) \times MF \qquad (4)$$

Where

$$MF = \frac{E_{Factor}}{E_{FactorE}} \qquad (5)$$

MF is the matching factor. The **matching factor** compensates for differences in fuel type, gas composition and engine operating conditions when matching a considered engine unit. E_{Factor} is the actual emissions factor of engine to be matched and $E_{FactorE}$ is the estimated emissions factor. When $MF = 1$, $E_{Factor} = E_{FactorE}$ this implies that no matching is required by the emissions estimating model. F_d represents the dry oxygen factor of the considered fuel type and $\%O_2$ represents the corrected oxygen concentration. **F_d, Molar Volume and $\%O_2$ are the gas properties associated with the considered fuel type**. The Molar Weight (MW) is associated with the considered pollutant properties.

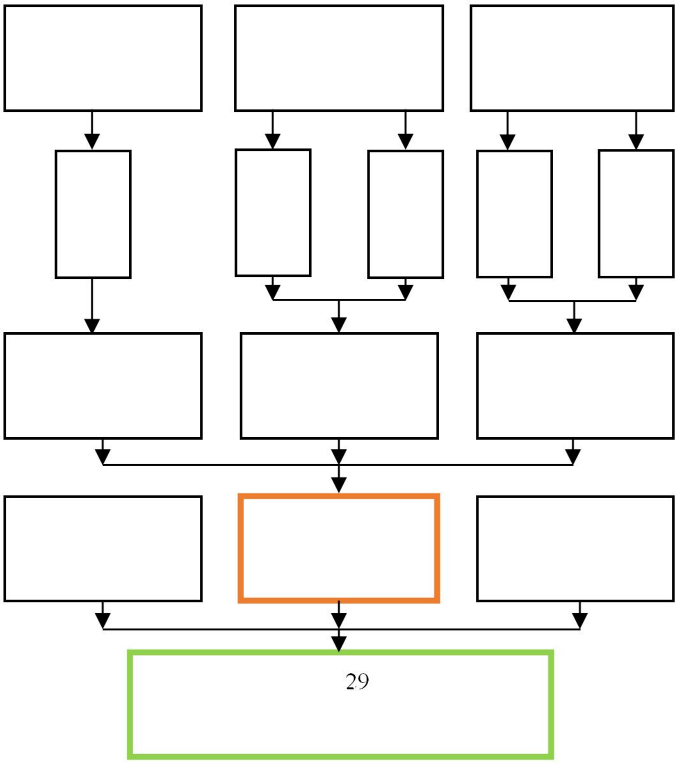


Figure 1: Emissions Evaluating Model

Emissions Tax

The implemented emissions methodology provides for the estimation of emissions tax per period, with respect to a set emissions charge, an evaluated emissions rate and engine operating hours for a considered unit. Equation (6) describes this aspect of the emissions model.

$$ETax = E_{charge} \times EMR \times EOH \qquad (6)$$

Where *ETax* is the emissions tax per period considered. *E* $_{charge}$ is the charge per tons of emissions generated. *EMR* is the emissions rate per period descried in Equation (3) and *EOH* is the engine operating hours per considered period.

Emissions Evaluating Methodology

Input information relating to fuel type (obtained from unit performance and operating point data), considered pollutant emission and emissions control type are retrieved for a considered gas turbine unit and supplied into the emissions model. **The fuel flow rate of the gas turbine is the emissions activity**. This is expressed in MMBTU/yr.

Based on considered pollutant emissions and emissions control technology, the EPA’s AP-42 data sheet is consulted to retrieve the appropriate emissions factor. The emissions factor retrieved from the AP-42 documentation is classed as the estimated emissions factor $E_{FactorE}$. Equation (7) is then applied to evaluate the actual emissions factor $E_{FactorE}$ in lb/MMBTU based on an associated matching factor (*MF*). This is usually a value of 1 for most evaluations. For scenarios where the actual emissions factor for a considered engine is known, then model estimates can be adjusted using a matching factor evaluated from Equation (5). As opposed to using the AP-42 data sheet, the engine’s pollutant concentration can be provided in PPMV (parts per million by volume) and Equation (4) applied to evaluate $EFactor$ in lb/MMBTU.

$$E_{Factor} = E_{FactorE} \times MF \qquad (7)$$

After obtaining the actual emissions factor E_{Factor}, the emission rate, EMR expressed in lb/yr is evaluated from Equation (3). Further conversion expresses the calculated emissions rate in tons/yr. The expression of emissions generated in tons per year enables the evaluation of additional variables like the cost effectiveness (*CE*) and the electricity cost impact (*ECI*) of an adopted emissions mitigation technology as described in Equation (8) and Equation (9).

$$CE = \frac{Owning\ Cost\ of\ Emissions\ Technology}{Amount\ of\ Emissions\ Removed} \qquad (8)$$

$$ECI = \frac{Owning\ Cost\ of\ Emissions\ Technology}{Electricity\ Generated\ per\ period} \qquad (9)$$

Finally, an annual emission tax is calculated from Equation (6) based on the evaluated emission rate (EMR), a retrieved annual engine operating hours (EOH) and a set emissions charge (E_{charge}) in dollars per ton of emissions generated.

Model Validation

As a validation to the implemented methodology, the developed emissions model has been applied to estimate the emissions rate for some gas turbines. Results from the estimates are compared with records from investigations, conducted for the U.S. department of energy, by ONSITE SYCOM Energy Corporation [9] and Investigations conducted by the California energy commission for the EL Segundo Power Redevelopment Project (ESPR) [10]. Table 1 and Table 2 respectively contain modelling parameters supplied to the emissions model for SYCOM and ESPR estimates. Figure 2 to Figure 4 compare results obtained from model estimates with those documented from SYCOM and ESPR investigations.

Table 1: Emissions Modelling Parameters (SYCOM Estimates)

Engine	Considered Pollutant	Fuel Flow MMBtu/hr	F_d	%O_2	Molar Volume
501-KB7	NO_x	61	8740	15	386.8
Centaur50	NO_x	49	8740	15	386.8
Frame7FA	NO_x	1585	8740	15	386.8
LM2500+	NO_x	206	8740	15	386.8
Taurus60	NO_x	57	8740	15	386.8

* *F_d dry oxygen F-factor for natural gas and molar volume are considered at 1 atm and 68°F*

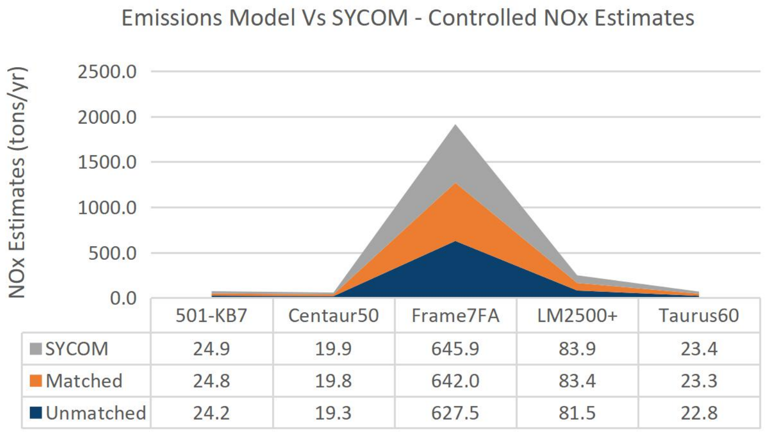
Table 2: Emissions Modelling Parameters (ESPR Estimates)

Engine	Considered Pollutant	Fuel Flow MMBtu/hr	F_d	%O_2	Molar Volume
Unit 5	CO	1691	8710	15	385.3
Unit 5	NO_x	1691	8710	15	385.3
Unit 5	VOC	1691	8710	15	385.3
Unit 5	PM10	1691	8710	15	385.3
Unit 5	SO_x	1691	8710	15	385.3

** F_d dry oxygen F-factor for natural gas and molar volume are considered at 1 atm and 68°F*

Outlined below, are assumptions made for emissions model validation.

- All engines are running at 80% capacity [9].
- All SYCOM engines operate 8000 full load hours per year [9].
- The considered ESPR engine operates 5456 full load hours per year [10].
- All engines operated burn Natural Gas with Identical fuel composition [9, 10].
- All engine units considered implement DLN combustor technology for emissions control [9, 10].



	501-KB7	Centaur50	Frame7FA	LM2500+	Taurus60
■ SYCOM	24.9	19.9	645.9	83.9	23.4
■ Matched	24.8	19.8	642.0	83.4	23.3
■ Unmatched	24.2	19.3	627.5	81.5	22.8

Figure 2: Emissions Model Vs SYCOM Estimates (Controlled NOx)

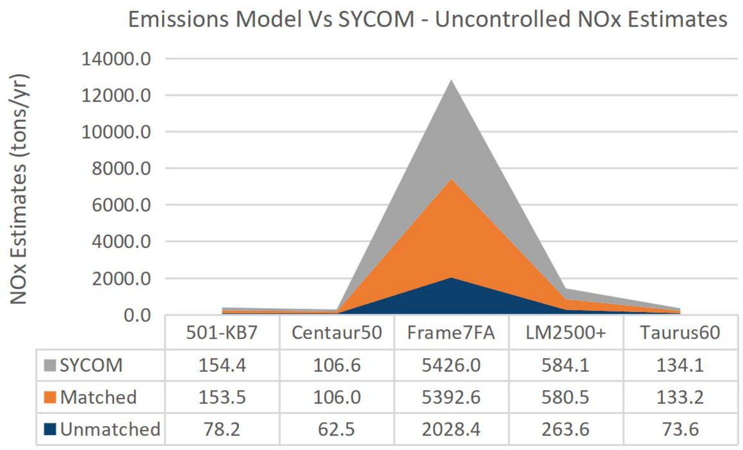


Figure 3: Emissions Model Vs SYCOM Estimates (Uncontrolled NOx)

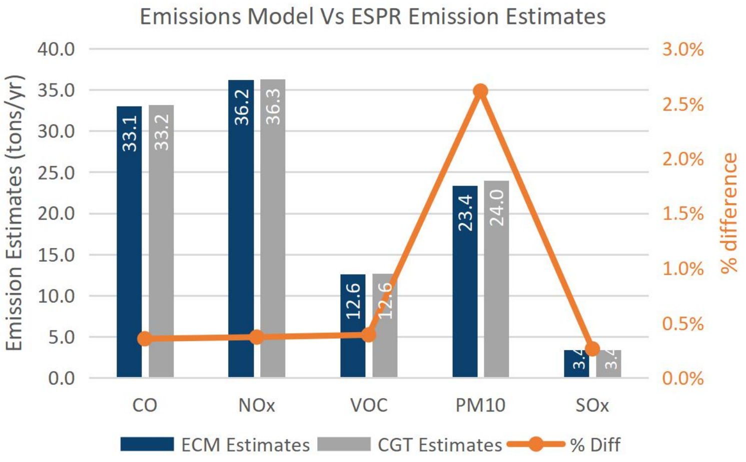


Figure 4: Emissions Model Vs CTG Estimates

In Figure 2 and Figure 3, the 'Matched' model estimates for NO_x emissions rate are very similar to actual estimates from SYCOM investigations, with less than 1% difference. This observation is consistent for model estimates with and without emissions control considered.

In the 'Unmatched' case, model estimates for the considered gas turbines, **with emissions control** (Figure 2**)**, are less accurate than the 'Matched' case. However, results obtained are still reasonably close to documented SYCOM estimates with less than 3% difference. Estimates for the 'Unmatched' case **without emissions control** **(**Figure 3**),** show large variations between model estimates and SYCOM. This is due to unaccounted variations in fuel composition and operating conditions for the 'Unmatched' model estimates.

The ‘Unmatched’ case for both the controlled and uncontrolled NOx estimates, does not account for differences in gas properties of the considered fuel type like dry oxygen factor, F_d, the Molar Volume and the corrected oxygen concentration, $\%O_2$. This results in variation in the model estimates when precise values of gas properties are unknown. However, these difference are accounted for by the matching factor in the ‘Matched’ case.

In Figure 4, ECM refers to ‘Economic Cost Model’. This is the name given to the economic modelling and evaluation approach from which the emissions model presented in this study has been extracted [12]. Results obtained in Figure 4 show that model estimates for emission rate in tons per year are very close to the actual estimates from ESPR investigations with percentage difference less than 3% for all pollutants considerations.

APPLICATION, RESULTS AND DISCUSSION

The emission estimating approach presented in this study has been applied to investigate the NOx emissions rate and potential emissions tax for a model turbojet engine repurposed for alternative profitable use in electrical power generation. Results obtained have been compared against those from potential competitor units. This comparison is done to evaluate the feasibility, from an environmental, performance and economic perspective, of applying the repurposed engine model for electrical power generation. Details of the repurposed engine model can be found in a study conducted by Rowlands and Savill in 2018. The study focused on techno-economic research analysis for effective power generation from aero-engines with minimal emissions [11] . Table 3 contains relevant details for the repurposed engine model (REM) and the considered potential competitor units investigated in this study.

Table 3: Emissions Modelling Parameters

Engine	Power Output (MW)	LAER (PPMV)	Fuel Flow (MMBtu/hr)	F_d (dscf/MMBTU)	Molar Volume (dscf/lb-mol)
$REM_{\_UC}$	17.27	87	164	8740	386.8
REM	17.27	25	164	8740	386.8
GG4/FT4	17.00	42	258	9220	406.7
LM1600	13.00	25	155	8740	386.8
LM2500	22.20	25	206	8740	386.8

** F-factor for natural gas and fuel oil and are considered at 68°F and 1 atm*

Assumptions

To ensure relevance of the considered scenarios to the investigation conducted, the following assumptions have been made.

- Each engine unit operates for 6000 hours each year at 80% capacity [11].
- Each unit is taxed 50$/ton of NOx generated.
- All engines except the GG4/FT4 burn natural gas and are fitted with a DLN combustor [11].
- The GG4/FT4 burns fuel oil and implements water/steam injection for emissions control [11].
- DLN emissions control incurs an owning cost of 19.2$/kW w.r.t. the REM power output [9].
- Water/steam injection emissions control incurs an owning cost of 37$/kW w.r.t. the REM power output [9].

In the following section, REM describes the repurposed engine model with DLN emissions control technology implemented and REM_UC describes the repurposed engine model without NOx emission control.

In Figure 5, results reveal that the GG4/FT4 unit generates 64% more NOx emissions, annually, than the REM. Similarly, the LM2500 unit generates about 20% more NOx than the REM. This higher emissions rate can be attributed to the higher fuel flow associated with the considered competitor units operating under identical conditions. For instance, the LM1600 unit generates about 6% less NOx at a fuel flow 5% less than that of the REM.

Further observation of results reveal that REM_UC generates about 71% more NOx than the REM with implemented NOx emissions control at the same fuel flow rate. This notable difference in emission rate is reflective of the effectiveness associated with the implemented emissions control technology.

Results obtained also suggest that at fixed emissions tax rate, units with greater NOx emission levels incur higher emissions tax over an operating period. This is reflected in Figure 6 which shows that the REM_UC and the GG4/FT4 incur the highest NOx emissions tax in proportions analogous to the quantity of NOx generated.

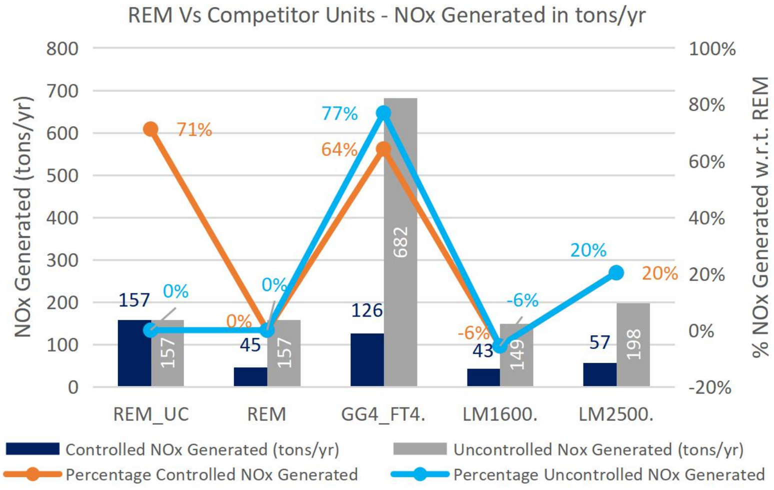


Figure 5: Model Estimates NOx Generated in tons per year

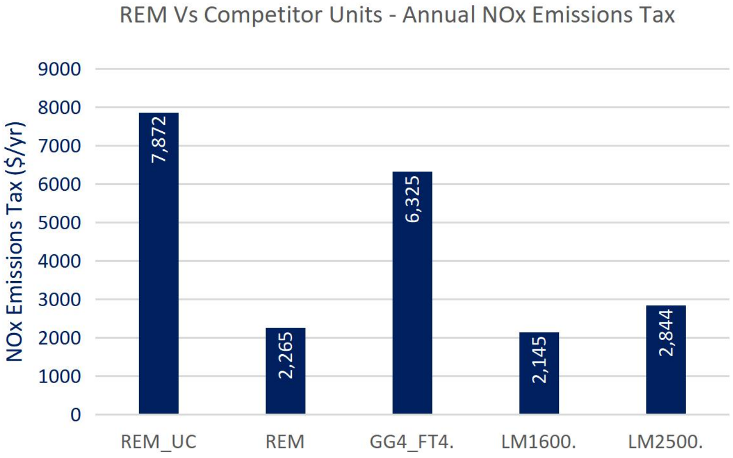


Figure 6: Model Estimates for Emissions Tax in dollars per year

Further investigations evaluated the quantity of NOx emissions removed annually with respect to controlled and uncontrolled considerations for each unit. In Figure 7, the evaluated amount (in tons per year) and percentage of NOx removed annually is presented. Result reveal that the GG4/FT4 records the highest amount of NOx removed in tons per year and LM1600 records the lowest amount of NOx removed in tons per year.

Expressed as percentage of NOx emission removed, it is observed that the DLN emissions control implemented on the REM, LM1600 and LM2500 engine models remove about 71%

of NOx emissions and the GG4/FT4 with water and steam injection implemented removes about 81%. This outcome can be attributed to two reasons; the lowest achievable emissions rate (LAER) associated with the implemented emission control on the investigated engines (Table 3) and the amount of NOx generated by each unit without emissions control implemented (Figure 5). The greater the quantity of NOx generated in an uncontrolled unit, the higher the percentage of NOx emissions removed when an emissions control is implemented. Though the GG4/FT4 unit operates water/steam injection (a less effective emissions control technology than the DLN) for emissions control, the quantity of NOx emissions generated in the uncontrolled scenario is significantly higher than other engines considered (Figure 5). This implies that when emissions control is implemented on the GG4/FT4, more NOx will be removed to achieve the LAER associated with the implemented control.

Figure 8 relates the cost of owning the implemented emissions control technology with the quantity of NOx emissions removed. This evaluates to the cost effectiveness of the implemented emission control technology described in Equation (8). In general, the higher the cost effectiveness the less desirable an investment option. **Higher cost effectiveness implies that the quantity of emissions removed does not adequately justify the cost of owning the emissions control technology.**

In Figure 8, the cost effectiveness of the REM is 20% higher than that of the LM2500 and 61% higher than the GG/FT4. This is so because in relation to the owning cost, the amount of NOx removed annually is higher on the GG4/FT4 and the LM2500 than the REM. A lower cost effectiveness is observed for the REM in comparison to the LM1600 as a result of the higher quantity of NOx emissions removed.

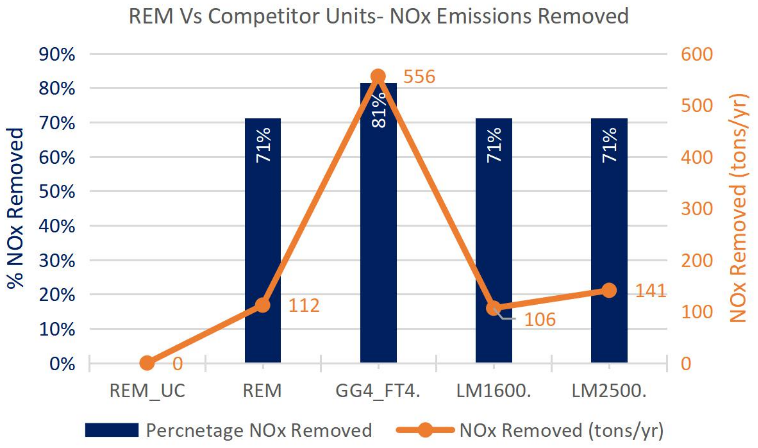


Figure 7: Model Estimates NOx Removed in tons per year

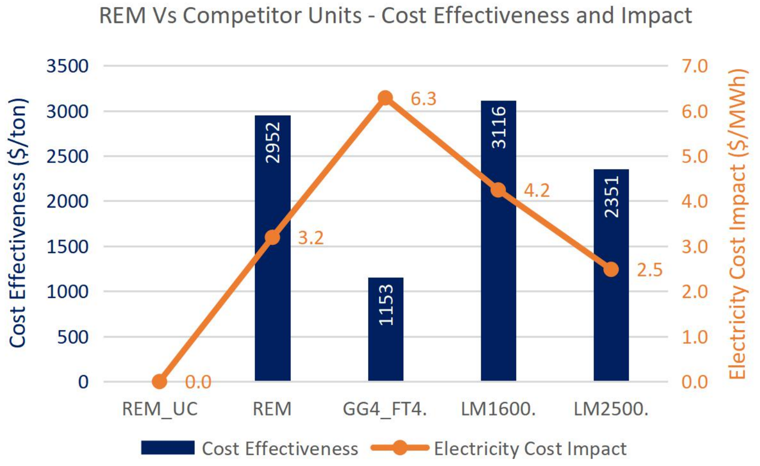


Figure 8: Model Estimates Cost Effectiveness and Electricity Cost Impact

Figure 8 also provides information on the electricity cost impact (*ECI*) of the implemented emissions control for all considered engines. ECI quantifies the impact that the cost of owning an implemented emissions control technology has over the cost of electricity generated annually. Results show that the REM has an electricity cost impact 22% higher than the LM2500 and 49% lower than the GG4/FT4. In general, the higher the electricity cost impact of an option, the less desirable that option.

Based on the assumptions made and conditions investigated in this study, results obtained suggest that the repurposed engine model, with an implemented emissions control technology, can compete, from an emission mitigation perspective, with the potential competitor units considered. To gain deeper insight into the potential feasibility of repurposing the considered engine model for alternative, profitable use in electrical power generation, an extensive techno-economic analysis will be required.

It is difficult to give a completely reliable evaluation of the performance and economic feasibility of the considered repurposed engine model without a working prototype and in-depth economic analysis. However, preliminary evaluations of emissions rate and any potential emissions tax can provide a good first hand estimate of the potential environmental benefits and limitations obtainable from the engine model. This is relevant in guiding subsequent organisational decisions and future projection in relation to environmental and economic policies, as it affects the proposed engine modification.

CONCLUSION

In this paper, an empirical approach for estimating the emissions rate and associated emissions tax for gas turbine engines has been presented. The approach utilises engine information on fuel type, considered pollutant emission and implemented emissions control to evaluate emissions rate and applies the evaluated emissions rate to estimate emissions tax, based on a set emission charge and engine operating hours per year.

The presented emissions evaluating approach has been applied to accurately estimate the known emissions rate for some gas turbine units. Results from the estimates are compared with records from investigations, conducted for the U.S. department of energy, by ONSITE SYCOM Energy Corporation [9] and Investigations conducted by the California energy commission for the EL Segundo Power Redevelopment Project (ESPR) [10]. The comparison reveals a difference of less than 3% between model estimates and recorded emissions estimates.

The developed emissions model has also been applied to evaluate the NOx emissions rate and associated emission tax for a model turbo jet engine repurposed for electrical power generation. Comparison is made between the estimated emissions rate for the repurposed engine model with those from potential competitor units. Results obtained suggest that the repurposed engine model can potentially compete from a NOx emissions mitigating perspective with the considered competitor units.

The scope of this study has been limited to emissions modelling and evaluation. In order to obtain a clearer insight into the potential feasibility of repurposing the considered turbojet engine model for alternative, profitable use in electrical power generation, it is recommended that an extensive techno-economic analysis be conducted. Although preliminary evaluations of emissions rate and potential emissions tax provide a good first hand estimate of the potential environmental benefits and limitations obtainable from the engine model, this does not provide the intrinsic technical and economic information required for adequately informed decision making.

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