CRANFIELD UNIVERSITY

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ASSESSING BIOMASS-FIRED GAS TURBINE POWER PLANTS: A TECHNO-ECONOMIC AND ENVIRONMENTAL PERSPECTIVE

SCHOOL OF ENGINEERING
Thermal Power

PhD Full Time

Academic Year: 2010 - 2013

Supervisors: Dr Giuseppina Di Lorenzo
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ABSTRACT

Fossil fuels continue to deplete with use as they are irreplaceable. In addition, the environmental impact with the continuous use of these conventional fuels has generated global concern due to the production of harmful emission gases. An alternative source of energy has become inevitable. Technological advancements in the area of biomass use for both aviation and power generation are at different levels of development.

There is however the need for an integrated approach to assess gas turbine engine behaviour in terms of performance, emission and economics when they are running on biofuels. The current research work is concerned with finding alternative fuel resources for use on stationary gas turbine engines for power generation with the necessary identification of suitable biofuels using a multi-disciplinary approach.

A techno-economic, environmental and risk assessment (TERA) model comprising the performance, emissions, economics and risk modules has been developed. There had been several simulations of two gas turbine engines (GTEs) to ascertain the effects of both ambient and operating conditions and the effect of fuel types on the engines. These simulations were done with the use of an in-house code-the Turbomatch and a code developed for the steam cycle which is employed for the combined cycle simulation.

A novel multi-fuel emission model has also been developed. The code is suitable for implementation of conventional fuels like the Jet A1 and the natural gas, in addition to liquid biofuels (Jatropha) and gaseous syngases derived from wood and sugarcane bagasse. The arrangement of the reactors depicting the combustors was done to adequately capture gas emissions especially NOx, CO and CO_2. The results show different levels of NOx, CO and CO_2 emissions when compared to those from fossil fuels which translates into reduced emission tax penalties. On a life cycle basis, the Carbon emission is zero as the biomass reuses the CO_2 during growth.

Finally, the levelized costing method was employed for the economic analysis. The result showed a lower fuel cost for biofuels than the natural gas. This consequently affects the overall cost of electricity. The cost of electricity for the natural gas fired GT in simple cycle is relatively lower than the biomass integrated gasification combined cycle power plants. This is largely due to the higher capital cost as a result of more system modules in the case of the biomass integrated gasification combined cycle (BIGCC). The risk module also showed the limit within which the BIGCC is viable and profitable in respect to all the necessary input variables of first year operation cost, specific fuel cost, plant capacity factor, tax and the specific total fixed cost.

Keywords:

Biomass, Biomass Integrated Gasification combined Cycle, Techno-economic, Risk Analysis, Emissions

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NOMENCLATURE

η_{Cis} - Compressor Isentropic efficiency

η_{Tis} - Turbine Isentropic efficiency

$\Delta p_4/p4$ - non-dimensional pressure drop

anf - annuity factor

ARR - Accounting Rate of Return

BC - Biomass total cost

BIFRCC - Biomass Integrated Fired Recuperated Combined Cycle

BIGCC - Biomass Integrated Gasification Combined Cycles

BIOPPEM - Biomass Power Plant Economic Model

BIPCC - Biomass Integrated Post-combustion Combined Cycle

BPC - Biomass production cost

BTL - Biomass to Liquid

CEA - Chemical Equilibrium and Application

CH4 - Methane

CHP - Combined Heat and Power

CO - Carbon monoxide

CO_2 - Carbon dioxide

Cp - Specific heat at constant pressure

ct - Project construction time

D - One-way distance to plant

DLN - Dry low NOx

DP - Book depreciation period

DP - Design Point

DZ - Dilution Zone

e - Inflation rate

ef - Fixed cost escalation factor per year

EFCC - Externally Fired Combined Cycle

eff - Fuel escalation factor

f_0 - Specific fuel price for 1st year investment

f_1 - Specific fuel cost for the 1st year operation

FAMEs - Fatty Acid Methyl Esters

FAR - Fuel-Air-Ratio

fc_0 - specific fixed cost 1st investment

fc_1 - Fixed cost for the 1st investment year

F-T - Fischer-Tropsch

GTCC - Gas Turbine Combined Cycles

GTE - Gas Turbine Engines

H_2 - Hydrogen

HI - Heat input.

HRSG - Heat Recovery Steam Generator

HVOs - Hydro-treated Vegetable Oils

i - Annual interest rate

Inv0 - Investment cost for 1st year

Inv1 - Investment for the 1st year operation

IRR - Internal Rate of Return

ISA - International Standard Atmosphere

IZ - Intermediate Zone

LBO - Lean blow out

LHV - Lower Heating Value

LPP - Low Premixed and Pre-heated

NGGT - Natural Gas Fired Gas Turbines

NOx - Oxides of Nitrogen

NPV - Net Present Value

O&M - Operations and Maintenance

OD - Off- Design

p_4 - Combustor inlet pressure and

PaSRs - Partially Stirred Reactors

PSR - Perfectly Stirred Reactors

pwf - Present worth factor per year

Pwr - Plant shaft power in MW

PZ - Primary Zone

R - Universal gas constant

RR - Revenue Requirements

STFC - Specific total fixed cost

t - Capital insurance taxes %/year

T_{amb} - Ambient Temperature

TERA - Techno-economic Environmental and Risk Assessment

TET - Turbine Entry Temperature

Tpz - Primary zone flame temperature.

UCC - Unit Capital Cost

UHC - Unburned hydrocarbons

UW - Useful work or power

Vc - Combustor volume

Vc - Combustor volume.

W - Mass flow

γ - Ratio of specific heat

ηcomb - Combustor chamber efficiency

η_{gasif}	-	Gasifier efficiency
π	-	Pressure ratio

1 GENERAL INTRODUCTION

1.1 Background

Demand for energy and its resources will continue to increase due to the rapid growth of population and urbanization [1]. With the depleting nature of conventional energy resources like petroleum, renewable resources have become a suitable alternative. These alternative renewable resources include biomass, wind, hydraulics, solar and other sources. Presently, most gas turbine engines (GTEs) run on fossil fuels with recent efforts towards the introduction of biofuels. Biofuels offer many advantages including sustainability, reduction of greenhouse gas emission, rural development and security of supply [2]. Biofuels have the potential to reduce CO_2 emissions because the biomass feedstock producing these biofuels use CO_2 as they grow resulting in near zero overall CO_2 emission [3].

Some inhibitions in the employment of biomass for power generation are relative higher investment and running costs, poor reliability and availability, the low energy density of biomass, presence of contaminants, and low acceptance by end users. However, evolving technologies would make it possible for these problems to be overcome and the use of biomass for power generation made more convenient. Another attraction for biomass utilization for power generation is the choice of dedicated biomass feedstock like wood, grass, sugarcane bagasse and other non-food plants like the Jatropha that do not compete with food requirements of human being.

The utilisation of biomass as a suitable energy resource was done by simulating the performance of gas turbines on biofuels utilising both solid and liquid biomass resources. The performance modelling excluded the gasification process. The emission prospects with the use of biomass were also determined in addition to the economic viability and risk considerations.

1.2 Biomass Use Projection

Miller C.A of the US Environmental Protection Agency [4] projected that the use of biofuels is expected to increase by 5.5% annually up to 2030: specifically, biomass for electricity generation would increase at the rate of 4.4% over the same period as reflected in Figure1-1.

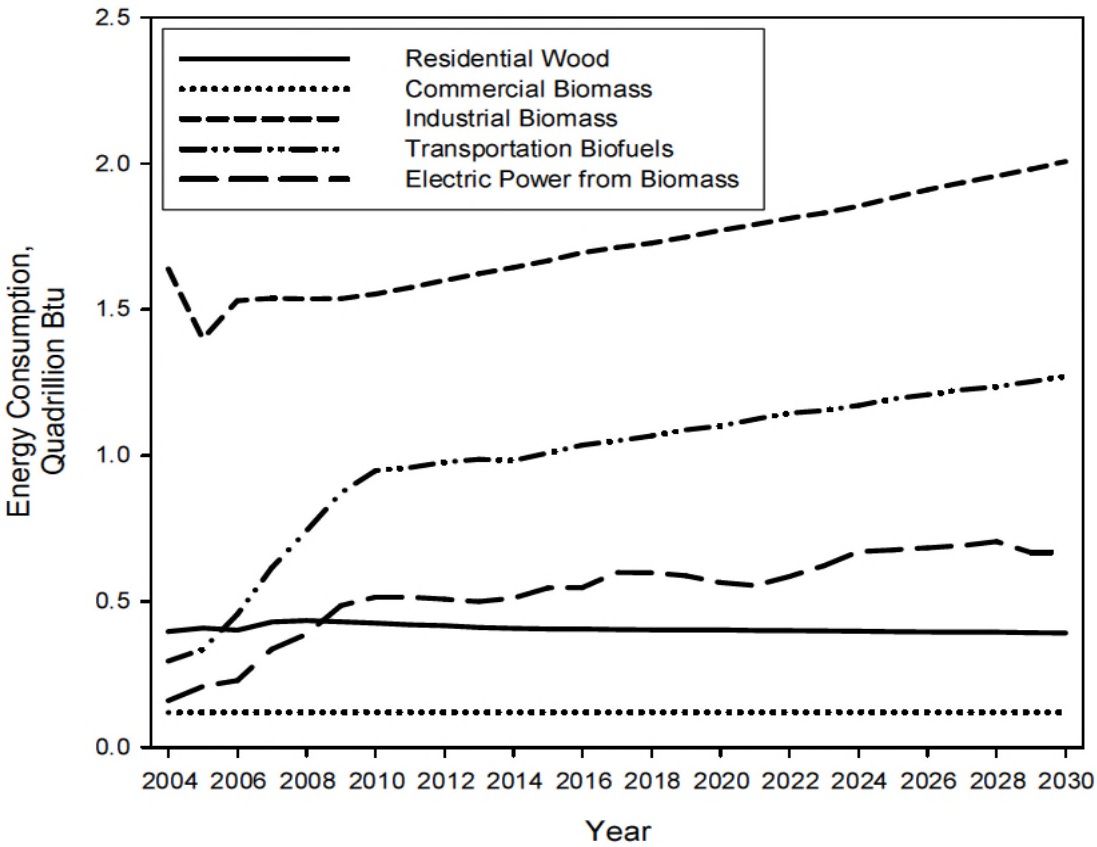

Figure 1-1 Projected Bioenergy Use by Sector through 2030 [4]

Nigeria has great potential for biomass production and it has currently increased the drive for more biomass production and utilization. From the Food and Agricultural Organisation (FAO) 2009 figures, [5][6] the country ranks high among nations of the world in the production of biomass resources. However, the main effort is in the conversion of these biomass into biofuels for transportation. Electricity production from biomass in the country is currently

negligible. The wastes from these resources can be gasified for power generation. There is equally abundant land mass for the production of more biomass in Nigeria from which the fibrous remains like sugarcane bagasse and cassava pulp can be further utilized for power generation. In addition, the productions of herbaceous biomass like wood and Jatropha which are exclusive resources can also be explored.

1.3 Problem Statement

The utilisation of biomass on gas turbines for energy generation present some challenges including non-competitiveness in terms of overall cost due largely to additional equipment modules especially those employed for biomass preparation. However, it presents a good outlook in terms of emission reduction. It is in this context that the present work has been undertaken to develop an integrated scheme which is able to estimate the emissions while using biomass and also present a method to assess profitable options when utilizing biomass on gas turbines for power generation.

1.4 Framework

A detailed overview of different biomass resources to ascertain the appropriate ones suitable for GTEs was done. To determine the appropriateness of the biomass, factors such as cost, freedom from competition with food requirement for human consumption and social benefits were considered. Furthermore, computational and simulation tools and software like the Turbomatch were employed for simulation of different engines using conventional and bio-fuels. In order to reduce the negative impact on the environment, the gaseous emission trends were captured using a multi-fuel emission code. The emission code is based on the combination of the empirical and the perfectly stirred reactors model. The economic model was also developed to assess the profitability of the application of biomass on GTEs when compared to conventional fuels. Finally, there was a global integration of these various models in an overall techno-economic environmental and risk assessment (TERA) scheme which

represents a first step towards the implementation of TERA for biofuel. TERA is an in-house tool developed for power plant asset management and multi-disciplinary influence of plant design and operation on the environment [7] [8]. The detailed flow chart is presented in Figure 1-2:

:

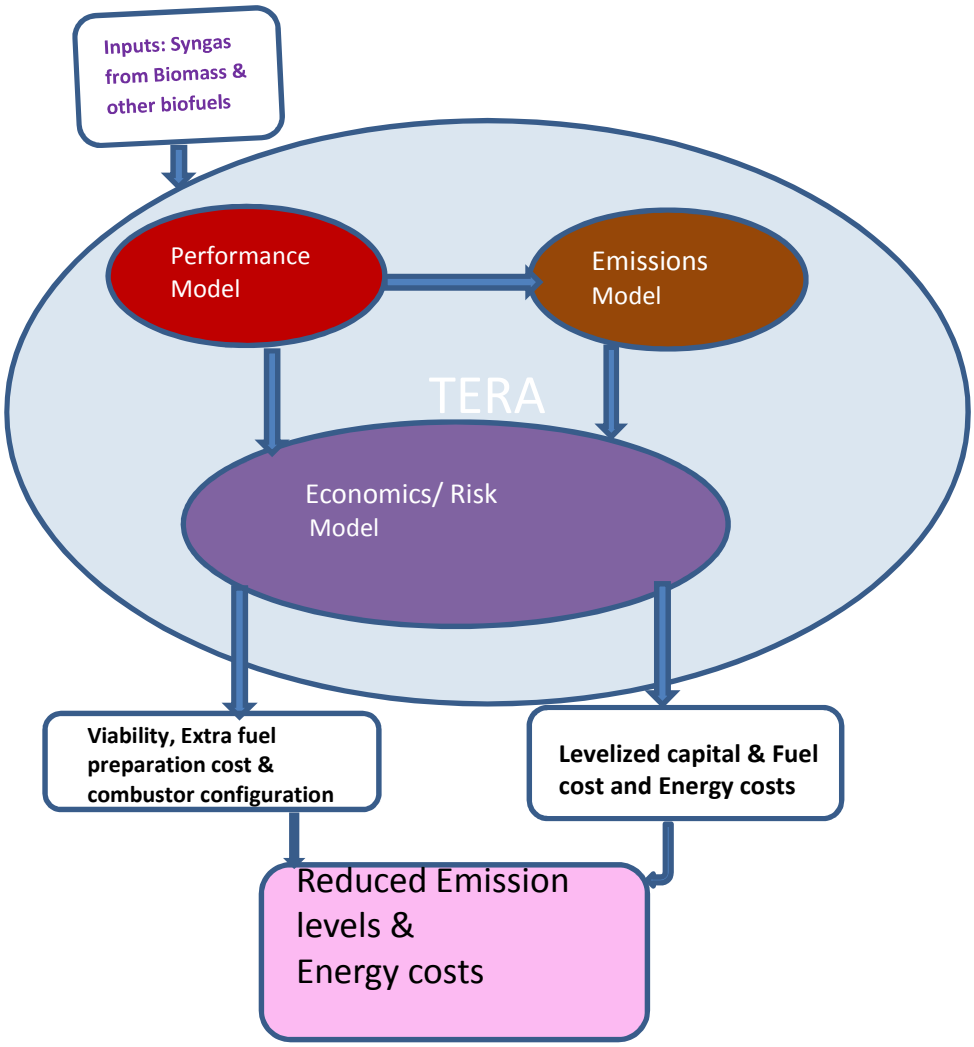

Figure 1-2 A TERA Model for Biomass Utilization on GTEs

1.5 Aims and Objectives of the Research

The aim of the research is to assess stationary gas turbine engines running on biofuels in terms of performance, emissions and economics. There is a deliberate effort to choose non-food biomass feedstock in order to avoid competition with food requirements for human consumption: wood, sugarcane bagasse and Jatropha were considered in the present work as fuels for GTEs. A TERA is employed to serve as a tool for the selection of the right conditions for biomass fuelled stationary engines for an optimum plant performance.

The main objectives of the research therefore include the following:

a. Development of a multi-fuel emission model to capture gas emissions when gas turbines run on biofuels.
b. Carrying out a detailed economic and risk analysis on biomass to energy using the gas turbines.
c. Assessment of performance, emission and economic trade-offs when utilizing biomass on stationary gas turbines.

In order to achieve the objectives of the research work, the following are the set major milestones:

- a. Carry out detailed analysis of the various biofuels that are best suited for gas turbine engines. An evaluation of their production, properties and appropriateness for utilization on industrial and aero-derivative gas turbine engines was done.
- b. Carry out a design point and off-design performance analyses of two GTEs running on biofuels using the Turbomatch software and other tools in simple and combined cycle configurations.

- c. Modification of a conventional fuel based emission model into a multi-fuel emission one capable of carrying out emission analyses of exhaust gases when the GTEs run on biofuels.
- d. Develop a techno-economic model for the assessment of the gas turbine engines when running on bio-fuels.

1.6 Author's Contribution to Knowledge

The main contributions of the present work to knowledge include the development of a multi-fuel emissions prediction model capable of capturing the emission characteristics of gas turbine combustors running on biofuels. In addition, it also proposes the borders of economic factors variables to ensure project viability when using biofuels on gas turbines. A first version of the TERA model has therefore been developed to present an outlook in terms of engine performance, emission, economics and the risk limits. This contribution will be better highlighted against the existing literature in chapter II.

1.7 Thesis Structure

The thesis is structured into seven chapters:

Chapter I is an introduction of the work undertaken. It presents the current and projected trend in the utilization of biomass for energy generation, the rationale for the work, the thesis framework, milestones and an overview of the entire thesis structure.

Chapter II is a review of appropriate literatures on the subject matter. This covers biomass utilization on gas turbine engines and the appropriate engine configurations. It also highlights methods of emission estimation on gas turbines.

Chapter III is a general analysis and categorization of biomass resources. This chapter is devoted to specific characteristics of biomass, its processing and use especially for power generation.

Chapter IV presents the design-point and off-design performance analysis of the chosen engines – an aero-derivative engine and two industrial engines, it also presents the advantages in having the engine in combine cycles.

Chapter V presents a multi-fuel emission model simulation. The results of the various quantities of the emission gases when using varied fuels is hereby presented.

Chapter VI presents the economic assessment of running the gas turbines on biofuels. It highlights the merits of various engine configurations and also presented case studies reflecting the influence of several factors (atmospheric, operational, and policy) on the use of biomass on GTEs. An analysis of the risk factors and sensitivity to pertinent factors of production in the GT operation utilizing biofuels was also carried out.

Chapter VII presents the conclusions and recommendations for future work.

Though there is no dedicated chapter for the methodology, the methods used are adequately embedded in the various respective segments of the thesis.

2 Literature Review

Several research efforts are currently directed at improving the use of renewable energy resources and low caloric value fuels for power generation as it aids in the mitigation of current global environmental problems. This chapter highlights the technological and research efforts in the utilization of biomass for power generation as presented in literature. The review covers main subheads of different perspectives and engine configurations for biofuel use on gas turbine engines for energy generation, the economic evaluation approaches, and the emission modelling efforts when burning biofuels on GTEs.

2.1 Biomass Use on Gas Turbine Engines

Generally, biofuels like other fuels, can be solid, liquid or gaseous. The liquid biofuels are derived through refining of the biomass feedstock and they are then used as fuels like conventional fuels for different applications. The variety of biomass in this category includes Camelina, Jatropha, eucalyptus, groundnut and a host of others. Biomass provides a large amount of world's energy requirement of about 13%. According to Twidell [9], the flux of dry matter of biological materials in the biosphere is nearly 250×10^9 t/yr incorporating around 100×10^9t/yr of Carbon. The energy bound in photosynthesis is 2×10^{21}J/yr, out of which, about 0.5% by weight is food biomass for human consumption. This means that a high percentage of biomass is available for other uses such as power generation.

Solid Biofuel application in gas turbine engines is realisable through the conversion of biomass. Methods used for biomass conversion include combustion, pyrolysis, liquefaction and gasification. The gasification process is appropriate for a more elaborate energy generation. Two of the biomass selected for assessment in the present work (wood and sugarcane bagasse) are solid biomass requiring gasification. The third one (Jatropha) is got by

refining and used in liquid form on gas turbine engines. Gasification is the process whereby biomass and other fuel stocks are broken down into CO and H_2. Gasification may also serve the purpose of producing synthetic fuels such as methane (CH_4). These biomass derived fuels can be used to generate energy on the industrial gas turbines. The engines can either be in the simple cycle or in the combined cycle configuration. An example of the latter is represented by the so-called Biomass Integrated Gasification Combined Cycles (BIGCC). A general overview of the conversion process and various uses of gasified biomass are shown in Figure 2-1:

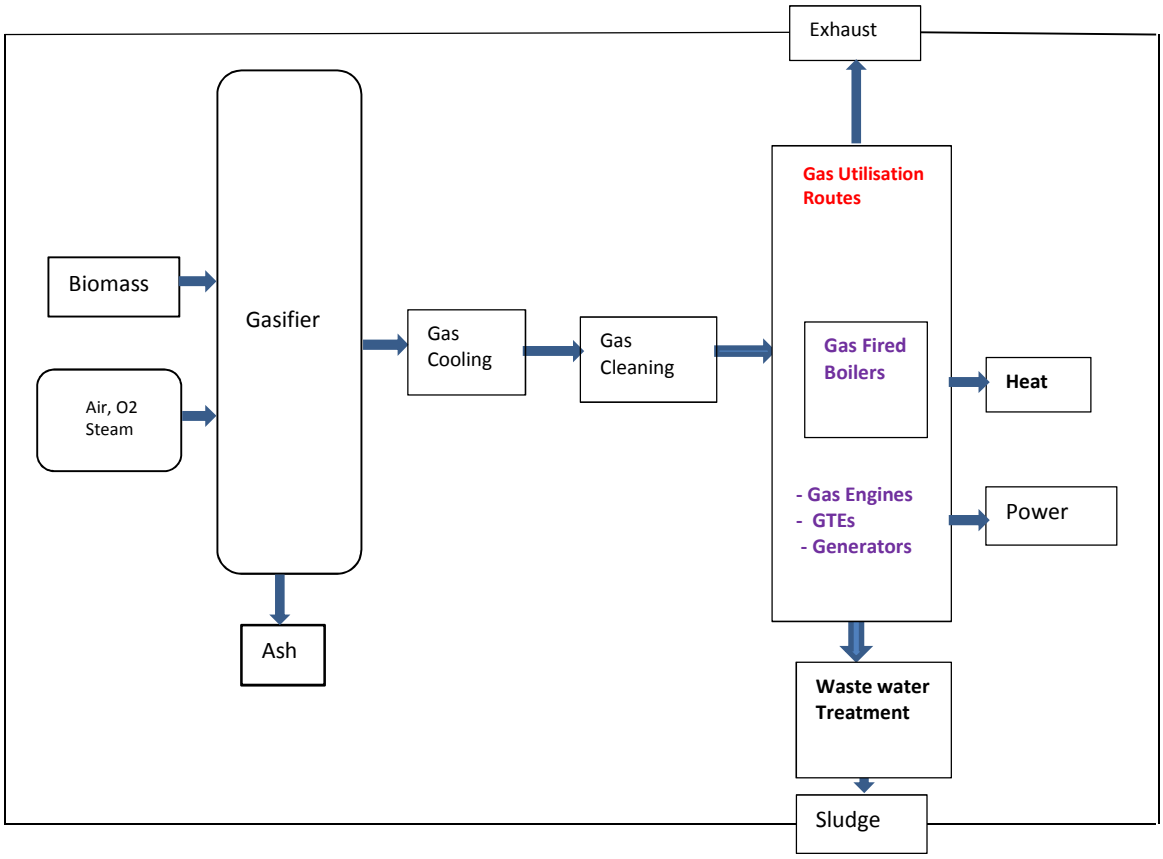

Figure 2-1 Biomass Conversion and Uses Diagram

2.2 Gasification Process

Gasification is the thermochemical conversion of carbonaceous fuels to a gaseous product with a useable heating value. It involves the partial oxidation of solid, liquid or gaseous feedstock to produce synthetic gases known as syngas. The oxidant may be pure oxygen, air and/or steam. The processes involved in the preparation and gasification of these fuels is as shown in Figure 2-2.

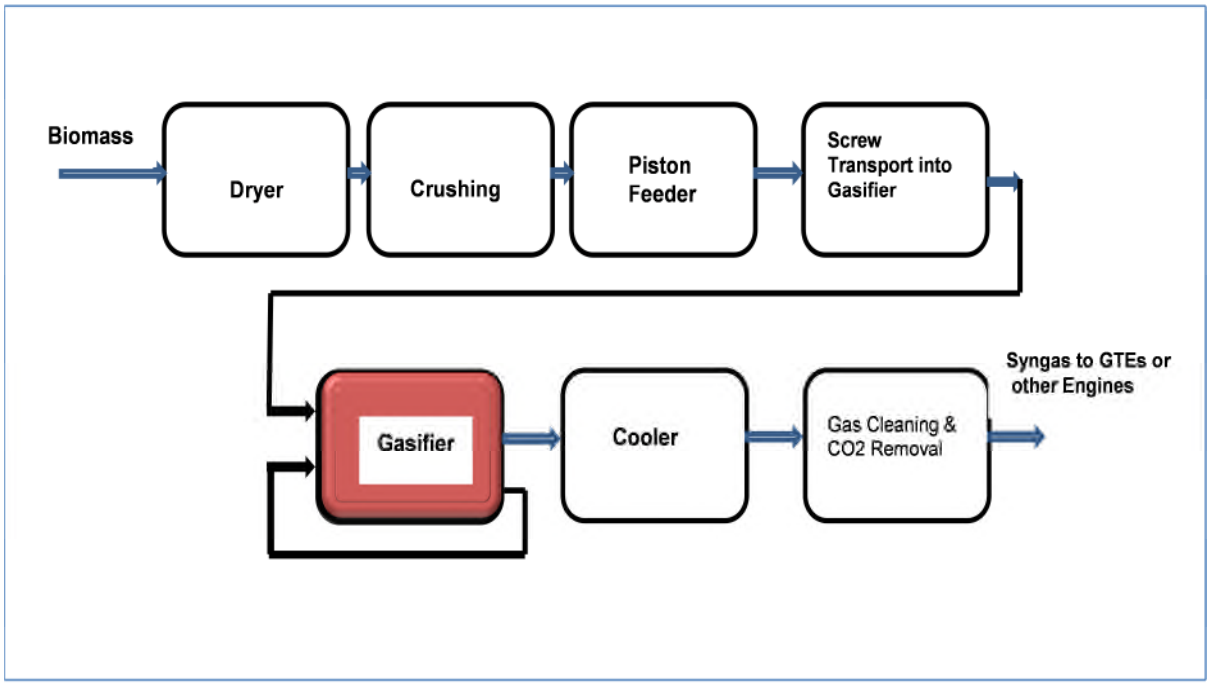

Figure 2-2 A Typical Biomass Gasification Arrangement

2.2.1 Biomass Gasification Reactions

As already highlighted, in gasification process, the biomass undergoes a partial oxidation at high temperature to produce producer gas containing Carbon monoxide, Hydrogen, Methane and also Carbon dioxide and Nitrogen of the air, and water vapour. It is an endothermic process involving multiple reactions.

Series of gasification reactions involving all solid biomass are reflected in equations 2-1 to 2-5[83]:

$$\boldsymbol{C_6H_{10}O_5 + {}^{7}/_{2}\, O_2 + Heat\ (1.82MJ/kg) \Rightarrow 6CO_2 + 5H_2}$$ Equation 2-1

$$2C + O_2 + 4\,N_2 \Rightarrow 2CO + 4N_2$$ *(O_2 & $4N_2$ are from the air)* Equation 2-2

$$\boldsymbol{C + O_2 \Rightarrow CO_2}$$ *(Boudouard Reaction)* Equation 2-3

$$H_2O + C \Rightarrow CO + H_2$$ *(Water Gas Reaction)* Equation 2-4

$$C + 2\,H_2 \Rightarrow CH_4$$ *(Methane Reaction)* Equation 2-5

The series of reactions from Equations 2-1 to 2-5 produce different percentages of various derived synthetic gases. Gasification processes can be carried out in either air or oxygen as medium but due to the high cost of oxygen, it is not competitive to use it as a medium of gasification of biomass and so air is preferred.

2.3 Types of Gasifiers

There are different configurations of gasifiers with their respective characteristics - the downdraft, updraft entrained flow and circulating fluid bed. The circulating fluid bed type has been extensively developed for wood conversion and other solid biomass and so it is the type adapted for the present work. Table 2-1 shows the different gasifier types in use today as outlined by Higman [10][11].

Table 2-1 Summary of Developed Gasifier Types

Serial	Gasifier Type	Operation Mode
1	Fixed Bed	
	Downdraft	Biomass and gas moves down
	Updraft	Solid moves down, gas moves up
	Cross current	Biomass moves down, gas moves at right angles
2	Fluid Bed	Some biomass material stays in reactor and some go with gas and are recycled
3	Circulating bed	Also referred to as twin-reactor systems; separates and recycles the solid.
4	Entrained Bed	Has highest gas velocity
5	Twin Reactor	Pyrolysis occurs in the first reactor and char in the second.
6	Moving Bed	Usually at low temperatures and biomass are mechanically transported
7	Rotary Klin	Has good gas-solid contact; requires good design
8	Cyclone reactors	Has high particle velocities
9	Vortex Reactors	Similar to cyclone type

Pressure and temperature have remarkable effects on the gasification process, hence, there is need to determine the conditions under which biomass is gasified. The broad categories of biomass gasification are outlined below [10]:

a. Atmospheric-pressure air-blown fluidized bed with wet scrubbing having heating value of 1500kcal/kg.

b. Pressured air-blown fluidized beds with hot gas clean up having heating value of 1300kcal/kg.

c. Atmospheric-pressure indirectly heated with wet scrubbing having heating value of 4300kcal/kg.

2.4 Biomass Integrated-Gasifier Gas Turbine Combined Cycles (BIG/GTCC)

The Biomass Integrated-Gasifier Gas Turbine Combined Cycles (BIG/GTCC) power plant comprises the following: the dryer, the gasifier, a cleaning system for cleaning the fuel gas from the gasifier, the gas turbine island, the heat recovery steam generator (HRSG) that raises steam from the hot gas turbine exhaust gases and the steam turbine [12]. For industrial application, the biomass gasifiers are integrated with the gas turbine engines in same location to minimise cost of transportation of fuel over long distances. A simplified BIG/GTCC is as shown in Figure 2-3.

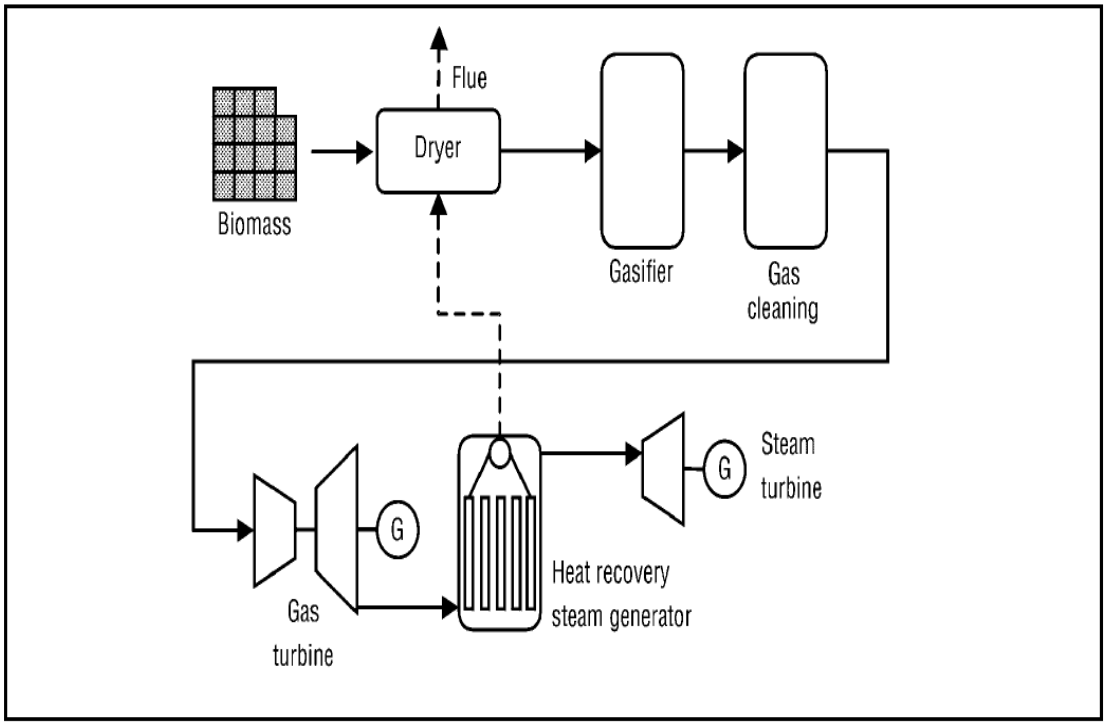

Figure 2-3 Typical BIG/GTCC Components Outlook [12]

Andrea Corti et al [13] carried out simulations for the production of clean biomass syngas and its use on a Brayton cycle. The main thrust of the modelling was to obtain a syngas containing a high amount of hydrogen with high energy content as possible. There was the incorporation of a shift reaction section and CO_2 chemical absorption process. An atmospheric gasifier was modelled and fed with 31kg/s biomass (made of dry poplar) mass flow. In order to achieve syngas of higher caloric value, the gasification air ratio (e) has to be kept low. The study generally emphasized the possibility of efficient utilization of biomass under atmospheric pressure with a life cycle economic assessment. It gave no details on the emissions during GTE processes.

2.5 Modes for Biofuel use on Gas Turbines

Apart from the BIGCC option, there are other patterns at utilising fuel from biomass in gas turbine engines. One of these is, Externally Fired Gas Turbines

(EFGT). Whichever scheme is used, the plants could be used for electricity generation or as combined heat and power plant (CHP).

2.5.1 Externally Fired Gas Turbine

The Externally Fired Gas Turbine consists of the compressor, heat exchanger, the combustor and the turbine. It can be further connected to a HRSG to raise the temperature of the steam in combined cycle configuration. It has the thermodynamic advantage of the preheated air and that the combustion gases do not need to pass through the turbine [14]. The component parts of the EFGT are as shown in Figure 2-4.

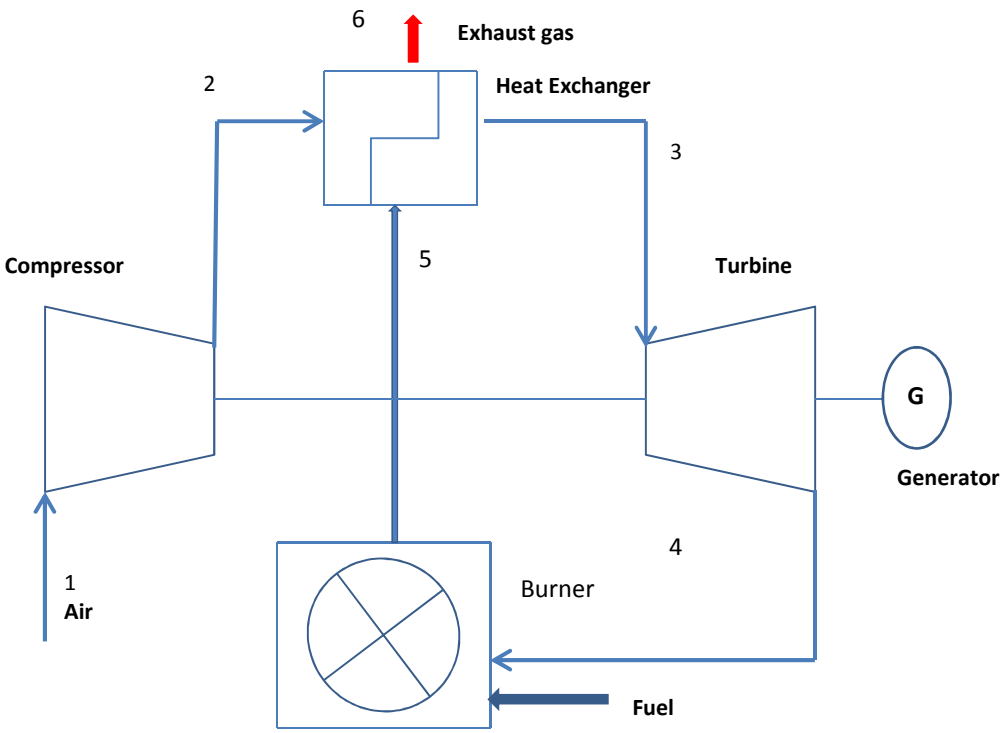

Figure 2-4 Externally Fired-Gas Turbine Configuration [14]

The most important component of the EFGT is the counter-flow heat exchanger and the most important parameter is the temperature difference between the hot and the cold gas (which is a function of the heat exchanger) that determines the efficiency. The EFGT combines the advantages of elimination of the gasifier, versatile combustor capable of burning many fuels and a reduced overall cost [15]. It is however, low efficient when compared to other cycles. Its prospect lies in a well-developed heat exchanger that can withstand higher temperatures so that the efficiency could be enhanced

2.5.2 Biomass use as Integrative Fuels in Combined Cycles

One way to use biomass for energy is to bring in the derived thermal energy in a gas fired combined cycle plant. Another option is co-firing of natural gas and fuel (syngas) derived from biomass gasification in which case the syngas is mixed with the natural gas and then burnt in the combustor [16]. This is a convenient option in the co-combustion of natural gas and syngas derived from biomass. The main advantage of co-firing is that the limited availability of biomass can be redressed by supplementing with other fuel resources. However, this is of thermodynamic consequence as thermal power from the biomass is introduced in the topping cycle at a higher heat level. This application requires some modification of the gas turbine to be able to receive about 5 times the volume of flow of gas.

Yet another mode of biomass use is the concept proposed by A. Franco et al [17]. The use of biomass for post-combustion after discharge from the gas turbine was suggested. Contrary to what happens in co-firing, gas and biofuel are used in succession according to their quality: natural gas in the topping cycle while biofuel or derived fuel in the bottoming cycle in two distinct ways:

a. Post-combustion with additional firing of biomass before reaching the HRSG. This is dubbed Biomass Integrated Post-combustion Combined Cycle (BIPCC) as illustrated in Figure 2-5.

b. Combustion of biomass or derived syngas to preheat air before entering the gas turbine – a Biomass Integrated Fired Recuperated Combined Cycle (BIFRCC) as shown in Figure 2-6. Overall plant efficiency and thermal power is a function of the heat delivered by the biofuel and the gas.

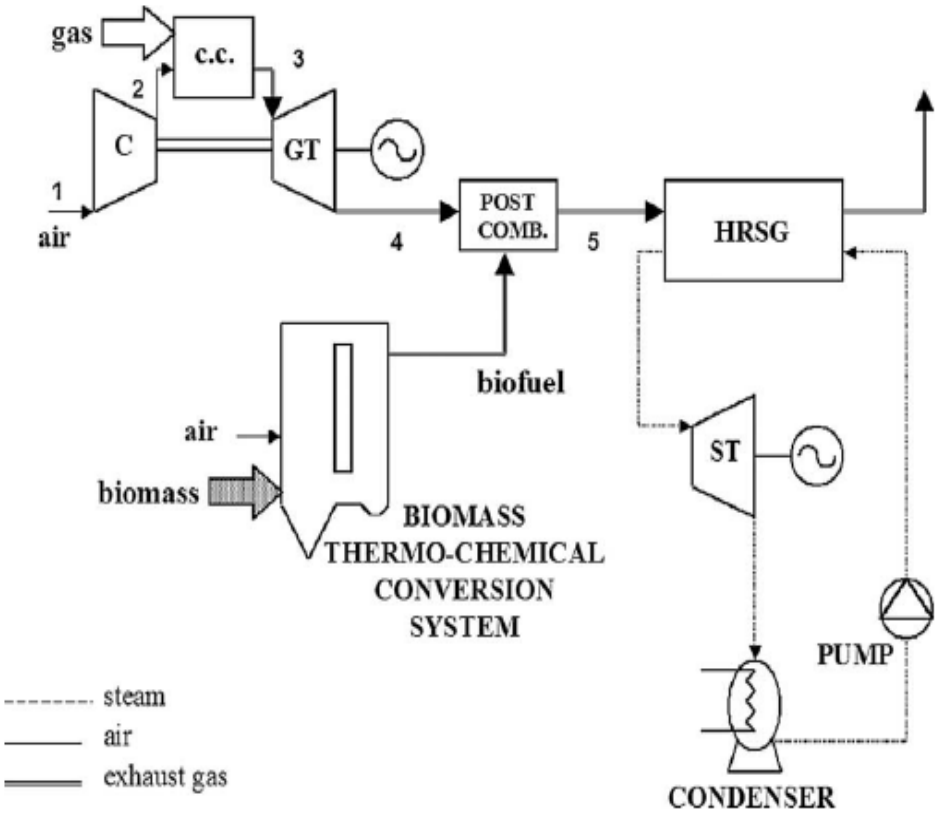

Figure 2-5 Schematic of the BIPCC Plant Configuration [17]

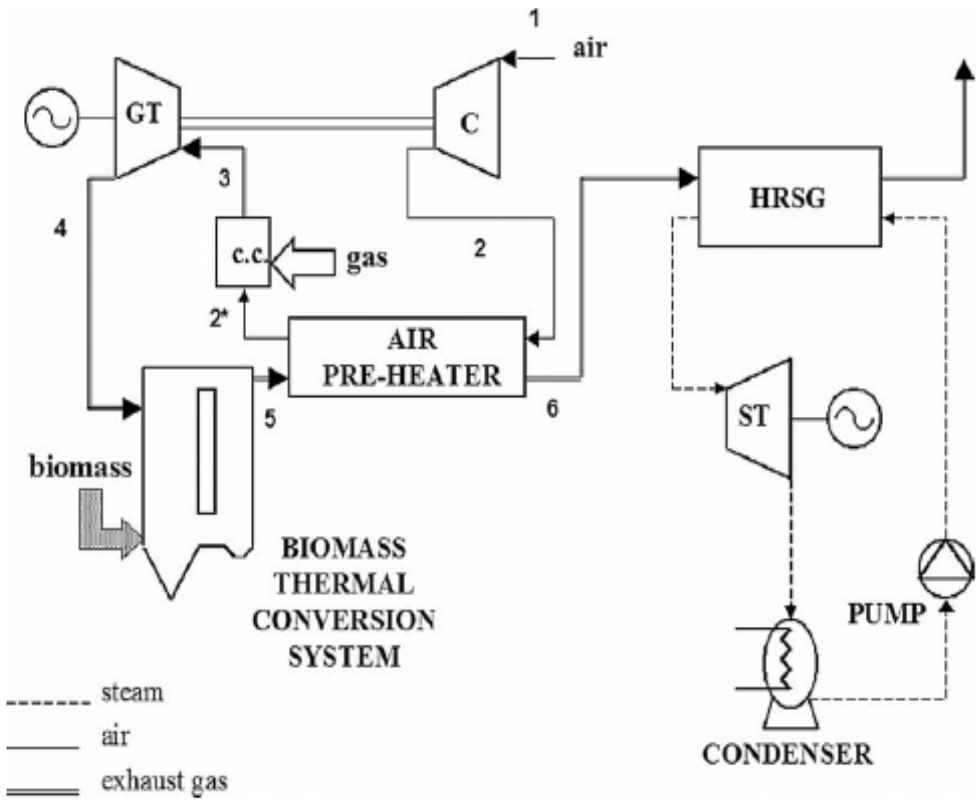

Figure 2-6 Schematic of the BIFRCC Plant Configuration [17]

There are other works carried out in the area of biomass application on gas turbine engines, including also the ones for aero application. These include one by Zehra et al [18] who conducted a performance analysis of a small gas turbine burning jet A, soya beans methyl esters, canola methyl ester, rapeseed and hog-fat biofuel. Similarly, Rodrigues M et al [19] also carried out a performance modelling of a BIG/CC for power generation employing de-rating strategy due to reduced pressure ratio when using the low caloric value derived syngas from biomass. Overall, the use of the biofuel resulted in increase in power output but decreased cycle efficiency. The NOx and CO emissions were also evaluated and found to be reduced with biofuel use.

Neto [20] and Ferreira [15] presented methods for assessing the performance of advanced gas turbine power plants for electricity generation in Brazil. Gas turbine cycles like gas/steam, gas/air, gas /steam/freon and other advanced

turbines were investigated. Other configurations like the externally fired cycles utilising biomass fuels were also analysed. Though the assessment involved fuels like the sugarcane bagasse and wood, there was no detailed analysis on emissions. Furthermore, they emphasised the gasification modelling and the effect on the GT performance but did not consider economic risk factors. The present work considered both emissions and economics in details.

2.6 Economic Considerations in Biomass for Power Generation

Besides the thermodynamic performance, the economic viability of these technologies has received an increasing interest in the scientific community. Larson et al [21] outlined the several factors that affect the cost of power from biomass fuels. One of them is the cost of delivered biomass. This involves estimating the cost of growth and transportation of biomass feedstock to the power plant site. Costs can also vary significantly due to the climate, soil quality, land rent, labour costs, the biomass type selected for utilization and other parameters. A detailed economic appraisal of the commercial viability of fuelling the first generation BIG/GTCC with dedicated plantation-derived biomass was carried out.

Larson [21] was able to characterise cost behaviour for biomass based power plants as a result of some of these factors. Other factors that have a direct correlation with the energy price are the plant installed capacity and the capacity/load factors. The plants of lower capacity have higher energy costs than those with higher capacities.

Larson emphasized the impact of plant scale and those factors affecting the cost of biomass including biomass planting density for dedicated biomass feedstock and the choice of alternative biomass sources like residues of industrial and agricultural processes.

2.6.1 The Biomass Cost Element

Larson's sensitivity analysis was based on US Southeast region with a projection up to 2020. The various costs of electricity corresponding to the plant power output in Megawatts are as reflected in Table 2-2. A particularly important parameter is planting density i.e. the fraction of available land around the power plant that is used for biomass production. The trend shows that reduction of the planting density raises the transport cost and hence increasing the distance of the biomass from the power plant which translates into an increase in the cost of electricity and a drop in the plant output. In the present work, the whole influence of the individual factors affecting biomass availability for power generation is captured and reflected in the price of biomass.

Table 2-2 Sensitivity Analysis for South East Region (USA) for 2020 (CoE in Cents/kWh) [21]

Parameters	**LP-BIG/GTCC**		**HP-BIG/GTCC**		**Steam Cycle**	
	COE	MW	COE	MW	COE	MW
Base Case	4.57	142	4.33	319	6.05	520
Transport Variation=$0.09/t-km	4.48	183	4.33	415	5.85	691
Transport Variation = $0.36/t-km	4.71	100	4.50	208	6.39	304
Planting Density = 0.47	4.62	127	4.38	277	6.10	362
Planting Density = 0.094	4.76	87	4.59	121	6.80	75
Yield = +25% (t/ha/yr)	4.24	147	4.03	337	5.57	525
Yield = -25% (t/ha/yr)	5.10	123	4.83	301	6.83	447
Land Rent = +$123/ha/yr	5.00	142	4.73	319	6.66	520
Land Rent = -$123/ha/yr	4.13	142	3.93	319	5.43	520

The values of the cost of electricity for the BIG/GTCC are better compared to the steam turbines at smaller capacities and makes BIG/GTCC competitive. At any scale, the higher efficiency and the lower capital cost of the BIG/GT systems make them significantly less costly source of electricity than the steam turbines [22].

Another economic assessment which was limited to design point was carried out for aero-derivative engines within the range of 25-30MW power output [20]. Consonni [23]compared the economics of three BIG/GT designs: the air blown, near atmospheric pressure and near atmospheric pressure, indirectly heated fliudized bed gasifiers for power plants of capacities between 20MW – 80MW. It was established that the various configurations have effects on the overall electricity cost. In addition, it was averred that an enhanced technological development for growing biomass would reduce the biomass cost from $3.0/GJ to about $2.1/GJ. While the reduction in price of the biomass is paramount, there is need to also consider holistically the effects of other factors of production. The present work undertaken sets out to achieve this.

Further efforts at thermo-economic assessment of biomass fuelled gas turbines is the incorporation of the exergy method which considers the interaction between the power plant and its surroundings. Losses are then computed component by component and the rates of exergy transfer, work transfer and the heat transfer are duly captured. Neto and Ferreira [15; 24] were able to determine the costs of producing electricity in different configurations using biomass and comparing with conventional fuel powered gas turbines.

The previous works did not adequately address all the factors involved in constituting risk in biomass for power generation. There is therefore need to carry out a more encompassing assessment. In particular, there is need to highlight the risk elements in the application of biofuel for power generation bearing in mind the several factors of production involved. The work aims at developing a model that incorporates elaborate risk factors in addition to several other features.

2.7 Gas turbine Emission Analysis

Another important aspect that needs to be addressed when evaluating biofuel fired power plants is their emissions. Gas turbine combustors or burners operate under severe temperature and pressure conditions if the engine is to deliver the required energy. A balance is therefore to be maintained between delivery of satisfactory combustion stability and reduced pollutants emission. Emissions are dependent on combustor type, ambient & combustor operating conditions, and fuel types.

The major types of pollutants exited at the turbine exhaust are the NOx, CO, CO_2 and UHC. The concentration levels of these pollutants are directly related to the operating temperature and pressure within the combustor and to the residence time in various combustion zones. Earlier emission predictions were based on operating conditions and later the numerical approach. The incomplete understanding of the combustion processes within the entire length of the combustor made these methods not fully reliable. However, in recent times computational and empirical methods are being employed in emission analysis. These give insights into the combustion and mixing processes within the combustor fuel flow field.

There are several emission prediction methods being used in the industry for the prediction of emissions from industrial gas turbines. These are broadly classified into four methods: the empirical, semi-empirical, physics based or perfectly stirred reactors and the computational fluid dynamics methods [25]. Different models had adopted one or a combination of these methods to capture gas emissions.

2.7.1 Empirical Models

Empirical models are formulated from experimental data and used to determine constants and specific engine conditions like the P3, T3, mass and fuel flow

rates. They are suitable for the design and development of low emission combustors. It is appropriate for the modelling of single annular combustors and also adaptable for other combustor types such as staged-dual annular combustors. It is mostly used for NOx emission modelling and limited to specific combustors. This type of model is only reliable for particular engines for which the data is generated and so unreliable when there are modifications done on the combustors. A typical empirical model as given by Allaire [25] is as shown below:

$$\boldsymbol{EINOx = 0.0042\left(\frac{P_3}{439}\right)^{0.37} \exp\left(\frac{T_3 - 1471}{345}\right) T_4} \qquad \text{Equation 2-6}$$

2.7.2 Semi-Empirical Models

These models consist of equations that have empirically determined constants, engine parameters like the residence time, the primary zone flame temperatures, characteristic kinetic times and other parameters. Some of them are those by Lefebvre [26]:

$$\mathbf{NO} = \frac{9*10^{-8}\, P_3^{2.5}\ V_c\ \ \exp\ (0.01\, T_{st})}{T_{PZ}\, M_A}\, g/kg \qquad \text{Equation 2-7}$$

$$\boldsymbol{CO = \frac{85 m_A T_{PZ} exp-(0.00345 T_{PZ})}{(V_c - V_e)(\nabla P/P)^{0.5}\, P^{1.5}}} \qquad \text{Equation 2-8}$$

Where

A = Constant

Vc = Combustor volume.

Ve = Volume employed in fuel evaporation

Tpz = Primary zone flame temperature.

m_A = Primary zone air flow rate

$\Delta p_4/p4$ = Non-dimensional pressure drop

The limitation of semi-empirical models is that they are sensitive to the input types. To further aggravate the situation, these inputs are hard to be generated as they can only be obtained through constant experimentation or expert knowledge. This renders the semi-empirical model unreliable as a tool for decision making.

2.7.3 Physics-based or Stirred Reactors Model

The physics based or the chemical kinetics model captures to an extent the turbulent flow and the physical processes that take place within the combustors. They are a compromise between the empirical and the computational methods. The concept of modelling a combustor as a network of reactors is used in this model. This approach to modelling was adopted by Rizk and Mongia [27] and Zakharov [28] and was used in the present work; detail discussions on the method are in Chapter five.

2.8 Reactors Arrangement for Different Combustor Configurations

Hamdi et al, [29] Celis [30] and Samaras [31] adopted the reactors model for the simulation of pollutant emissions from gas turbine conventional combustors. The structure of this reactor model is as shown in Figure 2-7:

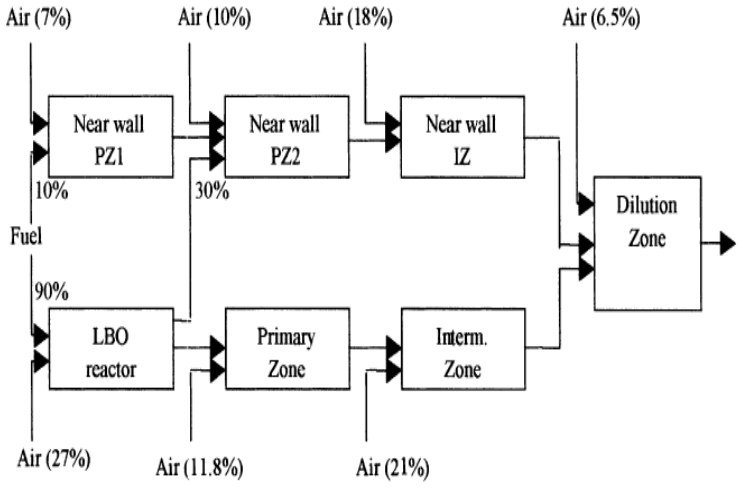

Figure 2-7 A Typical Reactors Arrangement for Emission Modelling [27]

In the above arrangement, the combustors are represented by several stirred reactors. The primary zone of the combustor is represented by two central reactors in series with the first one containing the initial mixing and reaction of fuel spray with the nozzle and swirler air, and defines a lean blow out (LBO) zone. The reaction continues into the second reactor (primary zone). Two other reactors occupy the near-wall region in the primary zone where the fuel, either in droplet or vapour form that escapes the recirculation zone in the combustor core mixes with the rest of the dome air in the first near-wall reactor. Reactors representing other combustion zones (intermediate and dilution zones) are also considered in this model. This is a semi analytical emission modelling approach utilizing a detailed chemical kinetic scheme to evaluate the key elements of pollutant formation and destruction in the combustor simulated by a number of stirred reactors. This model is suitable for conventional diffusion flame combustors.

2.8.1 Model for Lean-premixed Combustors

One or multi-dimensional model to simulate different gas turbine combustor types have been developed. Andreini and Facchini [32] developed a 1-dimensional model which can be adapted for conventional, Lean-Premixed Combustors (LPC) and Dry-Low NOx (DLN) combustor typologies. NOx reduction for industrial gas turbines are essentially based on lowering of flame temperature by either water or steam injection but this at some stage has the adverse consequence of lowering turbine thermal efficiency and engine durability in addition to worsening the CO and UHC emission trend. Therefore most combustor designs are fashioned in a way to have the potential for reducing NOx emission without water or steam injection, this is referred to as DLN. At the moment, the LPC approach to DLN is the most developed. LPC achieves low NOx emission in a small combustion range so the LPC makes the use of fuel/combustion staging and variable geometry. Since combustion stability cannot be totally guaranteed, the employment of airflow modulation by means of compressor mass flow bleeding and inlet guide vanes (IGV) is also considered. Figure 2-8 is a typical reactor model for LPC:

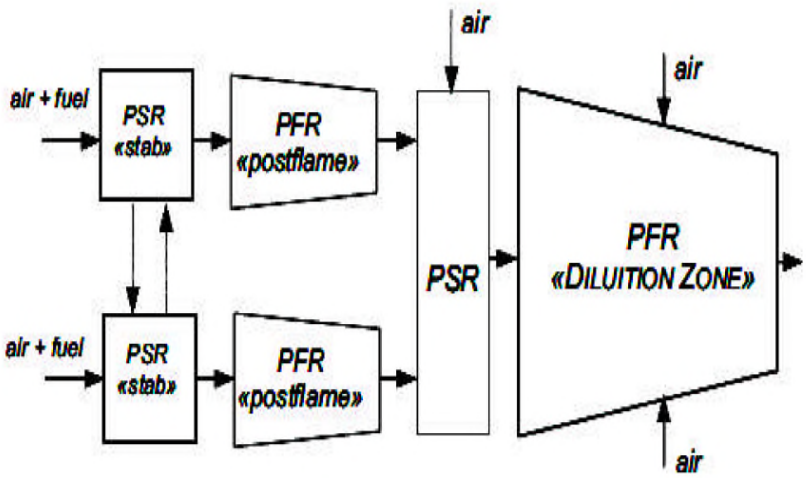

Figure 2-8 Chemical Reactor Network for Lean-Premixed Combustors [32]

The main difference is that the primary zone is modelled with a combination of both perfectly stirred reactor (PSR) and plug flow reactor (PFR) according to a typical turbulent premixed flame representation. At the intermediate zone, air jets are provided for secondary and primary hot gases to mix with a further mixing of the combustion products at the dilution zone.

A further improvement was in the model developed by Lebedev and others [33]. This was based on a 3-dimensional CFD simulation of simple reactor model to predict the pollutant formation in a burner operating in a diffusion mode. It was found to be consistent when validated with measured NOx emission from an aero engine running on both methane and kerosene. It is also useful for the estimation of other different gases like sulphur oxides, CO and UHC. There are other emission models and correlations in other literatures. These models include the NLR T3- P3 [34] and the Boeing model [35].

The shortfalls of these models are levels of unreliability and their being specific to engine types. The empirical model for instance is based on experimental data which precludes all the complex combustion processes that take place inside the combustor. It equally requires new data for different combustor types and technologies. The multi-fuel emission model developed in the present work is able to carry out emission computation for both conventional and biomass fuels.

2.9 Multi-fuel Emission Modelling

As already stated in the introduction, biomass use for power generation is viewed to mitigate to some extent the emission issue when compared to the use of fossil fuels. Orbegoso et al [36] carried out an emission prediction study using a chemical reactor network that employs chemical kinetic mechanisms but limited to only a particular fuel type – the natural gas. An evaluation of the

effects of the impact of the various species of the natural gas on the formation of CO and NOx within a gas turbine combustor was achieved.

The chemical reactors were arranged in two configurations and different species of CH_4 were introduced at base and part loads. It shows that the CO concentrations predicted by the two configurations at the primary zone were higher than those at both the intermediate and dilution zones. Similarly, the NOx formation is initiated at the primary zone of the combustor and then decreases slightly as the burnt gases move along the intermediate and dilution zones. This model was also limited to a single fuel. The reactor arrangements suggested by these authors are shown in Figures 2-9 & 2-10. The present work presents a model with multi-fuel capability and with an arrangement of the reactors as shown in Chapter 5.

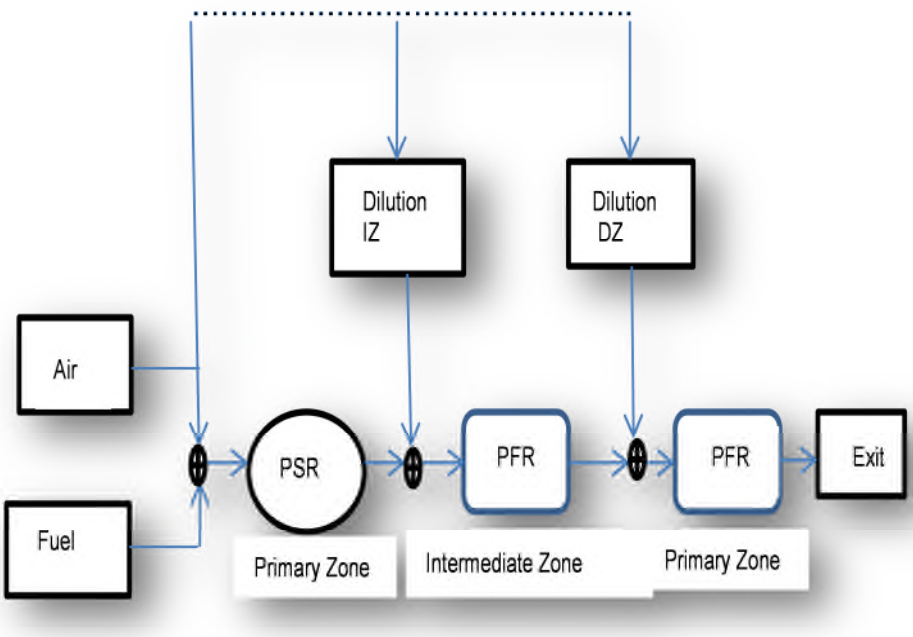

Figure 2-9 Improved Reactor Configuration for Biomass Emission Computation [36]

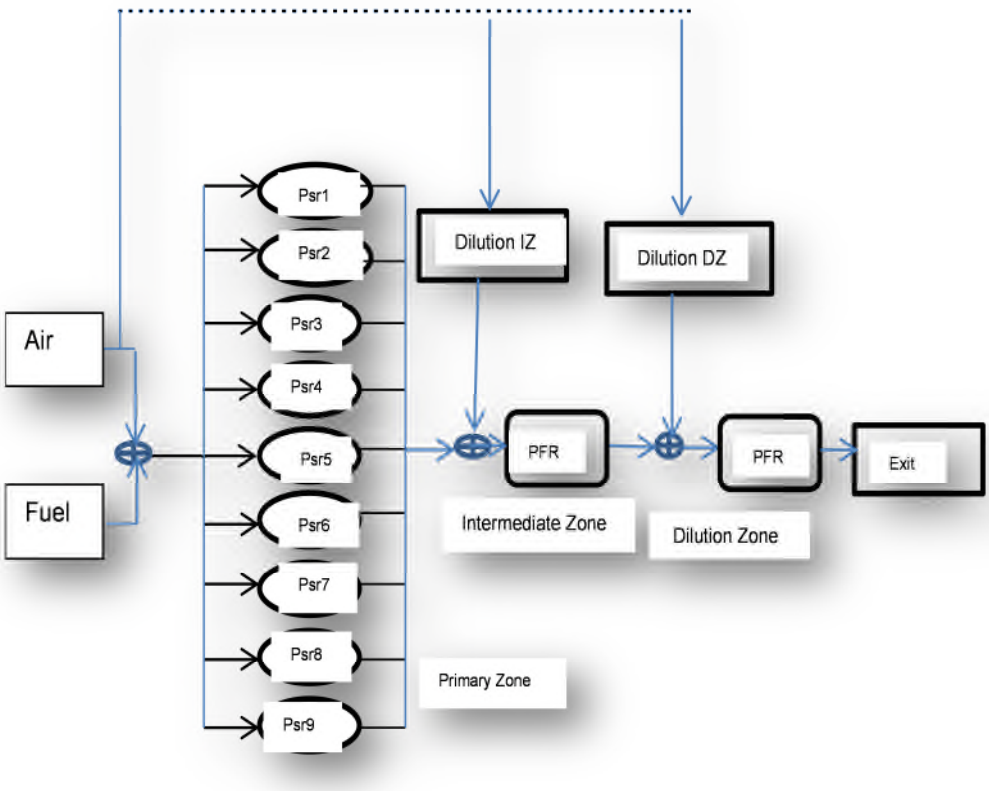

Figure 2-10 Another Reactor Configuration for Biomass Emission Computation [36]

With the availability of biomass burning combustors, there exists the possibility of the application of biomass derived fuels on gas turbines. Details of the characteristics of suitable features and merits of current combustor design for biofuels is elaborately covered in [37]

The effects of the various fuels will reflect on the combustor efficiency, combustor lean blow out and ignition. Lefebvre presented correlations for both NOx and CO emissions to capture the fuel type(s) effects as follows [38]:

$$\boldsymbol{NOx} = \frac{C_2 P_3^{1.25} V_c \exp(0.01 T_{st})}{(T_{pz} m_A) g} \boldsymbol{g/kgfuel} \qquad \text{Equation 2-9}$$

$$\boldsymbol{CO = C_3 m_A T_{pz} P_3^{1.25} \exp\left(0.0035 T_{pz}\right) / (V_c - V_e)\left(\frac{\nabla P}{P}\right)^{0.5} P^{1.5}}$$ Equation 2-10

Where C_2 & C_3 are constants, Vc is combustor volume, Tpz is the primary zone flame temperature, Tst is the stoichiometric temperature and m_A is the fuel mass.

Though there are increasing interests in the evaluation of biomass for power generation, to the author's knowledge, the biofuels selected for these investigations have been studied partially with some limited assumptions. There is therefore the need for an integrated approach in the assessment of gas turbines utilizing biomass fuels. The model incorporates the performance, emission, economics and the risk modules. The appropriate plant configuration for a suitable and profitable operation with the use of biofuels is necessarily important. The emission model presents reactors arrangement and fuel and air distributions at the various regions of the combustor that elicits clearer emission computation. In addition, a comprehensive economic analysis that employs a systematic management of uncertainties/risks as regards biomass use on gas turbines was carried out.

3 Biomass General

Biomass has been used as primary energy resource since the discovery of fire for heat generation but this has changed since the invention of boilers and the steam engines. Compared with other conventional energy resources, biomass is a renewable organic matter. In addition, due to the emission concerns with the use of other conventional fuels, biomass fuel is deemed suitable as energy source. In this chapter, a synopsis of relevant biomass resources that are suitable for utilization on the gas turbine engines for power generation and their characteristics has been carried out.

3.1 Biomass Categorization

Biomass are categorized into four main groups based largely on their competition or otherwise with food requirement for human being and method of production. These groups are as follows [39]:

a. The first generation biomass are made from food crops such as corn, wheat and sugar cane. The bio-fuels derived from them include biodiesel, ethanol and others. These bio-fuels are environmentally friendly but some of them compete with food requirement for human being and they require substantial input to grow them.

b. The second generation bio-fuels are made from lingo-cellulose stocks such as wood and grasses. They are cheap and can be found in abundance. They are environmentally conducive, do not compete with food crops and require low input to grow them.

c. Third generation bio-fuels are made from algae and cyanobacteria. Products such as biodiesel, methane, hydrogen are derivable from this category of biomass. It is exclusive bio-fuel source and do not compete with food, photosynthetic and so there is reuse of CO_2, it

has very high yield of bio-fuel (as much as 30 times the yield of soybeans and corn) and require simple inputs.

d. Fourth generation biomass is similar to the third generation as it relates to biofuel production from algae but with an advanced technology. It is the employment of metabolic engineering of algae for producing biofuels from oxygenic photosynthetic microorganisms.

3.2 Biomass Resources

The biomass that would be suitable for energy production will need to combine certain characteristics. They must have a high yield, ready availability, very low energy requirement to produce them, low cost, contain low contaminants and as much as possible not deplete food requirement for human being. These requirements make fibrous feedstock suitable for biofuel production [40][41].

3.2.1 Energy Contents of Different Biomass

There are several types of biomass from where biofuel can be derived. Demirbas [42] highlighted some of them to include fatty acid methyl esters (FAMEs), bio-ethanol, bio-methanol, bio-hydrogen and Fischer-Tropsch synthesis fuel. According to Golkap and Lebas, the selection of any particular biofuel for use on an engine would depend on availability, composition, physical properties and cost of the fuel [43] [44].

Table 3-1 Energy Content and CO_2 Emission with Fuel Use [45]

Fuel Type	Specific Energy Density (MJ/kg)	Volumetric Energy Density (MJ/L)	CO_2 Gas made from Fuel Used (kg/kg)	Energy/CO_2 (MJ//kg)
Bagasse	9.6 – 19	-	1.30	7.41
Dried Plants ($C_6H_{10}O_5$)	10 – 16	1.6 - 16.64	1.84	5.44-8.70
Wood fuel ($C_6H_{10}O_5$)	16 – 21	2.56- 21.84	1.88	8.51-11.17
Charcoal	30	-	3.63	8.27
Pyrolysis Oil	17.5	21.35	0.84	20.77
Methanol (CH_3-OH)	19.9 22.7	15.9	1.37	14.49-16.53
Ethanol (CH_3-CH_2-OH)	23.4 – 26.8	18.4 - 21.2	1.91	12.25-14.03
Biodiesel	37.8	33.3-35.7	2.85	13.26
Sunflower oil ($C_{18}H_{32}O_2$)	39.49	33.18	2.81	14.04
Castor oil ($C_{18}H_{34}O_3$)	39.5	33.21	2.67	14.80
Olive oil ($C_{18}H_{34}O_2$)	39.25 - 39.82	33 - 33.48	2.80	14.03
Fossil Fuels (comparison)				
Coal	29.3 – 33.5	39.85-74.43	3.59	8.16-9.33
Crude Oil	41.868	28 – 31.4	3.40	12.31
Gasoline	45 – 48.3	32 – 34.8	3.30	13.64-14.64
Diesel	48.1	40.3	3.40	14.15
Natural Gas	38 – 50	(Liquefied) 25.5 – 28.7	3.00	12.67-16.67

3.2.2 Biomass Yield

From Table 3-1, higher values in the second column (specific energy density) are desirable, as that implies that the particular fuel source is high energy yielding. It is equally desirable to have the fifth column (Energy/CO_2) as high as

possible as that indicates low $C0_2$ emission during biofuel utilization. Any particular biomass combining these two features would meet good economic and environmental requirements of a good fuel.

Table 3-2 Biofuel Crop Oil Yields [45]

Crop	Oil (kg/ha)	Oil (L/ha)	Oil (lb/acre)	Oil (US gal/acre)
Corn (maize)	145	172	129	18
Cashew nut	148	176	132	19
Coffee	386	459	345	49
Linseed flax	402	478	359	51
Camelina	490	583	438	62
Rice	696	828	622	88
Sunflower	800	952	714	102
Cocoa (cacao)	863	1,026	771	110
Peanuts	890	1,059	795	113
Rapeseed	1,000	1,190	893	127
Castor beans	1,188	1,413	1,061	151
Jojoba	1,528	1,818	1,365	194
Jatropha	1,590	1,892	1,420	202
Oil palm	5,000	5,950	4,465	635
Algae		95,000		10,000

Another related feature is the oil yields from crops that produce biofuel or biodiesel. Oil yields per landmass as captured in [45] are shown in Table 3-2: as can be seen, there are several sources from which biofuels can be produced. There is also remarkable disparity in the quantity of oil yields from one biomass to the other. Algae for instance have a very large oil yield per hectare and would serve as a suitable biofuel source. From the list of these biomass, some of them are exclusive energy crops while some of them are derived from food crops.

3.2.3 Significant Properties of Biofuels

Biofuels have distinct properties which make them different from fossil fuels. Some of these features are carbon content, viscosity, boiling point, specific energy content and cetane number. Several comparisons have been made to show the contrast of these characteristics and those of conventional fuels. Some general ones are reported in Table 3-3:

Table 3-3 Some Liquid Bio-fuels Characteristics [37][18][40][46]

Properties	Straight Veg. Oils	Biodiesel	Bio-ethanol	Bio-methanol	Pyrolysis oil	Diesel	Jet As
Densitykg/m3	827.4	807	900-940	860-900	794-810	796	984-1250
Kinetic Viscosity@4°^{C}	1.7	0.88	30-40	35-50	1.4-1.7	1.4-1.7	32-45
Flash point ^{oC}	44	38	230-280	120-180	13	11	56-130
Cloud point ^{oC}	-6	-	-4-12	-3 to -12	-	-	-
Pour point ^{oC}	-16	-47	-12-10	-15-5	-117	-161	-35to-10
LCVMJ/kg	43	43.23	38	39-41	25-26	20	41-45
Ignition temp	250	220	325-370	177	423	463	580
Cetane No	45-55	55	37-42	48-60	8	5	10
Stoi.. FAR	14.6	14	13.8	13.8	9.79	6	34
C	80.33	80-83	76.11	77-81	52.2	37.5	32-48
H_2	14	10-14	-	12	13.1	12.6	7-8.5
N_2	1.76	-	0	0.03	-	-	<0.4
O_2	1.19	-	11	9-11	34.8	49.9	44-60
Sulphur	<0.4	<0.4	0	<0.03	-	-	<0.05

From the properties match up, the main attractions of the biomass compared to the gas oil are: [47]

a. Perpetual availability, hence no restriction of Reserve: Production ratio[1].
b. Potential of growing close to area of application.
c. Carbon neutrality since CO_2 produced on combustion can be considered as absorbed by subsequent crops.
d. Lower Carbon content.
e. Higher flash point giving greater fire safety in handling.
f. Low Sulphur content.
g. Rapeseed Methyl Esters is miscible in any proportion with gas oil.
h. Higher cetane number of Rapeseed Methyl Esters (RMEs) with comparable ignition delay.
i. Spillage of RME degrades rapidly.
j. Lower RME emissions of hydrocarbons and particulates.
k. Stimulus for agriculture in production of fuel resource and utilization of wastes.
l. Lower toxicity with no dermatological effects.

However, the drawbacks include:

a. Higher viscosity and cold filter plugging point, hence need for warming and gum removal.
b. Lower specific energy and energy density, hence higher fuel consumption for given power output.
c. Carbon deposition on inlet valves.
d. Greater corrosion.

The distinctiveness of the biofuel is as a result of other peculiar characteristics such as flash point, cloud point, heating or caloric value which is adequately

[1] Reserve: Production ratio is the ratio of how much longer natural resources will last at current rate of production i.e known amount of resources divided by the amount used per year.

elucidated by Goodger [48]. Typical values of some physical and chemical compositions of some biomass types are as shown in Tables 3-4 & 3-5 for illustrative purposes.

Table 3-4 Physical Characteristics of sugar cane bagasse and trash [49]

	Chopped Trash	Bagasse	Wood
Particle Size	<1-10cm^{-3}	<5cm	<10cm
Bulk Density (Kgm^{-3})	95-130	50-75	90-110
Moisture Content (Wt%wet)	30	50	30

Table 3-5 Higher Heating Value and Chemical Analysis of Some Solid Biomass Fuels [17]

Biomass Composition	Rice Hull	Rice Straw	Sugar cane Bagasse	*Switch grass*	Wood/ straw	Paper	MSW	Lignite
C(%)	38.8	38.2	48.6	*46.7*	47-52	48	39.7	61
H(%)	4.7	5.2	5.9	*5.8*	4-6	6.6	5.8	4
02	35.5	36.3	42.8	*37.4*	38-42	37	27.25	18.5
N2	0.5	0.9	0.16	*0.8*	0.3-0.7	0.14	0.80	1
S	0.05	0.2	0.04	*0.2*	.03-.01	0.07	0.35	1.8
Cl	0.12	0.6	0.03	*0.2*	0.013			0.05
Ash	20.3	18.7	2.44	*8.9*	3-8.2	8.3	26.1	13.7
HHV(MJ/kg)	15.84	15.09	18.99	*18.06*	16-21	20.78	15.54	23.35

3.3 Biomass Production in Nigeria

Nigeria currently has increased the drive for biomass production. According to the Food and Agricultural Organisation (FAO)[6] figures for 2009, which is corroborated by the Dutch Agricultural Development & Trading Company [50] figures for 2013, the country ranks high among nations of the world in the production of biomass resources. However, the main effort is in the conversion of these biomass into biofuels for transportation. The wastes from these resources can be gasified for power generation. There is abundant land mass for the production of more biomass in Nigeria from which the fibrous remains like sugarcane – bagasse and cassava pulp can be further utilized for power generation. In addition, the production of herbaceous biomass which are exclusive resources can be stepped up. Suitable sources in this category include woodfuel and Jatropha.

Table 3-6 Nigeria Biomass Production Figures [5]

Crop	2007 Average yield in Metric Tonnes	Biofuel Type	Biofuel Yield (L/Ha)	Nigeria's Global Ranking
Sesame	100,000	Biodiesel	696	7th
Palm oil	1,300,000	Biodiesel	5,950	3rd
Palm Kernel	1,275,000	Biodiesel	5,950	3rd
Ground Nut	3,835,600	Biodiesel	1,059	3rd
Soybean	604,000	Biodiesel	446	11th
Coconut	225,500	Bio-ethanol	2,689	17th
Sugarcane	1,506,000	Bio-ethanol	6,000	51st
Cotton seed	212,000	Biodiesel	325	16th
Cassava	34,410,000	Bio-ethanol	4,000	1st
Corn	6,724,000	Bio-ethanol	172	10th

Table 3-7 Estimates of Nigeria's Biofuel Production Potential [5]**[12]**

Feedstock	Cultivated Area in 2007 (Ha)	Biofuel Type	Biofuel Production Potential Estimate (Million Litre)
Sesame	196,000	Biodiesel	136.4
Palm oil	3,150,000	Biodiesel	18,742.5
Palm Kernel	3,150,000	Biodiesel	18,742.5
Ground Nut	2,230,000	Biodiesel	2,361.6
Soybean	638,000	Biodiesel	284.5
Coconut	41,000	Bio-ethanol	110.2
Sugarcane	63,000	Bio-ethanol	378.0
Cotton seed	434,000	Biodiesel	141.1
Cassava	3,875,000	Bio-ethanol	15,500.0
Corn	3,440,000	Bio-ethanol	678.4

Table 3-6 indicates figures of the hectares of land cultivated and the corresponding biofuel resourses derived. This crop production data shows the high potential for biofuels production in Nigeria. The increase in output comes from crops like maize, rice, sorghum and cassava; with the nation currently ranked first in cassava production globally. An increase in percentage land utilisation would lead to more biofuel being derived as shown in Table 3-7 and more residues available for power generation in addition to herbaceous ones that are exclusive for energy generation.

3.3.1 Land Issue for Biomass Growth in Nigeria

Nigeria has a land expanse of 923, 768 sq km with land utilisation as shown in Figure 3-1. Out of this total, about 85% representing a total of 79.4 million hectares is land while 15%, equivalent of 13.0 million hectares is occupied by water. Total land for agriculture is about 71.9 million hectares (including 33% indicated as land area representing occupied land also available for farming in some cases) indicating a high potential for agricultural production and other non food biomass resources. There are great potentials in rural areas that would support the production of biofuel in Nigeria as about 70 per cent of the country's labour force resides in rural areas [51]. This labour capacity can be deployed for increased production of biofuel feedstock for power generation.

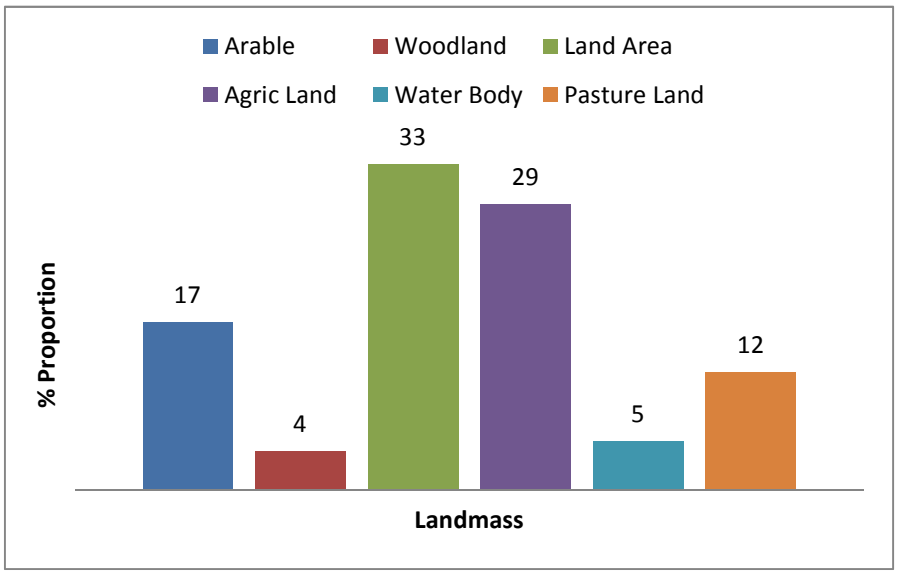

Figure 3-1 Nigeria land area and usage [39] [5]

Woodfuel is another resource in Nigeria owing to the nation's vast forest and existing woodland. Currently, wood is a major form of energy in the traditional way of heating and cooking food. Nigeria has a diversity of landscape with

different vegetation in the various geographical regions from the North to the South of the country. This diversity in vegetation encourages the production of different biofuel from different biomass resources across the entire country. The 2009 figure of bio energy reserves/potentials of Nigeria per annum from these non-food resources stands at: fuel wood 13,071, 464 hectares, animal waste 61 million tonnes per year, crop residue 8.3 million tonnes [17]. Figure 3-2 shows the energy equivalent of these resources when converted at approximately 13GJ/ton (based on 10 tons/ha/yr yield at an average of 12MJ/Kg LHV), 20GJ/ton and 27GJ/ton for wood, animal waste and crop residues respectively:

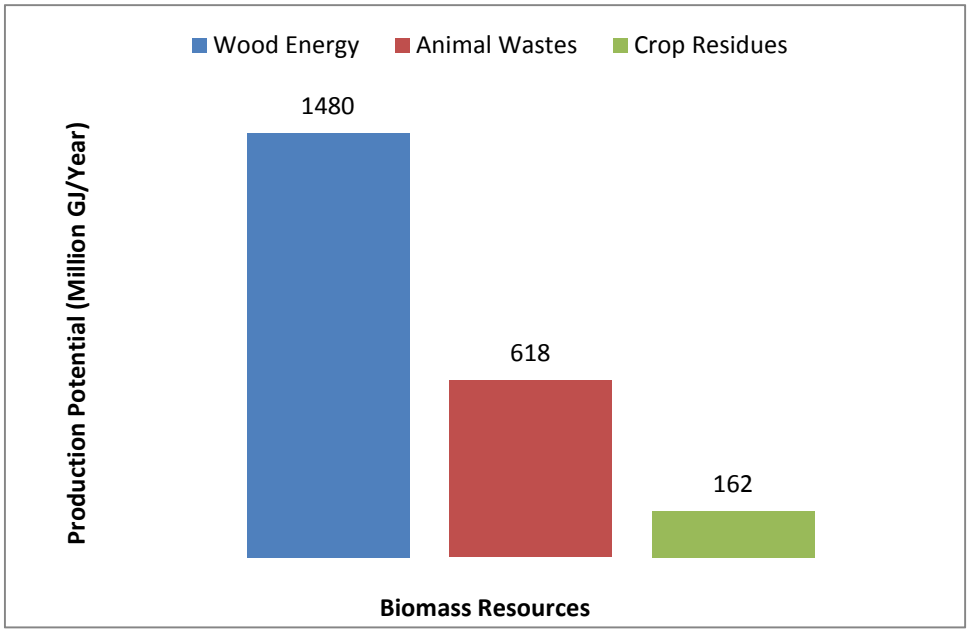

Figure 3-2 Non Food Biomass Types & Production Potentials [12]

3.3.2 Current Power Production by Fuel Types in Nigeria

Figure 3-3 shows an early 2012 power generation per energy resource, it can be seen that the bulk of power production is from gas fired turbines while the steam turbine and hydro power account for about 24% each. There are

currently no gas turbine engines that use biomass in the country despite the huge biomass resources available. Most of the biofuel produced in the country is either used as bio-ethanol or biodiesel (blend or whole) for transportation while the wood and other residues are directly burnt for domestic use. Woodfuel utilization by households in Nigeria is by far the largest single demand on forests and woodlands. If biomass is properly harnessed for power generation to supplement power from conventional resources, there would be more dependence on electricity for everyday domestic use rather than burning of firewood for heat. This would lead to a more efficient, cleaner energy and environment for the populace.

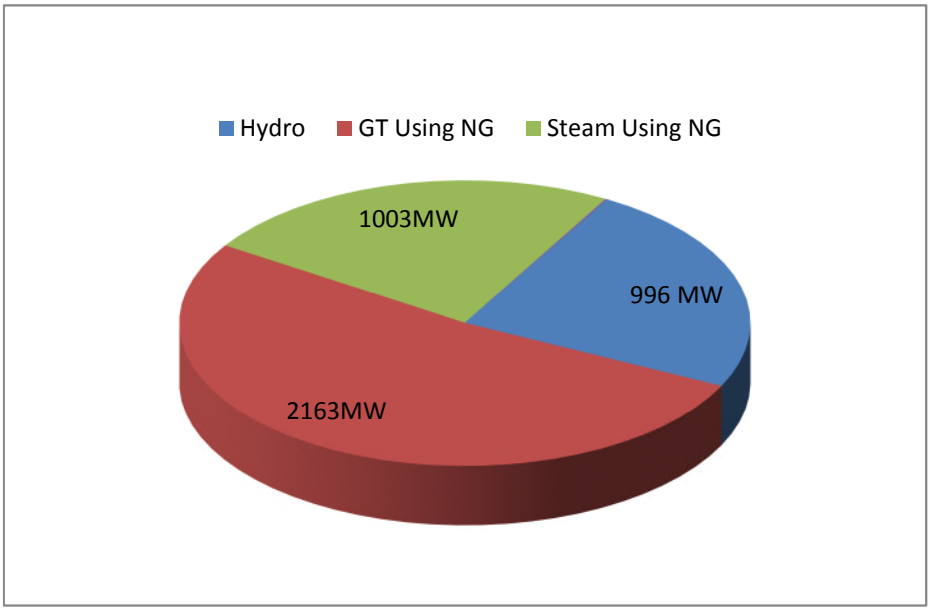

Figure 3-3 Power Production by Energy Types for 2012 [52]

Contrastingly, with this poor outlook in biomass to energy in Nigeria, there are countries in the world whose biomass power generation is in excess of current total Nigeria power generation figure. For instance, US exclusive biomass power generation is above 8,000MW [53]; sufficient to light over 8million American homes. Similarly, Brazil is currently relying on various biomass

resources for their power generation. Brazil currently generates a good percentage of their electricity from sugarcane bagasse and wood residues. Interestingly, the sugarcane mills in Brazil are self-sufficient in terms of power generation, with an installed capacity of over 600MWe [54]. With the sustenance of the current biomass production drive, Nigeria can generate electricity from biomass in no distance time.

3.3.3 Policy Framework

An extant National Energy Policy of 2003 [55] provides for optimal use of renewable resources for power generation. The thrust of the policy was to harness biomass resources and integrate it with other resources and also promote the use of efficient biomass conversion technologies. This was meant to achieve the objectives of using biomass as alternative energy resource and promote the use of agricultural, animal and human residues as sources of energy.

In addition, the power sector environment was further liberalized by the EPSR Act of 2005 with a follow-up Renewable Energy Master Plan in 2006 all aimed at achieving sustainable power with a diversified energy mix [55].

This provided the Nation with options of exploring sustainable renewable energy sources in large quantities at a highly competitive pricing. It also ensures considerable reduction of pollutants and green house gas emissions. The effort will accomplish an overall higher participation of rural dwellers and thereby enhance their well being in terms of electricity availability and standard of living. The benefits of biomass utilization will be further guaranteed by the grant of subsidy on agricultural production by the gorvenment.

3.3.4 Crops for Biofuel Production

There are concerted efforts at producing biofuel from cassava, wheat, sorghum, sugar cane & sugarcane bagasse, palm kernel and some exclusive non-food biomass resource like Jatropha. This has become imperative as diesel demand will continue to rise due to rising economic and industrial activities. A good energy alternative is bio-energy resources. Viable feedstock plants are therefore being sought for cultivation as renewable resources to augment and eventually replace fossil fuels.

Jatropha curcas has a great potential for bio-energy production. It has the advantage of high yield of up to 7.5 to 12 tons per hectare per year after 5 years of growth and the seed is resistant to a high degree of aridity and contains 27-40% of oil by weight and thus can produce high quality biodiesel for use on assorted standard engines running on fossil diesel [56]. Generally, biodiesel production is by trans-esterification of triglycerides into methyl esters using an alkali, acid or enzymes as catalysts.

3.3.5 Potential Nationwide Biomass Production

One of the challenges of utilizing biomass for power generation is the relatively higher initial cost. The major cost elements include the gasifier cost, cost of gas turbine engines and the feedstock production cost. In considering the feedstock cost, the several cost elements include biomass growth, transportation and the preparation of the biomass. It is desirable to locate the power stations near the biomass production sites for on-site power generation in order to lower the overall cost of energy through reduced biomass transportation cost.

Consonni et al [23] reported an estimated 2010 biomass yields and the corresponding costs in some States of America. This was based on maximum transport distance of 24km to the power station after considering many sites of

biomass plants in various States in America. Details of the yield and costs are as shown in Table 3-8.

Table 3-8 Biomass Projected Yields and costs in the US [23]

States	2010 Yield (Tons/ha/yr)	Cost ($/GJ)
Wood Crops		
Northeast	13.3	2.11
South/S.East	14.7	1.92
Midwest	14.7	2.37
Lake States	14.7	2.07
Northwest	22.1	1.67
Grasses		
Northeast	17.2	2.09
South/S.East	24.1	1.58
Midwest	20.7	2.14
Lake States	20.7	1.89

Nigeria has six geographical regions that are suitable for different biomass production. Biomass production can be distributed in these geographical locations depending on their potential for types of biomass resources. This way, the populace would be relevant in the feedstock production and the proximity of feedstock will ensure an overall reduction in the cost of energy. The projected type of biomass production along these geographical areas is as shown in Table 3-9. The production potential of wood, bagasse and Jatropha is high in all the regions and this accounts for their choice for analysis in the present work.

Table 3-9 Regions/Biomass Type Production in Nigeria

Regions	Biomass Type
North East	Municipal Waste, Agricultural Residue, sugarcane baggase
North/ West	Municipal Waste, Agricultural Residue, sugarcane baggase
North/ Central	Municipal Waste, Agricultural Residue, sugarcane baggase
South/ West	Wood, Jatropha, Municipal Waste
South East	Wood, municipal waste
South/ South	Wood, Jatropha, Municipal Waste

3.3.6 Residues as Fuel Source

The very common residues for power generation are sugarcane bagasse and forestry residues. Electricity generation from bagasse is a proven process which utilises waste products generated on-site from sugar refineries and re-use them directly for both power and heat generation. The seasonal nature of sugarcane growth may limit the application of bagasse as a stand-alone biomass source for electricity generation.

The option available therefore is to have a mix of other agricultural residues for a year round generation. The residues can result from wood, stalks, pruning and shells from rice, vegetables, cotton and even maize.

3.3.7 Dedicated Crops

In order for biomass to play a significant role in energy generation in the future, the viable option is the production of dedicated bio resources. Crops that are considered suitable in this category are poplar, willow, eucalyptus, switch grass, Jatropha and wood. Issues of concern with dedicated crops include the depletion of soil strength, organic matter and moisture holding capacity and loss of biodiversity. The later concern is due largely to continuous use of the land for a particular type of crop thereby requiring inputs like pesticides and fertilizers for the enhancement of high yield. In order to mitigate this shortfall, there is need to retain corridors of natural vegetation and also establishing native vegetation.

3.4 Prospects of Biomass for Power Generation

There are curent concerns of the appropriateness of biomass for energy generation generally tagged biomass ethics. These concerns ranges from the sustainability, environmental issues, economic viability and several impacts of biomass utilisation. The SWOT analysis done by Carniero et al[57] for a particular location can fairly represent a general outlook for most countries: This is detailed in Table 3-10.

Table 3-10 SWOT Analysis for Biomass for Power Generation [57]

	Strengths	Weaknesses
Internal	*Development of rural areas.* *Creation of direct and indirect jobs.* *Diversity of energy supply.* *Reduction of soil erosion during the replacement of energy fields by farmland.* *Independence from fossil fuel markets.* *Storage potential and possibility of generation prediction.*	*Possibility of affecting the quality of soil, air, water and biodiversity.* *Possibility of using land that could be needed for food production.* *Dependence on external conditions of climate and pest attacks, during the production*
	Opportunities	Threats
External	*Biomass is a heterogeneous energy and can be interesting for specific markets.* *Market growth perspectives.* *Energy and climate change priority on policy agenda.* *Revenues still protected by feed -in tariffs and by ensured access to the grid.*	*Competition with fossil fuels and other renewable sources.* *Instability of the energy market and liberalization trend of the market and of the tariffs.* *Possibility of social opposition.*

4 Performance Modelling and Analysis

Gas turbine engine modelling is carried out to determine the performance characteristics of the engines that have been selected as case studies in this present work. Effects of operating and ambient conditions on the performance of the gas turbine engines were assessed. The analysis is started at design point and also through the entire operating range of the engines (off-design). In addition, the engines were further modelled in combined cycle which shows an overall increase in thermal efficiency and the power outputs.

4.1 The Performance Model

To ascertain the performance of the engines at different ambient and operating conditions, two different engines that are suitable for use with biofuels were modelled. In addition, a third engine (industrial engine of 50MW) was modelled solely for the purpose of validation of the emission values.

Firstly, a conventional fuel (natural gas) was used as the baseline fuel and then the biomass derived fuels (syngases from wood and sugarcane bagasse which are products of gasification and the Jatropha biofuel). The performa nce of these engines which comprise an aero-derivative engine of 23MW (case 1) and an industrial engine of 77MW (case 2) were evaluated in both simple and combined cycle configurations.

4.1.1 BIGGT/CC Configuration for Present Work

Two of the selected biofuels selected for analysis in the present work (wood and bagasse) are solid biofuels requiring gasification. An atmospheric biomass integrated gasification combined cycle has been suggested bearing in mind the sizes of the plants chosen for modelling (23MW and 77MW). The component arrangements are as shown in Figure 4-1:

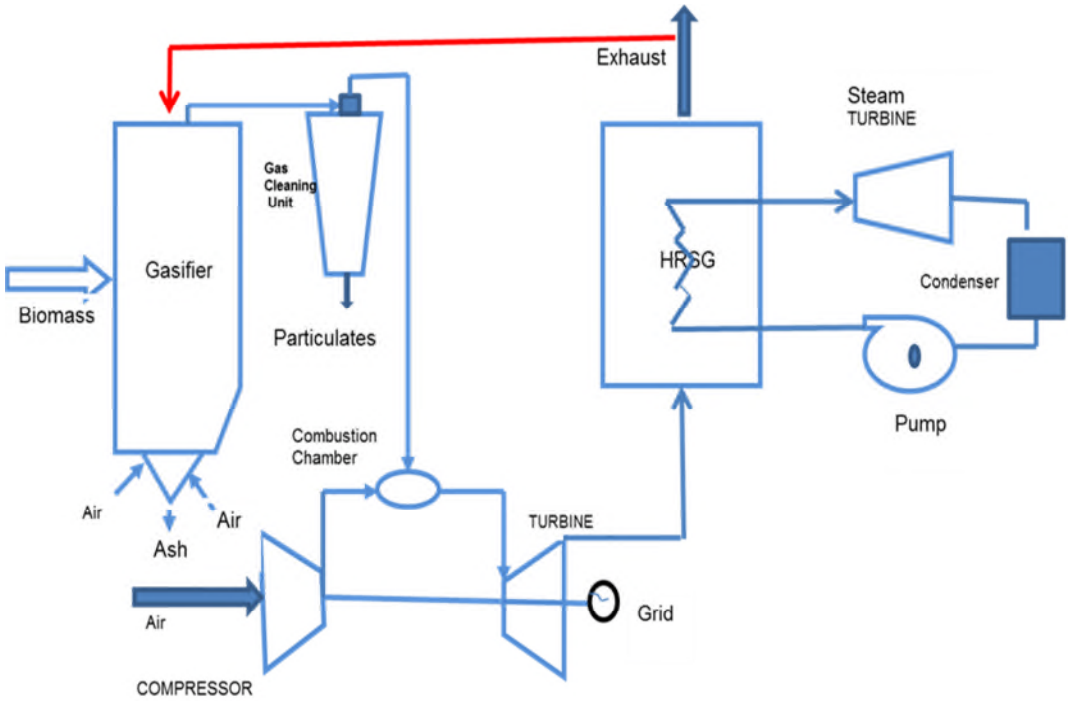

Figure 4-1 Schematic of a Biomass Integrated Gasification Gas Turbine (BIGGT/CC) Combined Cycle

Though the schematic includes the gasification unit, this portion would not be included in the modelling. However, appropriate compositions of syngas and other conditions in respect of the gasifier have been adopted from relevant literature.

The power plant is expected to be located near shared facilities like land and electrical sub-stations. It should be in close proximity to roads for easy access and delivery of biomass feedstock. Dedicated feedstock is desirable in which case the plant is sited at the centre of the agricultural area representing the biomass 'shed'. Additional consideration is the availability of good water source for cooling and other system water treatments.

The utilisation of biomass as a suitable energy resource was done by simulating the performance of gas turbines on biofuels utilising both solid and liquid

biomass resources. The performance modelling excluded the gasification process. The emission prospects with the use of biomass were also determined in addition to the economic viability and risk considerations.

4.2 Turbomatch Overview

Turbomatch is a Cranfield University in-house engine performance tool developed for both DP and OD performance calculations. The various components of the GTEs are represented by pre-programmed units called 'Bricks' whose characteristics are defined and can be called in modules during simulations. These bricks calculate the thermodynamic processes occurring within a particular component. The bricks are interfaced to describe the complete engine. The gas state from the inlet to the outlet of all component parts of the engine is described by quantities known as 'station vectors'. Each station vector contains the fuel-air-ratio, mass flow, static and total pressure & temperature, velocity and the area. The various parts and station numbering of typical GTEs are depicted in Figure 4-2.

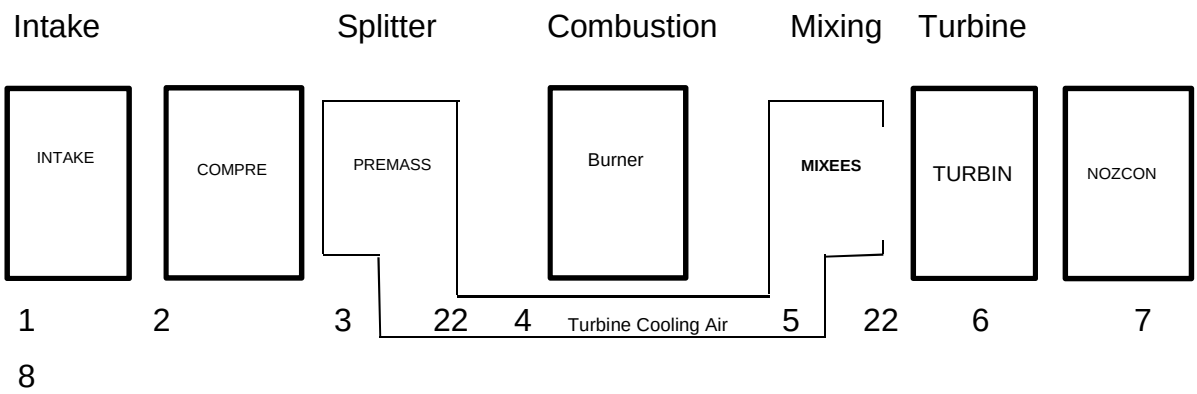

Figure 4-2 Typical Station numbering on Single Shaft Gas turbine Engine

4.2.1 Modelling Methodology for BIGCC

In order to model the plant utilizing biofuels, the Turbomatch with multi fuel capability is used. This version of Turbomatch also has water/steam injection capability in which case new brick data and output column are created. Details of this version of the Turbomatch simulation tool are found in [58]. Another simulation tool developed at Cranfield University and successfully used in previous studies within the Department with multi-fuel capability is the Pythia [59]. In either case, the fuel properties are obtained using the NASA Chemical Equilibrium and Application [60] and then used as inputs in the code to run simulations.

4.2.2 Standard Operating Conditions for GTEs

The atmospheric conditions under which the gas turbine operates are relative to an average or standard atmosphere known as the international standard atmosphere (ISA). Some of the ISA values at sea level include:

- Ambient pressure = 101.32kPa
- Ambient Temperature = 288K
- Universal gas constant (R) = 287J/(kg.K)
- Molar mass of air = 28.9644g/mol
- Specific heat at constant pressure (Cp) = 1000J/kg.K

4.3 Simple and Combined Cycle Performance Simulation

As earlier mentioned, the initial performance simulation covers an aero-derivative and an industrial engine; the third engine was meant for validation of

the emission values. The assessment is done in both design point and in off design.

The gas turbine in simple cycle comprises the compressor, the combustor and the expander that operate in harmony to produce power. The engine is measured by the aggregate of the work it produces in relation to the inputs into it and this is known as efficiency.

The gas turbine thermal efficiency in simple cycle is given by the equation:

$$\boldsymbol{\eta_{GT}} = \frac{\boldsymbol{Useful\ Work}}{\boldsymbol{Heat\ Input}} \quad \text{..... ....Equation 4-1}$$

Similarly, the equation defining specific work or power according to [61] is:

$$\boldsymbol{SW} = \frac{\mathbf{UW}}{\boldsymbol{W}} = \boldsymbol{C_p}(\boldsymbol{T_3} - \boldsymbol{T_2})\left\{\mathbf{1} - \frac{\boldsymbol{T_1}}{\boldsymbol{T_2}}\right\} = \boldsymbol{C_p}\left[\boldsymbol{T_3} - \boldsymbol{T_1}\boldsymbol{\pi}^{\frac{\gamma-1}{\gamma}}\right]\left[\mathbf{1} - \boldsymbol{\pi}^{\frac{-(\gamma-1)}{\gamma}}\right] \quad \text{Equation 4-2}$$

Where UW = Useful work or power,

W=mass flow,

Cp=Specific heat at constant pressure,

$\boldsymbol{\pi}$ = pressure ratio,

γ = ratio of specific heat and

HI = heat input.

4.3.1 Aero-derivative Engine Design Point Performance

The aero-derivative gas turbine engine chosen for modelling is inspired by the GE LM2500+ engine with a power output of about 23MW. The performance parameters resulting from the Turbomatch simulation with the base fuel are reported in Table 4-1 and they are in good agreement with the original engine manufacturer data as shown in the last column.

Table 4-1 Design – Point Parameters of the Aero-derivative GT Engine (Case 1)

Parameter	Manufacturers' Data[62]	Turbomatch	Deviation (%)
Mass flow (kg/s)	69.0	69.0	0.0
Pressure ratio	20.1	18.8	6
Fuel Flow (kg/s)	-	1.3777	-
Shaft Power (MW)	23.8	22.8	4
Thermal Efficiency (%)	37.5	37.77	0.7
Ambient Temperature (K)	288.15	288.15	0.0
Atm Pressure (Atm)	-	1.000	-
TET (K)	-	1505	-
Compressor Isentropic Efficiency	-	0.88	-
Turbine Isentropic Efficiency	-	0.885	-

4.3.2 Aero-derivative Engine Off Design Performance Simulation

The off design performance shows the considerable effects of both operating parameters like the turbine entry temperature and the ambient conditions of temperature and pressure on the gas turbines. The changes in the ambient temperature T_{amb} and the TET have effects on the engine power and efficiency. There is an increase in shaft power at lower ambient conditions and at higher TET.

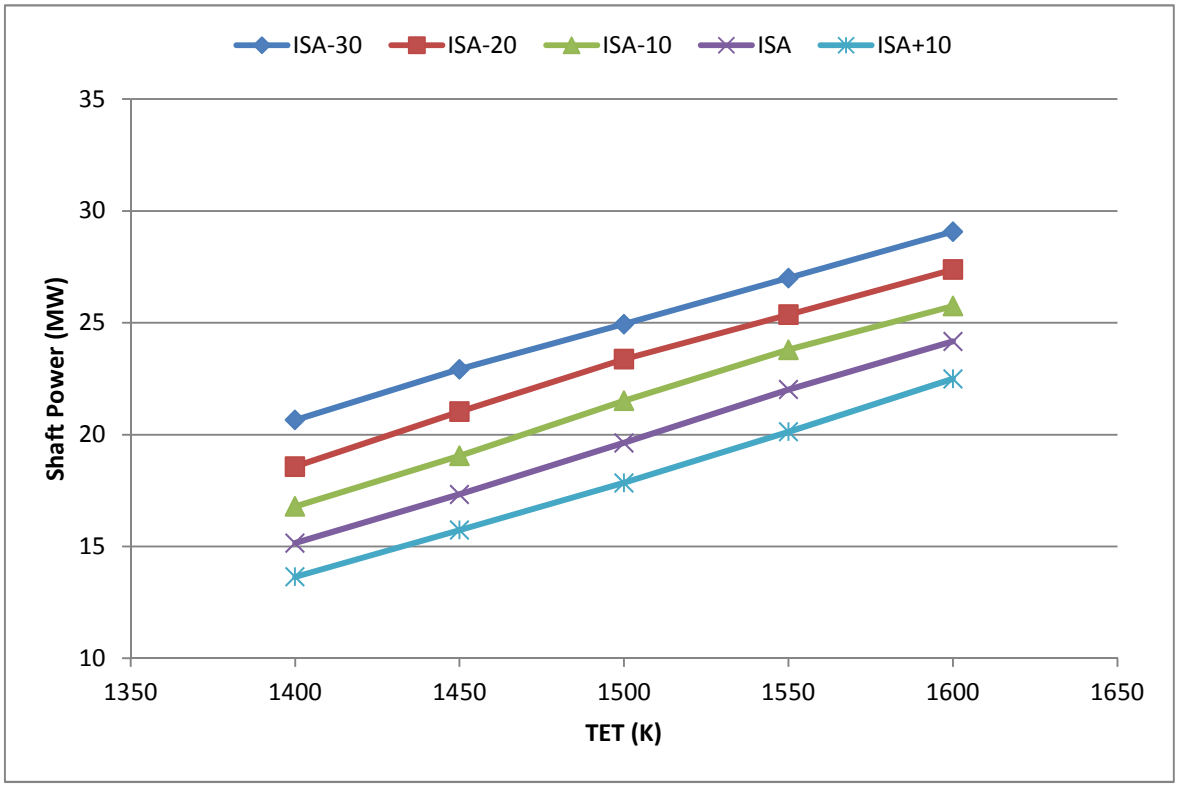

Figure 4-3 Influence of TET on Shaft Power at Different Ambient Temperatures

At constant TET, the efficiency reduces with rise in ambient temperature. This is because with increasing ambient temperature, the compression work required for hotter air is higher as a result of the reduced air density. To balance out, there is increase in TET in order to generate the same power output which means higher specific fuel consumption thereby affecting the overall efficiency.

Similarly, the effect of the ambient temperature on the shaft power can be seen. It shows a decrease in the engine shaft power as a result of rising ambient temperature for the same reason given above. However, at any particular ambient temperature, a rise in the TET will translate into rise in the engine shaft power. Details of these effects are shown in Figures 4-3 to 4-4.

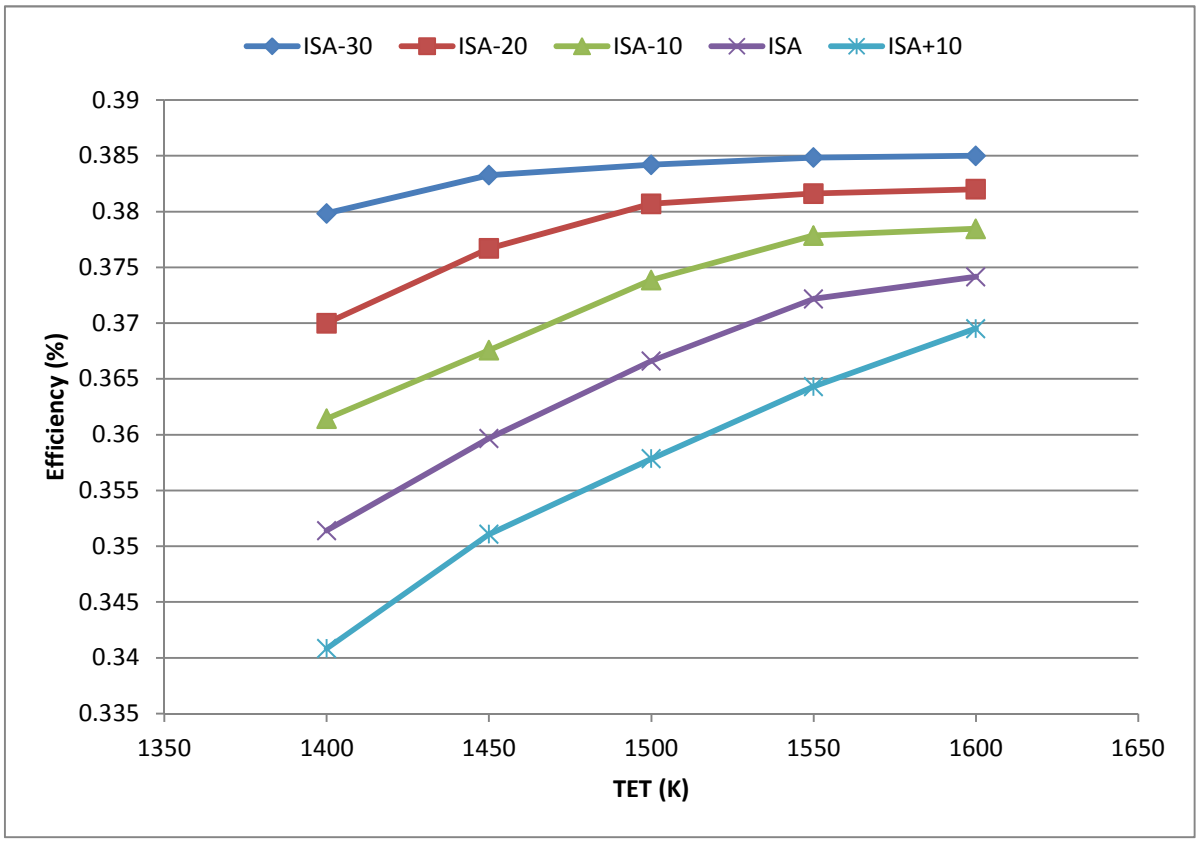

Figure 4-4 Influence of TET on Efficiency at Different Ambient Temperatures

4.3.3 Industrial Engine (Engine 2) Design Point Performance

The industrial engine simulated is inspired by the Frame 6FA engine with 77MW power output. The DP values and the variance with the Turbomatch model are represented in Table 4-2:

Table 4-2 Design – Point Parameters of Industrial GT Engine (Case 2)

	OEM[62]	Turbomatch	Difference (%)
Mass Flow (kg/s)	260	260	0
Pressure Ratio (%)	15.8	15.8	0
Fuel Flow (kg/s)	-	4.881	-
Shaft Power (MW)	77.1	77.1	0
Thermal Efficiency (%)	35.3	36.7	3.9
Ambient Temperature (K)	288.15	288.15	0.0
Atm Pressure	-	1.000	-
TET(K)	1450	1450	-
Compressor Isentropic Efficiency	-	0.88	-
Turbine Isentropic Efficiency	-	0.885	-

OEM and Turbomatch input data are close to one another and so the results from the engine simulation can be considered well aligned with the ones available in the public domain. Values in OD simulation in simple cycle are as shown in the various figures showing expected changes due to varying ambient temperature and the TET.

4.3.4 Industrial Engine (Case 2) Off-Design Simulation

The industrial engine was further simulated in all the range of operation. Like the aero-derivative engine, the off-design simulation was carried out between a TET range of 1450K to 1600K and an ambient temperature range of -25° C to 30° C to depict the wide range and variance of the operational temperatures of the industrial gas turbine from the artic to the tropical regions.

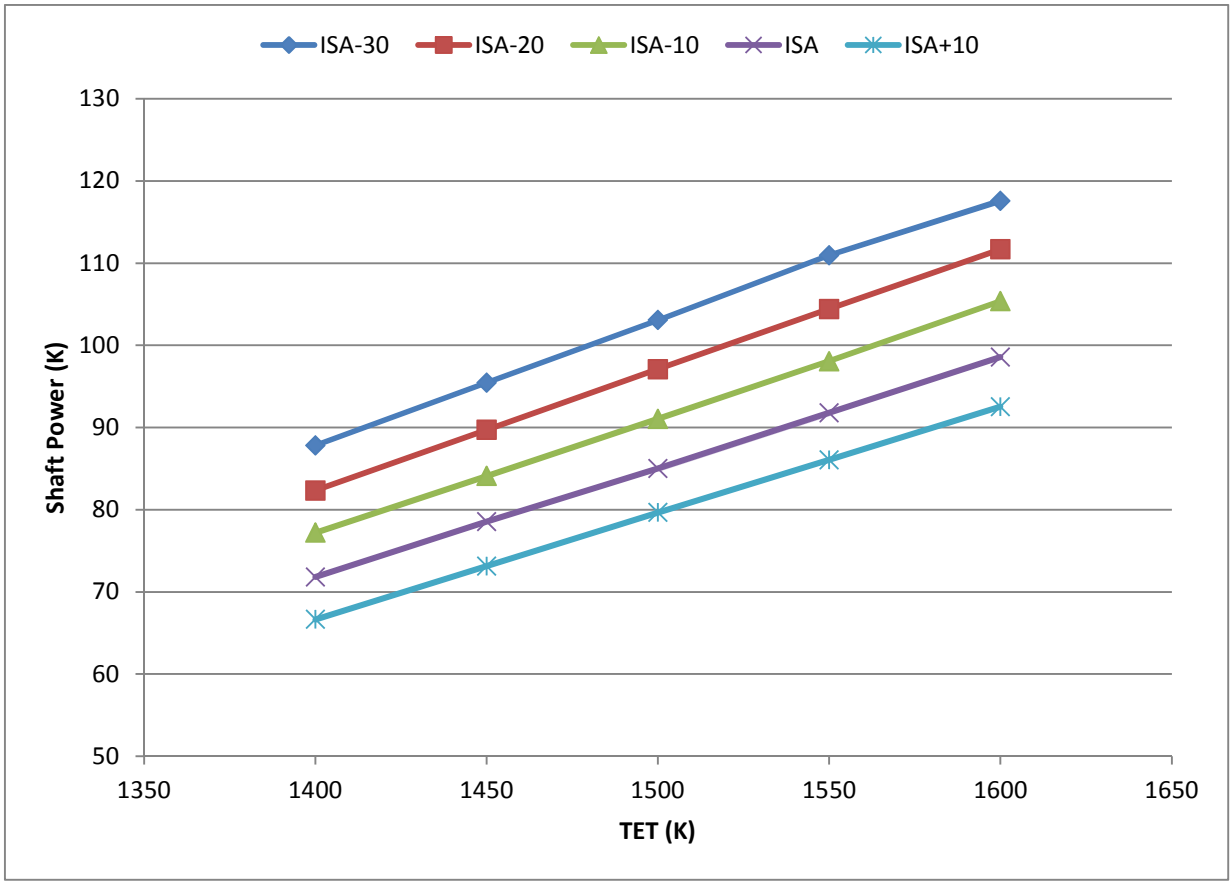

Figure 4-5 Shaft Power VS TET at Different Ambient Temperatures

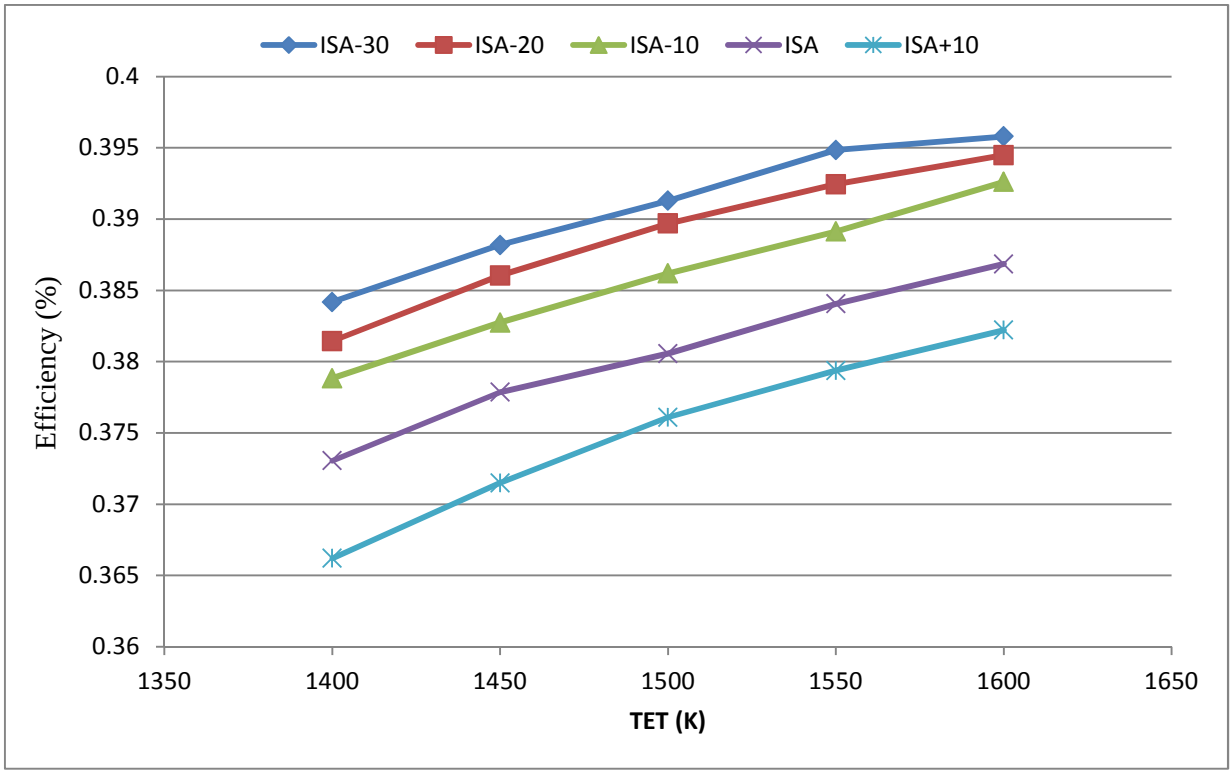

Figure 4-6 Efficiency VS TET at Different Ambient Temperatures

Details of the engine behaviour are as shown in Figures 4-6 to 4-7. The trend is same with varying ambient temperatures and the TET like the case of the aero-derivative engines but with different output values.

4.3.5 Engine 3 (Similar to Siemens' SGT Engine) Simulation

In order to allow for validation of the results from the emission model, a third engine similar to the Siemens SGT-800 of 50MW was further simulated. The design point values for the engine in comparison to the manufacturer data is in Table 4-3, while the OD engine behaviour in relation to changes in ambient temperature is shown in the later part of the report.

Table 4-3 Design – Point Parameters of Engine 3 (Industrial GT Engine)

	OEM[63]	Turbomatch	Difference (%)
Mass Flow (kg/s)	162.6	162	0.4
Pressure Ratio (%)	16.1	16.3	1.3
Fuel Flow (kg/s)	-	3.0387	-
Shaft Power (MW)	50.1	50	0.2
Thermal Efficiency (%)	36.3	36.3	0
Ambient Temperature (K)	288.15	288.15	0.0
Atm Pressure	-	1.000	-
TET(K)	-	1500	-
Compressor Isentropic Efficiency	-	0.88	-
Turbine Isentropic Efficiency	-	0.885	-

The outputs from this engine were used for the emission model in order to confirm an empirical result obtained by Siemens during an experiment on the engine for emissions trend computation. Details of the emission results are shown in Chapter 5.

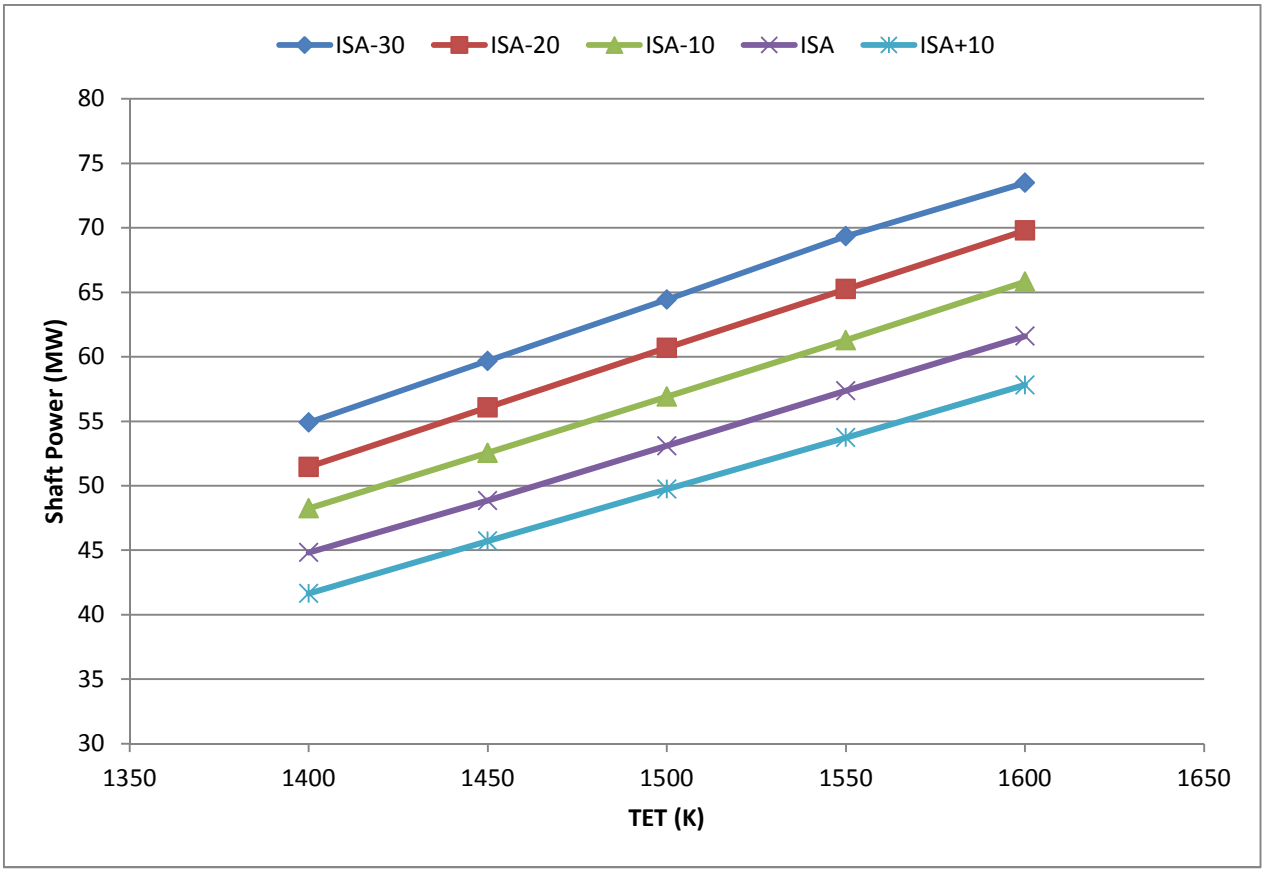

Figure 4-7 Effect of Ambient Temperature on the Shaft Power at different TET

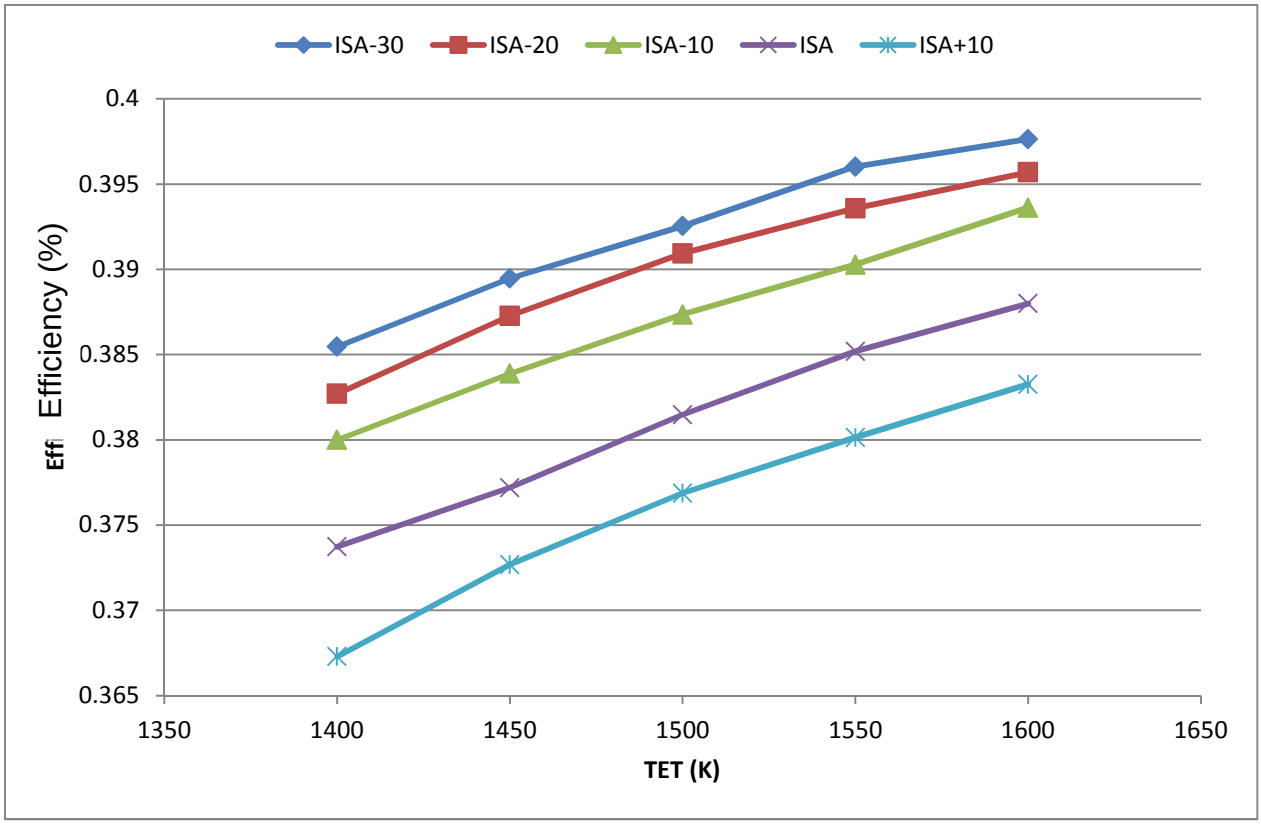

Figure 4-8 Effect of Ambient Temperature on the Efficiency at different TET

The changes in the different parameters (shaft power and efficiency) in relation to the varying ambient temperature and TET follow same correlation like the first two engines but at different rates. The identified changes are closer to the 77 MW industrial engines than the aero-derivative engine. These changes are detailed in Figures 4-7 & 4-8.

The percentage change in values of these parameters of the engines as a result of changes in the ambient temperature underscores the effect of site or location of the gas turbines. When determining the off-design performance, it is important to be able to predict not only the effect on specific fuel consumption of operation at part load, but also the effect of ambient conditions on maximum output [64].

4.4 Combined Cycle Simulation

As detailed in the previous section, the gas turbine cycle simulation is performed by the Turbomatch software. The steam cycle simulation code was developed by the author in Matlab language. The code relies on some essential input from the gas cycle for simulation. These include the exhaust temperature, fuel flow and mass flow. Other data which are required include steam pressure, condenser pressure, pinch point temperature difference, composition of the flue gases and pressure drop in the gas side of the HRSG. Others include the steam turbine isentropic efficiency, mechanical efficiency and pump efficiency. Detailed calculations within the steam cycle are contained in the code as Appendix 2.

Similar to the gas turbine cycle, stations are also defined in the steam cycle as reflected in the Figures 4-9 & 4-10. Thermodynamic values of the enthalpy and entropy are therefore calculated using relevant equations as contained in the code (see Appendix 3). From the supplied input data, principally from the topping cycle, additional power is generated in the steam cycle which leads to a remarkable increase in the overall plant efficiency.

The combined cycle is characteristic of a power producing engine or plant that employs more than one thermodynamic cycle. Though the GT can combine with several other cycles, the traditional combined cycle is composed of the gas and steam cycles.

In combined cycle, the efficiency equation is:

$$\eta_{CC} = \frac{Useful\ Work}{Heat\ Input} = \eta_{GT} * \frac{W_{GT} + Wsteam - Wpump}{W_{GT}} \qquad \text{Equation 4-3}$$

Where:

η_{CC} = Overall combined cycle thermal efficiency

η_{GT} = Gas turbine thermal efficiency

W_{GT} = Gas turbine shaft power

W_{steam} = Steam turbine shaft power

W_{pump} = Feed pump work

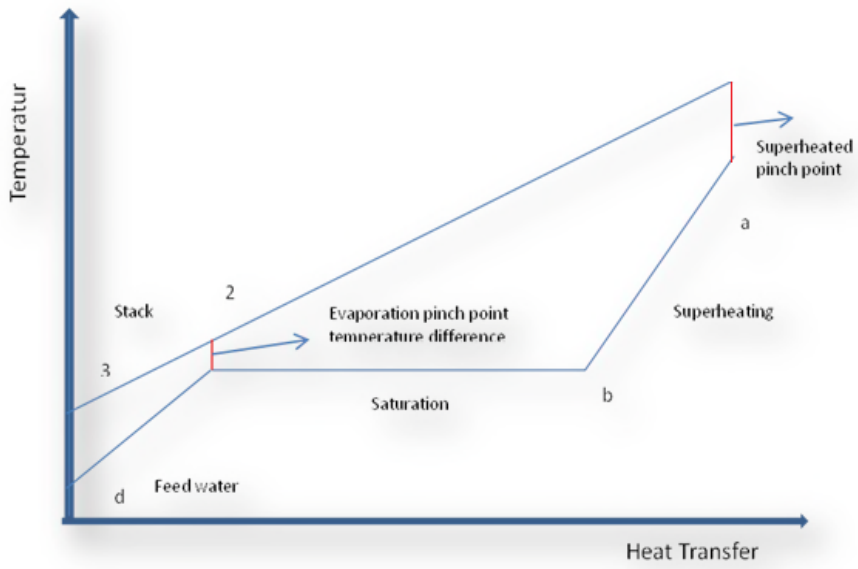

Figure 4-9 Heat Transfer Diagram for a HRSG

Some parameters of the steam turbine are as follows:

a.	Steam turbine pressure	=	70bar
b.	Pinch point temperature difference	=	10K

c. Pressure drop in the heat recovery steam generator (HRSG) = 0.02

d. Feed pump efficiency = 0.8

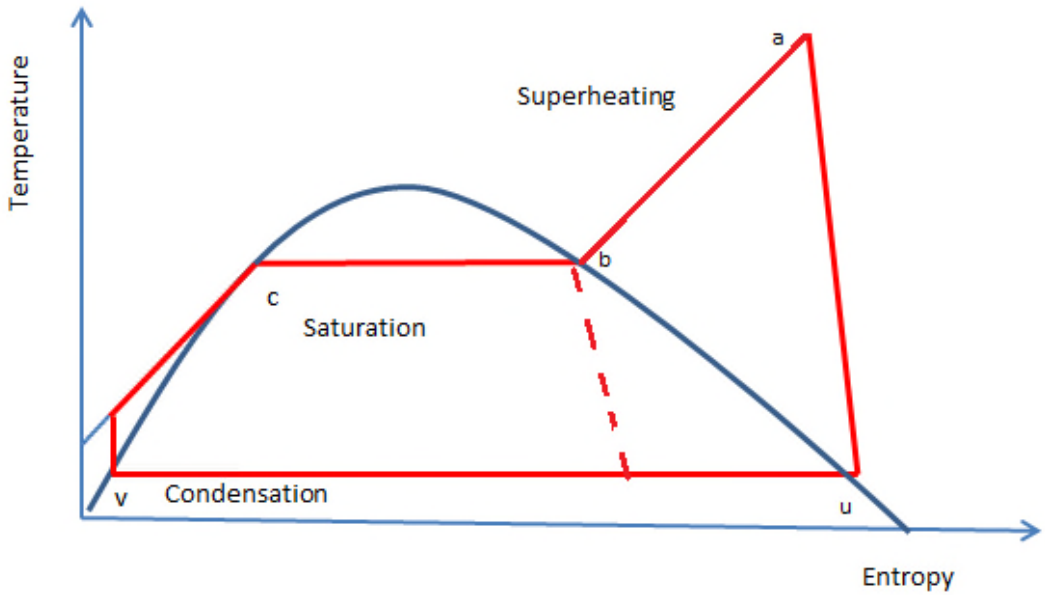

Figure 4-10 Temperature – Entropy Diagram of Steam Cycle

4.4.1 Data for the Combined Cycle Performance Code

There is need to validate the assessment method adopted for the single pressure combined cycle. Two codes, one being the Turbomatch and the other being the linked Matlab code for the steam cycle have been utilized. The input data for the combined assessment are as follows:

GT data

- Ambient temperature - 288K
- Ambient pressure - 1atmosphere
- TET - 1505 & 1400K for the two engines
- Molar composition, temperature, pressure, mass flow of the exhaust gases are sundry for the 3 engines
- Shaft power and thermal efficiency and fuel flow are also different for the two engines.

Steam cycle data

- Steam Turbine pressure - 70 bar
- Condenser pressure - 0.1bar
- Pinch point temperature - 10K
- Steam turbine isentropic efficiency - 0.8
- Feed pump efficiency - 0.8
- Mechanical efficiency - 0.95

In order to validate the results in combined cycle, the output results from simulations with both combined cycle code using the Turbomatch and the steamoMatch have been compared. The results shown in Table 4.4 show reasonable deviation majorly due mainly to losses in the bottoming cycle.

Table 4-4 Values in Combined Cycles Using both GTCC and the Steamomatch

Aero-derivative			Industrial (77MW)		
Overall Results	**Turbomatch**	**Steamomatch**	**Overall Results**	**Turbomatch**	**Steamomatch**
Steam power	11.8	12.2	Steam power	36	38
CC Power	33.6	35.4	CC Power	102	106
Steam Efficiency	0.36	0.34	Steam Efficiency	0.32	0.3
Overall Efficiency	0.57	0.546	Overall Efficiency	0.53	0.508
Stack Temperature	409	426	Stack Temperature	399	410

Values for both simple and combined cycles for the two engines were obtained at the design point as follows:

Table 4-5 Values in Simple and Combined Cycles

	Aero-derivative		Industrial (77.1MW)	
	Simple	CC	Simple	CC
Power	22.8	36	77.1	102
Efficiency	37	49.5	36	48

Integration of both Turbomatch and the steam code yielded values for the engines in combined cycle. The shaft power output in both simple and combined cycles are depicted in Figure 4-11. This shows an increasing power as the power setting increases.

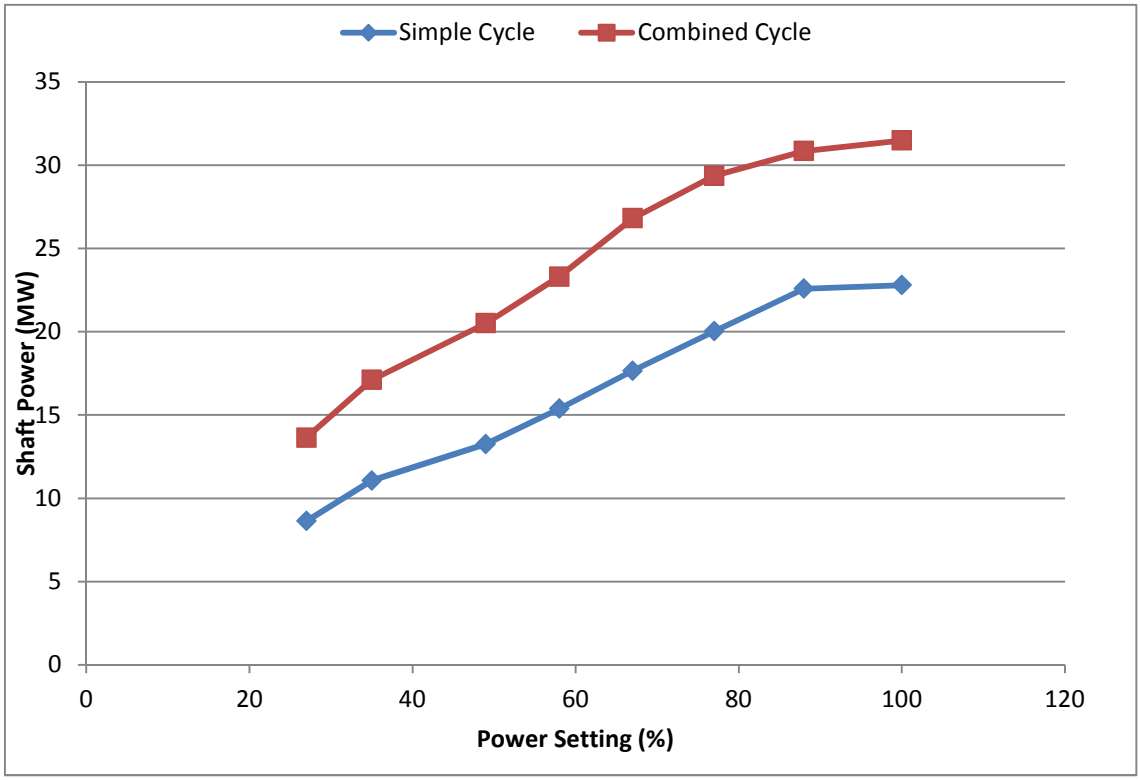

Figure 4-11 Shaft Power Values for Simple and Combined Cycles for Engine 1 (the 23 MW Engine)

4.4.2 Exhaust Temperature Effect on Steam Turbine

The exhaust gas from the gas turbine cycle is used as useful heat for the Heat Recovery Steam Generator. This heat is in turn transferred to the water pumped from the condenser changing it to steam which is expanded in the steam turbine. The more the exhaust gas heat, the more heat and the power produced in the bottoming cycle. There is however a limitation as too high exhaust gas temperatures can lead to damage of some components of the steam turbine. In

addition, there would be an overall lower efficiency of the combined cycle as the efficiency of the gas turbine with too high EGT would be compromised. Figure 4-12 shows an increasing power and efficiency resulting from increased exhaust temperature on the 23 MW engine while Figure 4-13 depicts power and mass flow trend on the 77MW engine.

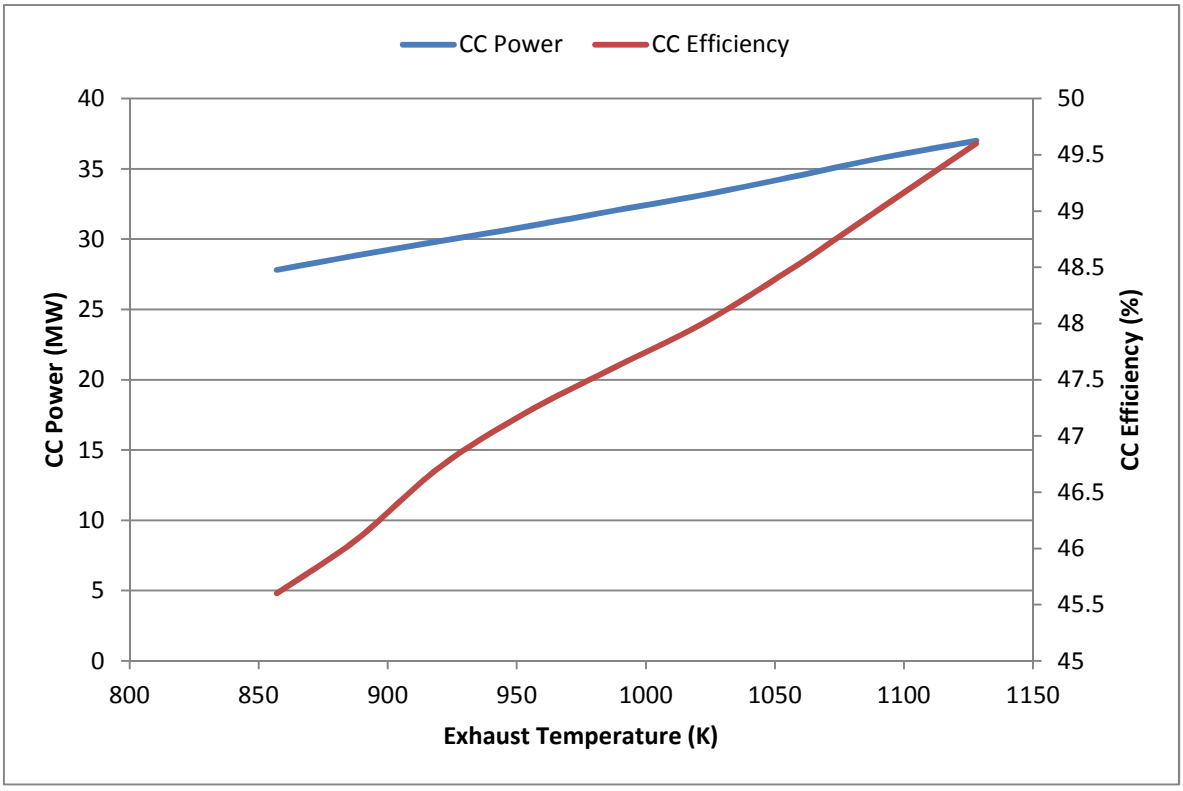

Figure 4-12 Effect of the Exhaust temperature on Combined Cycle Shaft Power & Efficiency Engine 1

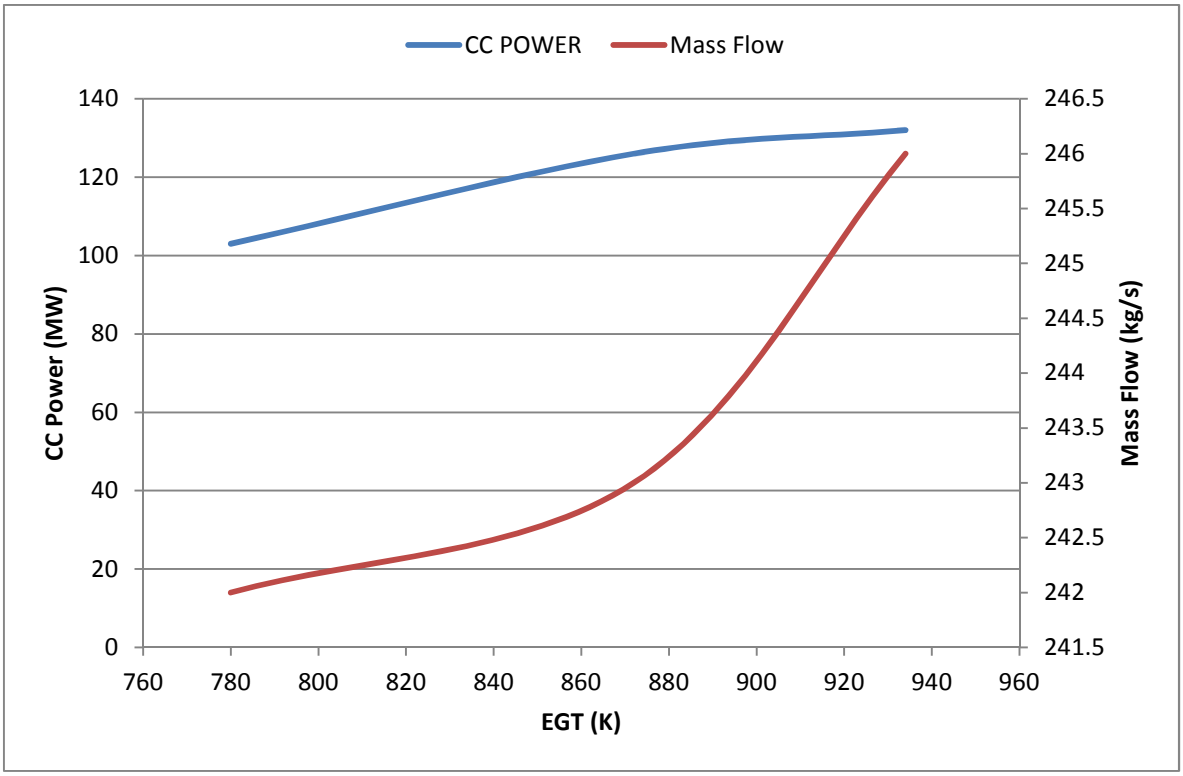

Figure 4-13 Effect of EGT on CC Power and Mass Flow on Engine 2 (77MW Engine)

4.4.3 Simple and Combined Cycle Efficiencies

From the chosen engines, there is a noticeable increase in the efficiencies of the engines in simple and combined cycles of over 20%. Following the efficiency equations for both simple and combined cycles defined in earlier part of the report, the general outlook of the efficiency of the plant at varying TET is as shown in Figure 4-14.

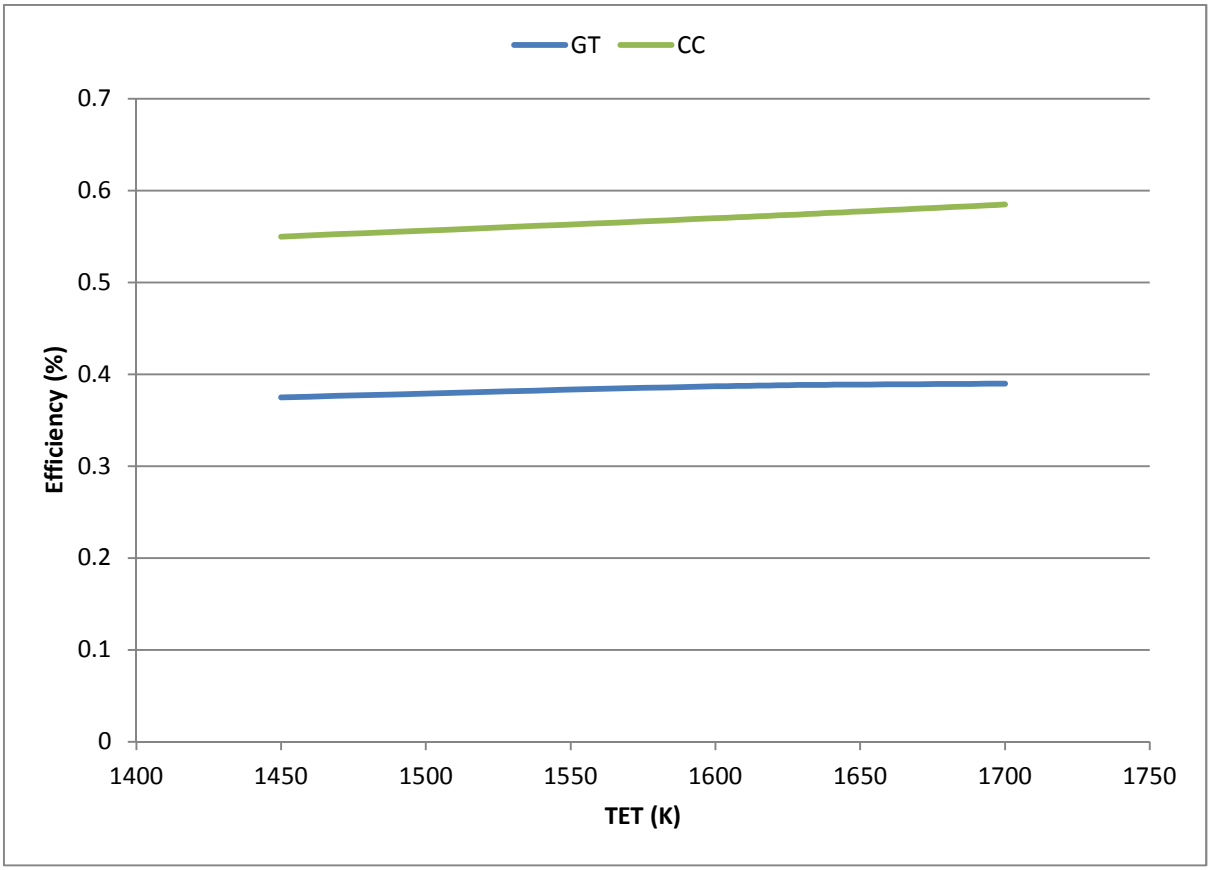

Figure 4-14 Combined Cycle Efficiency (Engine 2)

4.5 Influence of Biomass on GT Performance

The performance simulations of the engine with the natural gas and the biomass fuels were carried out to determine the effect of fuel composition on the power plants. The reference power plant is the NGGT cycle and the DP parameters have been selected to match those of available gas turbines in existence today. Details of these performance parameters are shown in Tables 4-4 and 4-5.

Table 4-6 Design Data for the Simulation of the NGGT and BIGGT

	NGGT	BIGGT
PR	3-30	3-30
Bleed	6%	6%
m_{air}	100kg/s	100kg/s
TET	1200 – 1600K	1200 – 1600K
η_{Cis} Compressor Isentropic efficiency)	0.88	0.88
η_{Tis} (Turbine Isentropic efficiency)	0.9	0.9
η_{comb} (Combustor chamber efficiency)	1.0	1.0
η_{gasif} (Gasifier)	0.75	0.75

Additional input is the composition of the various fuels that are to be implemented in the simulations. While the composition of the conventional fuel and the liquid biofuel are shown in Chapter 5, those for the gasified solid biomass are contained in Table 4-6:

Table 4-7 Ultimate Analysis % by Weight of Solid Biofuels (Dry basis)[65]

	Bagasse	Wood
Carbon	45.48	48.5
Hydrogen	5.96	5.87
Oxygen	45.21	44.49
Nitrogen	0.15	0.3
LHV (MJ/kg)	19.4	20

When assessing the specific work (power) $\boldsymbol{W_{GT}}$ and the thermal efficiency $\boldsymbol{\eta_{th}}$ of gas turbines, the $\boldsymbol{W_{GT}}$ is a differential between turbine and compressor works i.e. W_T -W_C. Other issues are the various airflows which are bled from the compressor and used for turbine cooling and the delicate nature of evaluation of the various energy losses.

Though one aim is to investigate the influence of fuels, a differential approach would remove the three issues raised above as the corresponding effects are fundamentally fuel-dependent and hardly affect cycle parameters. The reference fuel in this case is the most popular fuel for stationary gas turbines- the natural gas. Some basic parameters being the ratio $\boldsymbol{k_T}$ and $\boldsymbol{k_C}$ were introduced between turbine and compressor powers and the gas turbine output:

$$\boldsymbol{k_T} = {\boldsymbol{W_T}}/{\boldsymbol{W_{GT}}} \quad , \quad \boldsymbol{k_C} = {\boldsymbol{W_C}}/{\boldsymbol{W_{GT}}} \qquad \text{Equation 4-4}$$

Therefore,

$$\boldsymbol{W_T} = \boldsymbol{k_T W_{GT}} \quad \text{and} \quad \boldsymbol{W_C} = \boldsymbol{k_C W_{GT}} \qquad \text{Equation 4-5}$$

These parameters then allow the expression of each performance data (the specific power and the thermal efficiency) as a product of some physical factors and a logarithmic differentiation will yield a sum of terms accounting for specific effects.

The effect of fuel properties is evaluated by three main parameters including:

a. Fuel-Air-Ratio. The FAR is the fuel flow divided by the overall gas turbine air flow.

$$\boldsymbol{FAR = {}^{n_f}/_{n_a}} \qquad \text{Equation 4-6}$$

b. Specific gas flow: This is the combustion gas flow divided by the air flow.

$$\boldsymbol{GF_S = n_g 3 / n_a} \qquad \text{Equation 4-7}$$

c. The change in the fuel mole i.e. between mole number of air and combustion gas (q_f).

$$\boldsymbol{q_f = (n_g 3 - n_a)/n_f} \qquad \text{Equation 4-8}$$

These equations can be further expanded according to [91] to incorporate the properties of fuel as follows:

$$\frac{dW_{GT}}{W_{GT}} = k_T d\left(q_f FAR\right) - k_T \frac{dT_1}{T_1} + k_T \frac{dT_3}{T_3} + k_T(1-\beta)\frac{dCp_{34}^g}{Cp_{34}^g} +$$

$$\boldsymbol{(k_T\beta - k_C\alpha)\frac{dln\pi}{ln\pi} + k_C\alpha\frac{d\eta_C}{\eta_C} + k_T\beta\frac{d\eta_T}{\eta_T}} \qquad \text{Equation 4-9}$$

$$\frac{d\eta_{GT}}{\eta_{GT}} = k_C d\left(q_f FAR\right) - (k_C - \gamma)\frac{dT_1}{T_1} + (k_C - \gamma)\frac{dT_3}{T_3} + (k_C - k_T\beta)\frac{dCp_{34}^g}{Cp_{34}^g} +$$

$$(k_T\beta - k_C\alpha + \alpha\delta)\frac{dln\pi}{ln\pi} - de_{hf} + (k_C - \delta)\alpha\frac{d\eta_C}{\cap_C} + k_T\beta\frac{d\eta_T}{\eta_T} \qquad \text{Equation 4-10}$$

The coefficients $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$, $\boldsymbol{\gamma}$ and $\boldsymbol{\delta}$ are dependent only on the cycle temperatures (T_1 … T_4) and $\boldsymbol{e_{hf}}$ is the fraction of the energy input spent to heat the fuel from the room temperature to the compressor discharge temperature.

4.5.1 Case study Results showing the Influence of Fuels

These detailed reactions showing how fuel properties affect the GT performance were adequately indicated in the results from the engines utilising the various fuel types. It shows some variation in the outputs of the gas turbines like the efficiency and the shaft power. Details for the two engines are shown in Figures 4-15 to 4-18.

Figure 4-15 Engine 1 (Aero-derivatives engine)

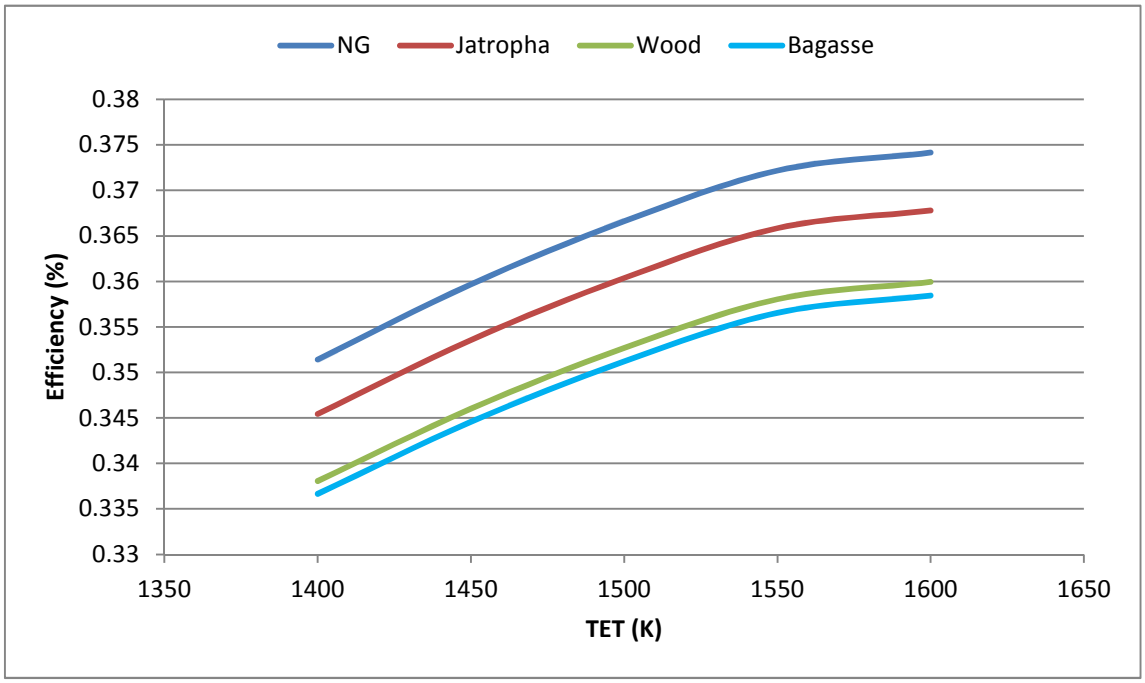

Figure 4-16 Efficiency Variation of the Gas Turbines Utilising the Different Fuels

Each fuel gives a different heat release rate. In addition, the combustor inlet conditions, pressure and temperature change when fuelling from different syngas fuels since the compressor performance is affected by the increase in the mass flow at the turbine [66]. This leads to a greater power due to the higher fuel flow required for syngas (which has low value of LHV) operation.

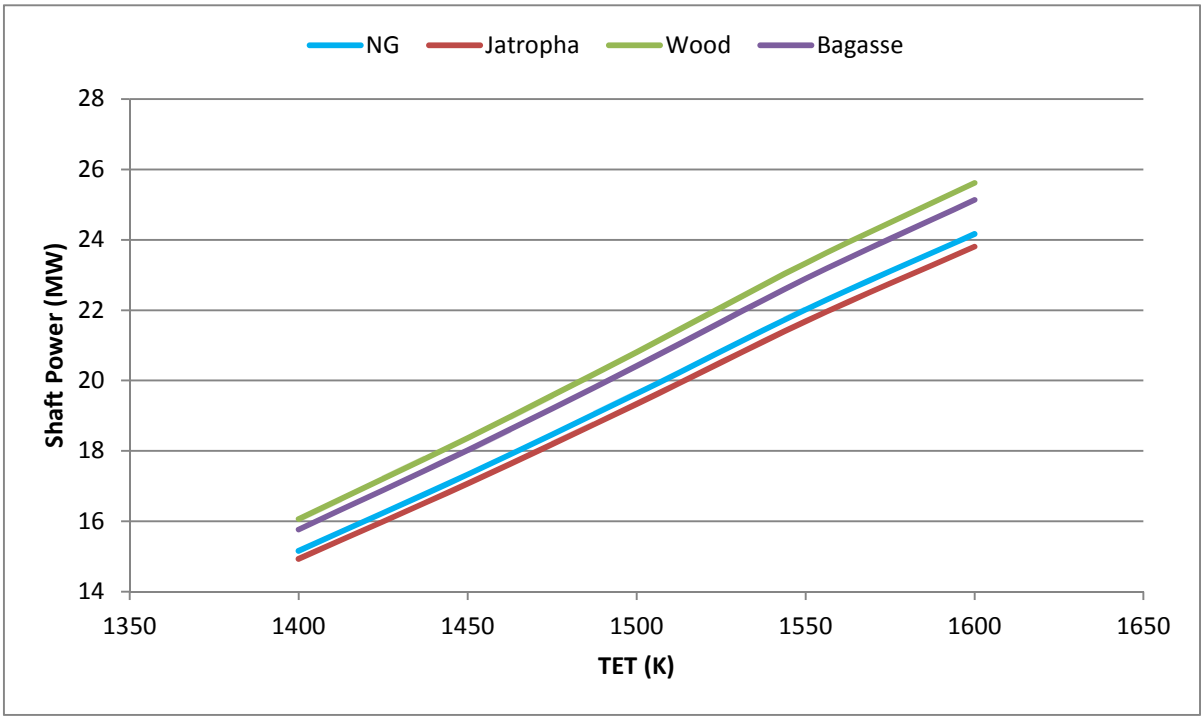

Figure 4-17 Power Variation of the Gas Turbines Utilising the Different Fuels

It is to be noted further that in addition to the effects of the properties of different fuels, the heavy penalty imposed by the gasification and cleaning system (not considered in the present work) also results in the lowering of the system efficiency of a BIGGT compared to the NGGT. The reason for the enhanced power can also be partly adduced to the much higher fuel mass flow for the syngas from biomass which produces more useful work for same TET. Ultimately, the type of syngas and indeed biomass significantly affects the gas

turbine operation and performance. The details of the gasification effects in a BIGCC are detailed in [67].

Engine 2 (Industrial Engine) Results

The results for the industrial engine when run on the biofuels present similar trends to the aero-derivative engine. Details are shown in Figures 4-17 & 4-18.

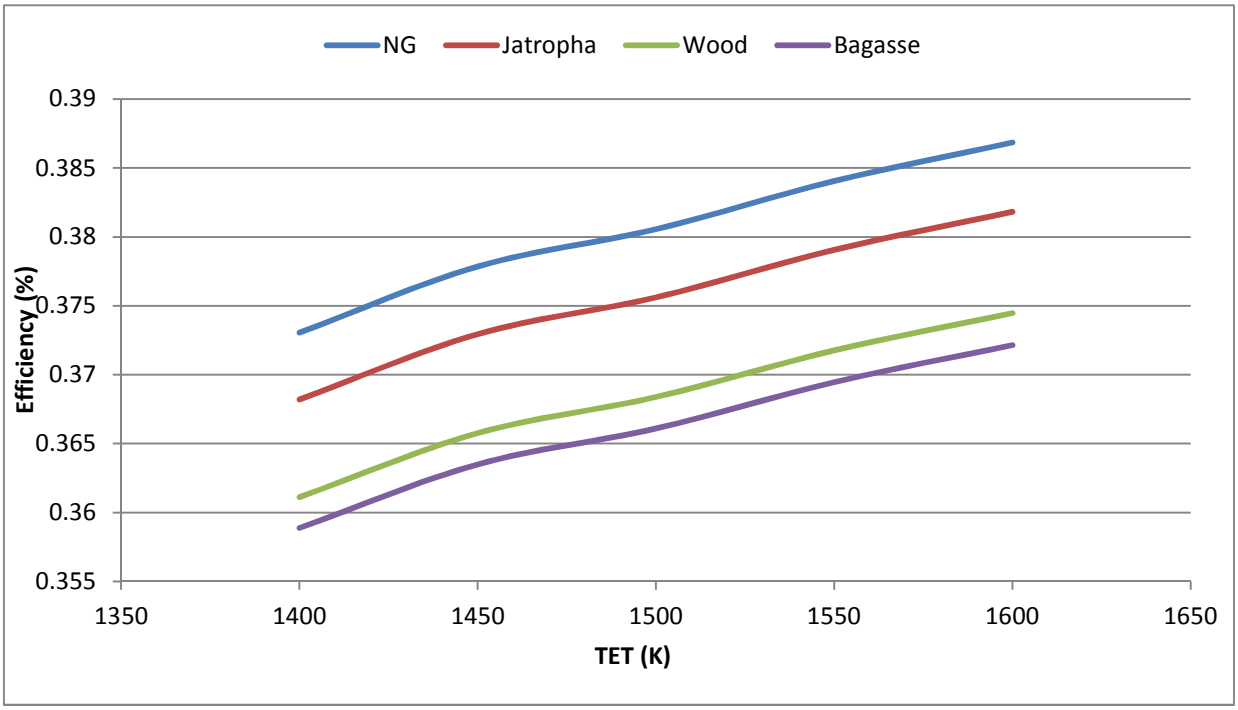

Figure 4-18 Efficiency Variation of the Gas Turbines Utilising the Different Fuels

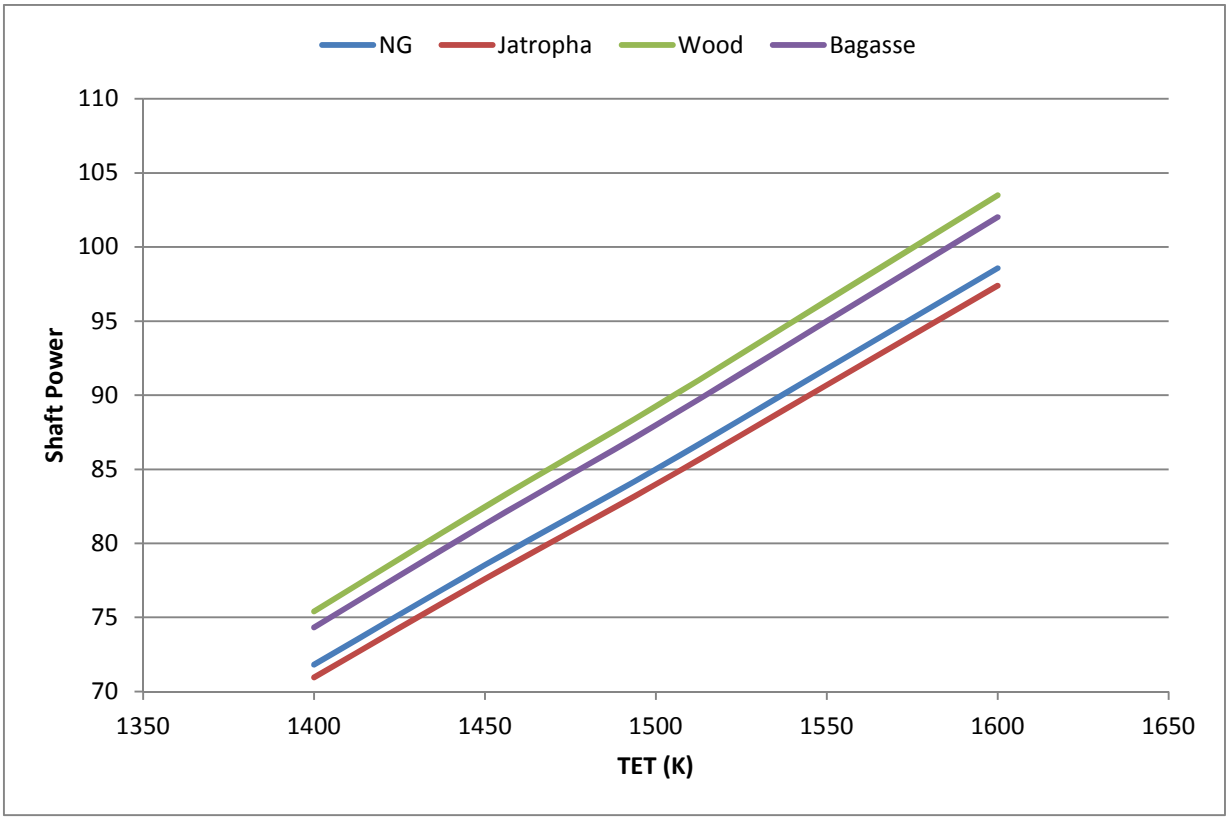

Figure 4-19 Power Variation of the Gas Turbines Utilising the Different Fuels

Another concern is the effect of exhaust gas temperature on the bottoming cycle when using the biofuels. Since the aim of the HRSG is to guarantee the generation of more power from the steam turbine by utilising the heat of the exhaust, there is need for exhaust gas to be of reasonable temperature. This way the efficiency of the cycle is maximized. From Tables 4-7 & 4-8, it can be seen that there is additional power from the steam cycle. The trend shows a decline with the biofuels when compared to the natural gas due to a reduced exhaust temperature with the biomass fuels.

Table 4-8 EGT using Different Fuels and additional Power generated – Engine 1 (23 MW Engine)

CH_4		Jatropha		Wood		Bagasse	
EGT(K)	Additional Power(MW)	EGT(K)	Additional Power(MW)	EGT(K)	Additional Power(MW)	EGT(K)	Additional Power(MW)
931	9.98	927	9.33	909	8.85	907	8.56
960	10.19	958	9.98	930	9.47	927	9.16
985	10.94	979	10.72	954	10.17	953	9.84
1013	11.35	1011	11.13	976	10.56	973	10.21
1038	11.82	1029	11.58	1012	10.99	1007	10.63

These varying values of the output parameters of the power plants are not resulting from only the heating values of the syngas, another factor is the degree of integration of the gasifier with the gas turbine engine (Degree of integration relates to the amount of gas bled from the gas turbine to be reused on the gasifier). Reduced integration degree (amount of gas bled from the gas turbine) yields larger power output for all fuels.

Table 4-9 EGT using different Fuels and additional Power generated – Engine 2 (77MW Engine)

CH_4		Jatropha		Wood		Bagasse	
EGT	Additional Power	EGT	Additional Power	EGT	Additional Power	EGT	Additional Power
787.22	42	782.26	39.58	765.11	36.83	762.35	34.84
819.62	43.5	815.18	40.9	796.86	38.05	792.72	36
851.77	44.4	848.01	41.92	829.42	38.02	825.92	37.12
882.34	45.5	879.21	42.63	862.13	39.98	877.75	38.01
916.99	46.2	909.3	43.93	888.98	40.51	879.33	38.87

The heating value of syngas from biomass resources consisting mainly of CO and H_2 is much lower than that of the natural gas that gas turbines are mostly designed for. Therefore more fuel is supplied to the combustor leading to larger mass flow in the turbine and the tendency of the engine to reach the surge line. This could limit the operations of gas turbines. However, turbine mass flows vary in relation to the percentage of air from the air separation unit of the gasifier supplied by the gas turbine compressor. But with an enhanced supply referred to as the degree of integration, such problems are reduced. Kim et al [67] established the effect of the degree of integration.

Through gasification of biomass and further gas cleaning, it is feasible to operate gas turbines with different types of biomass fuels. This way the biomass combustion products would not damage the turbine blades. Most combined cycles are based on heavy-duty industrial rather than on aero-derivative turbines with the distinction between the two turbine types being that the combustors of the latter operate at much higher pressures (25 atm or more, compared with 12-16 atm for heavy-duty industrial turbines) [53]. Heavy-duty industrial turbines are usually designed instead for optimal performance in the combined-cycle mode. For a given turbine entry temperature, the turbine exhaust of heavy-duty industrial turbines is hotter and capable of producing more steam than is possible with aero-derivatives. From the performance results, the steam turbine bottoming cycle provides about one-third of the total output of these combined cycles. However, combined cycles based on heavy-duty industrial turbines are not the best candidate engines for applications at modest scales needed for biomass fuels.

De-rating is another way of making gas turbines cope with a larger mass flow [49]. This is done by lowering the temperature, bleeding air from the compressor or through the inlet guide vane (IGV) control [19; 49][19; 47][18; 46][18; 46]. However, de-rating increases the plant reliability but lowers the efficiency. Gas turbines can also be designed for exclusive use on low caloric fuels in which case, it fitly operates at the design point with biofuels.

5 Multi-fuel Emission Model Simulation

An accurate estimation of both aero and industrial engines' gas emissions will ensure a more profitable engine operation. This is because any effort at reducing emissions will mean reduced emission taxes and or incentives leading to reduced overall operational cost of the power plant. Hence, it has become imperative to develop and implement an emission prediction model for the reliable estimation of emission gases. An emission model that can cater for both aero-derivative and industrial engines (as applicable in the present work) utilising multiple fuels including biomass was developed. Emission values when using Jatropha, bagasse and wood biofuels were computed and also compared to those of conventional fuels such as Jet A1 and natural gas.

5.1 Emission Prediction Modelling

The model is similar to the one existent in the Department but duly modified to cater for biofuels. The earlier version was developed by Cesar Celis [30] and adapted for industrial use by Samara [31]. A further modification was made by Hugo Pervier [68]. All these previous models were only limited to use with fossil fuels. The present effort had made it possible to adapt the model for the computation of emissions when the plant is utilizing biofuels.

5.2 Model Structure

The emission model relies on output from the Turbomatch for emission estimation. These include fuel and mass flows, fuel and air pressures and temperatures and ambient conditions. The model consists of several modules which interact with each other. The air and fuel properties are calculated using the NASA chemical equilibrium with applications (NASA CEA). Properties such as formation enthalpy, entropy, gamma, specific heat, viscosity at different pressures and temperatures were obtained. This helps to ascertain the composition of both air and fuel downstream of the combustor with the specification of the hydrogen/Carbon (H/C) ratio and the fuel heating values.

The use of the NASA CEA permits the user to specify several fuels including those generated from biomass gasification. This allows for detailed analysis of effects of alternative fuels on performance and emissions, taking the effects of deviations in combustion gas properties fully into account.

Other modules include the chamber, global, reactor, region, emission index (main module) and others. The emission index is the single most important module from where the rest ones are called from. The outputs of the model include, in addition to emission calculations, other useful information like the equivalence ratios, temperatures and the residence times of each combustor region. The sequence of the model operation is as shown in Figure 5-1:

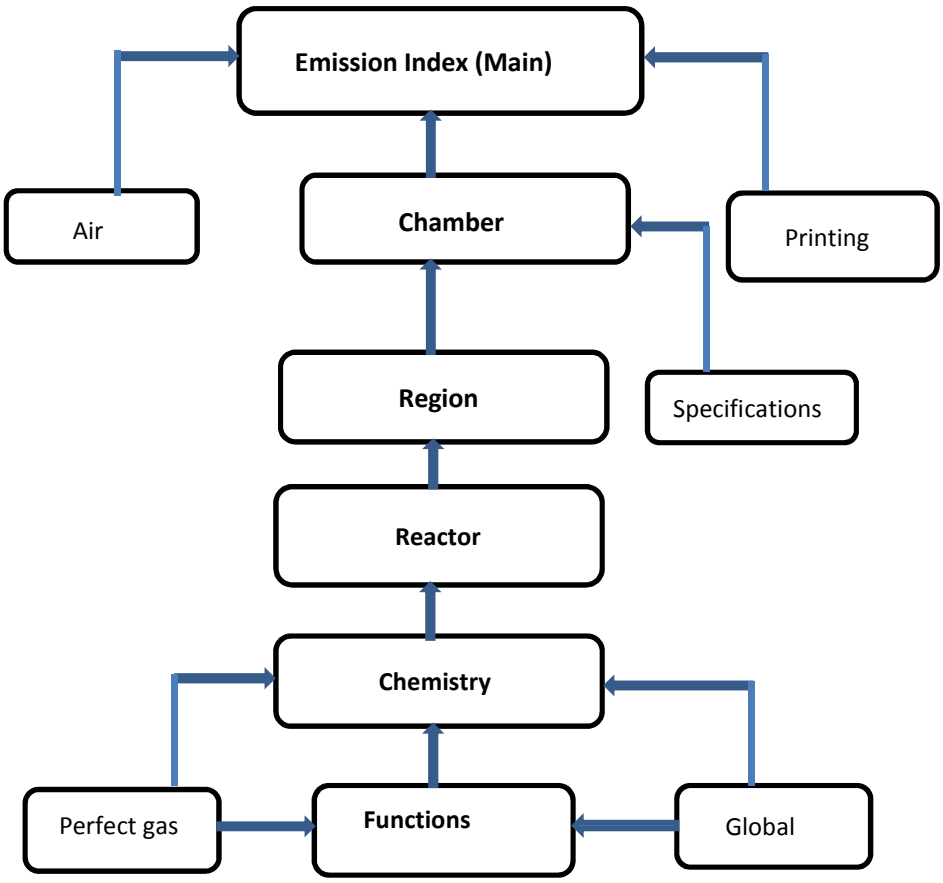

Figure 5-1 Emission Prediction Model Sequence of Operation

5.2.1 Arrangement of the Reactors

The model can be used for the simulation of conventional combustor configurations for diffusion flame. The combustor characteristics could be altered to make it suitable for other configurations like the Low Premixed and Pre-heated (LPP) and dry low NOx (DLE) combustors. The model is an arrangement of the engine combustors represented by reactors. There is a mix of the reactors to include the Perfectly Stirred Reactors (PSRs) and the Partially–stirred Reactors PaSRs. The various segments of the combustor from the flame front to the dilution zone are represented by these reactors in a new simplified model from the approach suggested by Rizk & Mongia for conventional combustors [7].

In the case of the Rizk & Mongia model from which the old model was derived, the flame front (FF) was modelled with PaSR which takes note of all the inhomogeneity of the region. PSRs were used to simulate the near-wall (NW) region of this zone. The three zones of the combustor - the primary zone (PZ), the intermediate zone (IZ) and the dilution zone (DZ) were simulated by a series of PSRs. Apart from the DZ, all the regions were represented with 2 reactor models in parallel to each other for the near wall and core segments of the combustor. Various arbitrary specific parameters were then defined to represent the air, fuel or gas proportions entering the different zones of the combustors. In the newly developed model, the arrangement of the reactors was well simplified and the values of the air, gas or fuel entering the different regions of the combustor were equally altered. The original and the modified models are as shown at Figures 5-2 to 5-4.

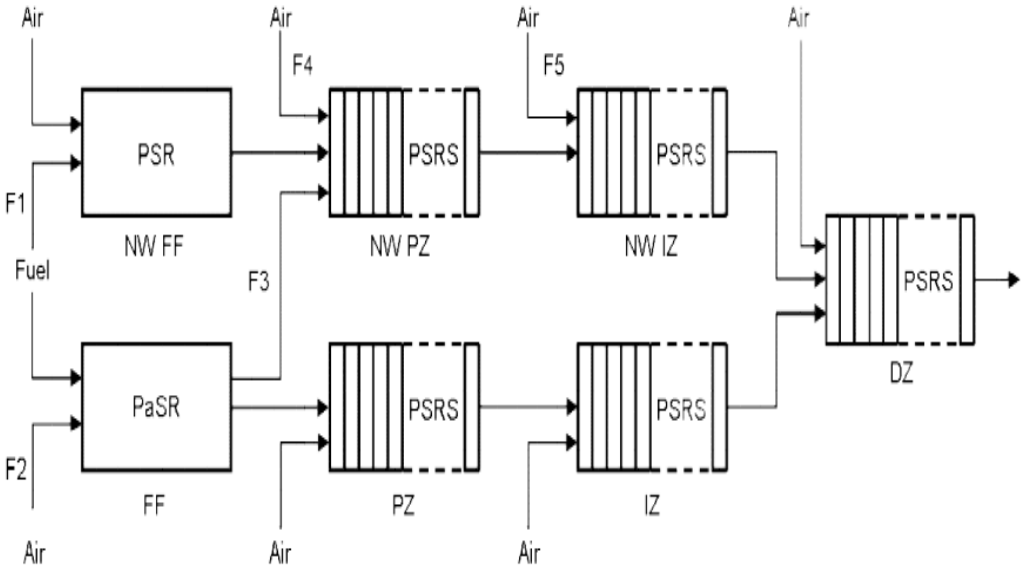

Figure 5-2 Reactors Layout for the Earlier Emission Model [8]

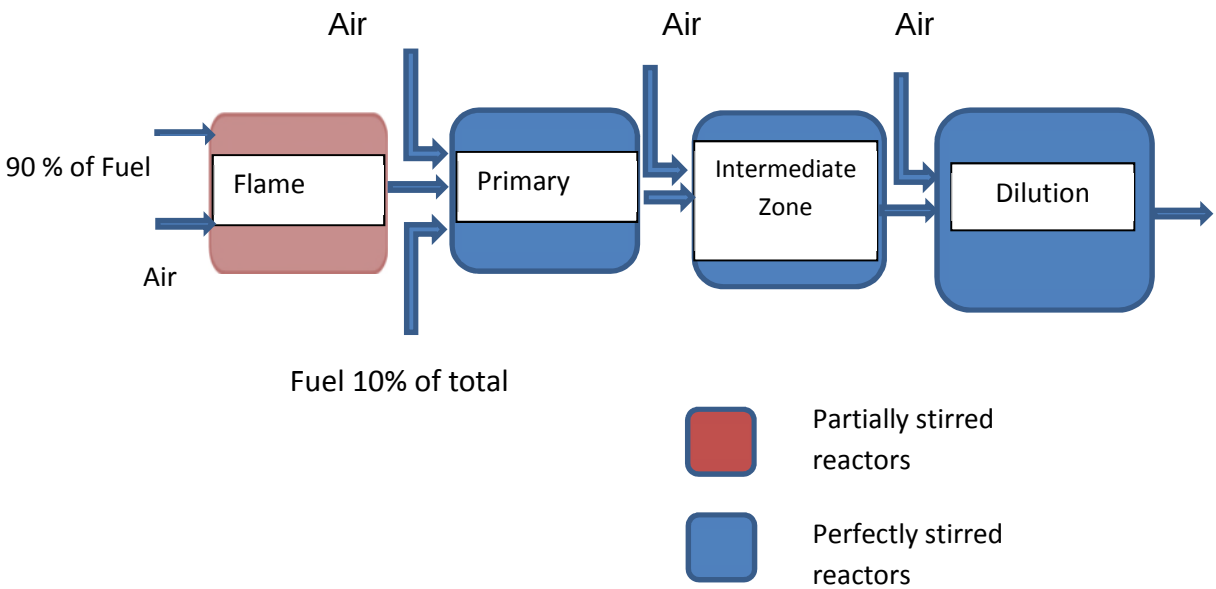

Figure 5-3 Reactors Layout for the New Emission Model

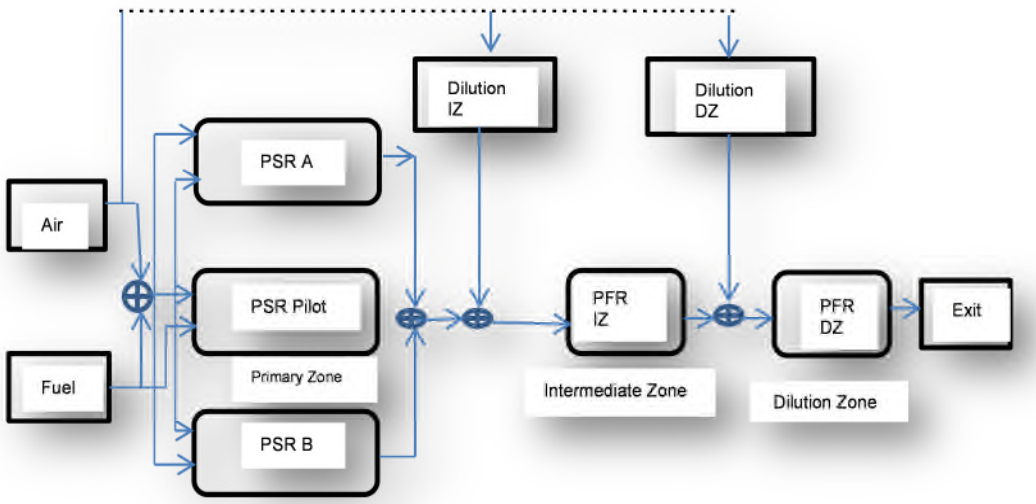

Figure 5-4 Adopted Reactor Layout for the new Emission Model

The results from the second and the third new reactor arrangements are similar. However, the further partitioning of the primary zone is necessary as the adoption of a single PSR as being a representative model of the combustion process in the flame/ignition zone of gas turbine combustors is not always appropriate due to the complexities associated with the flow field as well as the details on the feeding of oxidizer and fuel in that region [36]. This is essentially to cater for the unmixedness which happens to be a major factor in the formation of both NOx and CO in gas turbines and also to establish a good equivalence ratio distribution.

5.3 Requirements of the Model

The ultimate goal of the emissions prediction model developed is to allow the reliable calculation of emission values of both aero and industrial gas turbine combustors when running on more than one fuel type. The results obtained

from the utilisation of this code are expected to be used for analysing aero-derivative and industrial engines to determine the quantity of gas emissions. This will ensure proper design trade-offs, and also help policy-makers on emission mitigation and power providers in decision-making processes in the choice of particular engine type or fuel for power generation and other uses.

The main requirements of the emissions prediction models developed are as follows:

a. The model should be able to carry out reliable calculations of emissions. The emission results should compare well with any other mode of emission estimation and can be validated with available data on particular engine emissions.

b. Generality and simplicity. The model should be as simple as possible. However, simplicity should not compromise the reliability of the results to be obtained. Thus, a middle ground between the reliability of the results and the complexity of the model has to be achieved at some stage. This compromise can be achieved by capturing detailed physical and chemical processes occurring inside the gas turbine combustors that should be simulated.

c. The model computational time should be acceptable.

d. The model should have modularity for it to be adapted for other types of engines.

5.4 Emission Calculations

The model is a generic reactor one which allows the calculation of both chemical equilibrium and kinetics between the entry and exit of the reactors. The reactor receives the gas from a preceding reactor and exits into a successive reactor (the first and the last reactors will usually connect to compressor discharge and the turbine entry). Emission formations are modelled

by capturing the mechanisms in the arranged reactors in which case the changes in the emission concentrations due to chemical reactions as the fuel and air flow through the successive reactors are adequately estimated. The reaction kinetics (the kinetic scheme) is concerned with the integration of reaction rates, calculated at reactor junctions. The reaction rates are calculated depending on the type of gas emission.

The reactor model allows easy adaptation of equations for reaction rates of any emission type being it NOx, CO, unburnt hydrocarbon, or soot. The approach is an integration of average reaction rates at the entry and exit of the reactors. The prompt emission formation in a flame is in so short a time while the main mechanism is the subsequent change in emission concentrations as a result of chemical reactions during the flow through the reactors. The relations between reaction rate, gas composition and conditions can be derived as shown in section 5.6.

5.5 Emission Formation Mechanism

The pollutants of interest to be calculated using the models are NOx, CO, and CO_2. There would be no emphasis on oxides of Sulphur as the sulphur content from the fuel gas from biomass is insignificant. Unburned hydrocarbons and soot/smoke would also not be considered as that is almost non-existent due to the high technology of modern combustors. However, the model has capability to capture these values.

The new modified model is different from the older one as the total number of reactors and the amount of fuel entering various reactors have changed. In the earlier model it is assumed that 100% of the fuel enters the flame front as well as the primary zones distributed between the near wall and the core of the combustor, which is relatively inaccurate. In actual sense, it is expected that the air/fuel reaction should only take place mainly in the flame front and a little reaction in the primary zone where the temperature is high to produce NOx

emissions. The new arrangement reflects this as more reactions are expected at the flame front (90% of fuel) and the primary zones (10% fuel).

Thermal *NOx*

Thermal NOx is formed as a result of the chemical reaction sequence called the Zeldovich mechanisms. The rate of thermal NOx emissions is an exponential function of flame temperature and a linear function of the time the hot gases are at any given flame temperature. The following reactions depict NOx formation:

$$\boldsymbol{N_{2+}\,O} \longleftrightarrow \boldsymbol{NO} + \boldsymbol{N} \qquad R_1 \qquad \text{Equation 5-1}$$

$$N + O_2 \longleftrightarrow NO + O \qquad R_2 \qquad \text{Equation -5-2}$$

$$N + OH \longleftrightarrow NO + H \qquad R_3 \qquad \text{Equation -5-3}$$

And the N_2O contribution to the formation of NOx is according to the following reactions:

$$H + N_2O \longleftrightarrow N_2 + OH \qquad R_4 \qquad \text{Equation- 5-4}$$

$$O + N_2O \longleftrightarrow N_2 + O_2 \qquad R_5 \qquad \text{Equation 5-5}$$

$$O + N_2O \longleftrightarrow NO + \text{Prompt NOx} \qquad R_6 \qquad \text{Equation -5-6}$$

5.5.1 Prompt NOx

Prompt NOx is formed at a much faster rate than the thermal NOx. According to Bowman [69], prompt NOx formation is due to non-equilibrium between O and OH concentrations, the reaction of hydrocarbon radicals with molecular Nitrogen and reaction of atoms of Oxygen with N_2 to form N_2O and subsequently NO.

5.5.2 Carbon Monoxide (CO)

Carbon monoxide formation is as a result of incomplete combustion of the fuels during combustion. This can result from low residence time and or low reactant temperatures not allowing for complete combustion. The modelling work is carried out on the assumption that during combustion, all fuel reacts instantaneously to form CO and H_2O and then the CO oxidation:

$$CO + OH \longleftrightarrow CO_2 + H \qquad R7 \qquad \text{Equation-5-7}$$

5.6 Pollutant Emissions Reaction Rates

Pollutant emissions in gas turbines include NOx, CO, CO_2, SO_2, unburnt hydrocarbon (UHC) and soot/smoke. These are formed at varying rates during the GT operations at different conditions. Detailed kinetic reactions within the different regions of the combustor generate the emissions which are affected by the fuel(s) composition. Several approaches are being proposed for the estimation of pollutants, but in this current work, the kinetic reaction mechanism in arranged reactors is used.

5.6.1 Emission Formation Equations

<u>Thermal NOx</u>. The equation for thermal NOx as derived from [70] is:

$$\frac{dY_{NO}}{dt} = \frac{2M_{NO}}{\rho}(1 - \propto^2)\{\frac{R_1}{1+\propto K_1} + \frac{R_6}{1+K_2}\} \quad \text{.....Equation 5-8}$$

Where

R_i is the one-way equilibrium reaction rate (Equations 5 -1 to 5 -6)

i.*e at R_1, it will be $R_1 = k_{lf}\,[NO]/[NO]_e$; k_{lf} is the forward reaction rate coefficient and k_{lf} values are according to the values from Miller and Bowman*[71]

a = *[NO]/[NO]$_e$ (e stands for equilibrium)*

K_1 = $R_1/(R_2+R_3)$ and

K_2 = $R_6/(R_4+R_5)$

<u>Prompt NOx</u>

This is derived from the global empirical expression by De Soete

[72; 73]which was also adopted by Peng & Zhang [73]

$$\frac{dY_{NO}}{dt} = \left(\frac{M_{NO}}{\rho}\right) f_{pr} K'_{pr} [O_2]_e^a [N_2]_e * [CH_4] exp(\frac{-36499.507}{T}) \text{ ... ..Eq -5-9}$$

Where

$f_{pr=4.75+0.0819x+23.2\varphi+32\varphi^2-12.2\varphi^3}$: *$f_{pr}$ is a correction factor dependent on the number of Carbon atoms(x) in the fuel and the equivalence ratio(φ)*

$$k'_{pr} = 6.4x10^6 \left(\frac{0.0820575T}{P}\right)^{a+1};$$

k'_{pr} is the correction factor related to the pressure, temperature and the oxygen reaction order (a) calculated as a function of the oxygen mole fraction:

$$a = \begin{cases} 1.0, & X_{O2} \leq 4.1x10^{-3} \\ -3.95 - 0.9\, lnX_{O2}, & 4.1x10^{-3} < 1.11x10^{-2} \\ -0.35 - 0.1\, lnX_{O2}, & 1.11x10^{-2} < X_{O2} < 0.03 \\ 0.0, & X_{O2} \geq 0.03 \end{cases}$$

Carbon Monoxide

The CO conversion follows the order of equation 5-7. Assuming equilibrium conditions of OH and H, the rate of CO formation will be similar to the one adopted by Samaras [31]:

$$\frac{dY_{CO}}{dt} = -K_{7f}(\frac{M_{CO}}{\rho})[OH]_e\{1+\frac{[CO]_e}{[CO2]_e}\}([CO]-[CO]_e \text{ .....Equation-5-10}$$

Where, $\boldsymbol{K_{7f}}$ is the forward reaction rate constant of the CO conversion equation (Equation 5 - 7).

Unburnt Hydrocarbon UHC)

For the estimation of the UHC, we take the initial fuel reaction following the approach suggested by Visser et al [35] to be as follows:

$$Fuel + 6O_2 = CO_2 + H_2 \text{ .....Equation-5-11}$$

The rate of reaction equation based on the above equation is:

$$\frac{dY_{C_1H_{1.7}O_{0.7}}}{dt} =$$

$$-2x10^5[\frac{M_{C_1H_{1.7}O_{0.7}}}{M_{O2}}x(\frac{9T}{1000}-\frac{1}{2})p^{0.3}Y_{O2}\exp(\frac{-6916.947}{T})Y_{C_1H_{1.6}O_{0.7}})^{0.5} \text{ ..Equation 5-12}$$

Soot/smoke

The rate of soot formation is in accordance with an empirical expression suggested by Rizk & Mongia [27]. Rate of soot formation (S_f) in m^3 is in the form below:

$$S_{f=1.4887x10^{-4}}\left(\frac{\varphi.FAR_s}{m_aT}\right)P^2(18-H_{cont})^{1.5}(\frac{m_{gt}}{\rho_{soot}})$$ …….Equation 5-13

While the rate of soot oxidation ($\boldsymbol{W'_{02}}$) in kg soot/m^2 is determined by the formula in [74]:

$$W'_{02}=12\{\left[x_s\left(\frac{k_Ap_{02}}{1+k_zp_{o2}}\right)\right]+[k_Bp_{o2}(1-x_s)]$$…….Equation-5-14

Where $\boldsymbol{x_{s=}}[\frac{\boldsymbol{1}}{\boldsymbol{1+\frac{k_T}{k_BP_{O_2}}}}]$ ……. Equation 5-15

k_A, k_B, k_T and k_z are the rates of reaction constants showing temperature dependence.

5.7 Model Validation

Emissions obtained using the developed model can be validated using values obtained by Siemen when they ran an experiment with the SGT Series engines. The present model results for the various fuel types are similar to those obtained during the Siemen experiment. A major factor affecting emission levels is the composition of the syngas after gasification. Values from Siemen and the model are as shown in Table 5-1:

Table 5-1 Emission Values for various Fuels from the Model and Experimental Results [75]

Fuel		Siemens	Siemens	Present Work
		Expected Engine Results	Test Rig Results	Model Results
Jet A	NOx	-	-	27.4
	CO	-	-	12
Natural Gas	NOx	25	<25	15
	CO	10	<<10	7.2
Reference Syngas	NOx	15	<15	-
	CO	10	<<10	-
Biomass Syngas(Wood)	NOx	-	-	13
	CO	-	-	5
Biomass Syngas (Bagasse)	NOx	-	-	8.5
	CO	-	-	3.5

The objective of the Siemen experiment was to demonstrate that certain emission targets for both NOx and CO can be obtained. It was shown that the emission values are <15ppm NOx (at 15% O2) and <10ppm CO when the GTE is running on syngas from coke and <25ppm NOx and <10ppm CO while running on natural gas. It also established that the engine can run on both syngas and natural gas over the entire load range.

A further validation is the results obtained in the study undertaken by Zehra et al [18]. The results acquired in their performance and emission analysis when utilising biomass on small-scale gas turbines shows both performance and emission characteristics as shown in Figures 5-5 & 5- 6. Though the biofuels utilised are not exactly the same as those in view, their pattern of behaviour follows the trend with biofuels when compared to fossil fuels. There is however some slight variation when the two gaseous syngases from solid biomass are compared due largely to the losses in the course of compression of the large mass of the fuel gas.

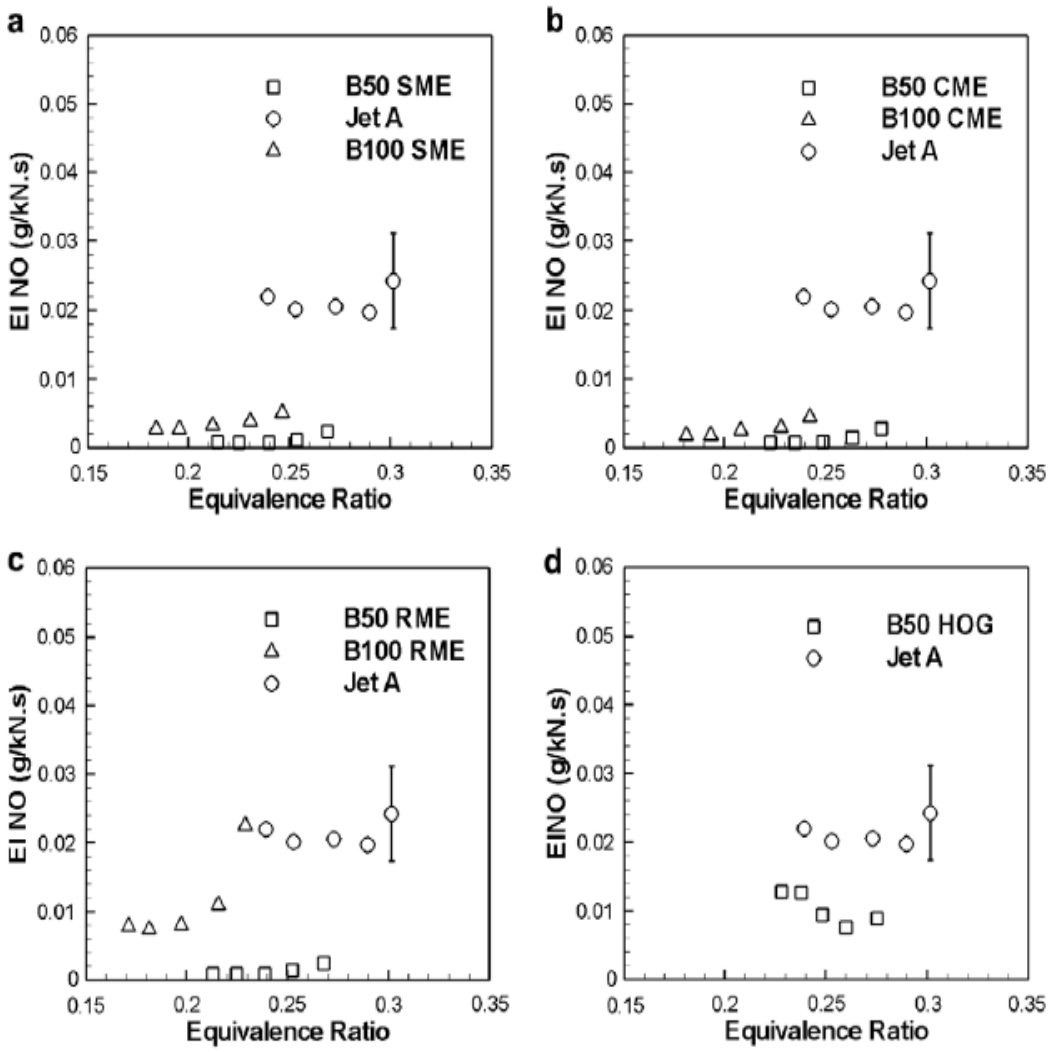

Figure 5-5 EINOx versus versus Equivalence Ratio for Jet A and Biofuels [18]

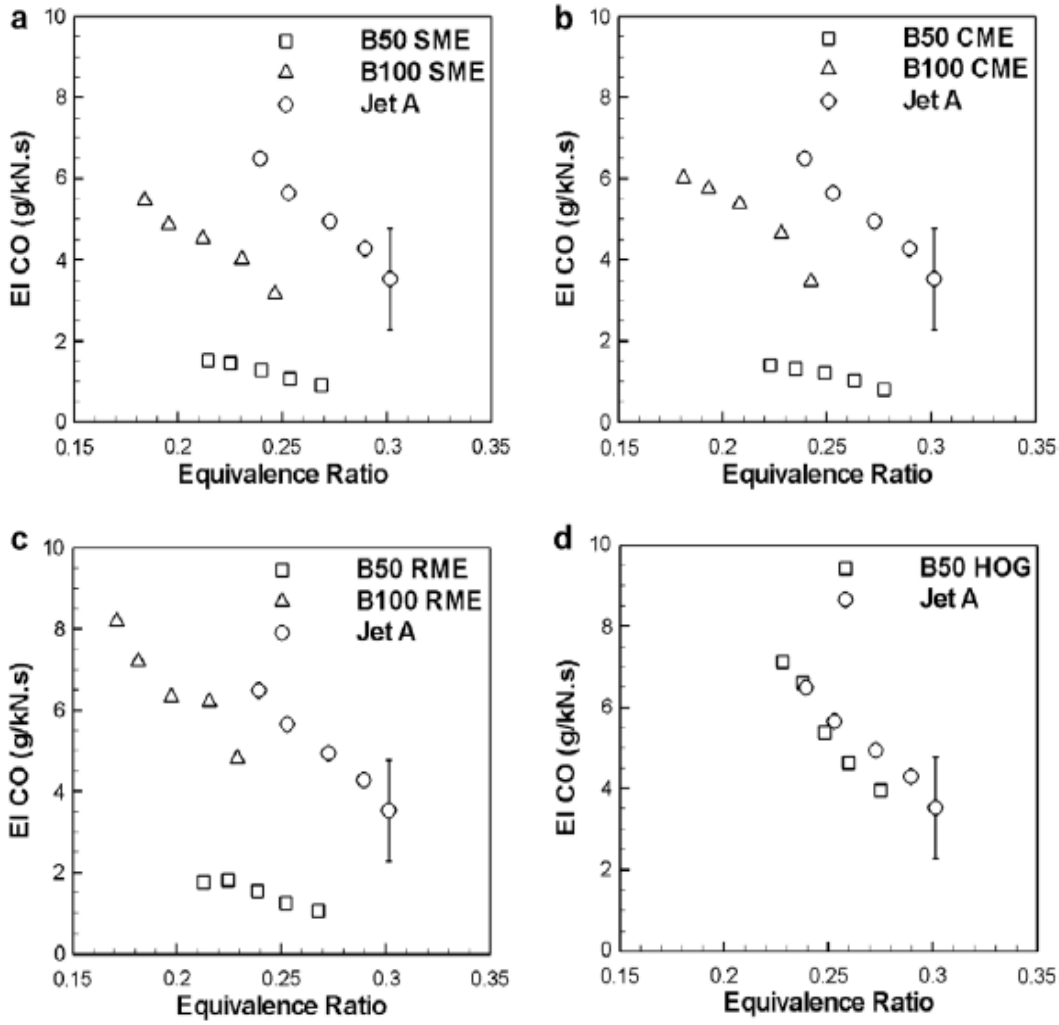

Figure 5-6 EICO versus Equivalence Ratio for Jet A and Biofuels [18]

5.8 Results from the Modified Emission Model

The strength of the emission results from the new model against the old one was established by Hugo [68]. The result from a particular engine gauged against ICAO emission data is as reflected in Figure 5-7. It shows that there was an underestimation of NOx emission from the model by the first author while the new one shows close relationship and better accuracy with data in public domain.

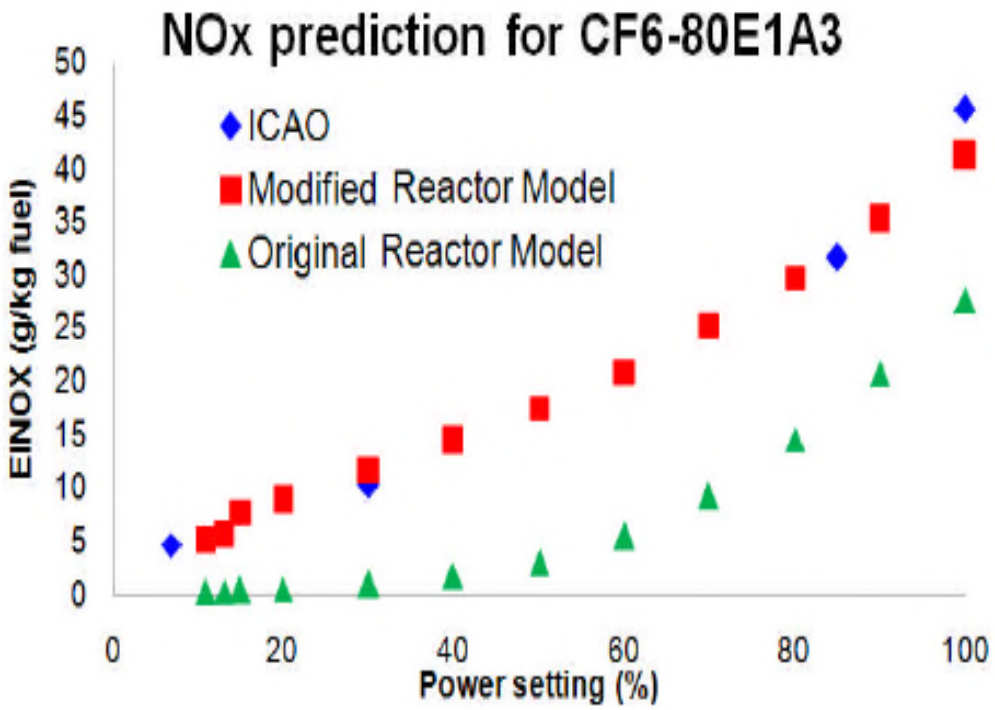

Figure 5-7 Comparison of NOx Emission Results from the two Models [68] [76]

The results from the multi-fuel model which incorporated three other biofuels – wood, Jatropha and bagasse proved to be consistent with emissions for the major greenhouse gases including oxides of Nitrogen, Carbon monoxide and Carbon dioxide. It also captured unburned hydrocarbons and soot though these would not be reported. The engine used for the simulation is similar to the 50MW industrial engine as detailed in Chapter 4. Data from the Turbomatch was used as input data for the emission code. For a particular fuel type (Jet A1) and for varying power settings, the emission values are presented in Figure 5-8:

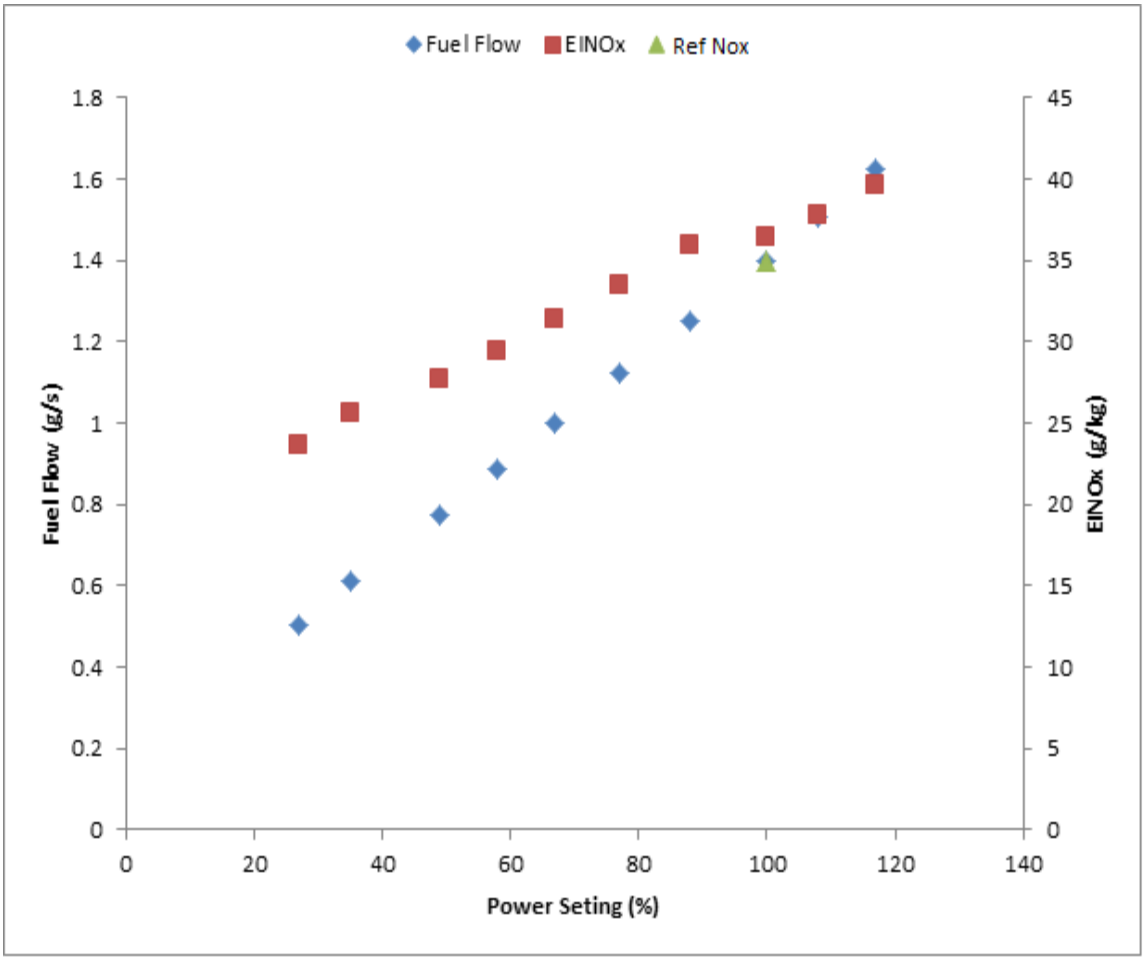

Figure-5-8 NOx Emission, Fuel Flow and the Percentage Engine Power Settings for the 50 MW Industrial GT

The emission values from the engine manufacturer could only be gotten for the design point only. However, this falls within a reliable range with what was predicted by the model and hence the model is adjudged to be reliable for planning and use.

5.8.1 Effect of Combustor Inlet Air Temperature on Emissions

The inlet air temperature has an effect on the quantity of emissions of the various greenhouse gases as portrayed by Figure 5-9 & 5-10. As the air inlet

temperature rises, the temperature developed within the combustor equally rises resulting in increase in NOx emission. However, the corresponding CO values reduce. The CO2 is also seen to increase with increasing temperature.

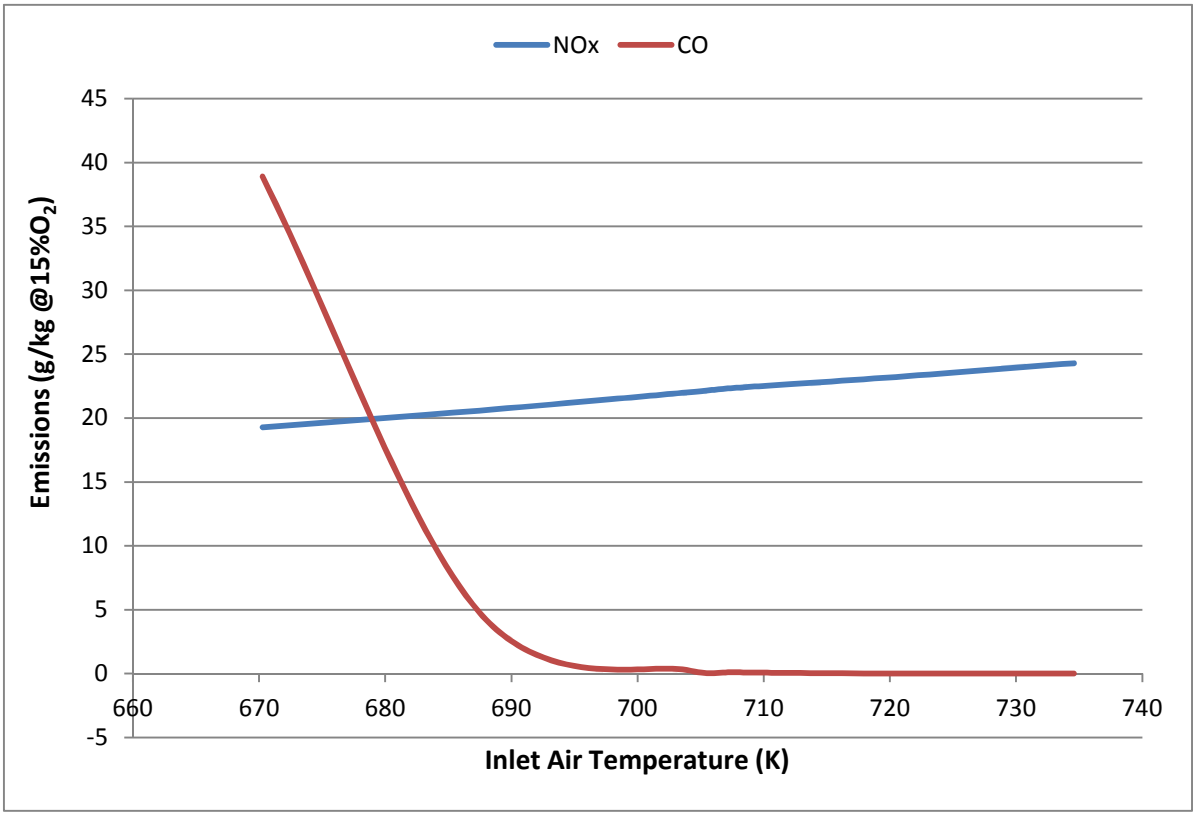

Figure 5-9 Effect of Inlet Air Temperature on Emissions

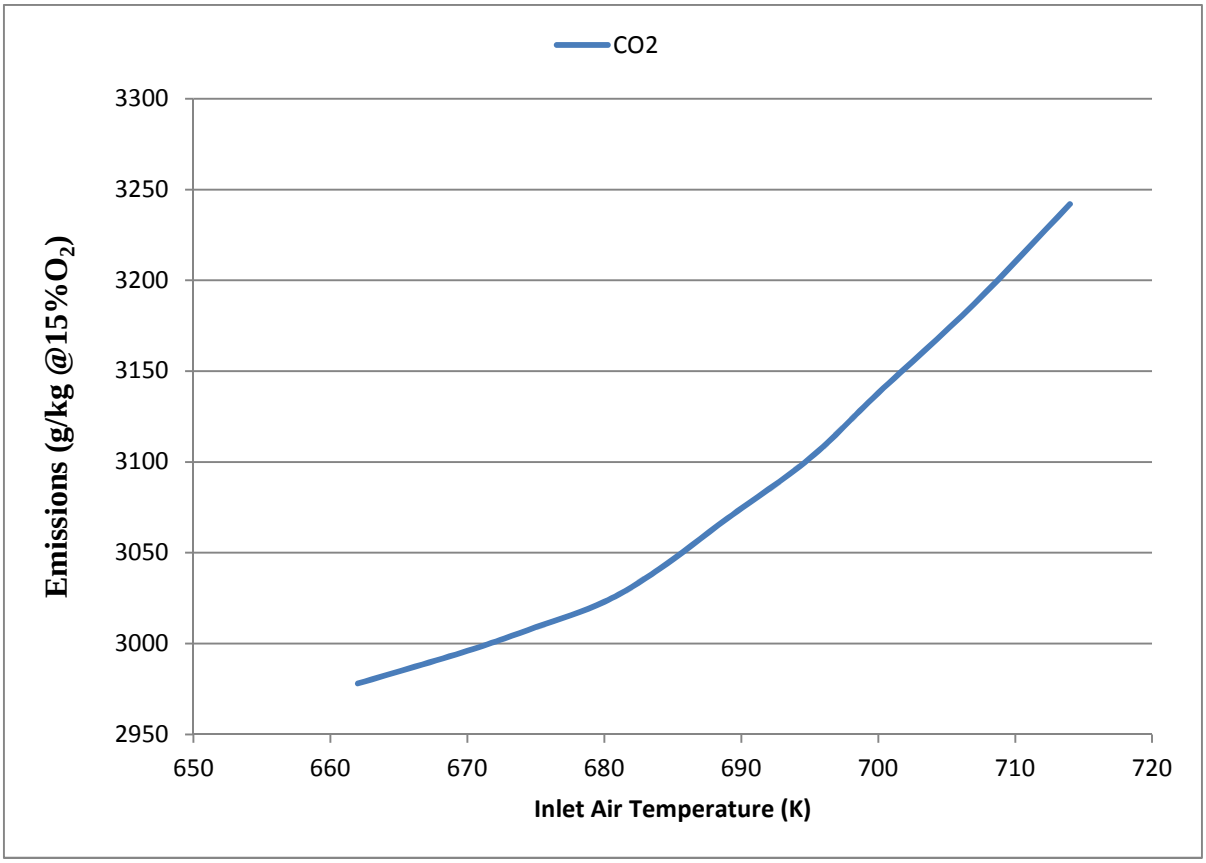

Figure 5-10 Effect of Inlet Air Temperature on CO_2 Emissions

Other factors that have similar effects on the quantities of emission include the ambient temperature and the fuel inlet temperature. The case of the ambient temperature underscores the location the GT is sited. The engine is expected to produce higher NOx when installed in areas close to the equator with hotter temperatures compared to the poles with relatively lower temperatures. Certain locations of any particular country are colder than other parts as a result of their elevation from the ground; due consideration is therefore essential when siting a power plant.

5.8.2 Effects of Flame Temperature on Emissions

The flame temperature is a single most important factor affecting the formation of NOx; this is theoretically a maximum at stoichiometric conditions and will fall off at both rich and lean mixtures [64]. There is an increasing NOx with increasing flame temperature as shown in Figure 5-11. So the key factor in reducing NOx would be in the reduction of the flame temperature.

Rising turbine entry temperature and the equivalence ratio will also increase NOx emissions with a corresponding decrease in Carbon emission (Figure 12).

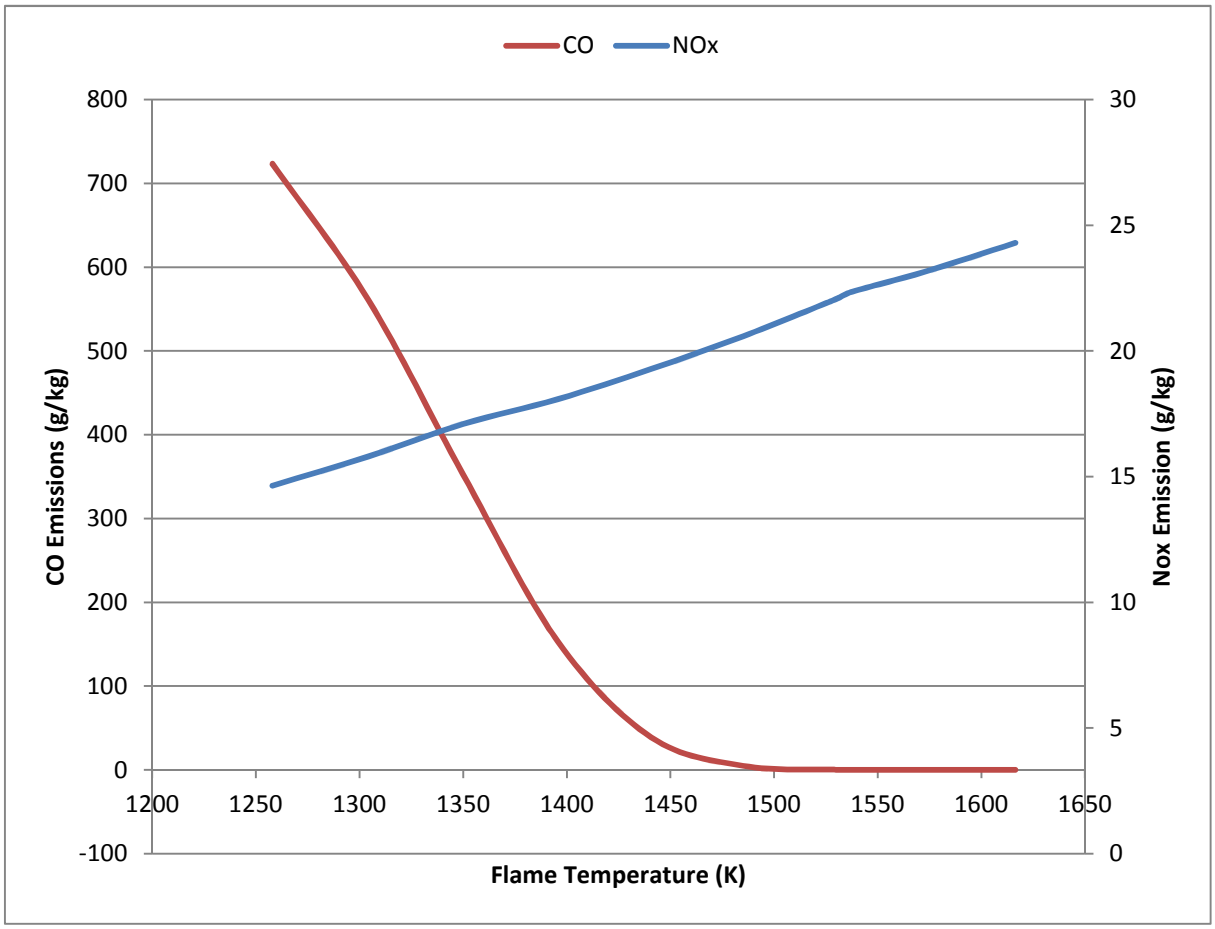

Figure 5-11 Effect of Flame Temperature on CO & NOx Emissions

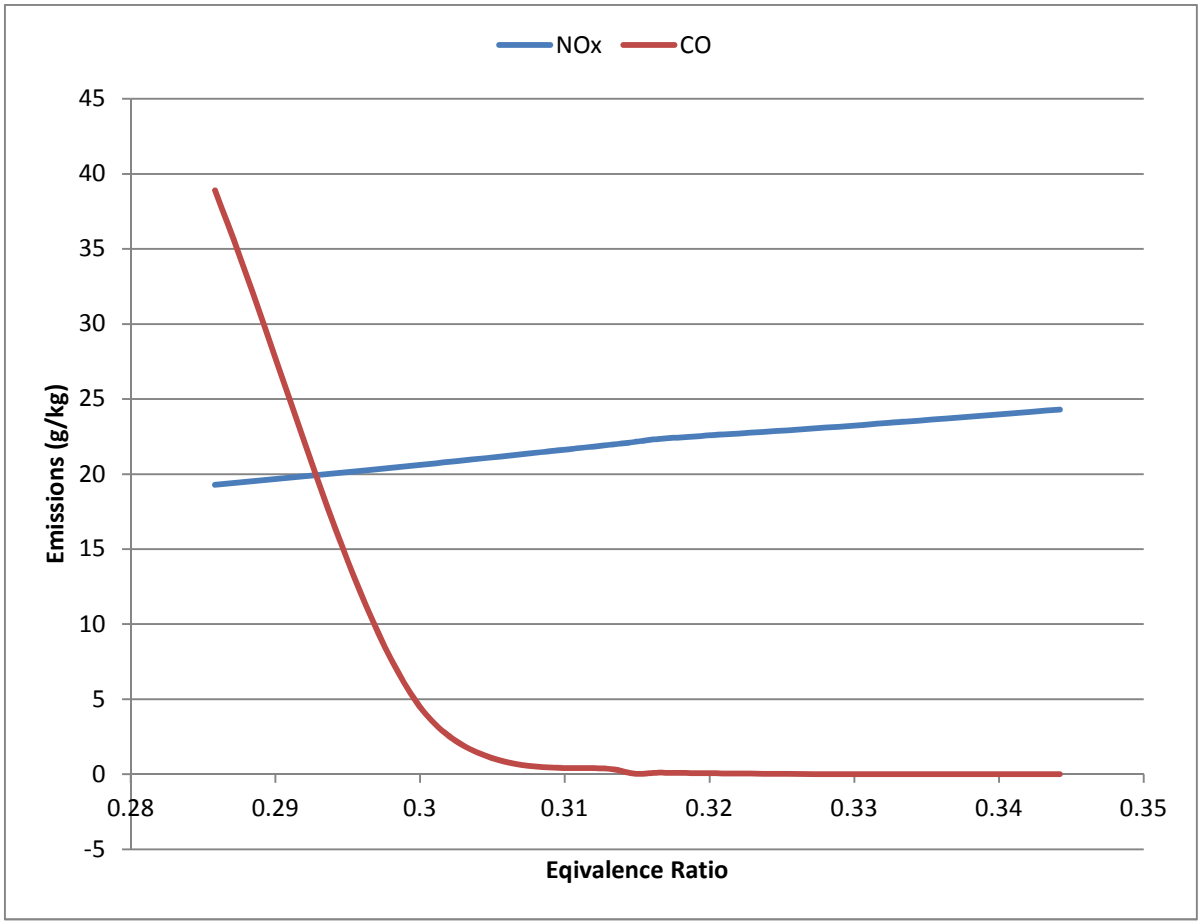

Figure 5-12 Effect of Equivalence Ratio on CO & NOx Emissions

5.9 Fuel Influence on Emissions

In order to ascertain the effects of fuel composition on the emissions produced, the different fuel properties were fed into the model; these include the molar composition of the Hydrocarbons and other elements of any particular fuel type. Different fuels may contain same elements but in different proportions while others contain different elements entirely. The composition by molar fraction of the fuels is at Table 5-2.

The syngases from the solid fuels are products of rigorous processes of gasification. The NASA CEA gives the fuel properties after being supplied with

the parameters of temperature, pressure, equivalence ratio and the moisture content where applicable.

Table 5-2 Composition of Some Selected Biofuels

	Bagasse [90]	Wood [90]	Jatropha [77]	CH_4 [34]
CH_4	0.02	0.15	0.625	0.862
CO	0.217	0.42	0.01	-
CO_2	0.11	0.11	0.335	0.05
H_2	0.172	0.24	0.02	-
N_2	0.47	0.04	0.01	0.025
Others	-	-	-	0.106 (C_3H_8)
LHV	19.4MJ/kg	20MJ/kg	39.5MJ/kg	49MJ/kg

The levels of emission for the various gases vary with different fuel types. In the case of NOx when the engine is running on gaseous fuels, the emission levels vary significantly with the constituents of the fuel. Hydrocarbon constituents with molecular weights higher than that of methane burn at a higher flame temperature and so can have NOx emissions above 50% over that for methane gas [78]. In addition, gaseous fuels that have a substantial amount of inert gases like N_2 and CO_2 produce lower NOx emissions as the inert gases act as diluents absorbing the heat generated during combustion. Such fuels include

those from air blown gasifier fuels like the ones under consideration. However, the combustion of H_2 leads to higher flame temperatures and so fuels with high H_2 content produce higher NOx emission.

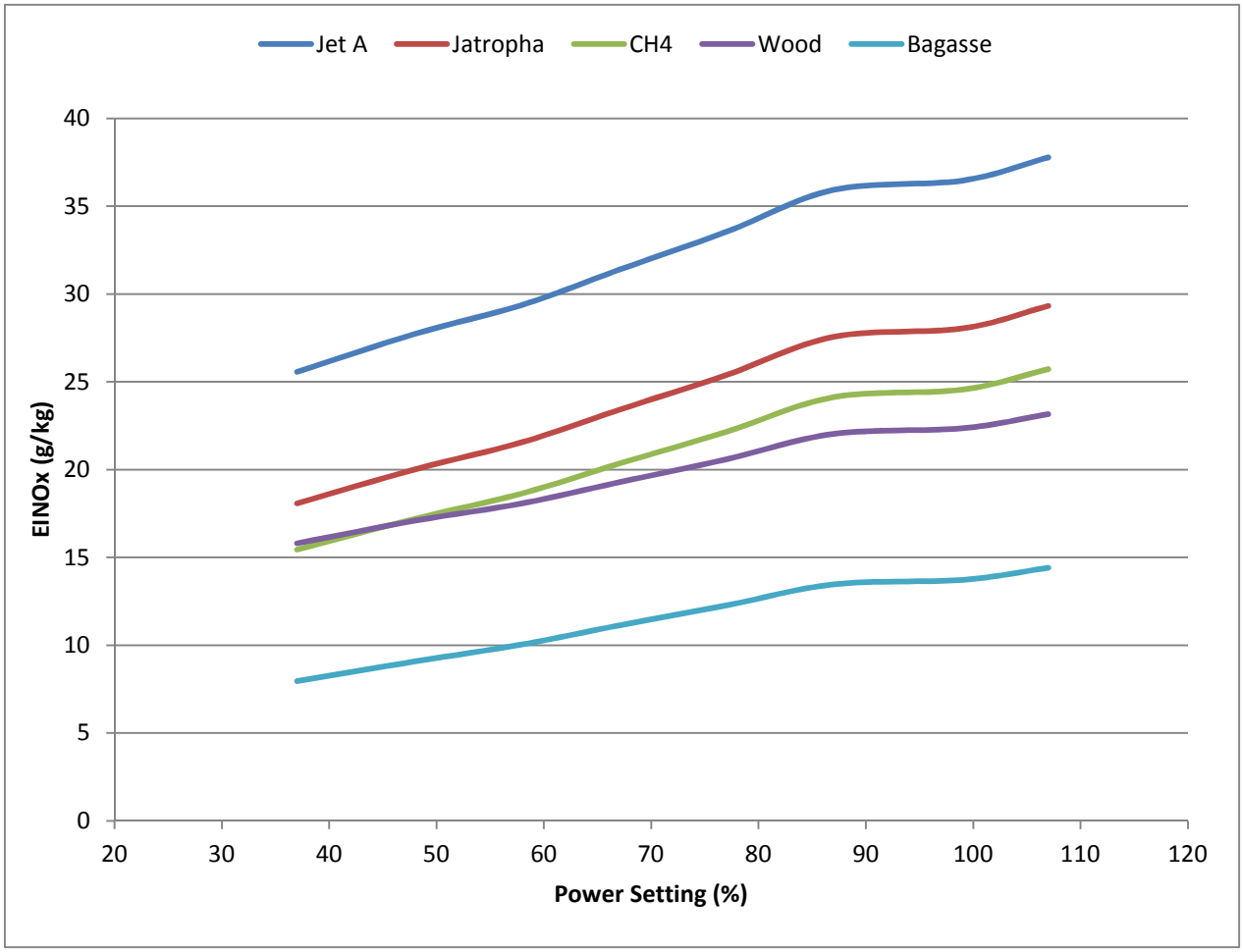

Figure-5-13 Multi-fuel NOx Emissions at Different Power Settings for a 50MW Industrial GT

Fuel influence on CO emission is in contrast to that of the NOx. Carbon monoxide emission is less for gaseous fuels than liquid ones and it is significant only at lower firing temperatures, power setting or equivalence ratio.

The emissions recorded by burning the different types of biofuels (woodfuel, sugarcane bagasse and Jatropha) were plotted against those of other conventional fuels like the Jet A1 and the natural gas and it is depicted in Figures 5-13 to 5- 15 for NOx, CO and CO_2 respectively.

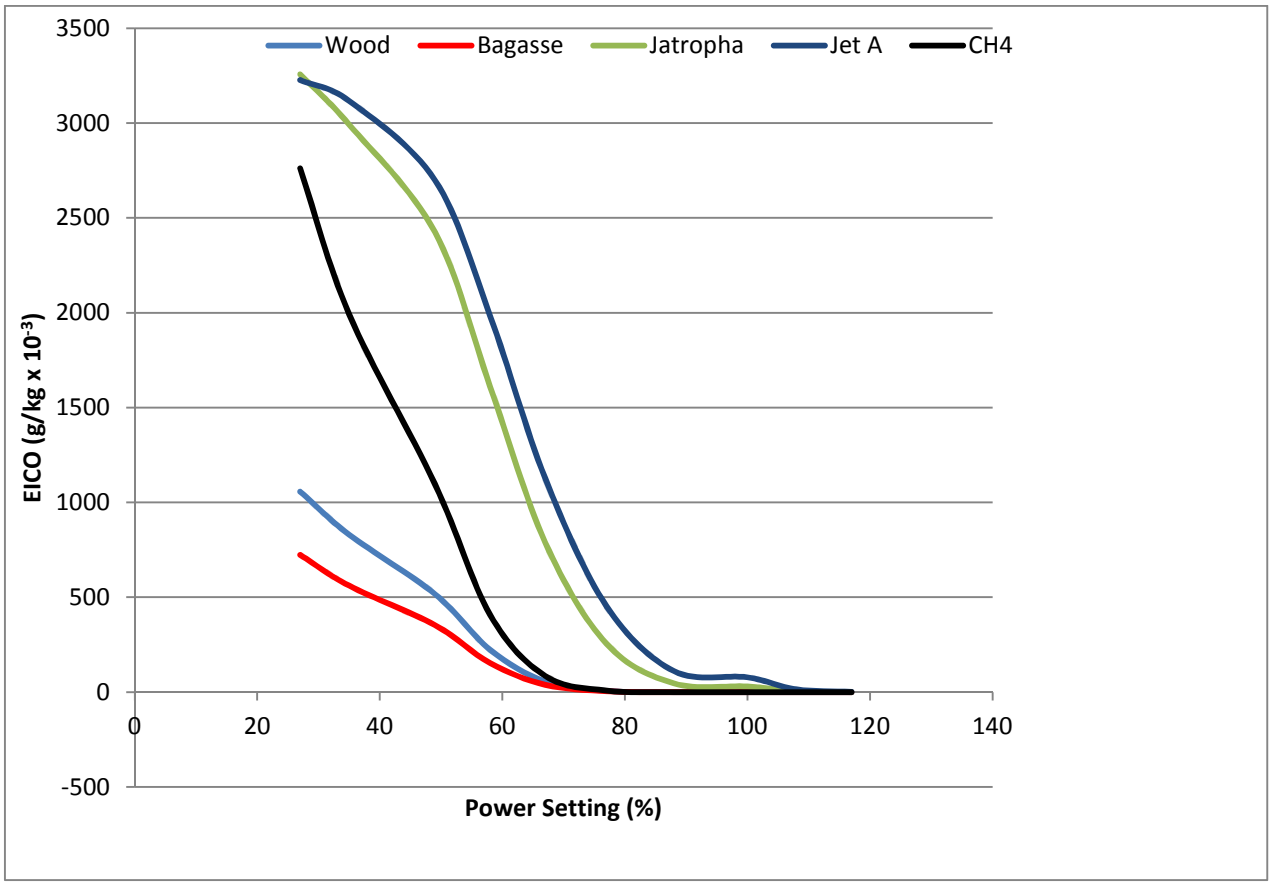

Figure 5-14 Multi-fuel CO Emissions at Different Power Settings for a 50MW Industrial GT

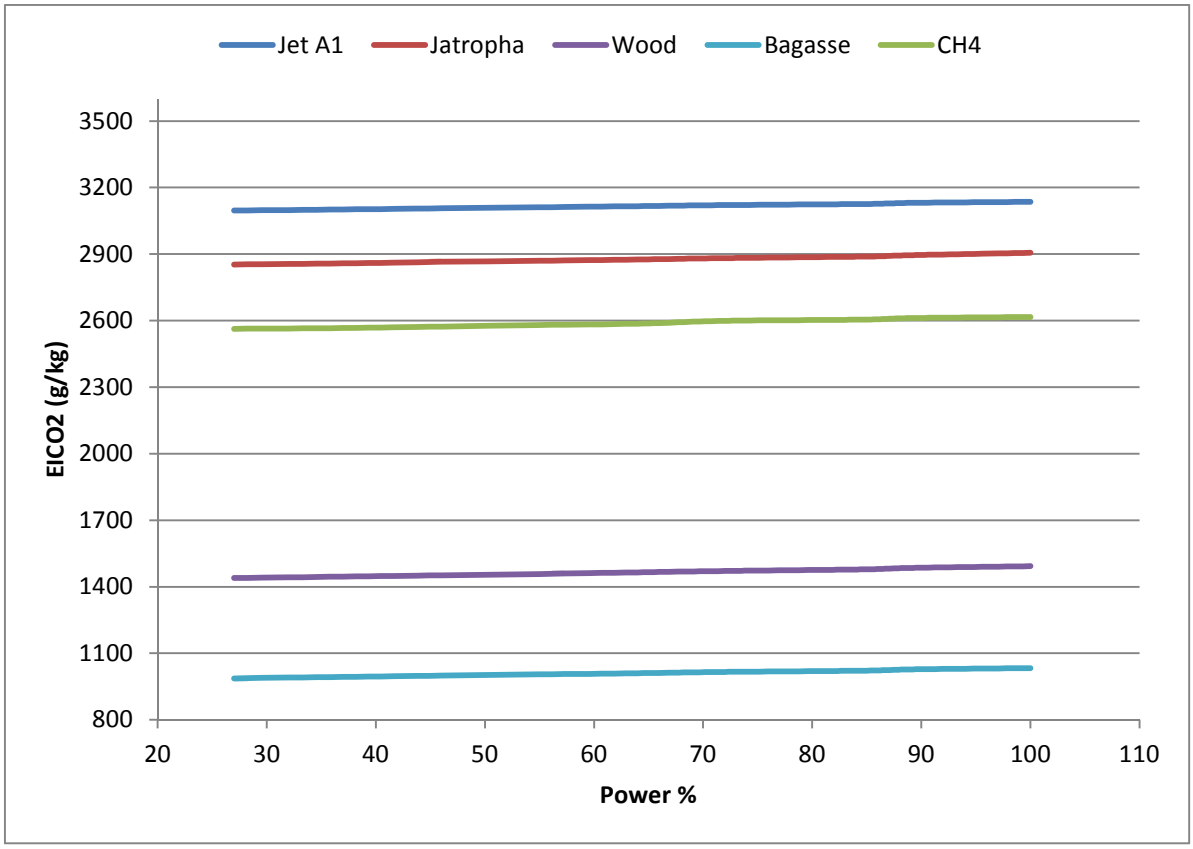

Figure 5-15 Multi-fuel CO_2 Emissions at Different Power Settings for 50MW Industrial GT

Both NOx and $C0_2$ show rising trends as the engine power setting increases though at different proportions while the CO values decreases. Higher temperatures support better combustion but with a higher NOx formation. The balance between the two is to be reached bearing in mind the environmental and the operational requirements.

The emission trend for the three engine types considered in the present work are similar with varying quantities of emissions. The NOx and CO emission for the three engines are as shown in Figures 5-16 & 5-17.

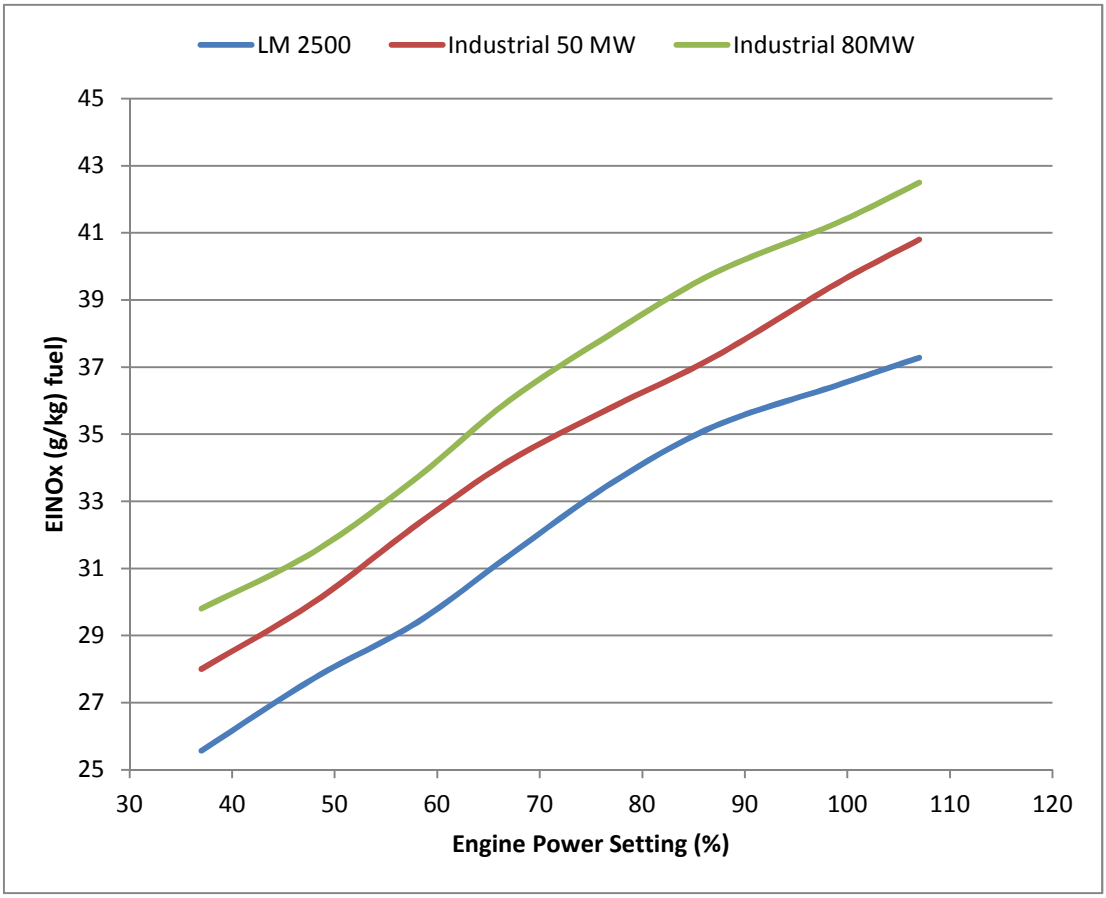

Figure 5-16 Variation of NOx Emissions for the 3 Different Power Plants

The smaller aero-derivatives engine shows a lower emission compared with the industrial ones of capacity 50MW and 77 MW. The power output is a factor as well as the combustor configuration. Meeting low pollutant emissions targets is highly dependent on the design of both the engine cycle and the type of combustor and these two are influenced by the type of fuel to be used [79].

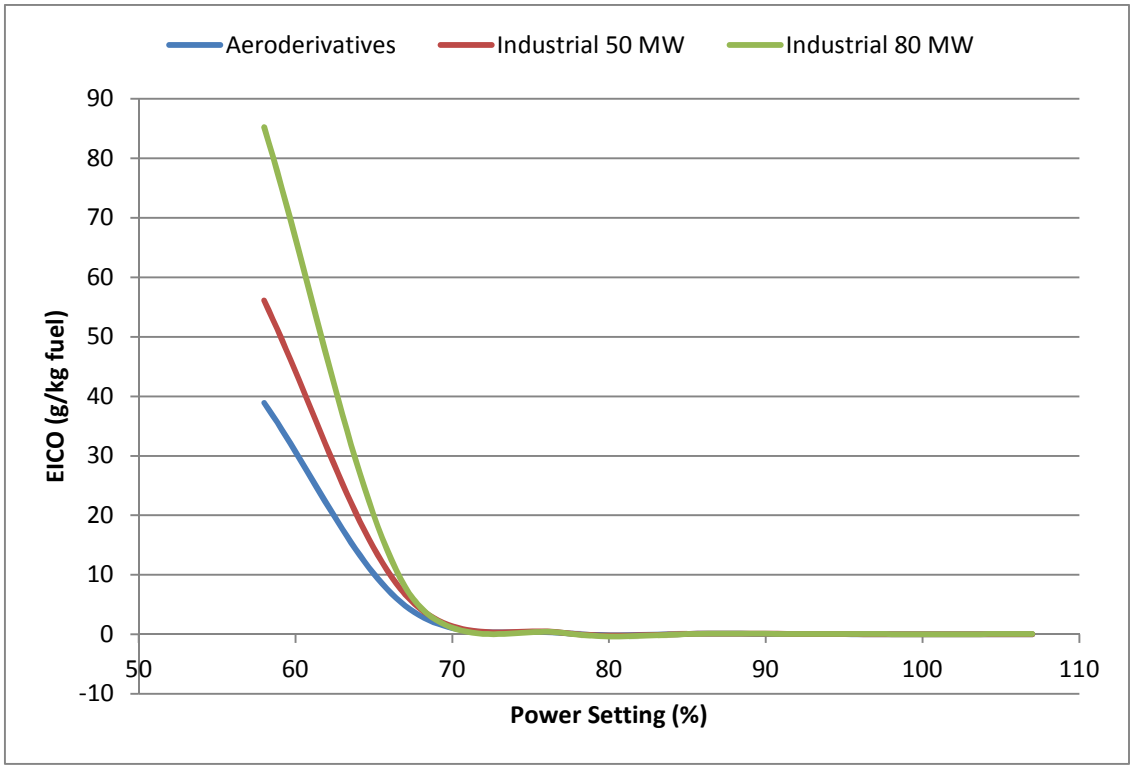

Figure 5-17 Variation of CO Emissions for the 3 Different Power Plants

The choice of the diffusion type of combustor used in this modelling is due to the fact that burning syngas on lean – premixed combustors present two main issues namely: shorter auto-ignition delay and faster flame speed of hydrogen contained in a reasonable proportion in the syngas from the biofuels. This combination produces an unacceptable risk of the combustion flame propagating upstream or ''flashing back'' into the lean-premix zone [66]. The suitable gas turbines adapted for syngas fuels would use single-stage diffusion combustors until lean-premix combustors are developed adequately to burn syngas. As earlier explained, the emission trends for the gases are as a function of volumetric fractions of the syngas constituents and the presence of diluents like the CO_2.

The results from the developed multi-fuel emission model compare favourably with results in open literatures and can be adjudged as reliable for use on

engines to capture gas emissions. There is a percentage reduction in the various emissions when utilizing biofuels on gas turbines. When this is taken on a life cycle assessment, the carbon emission value for instance is a net zero as those released during gas turbine operations are utilised by the crops during growth. The overall aim is to factor in the reduced emissions in the economics of GT operations. The enhanced environment with biofuel use leads to reliefs that will lead to reduction in operational cost of the power plant.

6 TERA Economic Assessment

All thermal design projects, like any other project, require adequate assessment of the major costs involved in the project because of its high capital intensive nature. These costs include total capital investment, operating and maintenance cost, fuel cost and other ancillary costs. The values of these different costs determine the final cost of electricity which defines the project viability and selection. This was underscored by Adrian B et al [80] when they stated that one of the most important factors affecting the selection of a design option for a thermal system is the cost of the final products.

The cost of biofuels from biomass feedstock is a major determinant in the overall cost of the product in this case – electricity. This chapter will analyse the effects of all the cost constituents on the cost of electricity utilising the selected biofuels from wood, bagasse and the Jatropha and then the natural gas as the baseline fuel.

6.1 Cost Elements

To carry out a successful economic assessment, the various cost elements are very important aspects that must be given due considerations as this will lead to a successful completion or otherwise of a project - in this case, a thermal project.

The product cost is the amount of money paid to acquire or produce an item. The value or the market price of an item is not only affected by the cost of production and the intended profit but also by other factors such as demand, supply, competition, regulation and reliefs. Broadly, costs are classified as fixed or variable costs:

a. Fixed Costs. Fixed costs are those costs that do not depend on the production rate. These include depreciation, taxes, insurance, rent, capital cost and maintenance.

b. Variable costs are those costs that vary more or less according to the volume of production. Those in the category are costs of materials, fuel, labour and energy needed to produce them.

The specific costs for the power plants modelled in this present work are detailed at section 6.7.1.

6.2 Types of Projects' Economic Assessments

There are several methods of evaluating the economic viability of projects of which thermal project is one. Bejan A. et al [80] suggested some of them which include:

a. Net Present Value (NPV) method.
b. Levelized Costing method.
c. Accounting Rate of Return (ARR).
d. Payback and Discounted Payback methods.
e. Internal Rate of Return (IRR) method.

While these methods are suitable for economic appraisal of projects, each of them has its merits and demerits as covered in [80]. In this study, the levelized costing method is used as it makes it possible for varying costs over the entire life of the project to be made constant by the introduction of certain factors.

6.3 Economic Model Methodology

The economic model comprises of codes incorporating the different inputs of the engine performance as detailed at chapter 4 including the plant efficiency, specific fuel consumption and other engine parameters. In addition, relevant economic parameters are used as inputs. The model which is called the ''Biomass Power Plant Economic Model (BIOPPEM)'' was developed based on the levelized costing method.

Technical data from the Turbomatch used as inputs together with several other economic values. Details of the data which the model uses as input are in

section 6.6.1. The code is based on detailed calculations of the various cost elements in the biomass based power plant as outlined in section 6.4. The various costs including major ones like the capital, operations and maintenance (O&M) and fuel costs are levelized and annuity factors are introduced.

It computes the depreciation schedule on the capital assets, the annual cash flow for the entire life of the power plant and then calculates the Cost of Electricity both in current and constant dollars. The model is capable of determining the revenue requirement for the production of electricity from where the cost of electricity (CoE) is established.

An economic analysis can be conducted in either current or constant dollars by including or otherwise the effects of inflation on capital expenditures, fuel and O&M costs. Whichever is used has its merits and demerits. Generally, the relationship between the two at the nth year of the project is given by:

C.constant $= \mathbf{Co(1 + r_r)^n}$ …… Equation 6-1

C.current $= \boldsymbol{Co(1 + r_n)^n}$ …… Equation 6-2

Where, $\boldsymbol{Co}$ is the cost of the same asset in the reference year and r_r and r_n are the inflation rates for the reference and the nth years respectively.

Longer term projects may be best represented in constant dollars so that the effect of many years of inflation does not distort the costs to the point that they bear no resemblance to today's cost values [80]. The constant dollars approach is used in this present model bearing in mind the 20 years lifespan of the project.

6.4 Levelized Costing method

Factors such as inflation, expenditure escalation during the life span of the project make costing not a direct and easy task. So the concept of cost

levelization involves the use of time-value of money to convert a series of varying quantities of a financially equal constant amount called annuity over a specified time period usually the project life span. This is done in respect of the capital, O&M and the fuel costs. This then leads to the determination of the revenue requirements (RR) and eventually the levelized total cost of the main product of a thermal system (electricity).

6.4.1 Biomass Fuel Costing

The cost of fuel is a significant factor in a power plants' economic performance. So every effort at reducing fuel cost would have a significant effect on the overall energy cost. Biomass cost encompasses the production and transportation to site costs. The effect of distance where biomass is produced to the power plant location was therefore adequately considered. The equations used for the calculation of the biomass cost per dry tonne and the capital cost as shown below was modified from the one suggested by Larson and the values for the various variables were assigned in the light of current economic realities [21]:

$$BC = \boldsymbol{BPC} + [\,\mathbf{3} + \frac{\mathbf{0.18} * \boldsymbol{D}}{\mathbf{0.9}}] \qquad \text{Equation 6-3}$$

Where BC = Biomass total cost

BPC = Biomass production cost

D = One-way distance to plant

The value 0.9 accounts for a 10% post-harvest loss or loss during storage of the biomass feedstock while 0.18 and 3 are baseline values defined by experts. With an estimated biomass production cost, the total biomass cost can then be calculated using equation 6-3.

For bagasse, a by-product of sugar production, the total cost (BC) is assumed to be $5/dry tonne, wood at $76/tonne and dry Jatropha seed, $140/tonne.

6.4.2 Unit Capital Costing

There are several factors affecting capital costing of biomass fuelled power plants including the costs of the engine and the gasifier, installation cost, piping and others. The following equations had been adapted from the one suggested by Larson [21] for the calculation of the capital cost.

$$UCC = C+D*(Capacity)^{E} \qquad \text{Equation 6-4}$$

Where, C & D are constants that depend on plant configurations.

Capacity is the engine power output in MW

E is a negative factor which indicates that unit cost falls with increasing capacity

The values of C are based on estimates from existent power plants with necessary interpolation and also dependent on whether the gasification is under low or high pressures. Consequently, the C values for low pressure, high pressure gasification and the steam engines are taken to be $1200, $1050 and $1200 respectively based on prevailing market values. The equations for the computation of the capital cost in these configurations are as follows:

HP-BIGCC: $1050 + 110420 \times MW^{-1.42}$ Equation 6-5

LP–BIGCC: $1200 + 47198 \times MW^{-1.56}$ Equation 6-6

Steam Cycle: $1200 + 22195 \times MW^{-0.93}$ Equation 6-7

From the above equations, the outlook of the unit capital costs of the various plants will have a trend as shown in Figure 6-1: The trend indicates that the unit capital cost for a low pressure (LP) gasification system would be lower than those for a high pressure system in the power range of between 25-80MW [19]. However, with increasing power output of more than 80MW, the HP system is lower in capital cost. The low pressure gasification configuration is therefore appropriate for the various gas turbines chosen for modelling in the present work as they fall within the power range of 25-80MW.

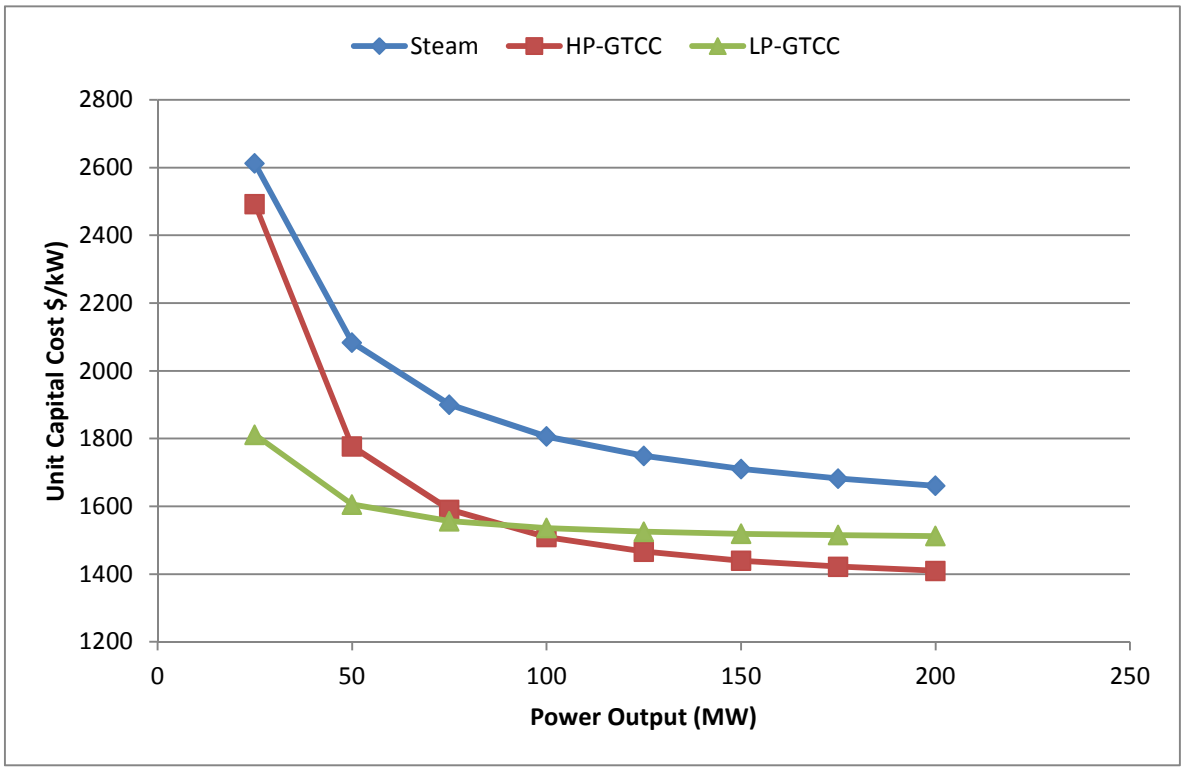

Figure 6-1 Effect of Engine Capacity and Configuration on Capital Cost

6.4.3 Plant Total Cost Computation

The costs involved in the establishment of the power plant have been computed sequentially to enable one arrive at the revenue requirements: these equations are based on those suggested by Dechamps [81] and adapted by Neto [24].

Investment for the 1st year operation is given as:

$$inv_1 = inv0\ [\ \mathbf{1} + \frac{\boldsymbol{i+e}}{\mathbf{100}}]^{ct/2} \qquad \text{Equation 6-8}$$

Where; inv0 = Investment cost for 1st year

i = Annual interest rate

e = inflation rate

ct = Project construction time in years.

For cost levelization, compound interest (q) and annuity factor (anf) are defined:

$$q = \mathbf{1} + \frac{\boldsymbol{i+t}}{\mathbf{100}} \qquad \text{Equation 6-9}$$

$$anf = \frac{\boldsymbol{qDP} * (\boldsymbol{q-1})}{\boldsymbol{qDP-1}} \qquad \text{Equation 6-10}$$

Where DP is the book depreciation period of the investment in years

The compound interest caters for the annual interest rate, capital insurance taxes and the annuity factor expresses the amount of money to be paid back every year on investing capital.

Therefore, Levelized Capital Cost (LCC)

$$LCC = \mathbf{1000} * \mathbf{Pwr} * \mathbf{inv1} * \mathbf{anf} \qquad \text{Equation 6-11}$$

Where, t = capital insurance taxes and i = interest rate both in %/year,

DP = Book depreciation period in years and Pwr is plant shaft power in MW.

Similar to the 1st year operation investment equation, the fixed cost for the 1st investment year is given as:

$$fc_1 = fc_0 \text{ x } [\mathbf{1} + \frac{\boldsymbol{ef}}{\mathbf{100}}]^{ct} \text{ x } 1000 \text{ x } P \qquad \text{Equation 6-12}$$

And Levelized Fixed Cost is:

$$LFC = fc_1 \text{ x } anf \text{ x } pwf \qquad \text{Equation 6-13}$$

fc_1 = fixed cost 1st operation year, fc_0 = specific fixed cost 1st investment year both in $/year,

ef = fixed cost escalation factor and pwf = present worth factor per year.

It derives that specific total fixed cost is the sum of LCC and LFC given as:

$$STFC = \frac{\mathbf{LCC+LFC}}{\mathbf{100*Pwr}} \qquad \text{Equation 6-14}$$

6.4.4 Computing Specific Fuel Cost

Specific fuel cost for the 1st year operation

$$(f_1) = f_0 \left[\mathbf{1} + \frac{\boldsymbol{eff}}{\mathbf{100}} \right]^{ct} \qquad \text{Equation 6-15}$$

Where f_0 = specific fuel price for 1st year investment in $/GJ,

eff is the fuel escalation factor in %/year.

And fuel cost 1st year operation is defined as:

$$cf1 = \mathbf{f1} * \mathbf{3.6} * \frac{\dot{\eta}\boldsymbol{th}}{\mathbf{100}} * Pwr * 8760 * lf \qquad \text{Equation 6-16}$$

where, *lf* = load factor, $\dot{\eta}th = thermal\ efficiency\ (\%)$ and 8760 is the total number of hours per year.

$$LCF = cf1 * anf * pwf \qquad \text{Equation 6-17}$$

And the specific fuel cost (SFC) in $/kW is then:

$$SFC = \frac{\boldsymbol{LCF}}{\mathbf{100}*\boldsymbol{Pwr}} \qquad \text{Equation 6-18}$$

Where the LCF = Levelized cost of fuel in $/year and SFC = Specific fuel cost in $/kW.

After obtaining the specific fixed costs and fuel costs, they are then summed up to arrive at the total specific cost (TSC) and the revenue requirements (RR):

$$TSC = STFC + SFC \qquad \text{Equation 6-19 and}$$

$$RR = \frac{\boldsymbol{TSC}}{\mathbf{8760}*\boldsymbol{lf}} \qquad \text{Equation 6-20}$$

6.5 Typical Temperatures in Locations of Nigeria

The effects of the ambient temperature on the performance of the gas turbine engine are expected to manifest in the economics as can be seen in subsequent sections. Three locations in Nigeria with contrasting ambient temperature ranges (Figure 6-2) have been chosen and their respective temperatures defined. This is meant to show cost variations as a result of day temperatures. The choice is based on their peculiarity for extreme heat and cold conditions and also their suitability for growing assorted biomass feedstock as shown in Table 3-9. Maiduguri has very high temperatures most part of the year while Jos and Obudu are mountainous towns with cold temperatures most part of the year. These temperatures are viewed with the prevailing country average as shown in the figure.

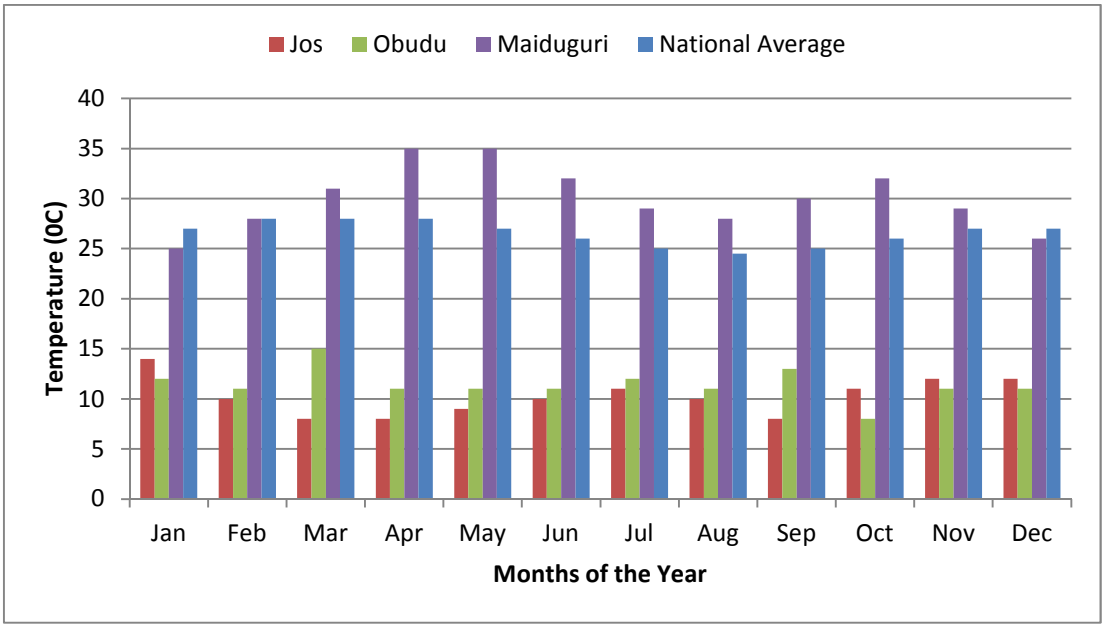

Figure 6-2 Average Monthly Temperature Profile for 3 Locations in Nigeria [82]

6.6 Comparing Energy Costs with the BIGCC Plant Utilising the Two Different Engines and the different Biofuels

Certain input figures were duly defined and used in the developed model corresponding to the various plant configurations and the different fuel types in order to arrive at a reliable assessment.

6.6.1 Economic Assumptions

Certain parameters required for completing the analysis are defined based on information from open literature and informed assumptions. These are as reflected in Tables 6-1 & 6-2: The capital cost value at serial 6 was obtained from the Energy Information Agency (USA) [83].

Table 6-1 Input Data for Economic Assessment of the NGGT and BIGCC using the two Engines and Biofuels

Serial	Economic Data	Reference Plant (NGGT)	BIGCC
1	Average Inflation rate	2%	2%
2	Escalation rate	6%	6%
3.	Construction Period	2yrs	3yrs
4.	Plant economic life	20yrs	20yrs
5.	Combined Tax rate	10%	10%
6.	Capital Cost (US$)	74,000.000	88,000,000/104,000.000
7.	Capacity Factor	85%	85%
8.	Interest Rate	5%	5%
9.	Investment Cost for 1st year ($/kW)	800	1400
10.	Specific fuel cost (US$/GJ)	4	1.3 to 2.5
11.	Fuel escalation rate (%/year)	3	2
12.	O&M Cost (US$/GJ	0.002	0.008 & 0.011

Other parameters required for the economic assessment are the performance values obtained in Chapter 4. These values as obtained from the simulations described in Chapter 4 are shown in Table 6-2:

Table 6-2 Engines Performance Data for Economic Assessment

	Aero-derivative		**Industrial (77MW)**	
	Simple	CC	Simple	CC
Power	22.8	36	77.1	102
Efficiency	37	49.5	36	48

6.6.2 Case 1 - Aero-derivative Engine running on the Biofuels

An assessment of the three fuels running on the two different engines in a BIGCC configuration starting with the aero-derivative engine was done. In chapter 4, the thermodynamic effects of the fuel properties on the engine were highlighted. However, the economic evaluation reflects more of the effects of the economic parameters including the prices of the different fuels utilised. Table 6-3 shows the values of major economic outputs for the 23MW aero-derivative engine.

Table 6-3 Economic Outputs for BIGCC Utilising the Aero-derivative Engine

Serial	Economic Parameter	Values with Bagasse	Values with Wood	Values with Jatropha
1	1st Year specific Investment inv1(US$/kW)	1.55E+03	1.55E+03	1.55E+03
2	Compound Interest – q (%/Year)	1.15	1.15	1.15
3	Annuity factor – anf (%/Year)	0.16	0.16	0.16
4	Cost of fuel 1st operational year-cf1 (US$)	0.97E+06	1.16E+06	1.76E+06
5	Specific fuel price 1st operational year-f1 (US$/GJ)	1.21	1.74	2.15
6	Levelized cost of fuel-LCF (US$/Year)	4.60E+06	5.98E+06	6.43E+06
7	Specific fuel cost-SFC (US$/kW.Year)	24.87	30.02	35.57
8	Total specific cost-TSC (US$/kW.Year)	435.1	470.06	485.05
9	Cost of Electricity (CoE) (US$/kWh)	0.0584	0.0631	0.0651

6.6.3 Case 2 - Industrial Engine running on the Biofuels

Table 6-4 shows the values of major economic outputs for the 77MW industrial engine. The values show disparity in the overall cost of electricity majorly resulting from the different fuel prices in addition to other factors such as the capital costs of the power plants.

Table 6-4 Economic Outputs for BIGCC Utilising the 77 MW Industrial Engine

Serial	Economic Parameters	Values with Bagasse	Values with Wood	Values with Jatropha
1	1st Year specific Investment inv1(US$/kW)	1.35E+03	1.35E+03	1.35E+03
2	Compound Interest – q (%/Year)	1.15	1.15	1.15
3	Annuity factor – anf (%/Year)	0.16	0.16	0.16
4	Cost of fuel 1st operational year-cf1 (US$)	1.30E+06	1.66E+06	2.21E+06
5	Specific fuel price 1st operational year-f1 (US$/GJ)	1.2	1.87	2.33
6	Levelized cost of fuel-LCF (US$/Year)	6.40E+06	8.15E+06	8.90E+06
7	Specific fuel cost-SFC (US$/kW.Year)	27.98	35.96	40.97
8	Total specific cost-TSC (US$/kW.Year)	315.3	350.2	365.2
9	Cost of Electricity (CoE) (US$/kWh)	0.0458	0.0535	0.0558

From the two cases scenario, it is evident that the CoE when utilising bagasse is least for all the engines while the Jatropha has the highest CoE. This can be attributable to the prices of the respective biomass fuels. In a related assessment, the CoE for the aero-derivative engine is higher than the industrial

engine. Though the aero-derivative engine has a higher efficiency, and consequently lower fuel consumption and specific fuel cost, other cost ingredients like the unit capital cost is relatively high due to the relative small scale of the engine leading to an overall higher CoE.

6.6.4 Comparing the Natural Gas Fuelled Gas Turbine and the Biomass Integrated Gasification Gas Turbine

Corresponding values for the natural gas fired gas turbine engine (reference plant) is as shown in Table 6-5. Viewing the NGGT figures with the results of the biomass integrated gasification combined cycle plants produced results as summarized in Table 6-6.

Table 6-5 Equivalent Output Values for the NGGT Power Plant

Serial	Economic Parameter	Reference Plant
1	1st Year specific Investment inv1(US$/kW)	900.6
2	Compound Interest – q (%/Year)	1.15
3	Annuity factor – anf (%/Year)	0.16
4	Cost of fuel 1st operational year-cf1 (US$)	7.8E5
5	Specific fuel price 1st operational year-f1 (US$/GJ)	3.061
6	Levelized cost of fuel-LCF (US$/Year)	13.8E6
7	Specific fuel cost-SFC (US$/kW.Year)	123
8	Total specific cost-TSC (US$/kW.Year)	344
9	Cost of Electricity (CoE) (US$/kWh)	0.0462

From the results, the overall cost of electricity was found to be lower in the case of the NGGT than the BIGGC. It is expected that the lower price of the biomass derived fuels would have led to a lower CoE, however, the modules of equipment involved in the case of the BIGCC are more than those of the NGGT and a corresponding higher capital cost. They include the gasifier, the GT and the components of the steam cycle.

Table 6-6 Summary of Cost of Electricity for all the Cases

Power plant	NGGT	BIGCC with Aero-derivatives			BIGCC with Industrial Engine		
Fuel	CH_4	Jatropha	Wood	Bagasse	Jatropha	Wood	Bagasse
CoE	0.0462	0.0651	0.0631	0.0584	0.0558	0.0535	0.0458

In addition, the operating cost is higher for the BIGCC. The operating cost consists of labour, ash disposal and maintenance costs. Labour cost increases with decreasing rate of plant capacity due to economy of scale. The cost for ash disposal in the case of biomass fuelled power plants would be eliminated when ash finds a useful use as fertilizers in the future. This would lead to a further reduction in the overall CoE of biomass plants.

6.7 Day Temperature Effect on Plant Economics

Figure 6-3 reflects the cost of electricity deviation from the baseline for the 12 months of the year in the locations chosen in Nigeria in section 6-5. As can be seen, the deviation for the location of higher temperatures

is positive while those for the locations of lower temperatures are negative due to reduced efficiency and shaft power at higher temperatures as explained in the earlier part of the thesis. This trend is applicable when considering the power plants' performance due solely to varying ambient conditions. When other factors are put into consideration the very clear influence would be narrowed. Such other factors include the quantity of fuel the power plant consumes, the seasonal nature of biomass production and the equipment capital costs.

In addition, the cost trend reflects a behaviour assuming the same type of biofuel (e.g. Jathropha) is used on the plant throughout the year. The consideration of the use of assorted biofuels would narrow the price gap throughout the year.

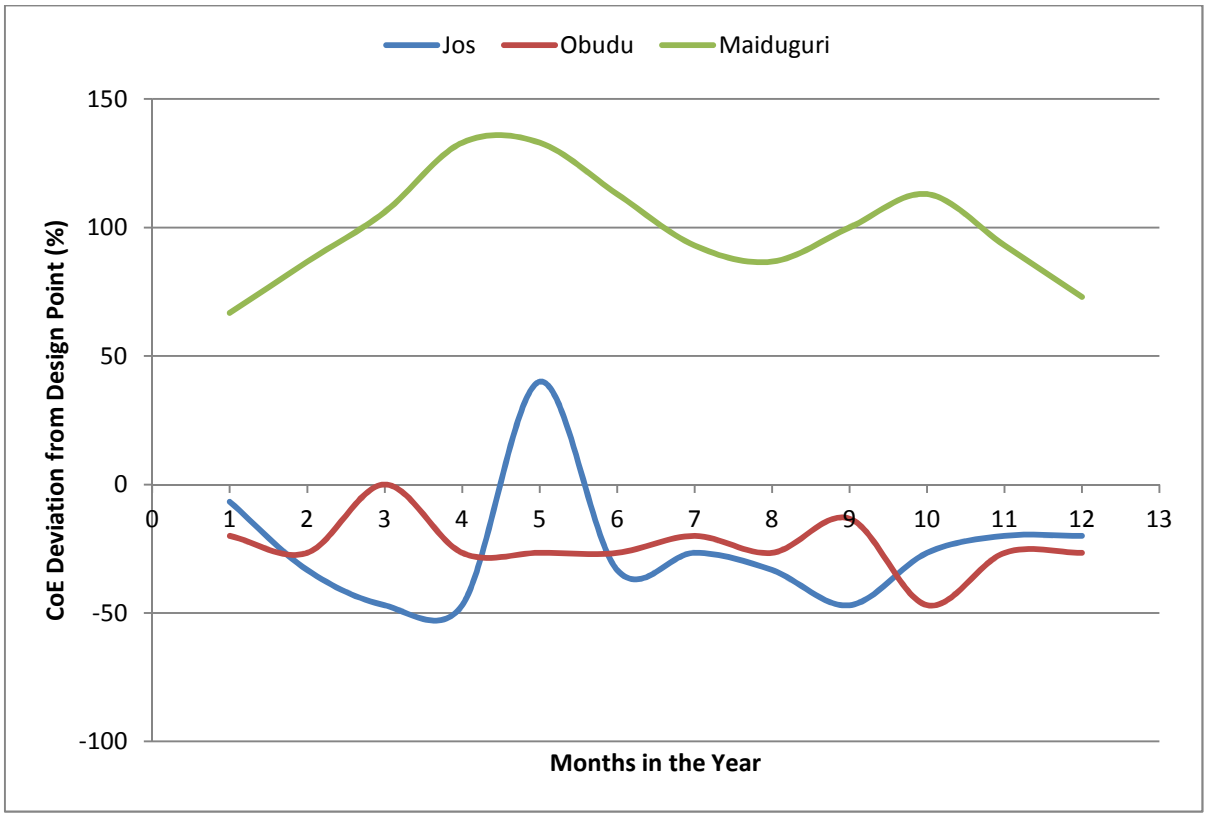

Figure 6-3 Monthly CoE Deviation for Each Location Using the BIGCC

6.8 Emission Economics

The use of biomass for power generation results in lower emission values as established in Chapter 5. In January 2007, Norwegian authorities set excise duty figures on emissions for (NOx) and carbon from energy production to fulfil Norway's commitment under the Gothenburg Protocol [84]. Other countries in Europe, America, Asia and indeed all countries of the world have introduced levies for gas emissions.

$$\boldsymbol{Emission = a * Engines * \sum\left(\frac{60 * Hours * Fuel\ Rate * Emission\ Index}{1000}\right)} \ldots \text{Equation 6-21}$$

Where

a = Factor depending on the HC (hydrocarbon) value of the fuel

Engines = Number of engines

Hours = Standard time period of operation of the engines (capacity factor)

Fuel Rate = The rate of fuel flow for different modes in entire period of operation

Several other considerations are given after which the emission values are computed using equation 6-21 above. The quantity of emission of the different greenhouse gases (NOx, CO, CO_2 and others) is therefore paid for in penalties.

In the context of the present work, the emission values differ for different types of fuels. The limit of the emission types also vary from country to country. An approximate amount of $2.5 per kilogram of NOx and $107/tonne of Carbon is adopted as the prices for the two types of emissions in estimating the cost of emission for the modelled engine [84; 85].

From the values of the emission from the various fuel types, the difference in the costs of emission can be compared. The emission values for the bagasse were found to be lower compared to both conventional fuels of Jet A1 and the natural gas. This results in reduction in the emission penalties to be paid. On a life cycle assessment, the value of Carbon emission when utilizing biofuels is a net zero as the CO_2 emitted is reused during the growth of the biomass from which the biofuels are produced thereby leading to a zero emission cost. This can then be rewarded to biomass fuelled power providers as incentives or Carbon tax 'leave' which would lead to an overall lowering of the energy cost. This makes the choice of biofuels as future fuel resource generally rewarding.

If we assume the following as aggregate reduction in emissions in particular plant operation when using natural gas and the biomass sources:

NOx reduction

Wood	-	21%
Bagasse	-	27%
Jatropha	-	minimal

Carbon reduction

Wood	-	20%
Bagasse	-	33%

Then the emission cost pattern is as reflected in Figure 6-4.

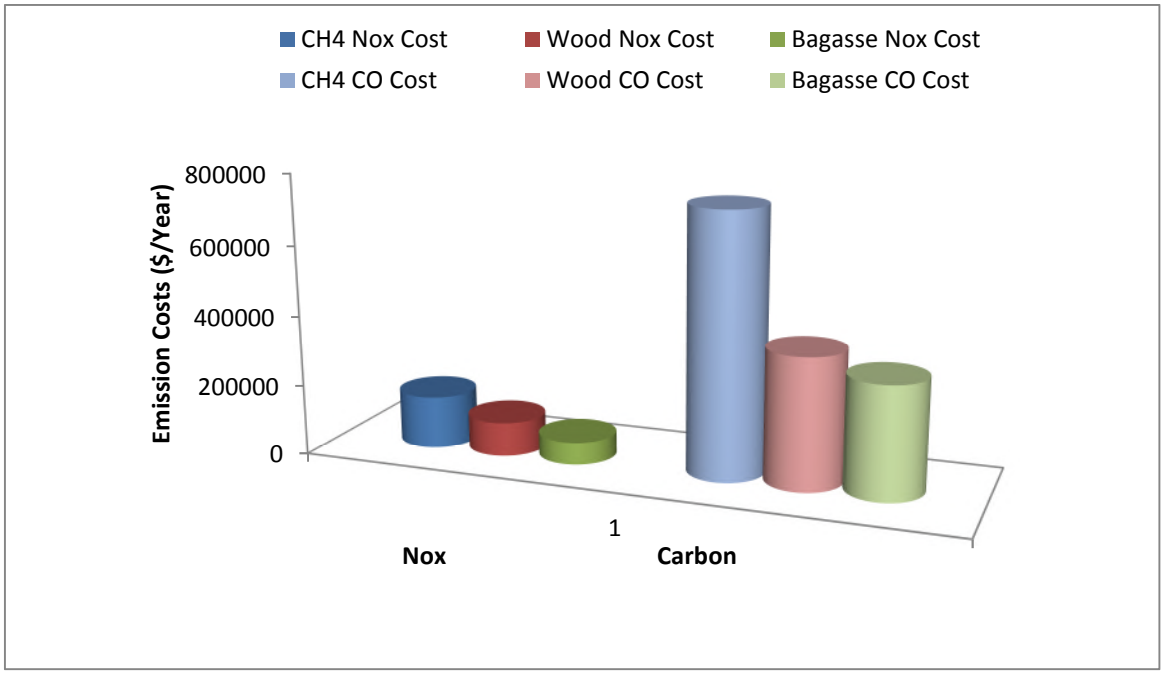

Figure 6-4 Cost Saving from Reduced Emission when Using Biomass

When we cater for the lower emissions of biomass in the overall cost of electricity, the gap between the CoE of the BIGCC reduces further with that of the reference conventional fuel (CH_4).

6.9 Summary on the economics assessment

Various cost components of biomass fuelled power plants affect the overall energy cost. The type of engine used and their capacities also affect the cost of the final product. The overall behaviour of the cost outlook indicate the fact that total cost of product from power plants of below 30MW is more costly than those of 50MW and above. This suggests that it is more cost effective to set up BIGCC plants of capacity in the range of 50MW and above. This is corroborated by Upadhyay et al in an economic feasibility of biomass for power analysis. Their model shows that the cost effectiveness of BIGGT/CC is higher for plants of above 50MW [82][86].

The levelized cost for power production for the two types of engines utilising the three types of biofuels also shows sensitivity to the plant efficiency, operating and atmospheric conditions and more importantly the cost of fuels. Keeping the price of biomass feedstock at an optimal level through various strategies is therefore essential to the overall energy cost.

The ready use of biomass energy through prioritisation of acceptance on the grid for biomass energy will ensure best capacity utilisation and this will lead to a reduced biomass derived energy cost. The emission economics also portends good outlook in emission penalty tax for biomass energy relative to conventional fuels.

6.10 The Risk Issue

Risk is often defined as the probability of occurrence of an undesirable outcome[87]. Risk in economic terms is the likelihood that an investment will be affected by macroeconomic conditions such as government regulation, taxes, exchange rates, or political instability. In other words, while financing a project, the risk that the output of the project will not produce adequate revenues to cover operating costs and repaying the debt obligations must be evaluated.

For biomass fuelled gas turbines, there are factors that constitute risks such as sustainability of the biomass supply, cost of biomass, the interest on investing capital, equipment procurement cost, load/capacity factor, capital cost and others. These factors were used as parameters for the risk analysis using the Monte Carlo simulation tool.

6.10.1 Monte Carlo Simulation

The Monte-Carlo is a sampling experiment whose purpose is to estimate the distribution of an outcome variable that depends on numerous probabilistic input variables. It is a reliable way of performing quantitative risk analysis. In Monte Carlo simulation, uncertain inputs in a model are represented using ranges of possible values known as probability distributions. By using probability

distributions, variables can have different probabilities of different outcomes occurring. Probability distributions are a much more realistic way of describing uncertainties in variables of a risk analysis. Common probability distributions as spelt out by Palisade [88] include:

a. *Normal – Or "bell curve." The user simply defines the mean or expected value and a standard deviation to describe the variation about the mean. Values in the middle near the mean are most likely to occur. It is symmetric and describes many natural phenomena such as people's heights. Examples of variables described by normal distributions include inflation rates and energy prices.*

b. *Lognormal – Values are positively skewed, not symmetric like a normal distribution. It is used to represent values that don't go below zero but have unlimited positive potential. Examples of variables described by lognormal distributions include real estate property values, stock prices, and oil reserves. The normal and lognormal distributions outlook are shown in Figure 6-5:*

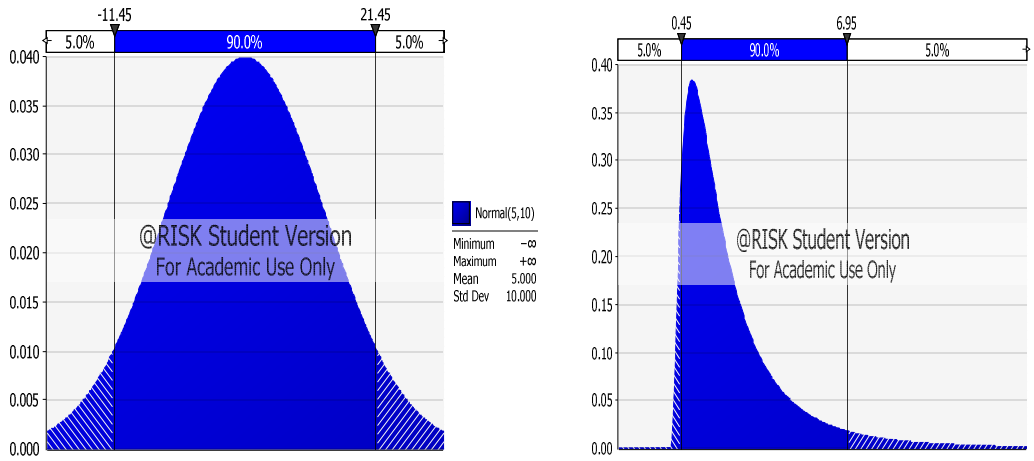

Figure 6-5 Normal and Lognormal Distributions

c. *Uniform – All values have an equal chance of occurring, and the user simply defines the minimum and maximum. Examples of variables that could be uniformly distributed include manufacturing costs or future sales revenues for a new product.*

d. *Triangular – The user defines the minimum, most likely, and maximum values. Values around the most likely are more likely to occur. Variables that could be described by a triangular distribution include past sales history per unit of time and inventory levels. Figure 6-6 shows the uniform and triangular distributions.*

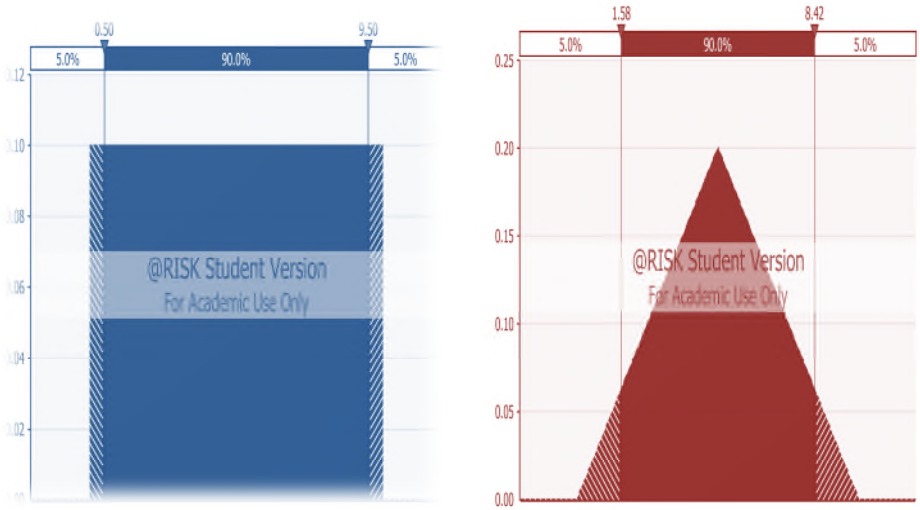

Figure 6-6 Uniform *and* Triangular Distributions

e. *PERT- The user defines the minimum, most likely, and maximum values, just like the triangular distribution. Values around the most likely are more likely to occur. It can generally be considered as superior to the Triangular distribution when the parameters result in a skewed distribution. An example of the use of a PERT distribution is to describe the duration of a task in a project management model.*

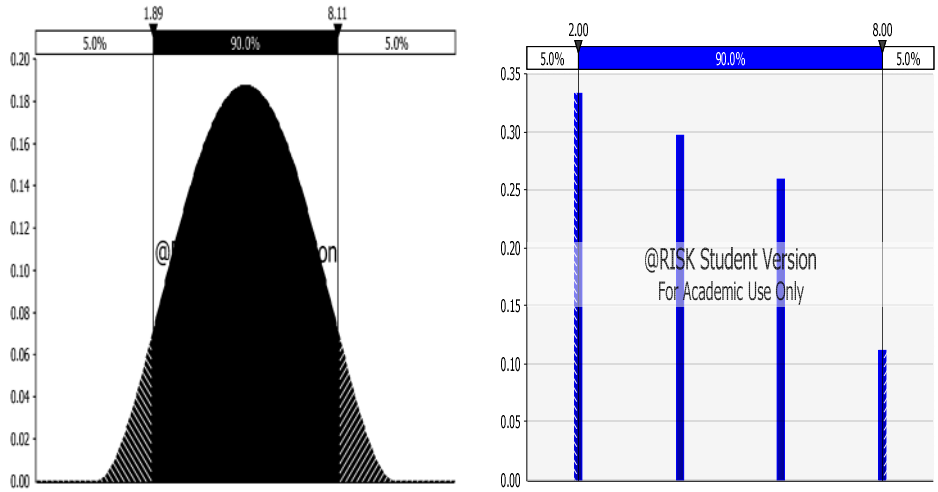

Figure 6-7 **Pert and Discrete Distributions**

f. *Discrete – The user defines specific values that may occur and the likelihood of each. An example might be the results of a lawsuit: 20% chance of positive verdict, 30% change of negative verdict, 40% chance of settlement, and 10% chance of mistrial. See the form of pert and discrete distributions at Figure 6-7.*

6.10.2 The Simulation Process

The Monte Carlo tool has capacity to carry out several iterations with so numerous values of the input variables. This allows for several scenarios to be viewed and assessed. A mix of values of the inputs that would finally affect designated output of interest is defined in different quantities and the several alterations of these inputs affect the output.

Figure 6-8 shows a sample of a reduced number of iterations for clarity. The trend shows variation from the baseline when the inputs are changed. This guides in decision making based on set outcomes in this case, the cost of electricity. The centre point is the desired outcome while the green circular irregular shape shows the variations of the outcomes from the desired outcome.

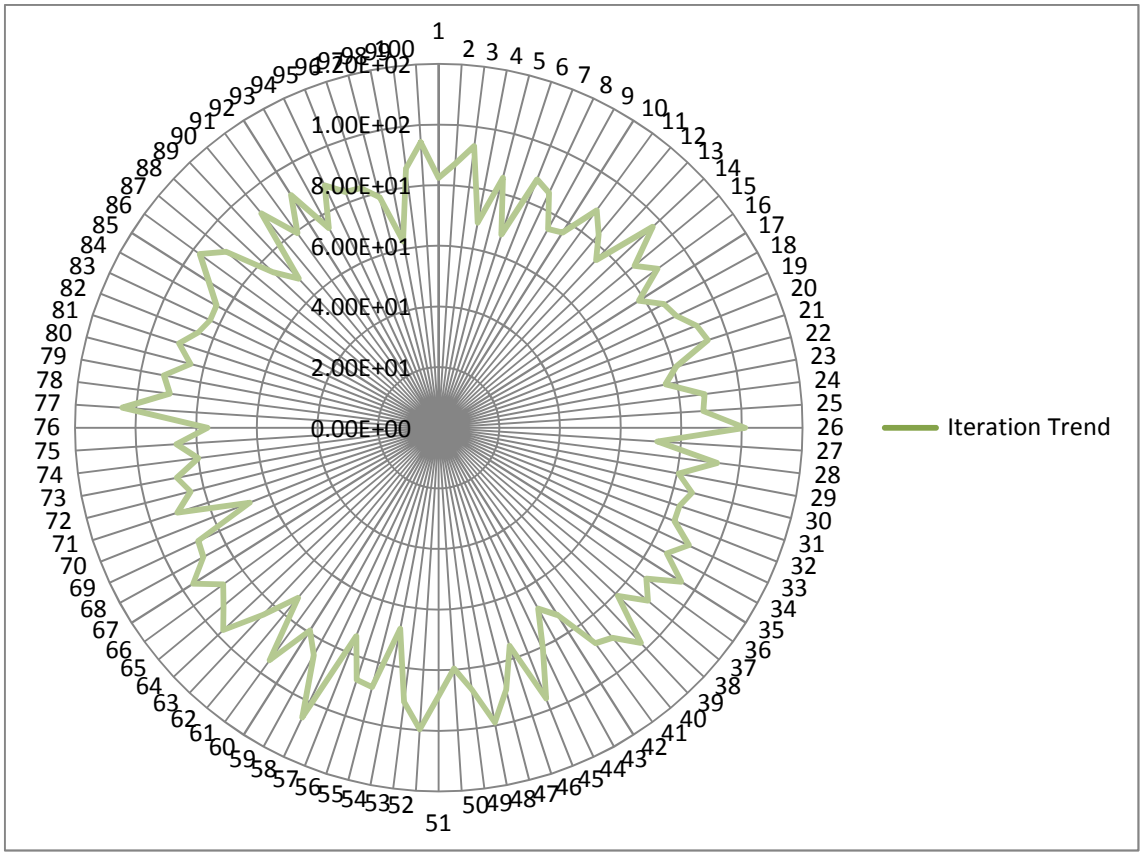

Figure 6-8 Sample of fewer Iteration Processes showing Variation from Baseline

The Monte Carlo risk analysis simulation tool as developed by palisade @Risk Inc. [88] has been interfaced with my particular model and used in this segment of work. Two scenarios involving the industrial gas turbine and the aero-derivative engine was carried out. The effects of the earlier mentioned relevant factors as they affect the overall cost of electricity are viewed on the respective engines.

Scenario 1. Risk Assessment of the BIGCC using Engine 1 (the 23MW Aero-derivatives Engine)

The risks associated with the BIGCC with either the aero-derivative or the industrial engines were assessed starting from the use of the aero-derivative

engine in this scenario. This is then compared to the base plant - the NGGT. For a proper risk analysis on BIGCC power plant, more representative quantities as close as possible to what is available in literature or published by power providers and agencies were used. The values indicated in Table 6-7 are in agreement with current values published by the Energy Information Agency of the United States [83]. Appropriate probability distributions were defined based on these data as indicated in the table.

Table 6-7 Input Values for the Aero-derivative Engine

Serial	Input Variables	From	To	Actual Value	Type of Distribution
1	First year Specific Investment-Inv0 ($/kW)	750.00	900.00	800	Triangular
2	Tax - t (%)	9	11	10	Normal
3	Specific fuel cost-f0 ($/GJ)	1.5	2.5	2.5	Triangular
4	Capacity Factor-cf (%)	75	85	85	Triangular
5	Specific Total Fixed Cost-STFC ($/kW.Year)	255.00	260.00	259	Normal

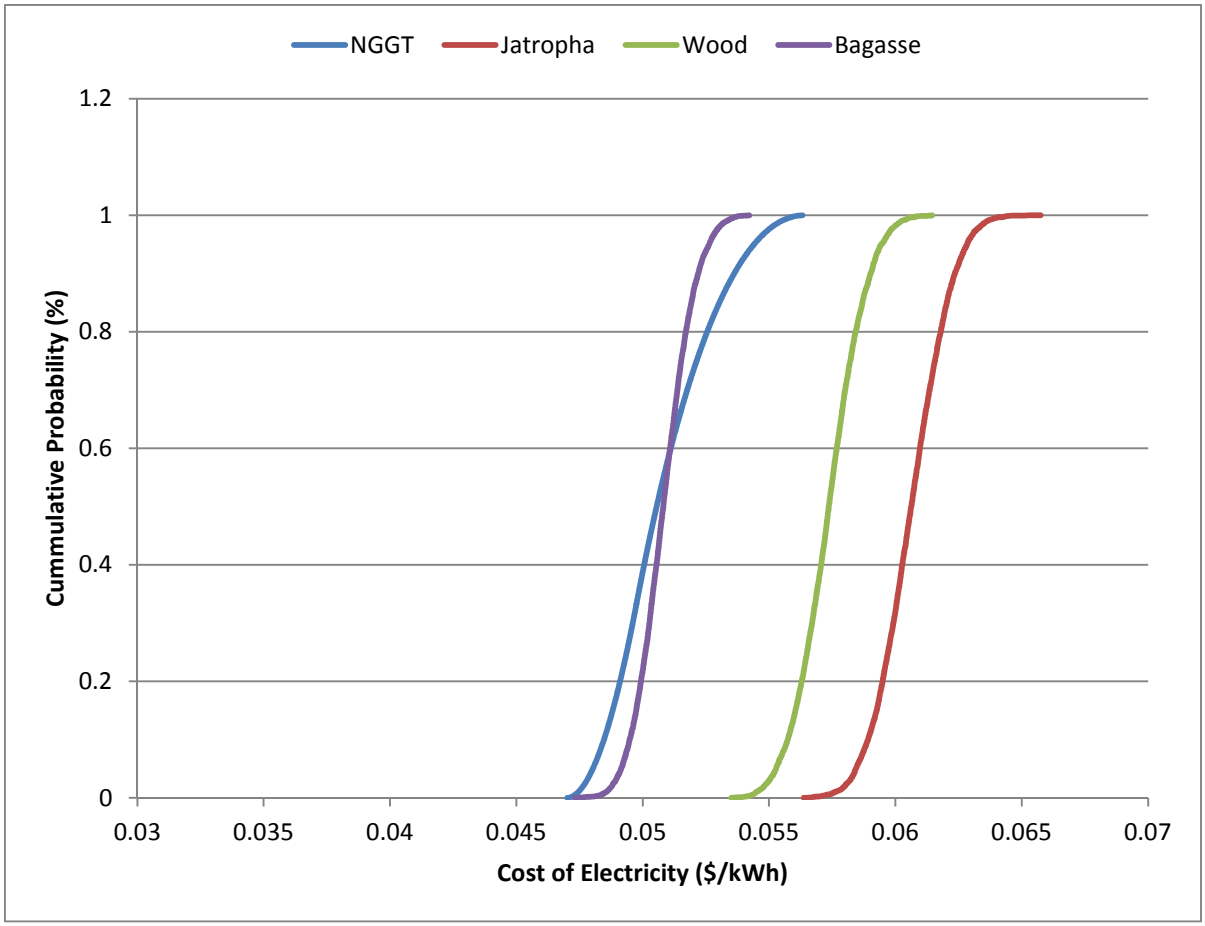

Figure 6-9 Cost of Electricity Predictions of Engine 1 running on the three biofuels and the Reference GT (NGGT)

Figure 6-9 shows the CoE predictions for all the cases involving the BIGCC on the three different fuels and the NGGT. As can be seen from the outlook, the various CoE values can be appreciated along the line of the engine and fuel types. Again, the least value is obtainable with the NGGT while the highest CoE is got with the BIGCC on Jatropha fuel.

With the deterministic value indicated in Figure 6-10, the variation of the CoE from the various options can also be determined. The NGGT and the BIGCC utilising bagasse are closest to the deterministic value while the BIGCC with wood and the Jatropha are far ahead of the deterministic value.

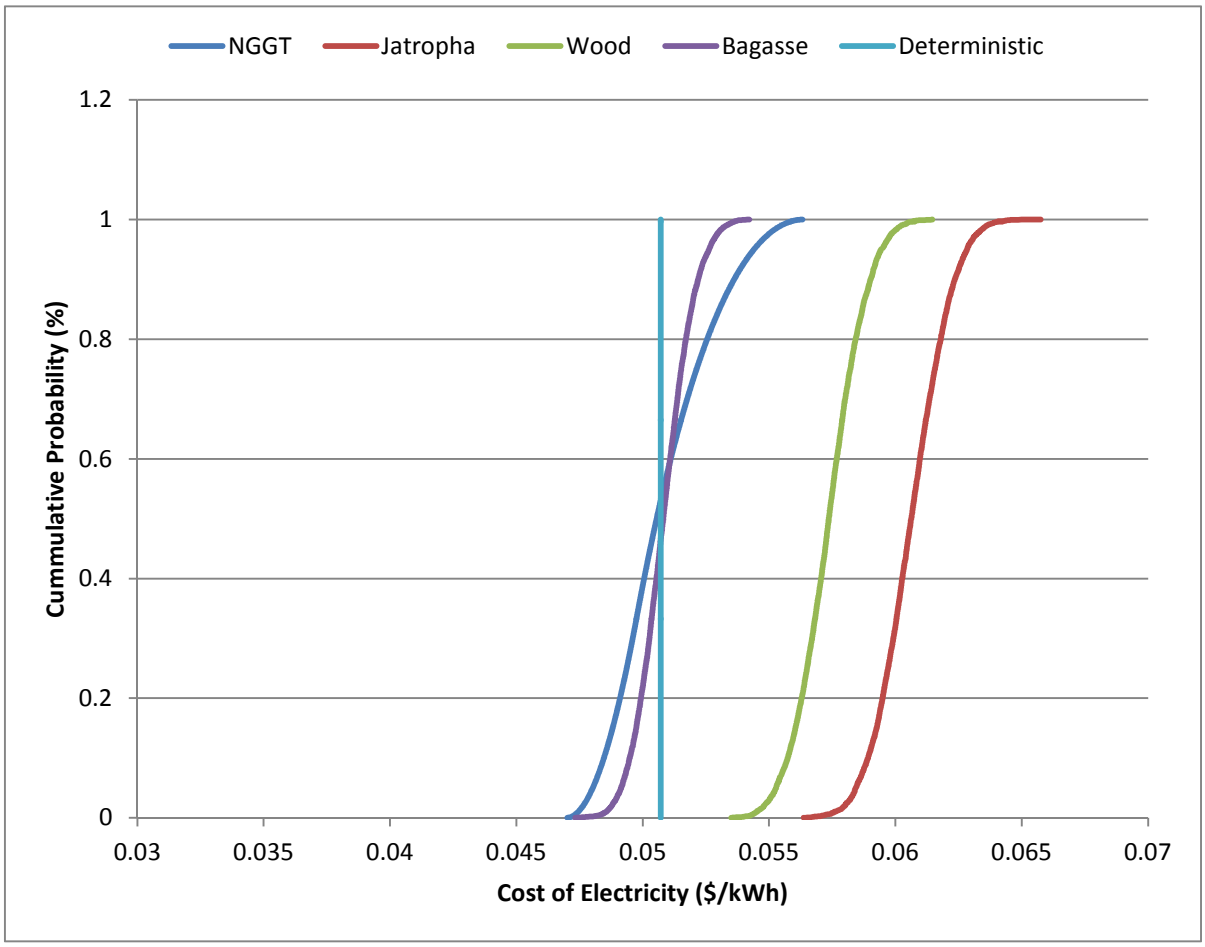

Figure 6-10 BIGCC with the Engine 1 - Effect of Uncertainties of the risk variables on the CoE

6.10.3 Sensitivity to Variable Factors

Figures 6-11 & 6-12 show the degree and nature of effect of these variables on the CoE respectively. This helps in the isolation of factors that are capable of determining the outcome of the project to be identified and properly dealt with for project viability and profitability. Some of the risk variables show direct correlation to the risks level while others shows the inverse.

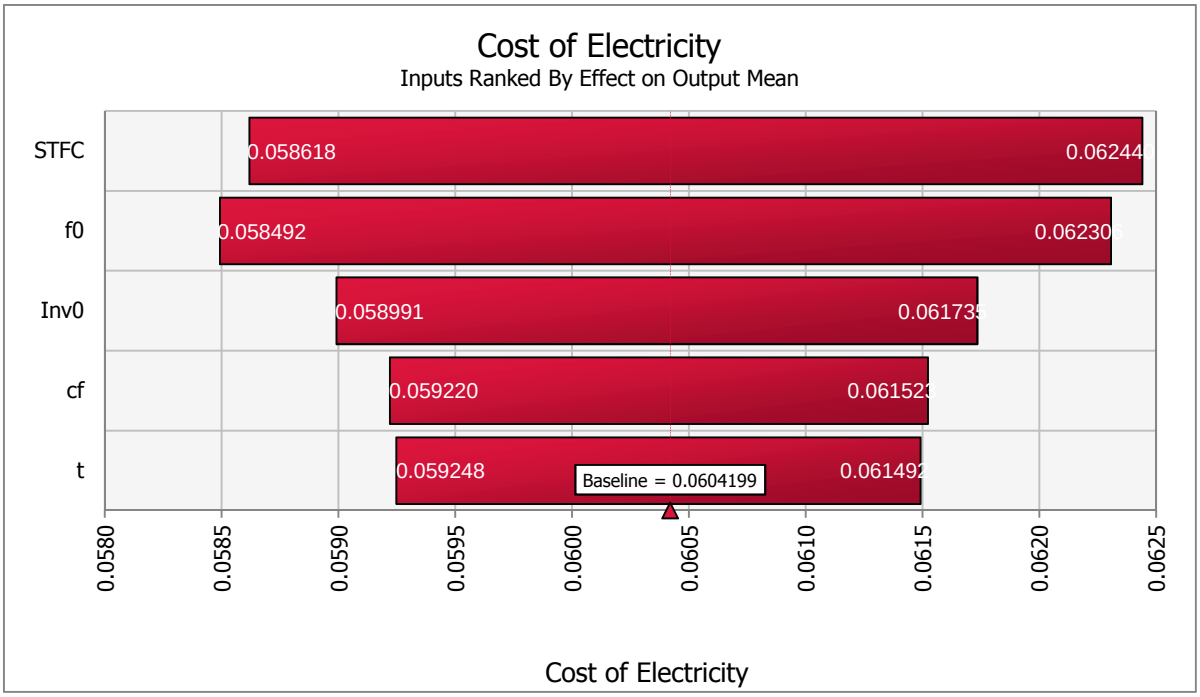

Figure 6-11Sensitivity Analysis showing the effects of the variables on the CoE

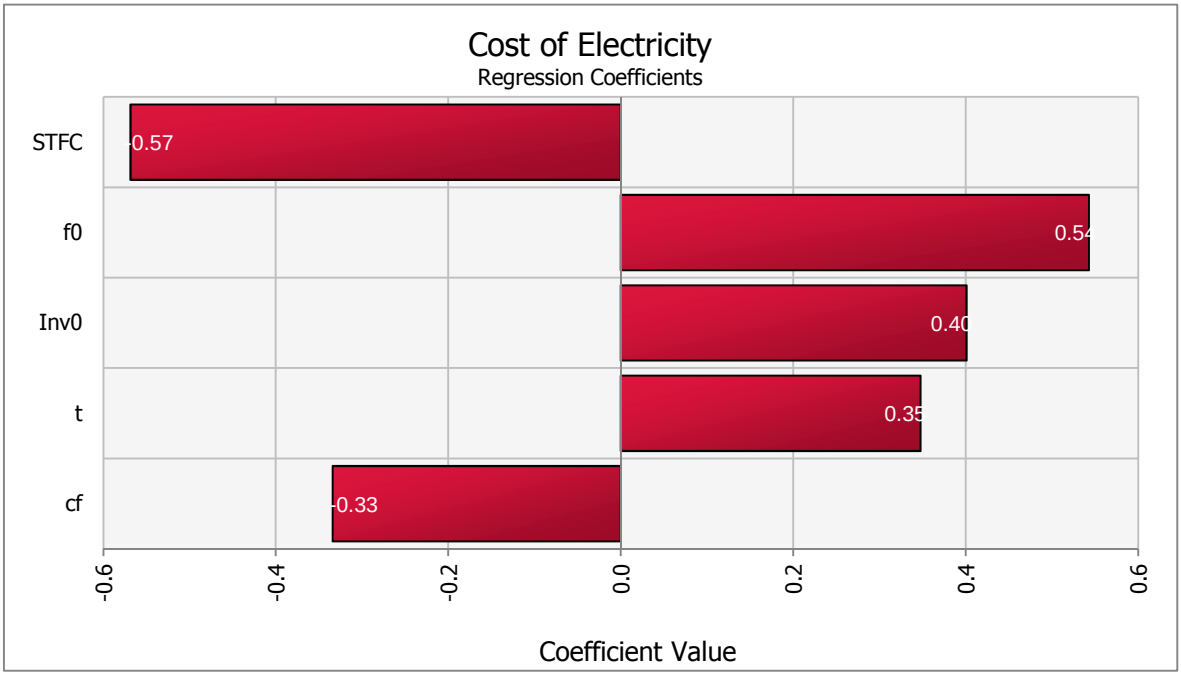

Figure 6-12 Sensitivity Analysis showing how various Inputs affect the CoE

The x-axis is the outcome - the cost of electricity (CoE) while the y-axis represents several factors which determine the values of the CoE. These include the capacity factor (cf), the specific cost of fuel (f0), tax (t), specific total fixed cost (STFC) and the first year investment cost (inv0).

The factors that have the most effect on the CoE in the case of the aero-derivative engine are the specific total fixed cost, specific fuel cost, the first year investment cost, the capacity factor and the tax in that order. Any effort at controlling the values of these factors of production will bring down the overall cost of electricity to an appreciable level.

The Monte Carlo tool offers a high flexibility and adaptable information as the whole details of occurrence can be visualised. As can be seen from the next two figures, the CoE change at any turn can be captured and necessary desired changes can be effected.

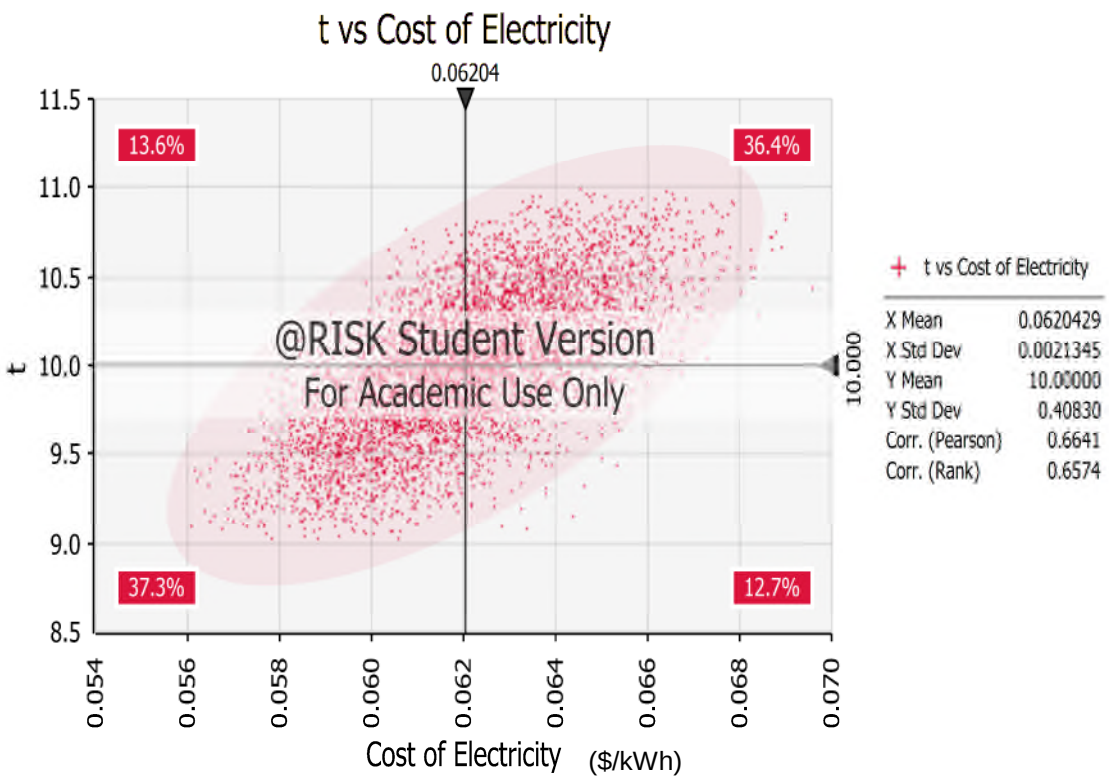

Figure 6-13 Response of CoE ($/kWh) to Tax

The horizontal slider allows one to have a feel of the trend in the costs of inputs when they are moved up and down corresponding to either an increasing or decreasing values of the tax (t) and specific fuel cost (f0). This in turn leads to a sideways movement of the vertical slider corresponding to the CoE. This makes the identification of risk values and regions possible.

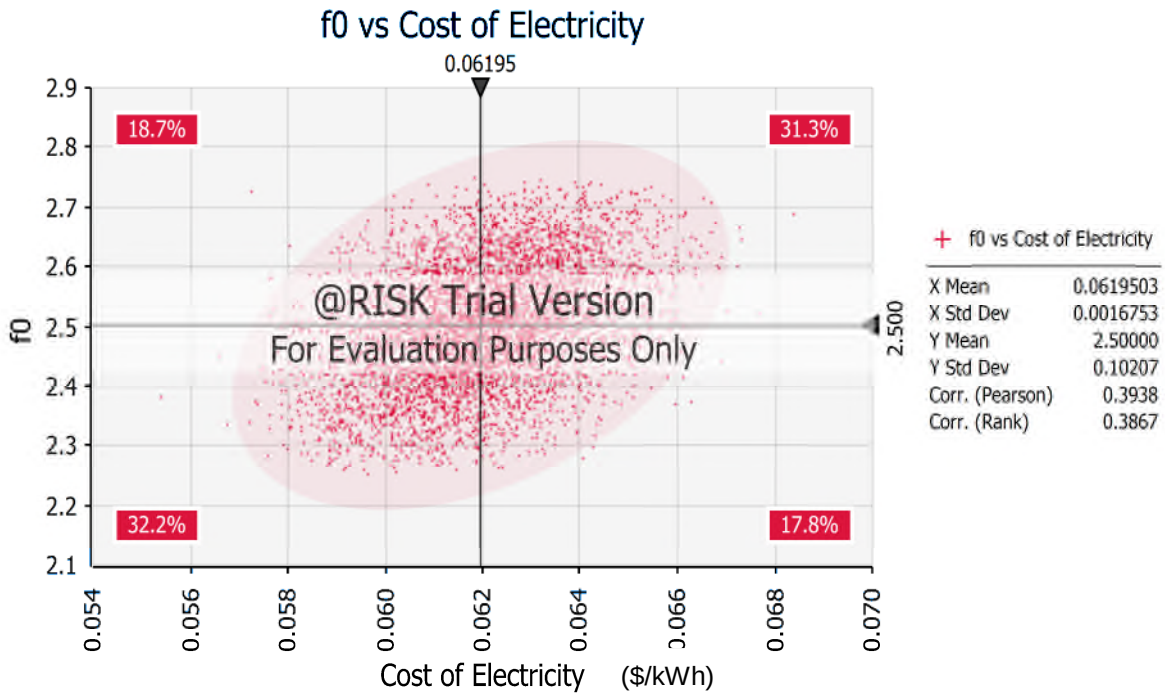

Figure 6-14 Response of CoE ($/kWh) to Specific Fuel Cost

These two have varying behaviour as it affects the CoE for all the chosen values for the iterations (a total of 5000 in the particular case). It gives reliable correlations between the variables and the outcome (CoE) with a good level of confidence. Correlations may be positive (rising), negative (falling), or null (uncorrelated). If the pattern of dots slopes from lower left to upper right, it suggests a positive correlation between the variables and outcome being studied. If the pattern of dots slopes from upper left to lower right, it suggests a negative correlation. These also offer the identification of the right correlation.

As can be seen from the two graphs both tax and the specific fuel cost present positive correlations. The scatter plots showing the effects of the other factors for both scenarios are at Appendix 5.

Scenario 2: Risk Assessment of the BIGCC using Engine 2 (the 77MW Industrial Engine)

There are differences in the values of certain parameters when using the industrial engine in the BIGCC configuration as against the aero-derivative engine. These differences include those of performance such as pressure ratio, the thermal efficiency, the power output and other economic factors such as the tax, fuel cost and capital cost among others. The values for the industrial engine like the aero-derivative one are detailed in Table 6-8:

Table 6-8 Range of Input Values for the Industrial Engine of 77 MW

Serial	Input Variables	From	To	Deterministic Value	Type of Distribution
1	First year Specific Investment-Inv0 ($/kW)	1200.00	1400.00	1300	Normal
2	Tax - t (%)	9	11	10	Normal
3	Specific fuel cost-f0 ($/GJ)	1.5	2.5	2.5	Triangular
4	Capacity Factor-cf (%)	80	90	85	Triangular
5	Specific Total Fixed Cost-STFC ($/kW.Year)	290.00	315.00	300	Normal

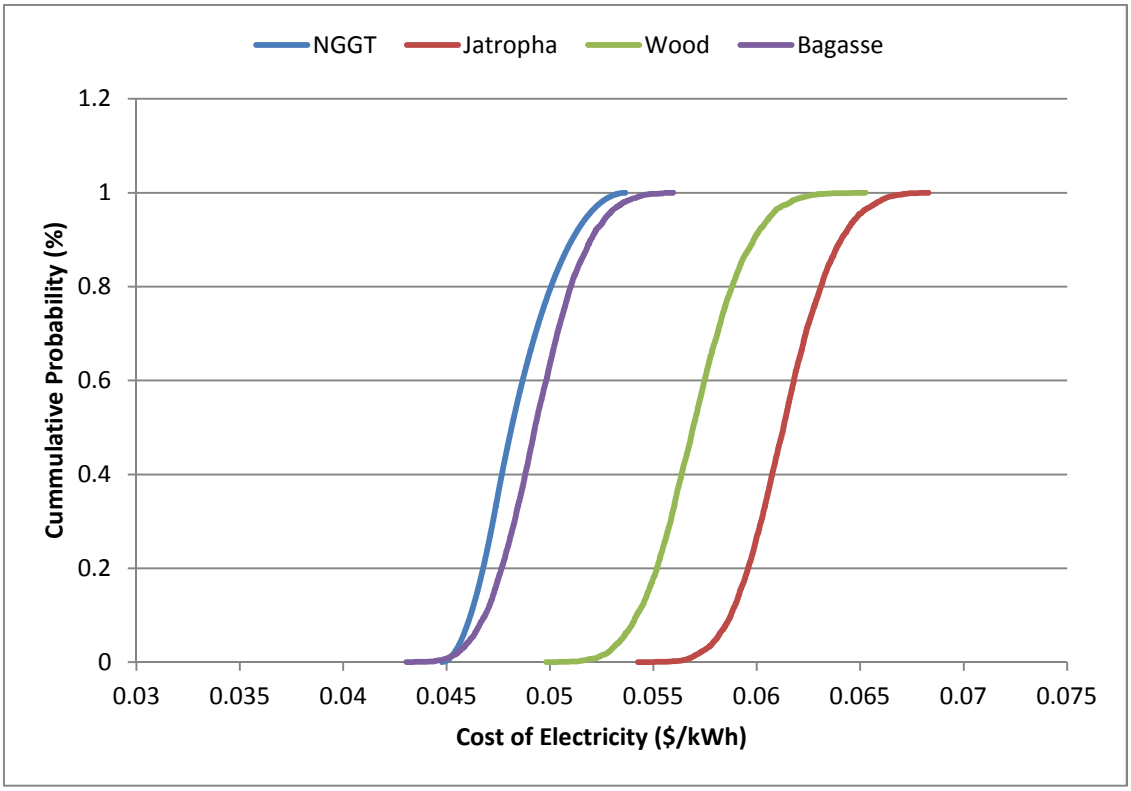

Figure 6-15 Cost of Electricity Predictions of Engine 2 on the three biofuels and the Reference GT (NGGT)

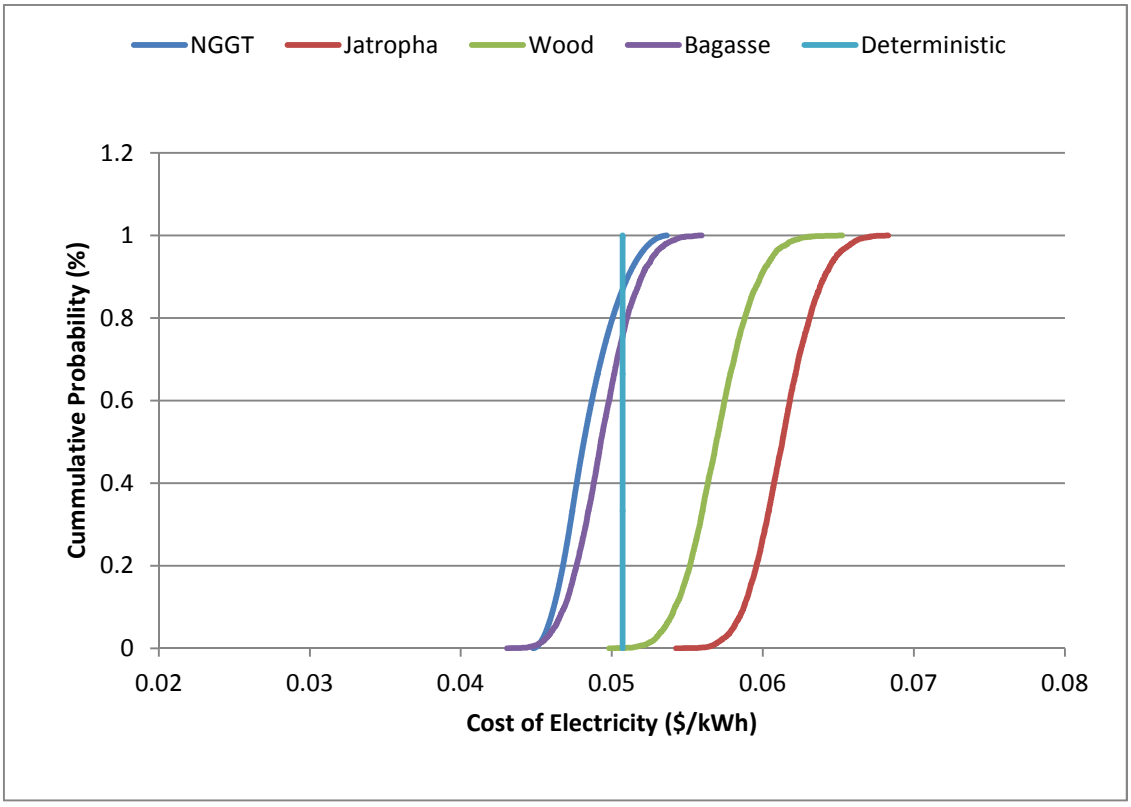

Figure 6-16 BIGCC with Engine 2 - Effect of Uncertainties of the risk variables on the CoE

6.10.1 Sensitivity to Variable Factors

Simulation offers managers and analysts the basis of evaluation of the performance of systems or aids them in decision making or even as a guide for the implementation of programmes and for proper organisation. It also presents an easy understanding of trends with little explanation. This helps in the isolation of factors that are capable of determining the viability or otherwise of ventures. The degree of effect caused by the individual values within the stipulated range is reflected in Figure 6-17 and the nature of effect is at Figure 6-18.

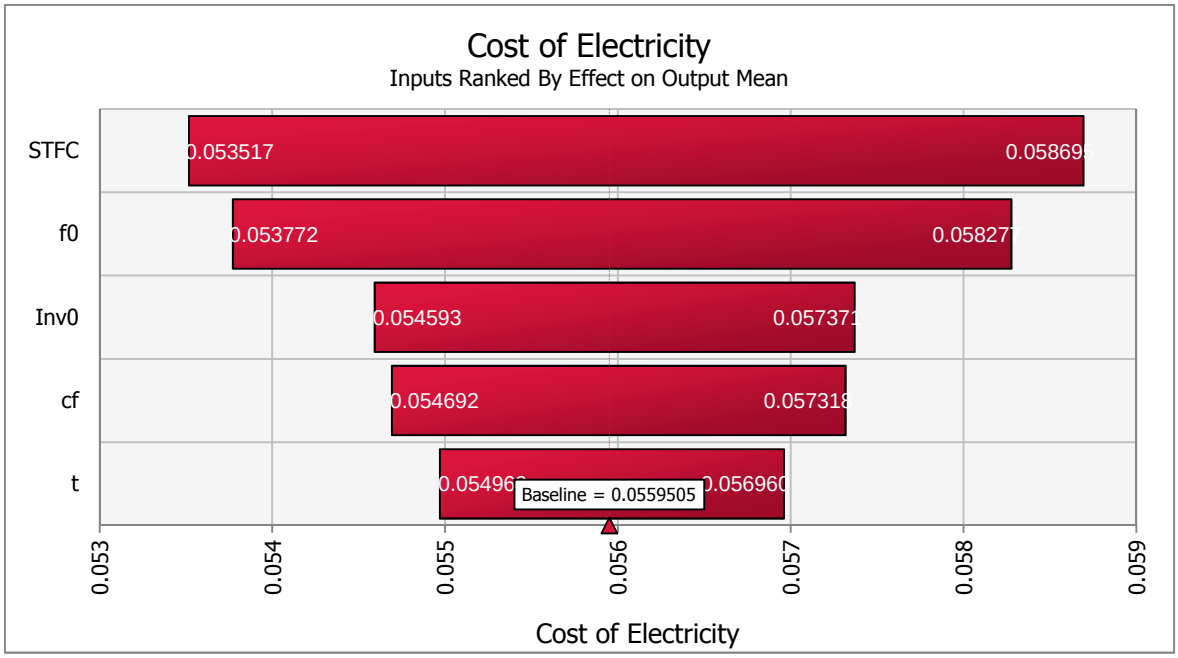

Figure 6-17 Sensitivity Analysis showing the effects of the variables on the CoE

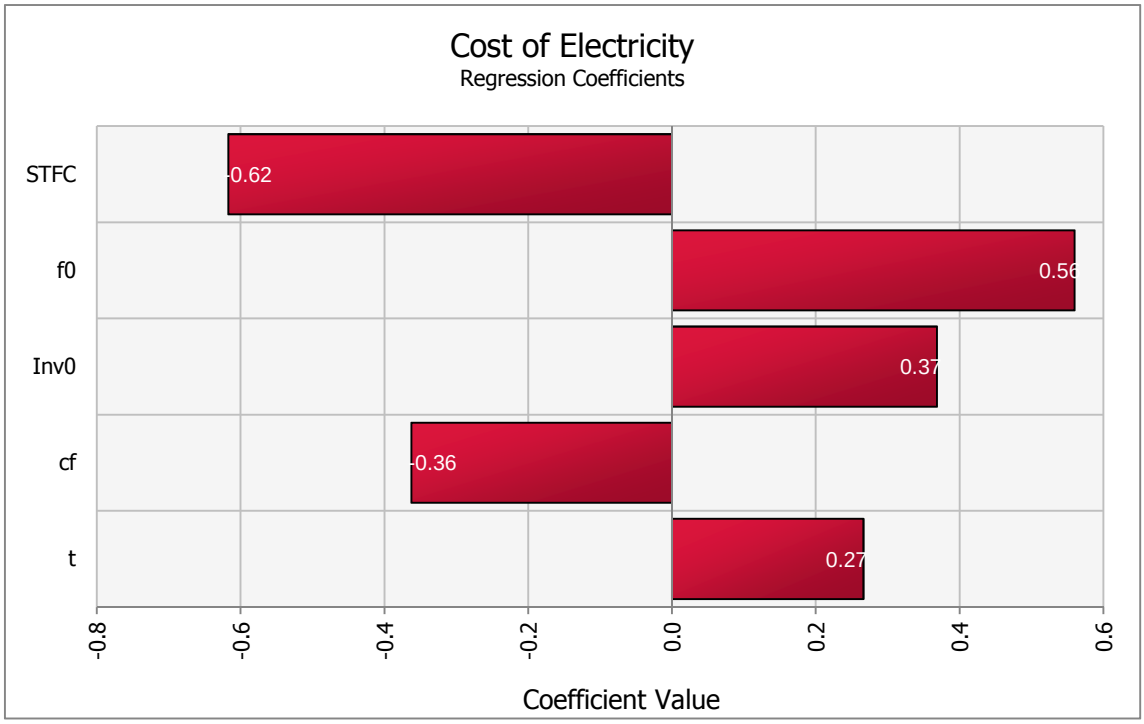

Figure 6-18 Sensitivity Analysis showing the nature of effects

The factors that also have the most effect on the CoE are the specific total fixed cost, specific fuel cost, the first year investment cost, the capacity factor and the tax in that order. The magnitudes of influence of these variables on the output mean are as depicted in Figure 6-17.

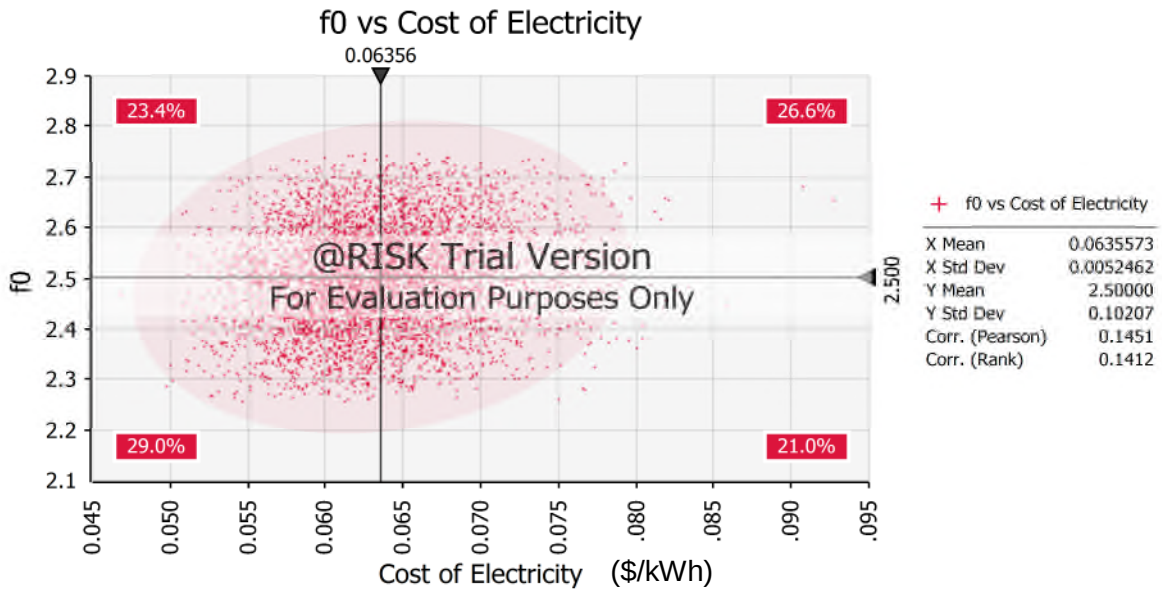

Figure 6-19 Response of CoE ($/kWh) to Tax for all Iterations

Similar to the aero-derivative engine, Figures 6-19 & 6-20 show the entire possibilities of the effects of any particular risk variable; the two figures showing the influence of the tax and the specific fuel cost. The correlation is similar to that of the aero-derivative engine.

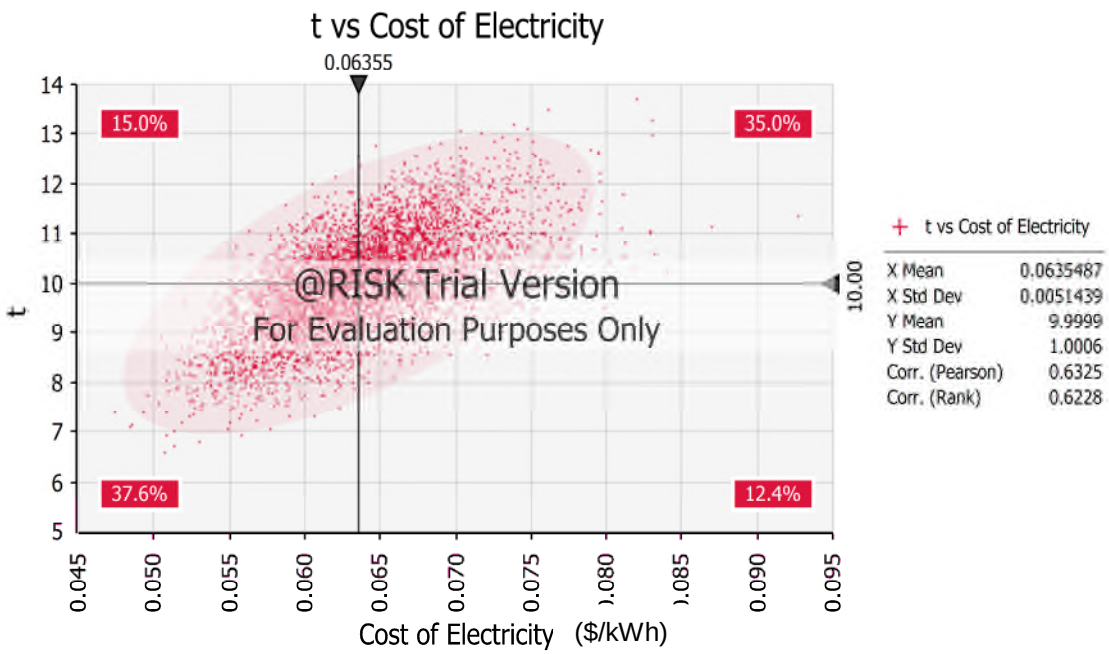

Figure 6-20 Response of CoE ($/kWh) to Specific Fuel Cost for all Iterations

A look at the effects of the various factors shows similar trends between the aero-derivative and the industrial engines. However, the CoE for the aero-derivative engine is higher than that of the industrial engine under similar conditions: it is in the range of 0.059-0.0657$/kwh and 0.045-0.055$/kwh respectively for the various fuels. This can be attributable to the respective capacities of the two engines (23MW and 77MW).

The CoE of the aero-derivative engine for both the NGGT and the BIGGT utilising bagasse is below the deterministic with about 50% while that of the industrial engine is below the deterministic with about 80%. This trend indicates a higher risk utilizing the aero-derivative engine for the chosen deterministic CoE value. On the whole, the Monte - Carlo analysis provides an insight into the dependence of the outcome parameter (CoE) on each risk variable [89].

7 Conclusions and Recommendation for Future Work

7.1 Conclusions

The aim of the research, as set out in chapter one, is to assess stationary gas turbine engines running on biofuels in terms of performance, emissions and economics with specific consideration of non-food biomass feedstock like wood, sugarcane bagasse and Jatropha in order to avoid competition with food requirements for human consumption. A TERA was employed to serve as a tool for the selection of the right conditions for biomass fuelled stationary engines for an optimum plant performance.

The main objectives of the research include the following:

a. Development of a multi-fuel emission model to capture gas emissions when gas turbines run on biofuels.
b. Carrying out a detailed economic and risk analysis on biomass to energy using the gas turbines.
c. Assessment of performance, emission and economic trade-offs when utilizing biomass on stationary gas turbines.

The ‘’Biomass Power Plant Economic Model (BIOPPEM)’’ was developed based on the levelized costing method to integrate all aspects of the assessment. It computes the depreciation schedule on the capital assets, the annual cash flow for the entire life of the power plant and then calculates the cost of electricity.

The integrated assessment involved case studies of an aero-derivative engine and an industrial one of moderate capacities of 23MW and 77MW respectively. A third industrial engine was introduced at certain points for the purpose of validation.

The findings of the current study are as follows:

Biomass utilization for power generation is viable and will contribute to rural development. Residues from food crops and other agricultural processes, dedicated energy crops and algae are suitable for use on gas turbines. Different energy crops can be grown in Nigeria's abundant landmass along the geographical zones and together with other municipal wastes harnessed for energy generation.

Performance simulation of the engines in the range of between 20-80 MW shows power plant sensitivity to atmospheric conditions and the turbine entry temperature. It also captured the effects of the different fuels. The Jatropha has more similar characteristics to conventional fuels and so its performance outlook is closer to those of the conventional fuel. The other syngases from wood and sugarcane bagasse which are of lower caloric values show overall performance characteristics slightly deviating from that of the conventional fuel. These power plants can be deployed for rural electrification to ensure participation of the local populace in feedstock production thereby achieving economic empowerment and energy provision.

The over 20% increase in the efficiency of the power plants in both simple and combined cycles accounts for a recovery of more energy that could have been wasted utilising the HRSG. This enhances the competitiveness of the biomass integrated gasification combined cycle (BIGGT/CC) when compared with plants fuelled with the natural gas.

The use of biofuels shows an overall lower efficiency compared to natural gas due to the lower caloric value of particularly the gaseous fuels derived from the solid biomass and the heavy penalty of the gasification and cleaning processes

of the biomass. There was an enhanced specific power from the BIGGT/CC as a result of the higher fuel mass required for same TET.

The emission code computed the levels of gas emission from the natural gas fuelled turbines as well as the biomass derived fuels. The influences of pertinent parameters like the inlet air temperature and the flame temperatures on the emissions production were adequately evaluated.

The emission trend for all the fuel types shows changes in the quantity of emission gases. There is about 20-27% reduction for NOx and 20-33% for Carbon respectively. The variation of the emission quantities for the natural gas and the other biofuels translates into reduced emission tax or penalties. The aggregate carbon emission for the biomass plants on a life cycle basis is zero which in addition to the tax relief also lowers the overall CoE when the gas turbines operate on biofuels for energy production or lower operation costs when employed for aero application.

The lower emissions are in tandem with values in literatures. Hence, if the power plant were to operate for most part of its life close to the design point, the choice of syngas from biomass feedstock as fuel is a good choice. Its validation with 2 separate works (one by experimentation done by an engine manufacturer and the other with a similar simulation run with comparable fuels) makes the results from the model adjudged as reliable.

When the emission results from the 3 engines were compared, the values for both NOx and CO were least for the smaller aero-derivative engine and highest for the 77MW industrial engine.

The economics evaluation was done using the levelization method. It reveals that there is a high influence of the capital cost, fuel cost and operations and maintenance cost on the overall cost of electricity. The employment of strategies including optimal land use, use of crop hybrids, short rotation would ensure higher biomass yield and this will contribute to the lowering of the overall cost of energy from biomass fuelled gas turbines.

The energy cost depends also on distance from the place of production to the power plant site, capacity and load factors as well as government regulatory taxes and other economic indices. The power plant should be kept as close as possible (within 100 kilometres) to the power plant for onsite electricity production for an optimal and competitive electricity pricing.

The CoE was found to be higher for the BIGGT/CC than the NGGT and the CoE values utilising the 4 fuels were lower for the industrial GT than the aero-derivative engine due to higher plant size of the industrial engine. The higher CoE for the BIGGT/CC is as a result of the higher capital cost for the extra components such as the gasifier, and the steam turbine components in combined cycle configuration. In addition, the high penalties as a result of gasification and other requirements in biofuel preparation led to a reduced efficiency and hence higher cost of energy production. The reduction in the emission gases per period of operation leads to a reduced emission tax. This value becomes a net zero on life cycle assessment for carbon which further contributes to lower CoE for the BIGGT/CC.

The Monte Carlo risk analysis tool was employed to determine the risk associated with the bio-fuelled gas turbines with the various risk variables. Different scenarios were run to determine the viability or otherwise of the project by comparing the values of the CoE using different biofuels with deterministic value. The uncertainties relating to the first year investment cost, tax, specific fuel cost, capacity factor and emission values lead to differences between outcomes and the deterministic value.

The CoE for the aero-derivative engine is higher than that of the industrial engine under similar conditions: it is in the range of 0.059-0.0657$/kwh and 0.045-0.055$/kwh respectively for the various fuels. In addition, in the case of the aero-derivative engine, the CoE for both the NGGT and the BIGGT utilising bagasse is below the deterministic with about 50% while that of the industrial

engine is below the deterministic with about 80%. This trend indicates a higher risk utilizing the aero-derivative engine for the chosen deterministic CoE value.

Sensitivity considerations showed the effects of the specific total fixed cost, specific fuel cost and the first year investment cost as the ones having the most effect on the CoE. The degrees of effect of the variables on the CoE vary differently for the two engine types.

7.2 Future Work

It is recommended that an assessment code incorporating detailed factors such as yield, seasonal nature of the biomass should be developed in order to ascertain how these factors would affect the overall biomass cost and the cost of electricity. A life cycle assessment of the emission trend should be researched to get the emission balance through the entire process.

A further research would be in the area of modelling the effect of the method of mechanical loading of solid biomass into the gasifiers and the nature of the biomass (whether in pellet or hunks). This will aid in the determination of the energy expended on these processes and how it affects the overall cost of electricity.

Gasification modelling should also be embedded in the TERA scheme in order to estimate the effects of the integration penalty on the entire process. Similar area that should be considered in future is the incorporation of CO_2 capture in the entire assessment.

There is also the need to carry out the physical effects such as blade fouling of the different fuels on the gas turbine combustors and its overall economic implications. Finally there is need to carry out an optimization of the entire process.

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Appendix A

Engine Input Files Engine 1

```
! AERO-DERIVATIVES GAS TURBINE SIMULATION

MODELLED BY Daniel Ihiabe, 2011 ////

OD SI KE CT XP

-1

-1

INTAKE  S1-2     D1-4            R100

COMPRE  S2-3     D5-10           R101     V5  V6

PREMAS  S3,12,4  D11-14

PREMAS  S4,13,5  D15-18

BURNER  S5-6     D19-21          R102

MIXEES  S6,13,7

TURBIN  S7-8     D22-29,101              V23

MIXEES  S8,12,9

TURBIN  S9-10    D30-38                  V30 V31

NOZCON  S10-11,1 D39             R107

PERFOR  S1,0,0   D30,40-42,107,100,102,0,0,0,0,0,0

CODEND

DATA ITEMS////

!INTAKE

1 0.0         ! INTAKE ALTITUDE
```

```
2 0.0          ! ISA DEVIATION
3 0.0          ! MACH NO
4 0.9951       ! PRESSURE RECOVERY
!COMPRESSOR
5 -1.0         ! Z PARAMETER
6 -1.0         ! ROTATIONAL SPEED N
7 18.8         ! PRESSURE RATIO
8 0.88         ! ISENTROPIC EFFICIENCY
9 0.0          ! ERROR SELECTION
10 4.0         ! MAP NUMBER
!PREMAS
11 0.03        ! BLEED AIR
12 0.00        ! FLOW LOSS
13 1.0         ! PRESSURE RECOVERY
14 0.0         ! PRESSURE DROP
!PREMAS
15 0.10        ! BLEED AIR
16 0.8         ! FLOW LOSS
17 1.0         ! PRESSURE RECOVERY
18 0.0         ! PRESSURE DROP
!BURNER
19 0.07        ! FRACTIONAL PRESSURE LOSS DP/P
```

```
20 1.0        ! COMBUSTION EFFICIENCY
21 -1.0       ! FUEL FLOW
!HP TURBINE
22 0.0        ! AUXILIARY WORK
23 -1.0       ! NDMF
24 -1.0       ! NDSPEED CN
25 0.885      ! ISENTROPIC EFFICIENCY
26 -1.0       ! PCN
27 1.0        ! COMPRESSOR NUMBER
28 4.0        ! TURBINE MAP NUMBER
29 -1.0       ! POWER LOW INDEX
!POWER TURBINE
30 22800000.00 ! AUXILIARY WORK
31 -1.0       ! NDMF
32 -1.0       ! NDSPEED CN
33 0.885      ! ISENTROPIC EFFICIENCY
34 -1.0       ! PCN
35 0.0        ! COMPRESSOR NUMBER
36 4.0        ! MAP NUMBER
37 -1.0       ! POWER LOW INDEX
38 -1.0       ! COMWORK
!NOZCON
```

```
39 -1.0        ! THROAT AREA
!PERFOR
40 1.0         ! PROPELLER EFFICIENCY
41 0.0         ! SCALING INDEX
42 0.0         ! REQUIRED THRUST
-1
1 2 69.0       ! INLET MASS FLOW
6 6 1505.0     ! COMBUSTION OUTLET TEMPERATURE
-1
2 -25
-1
5 6 1450
-1
-1
5 6 1500
-1
-1
5 6 1550
-1
-1
5 6 1600
-1
```

-1

5 6 1650

-1

-1

5 6 1700

-1

2 -15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 -5

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

2 15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 30

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

-3

Engine Input Files Engine 2

```
! 50 MW INDUSTRIAL GAS TURBINE SIMULATION

MODELLED BY Daniel Ihiabe, PhD,  2012////

OD SI KE CT FP

-1

-1

INTAKE  S1-2     D1-4            R180

COMPRE  S2-3     D5-11           R182     V5  V6

PREMAS  S3,4,10  D12-15

BURNER  S4-5     D16-18          R184

MIXEES  S5,10,6

TURBIN  S6-7     D19-26,182,27            V19 V20

NOZCON  S7-8,1   D28             R107

PERFOR  S1,0,0   D19,29-31,107,180,184,0,0,0,0,0,0,0

CODEND

DATA ITEMS////

!INTAKE

1 0.0           ! INTAKE ALTITUDE

2 0.0           ! ISA DEVIATION

3 0.0           ! MACH NO

4 0.9951        ! PRESSURE RECOVERY

!COMPRESSOR

5 -1.0          ! Z PARAMETER
```

```
6 -1.0          ! ROTATIONAL SPEED N
7 22.4          ! PRESSURE RATIO
8 0.89          ! ISENTROPIC EFFICIENCY
9 1.0           ! ERROR SELECTION
10 4.0          ! MAP NUMBER
11 0.0          ! ANGLE
!PREMAS
12 0.97         ! BLEED AIR: cooling bypass: LAMBDA (W)
13 0.0          ! FLOW LOSS: DELTA (W)
14 1.0          ! PRESSURE RECOVERY
15 0.0          ! PRESSURE DROP
!BURNER
16 0.05         ! FRACTIONAL PRESSURE LOSS DP/P
17 0.998        ! COMBUSTION EFFICIENCY
18 -1.0         ! FUEL FLOW
!TURBINE
19 50000000.0   ! AUXILIARY WORK
20 -1.0         ! NDMF
21 0.6          ! NDSPEED CN
22 0.895        ! ISENTROPIC EFFICIENCY
23 -1.0         ! PCN
24 1.0          ! COMPRESSOR NUMBER
```

```
25 3.0          ! TURBINE MAP NUMBER
26 1000          ! POWER LOW INDEX
27 0.0          ! NGV ANGLE RELATIVE TO D.
!NOZCON
28 -1.0         ! THROAT AREA
!PERFOR
29 1.00          ! PROPELLER EFFICIENCY
30 0.0          ! SCALING INDEX
31 0.0          ! REQUIRED THRUST
-1
1 2 162.0        ! INLET MASS FLOW
5 6 1400.0       ! COMBUSTION OUTLET TEMPERATURE
-1
2 -25
-1
5 6 1450
-1
-1
5 6 1500
-1
-1
5 6 1550
```

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

2 -15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 -5

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

2 15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 30

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

-3

Engine Input Files Engine 3

```
!77 MW FRAME F  INDUSTRIAL GAS TURBINE SIMULATION

MODELLED BY Daniel Ihiabe  2012////

OD SI KE CT FP

-1

-1

INTAKE  S1-2     D1-4            R180

COMPRE  S2-3     D5-11           R182     V5  V6

PREMAS  S3,4,10  D12-15

BURNER  S4-5     D16-18          R184

MIXEES  S5,10,6

TURBIN  S6-7     D19-26,182,27            V19 V20

NOZCON  S7-8,1   D28             R107

PERFOR  S1,0,0   D19,29-31,107,180,184,0,0,0,0,0,0,0

CODEND

DATA ITEMS////

!INTAKE

1 0.0           ! INTAKE ALTITUDE

2 0.0           ! ISA DEVIATION

3 0.0           ! MACH NO

4 0.9951        ! PRESSURE RECOVERY

!COMPRESSOR

5 -1.0          ! Z PARAMETER
```

```
6 -1.0          ! ROTATIONAL SPEED N
7 16.3          ! PRESSURE RATIO
8 0.89          ! ISENTROPIC EFFICIENCY
9 1.0           ! ERROR SELECTION
10 4.0          ! MAP NUMBER
11 0.0          ! ANGLE
!PREMAS
12 0.97         ! BLEED AIR: cooling bypass: LAMBDA (W)
13 0.0          ! FLOW LOSS: DELTA (W)
14 1.0          ! PRESSURE RECOVERY
15 0.0          ! PRESSURE DROP
!BURNER
16 0.05         ! FRACTIONAL PRESSURE LOSS DP/P
17 0.998        ! COMBUSTION EFFICIENCY
18 -1.0         ! FUEL FLOW
!TURBINE
19 77000000.0   ! AUXILIARY WORK
20 -1.0         ! NDMF
21 0.6          ! NDSPEED CN
22 0.895        ! ISENTROPIC EFFICIENCY
23 -1.0         ! PCN
24 1.0          ! COMPRESSOR NUMBER
```

```
25 3.0          ! TURBINE MAP NUMBER
26 1000          ! POWER LOW INDEX
27 0.0          ! NGV ANGLE RELATIVE TO D.
!NOZCON
28 -1.0         ! THROAT AREA
!PERFOR
29 1.00          ! PROPELLER EFFICIENCY
30 0.0          ! SCALING INDEX
31 0.0          ! REQUIRED THRUST
-1
1 2 260.0        ! INLET MASS FLOW
5 6 1400.0       ! COMBUSTION OUTLET TEMPERATURE
-1
2 -25
-1
5 6 1450
-1
-1
5 6 1500
-1
-1
5 6 1550
```

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

2 -15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 -5

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

2 15

-1

5 6 1700

-1

-1

5 6 1650

-1

-1

5 6 1600

-1

-1

5 6 1550

-1

-1

5 6 1500

-1

-1

5 6 1450

-1

2 30

-1

5 6 1450

-1

-1

5 6 1500

-1

-1

5 6 1550

-1

-1

5 6 1600

-1

-1

5 6 1650

-1

-1

5 6 1700

-1

-3

Appendix B

! CODE FOR CALCULATIOON OF STEAM PROPERTIES AND THERMAL EFFICIENCY OF THE STEAM CYCLE

! ALGORITHM using thermodynamic functions

T1 = (((Log(Pressurecondenser) * 0.01953 + 0.2438) * Log(Pressurecondenser) + 2.388 * Log(Pressurecondenser) + 27.834 * Log(Pressurecondenser) + 99.69

T2 = (((Log(Pressureevaporator) * 0.01923 + 0.2438) * Log(Pressureevaporator) + 2.388 * Log(Pressureevaporator) + 27.834 * Log(Pressureevaporator) + 99.69

T3 = T2

T4 = Superheatedtemperature – 273

T5 = T1

T6 = T1

T1K = T1 + 273

T2K = T2 + 273

T3K = T3 + 273

T4K = T4 + 273

T5K = T5 + 273

T6K = T6 + 273

v = (T4 + 276.158) / 647.719

w = Pressureevaporator / 219.345

pr = Pressureevaporator / 219.1936

tr = (T4 + 271.8659) / 645.9763

tr4 = tr**4

pr4 = pr * tr * pr4

s1 = ((((8.73065 * 10 ** (-13) * T1 - 7.078056 * 10 ** (-7)) * T1 - 4.794256 * 10 ** (-5)) * T1 + 1.6119232 * 10 ** (-2)) * T1 - 0.008387074

s2 = ((((8.73065 * 10 ** (-13) * T2 - 7.078056 * 10 ** (-10)) * T2 + 2.341782 * 10 ** (-7)) * T2 - 4.794256 * 10 ** (-5)) * T2 + 1.6119232 * 10 ** (-2)) * T2 - 0.008387074

s3 = ((-1.18467 * 10 ** (-7) * T3 + 7.9544 * 10 ** (-5)) * T3 - 0.024623 * T3 + 9.13

s4 = ((0.907643 * tr - 3.646335) * tr + 6.57334 * tr + 2.13856 - 0.461853 * (Log(pr) + pr / tr4 + pr4 *pr4 * pr4)

s5 = s4

x5 = (s5 – s1) / ((((-1.18467 * 10 ** (-7) * T5 + 7.9544 * 10 ** (-5)) * T5 – 0.024623) * T5 + 9.13 – s1)

s6 = s1 + x6 * (((-1.8467 * 10 ** (-7) * T6 + 7.9544 * 10 ** (-5)) * T6 - 0.024623) * T6 + 9.13 – s1)

x6 = (s6 – s1) / (((-7.35167 * 10 ** (-6) * T60.00233298) * T6 + 2.43725) * T6 + 2491.695 + 6349.4 / (T6 – 387.449) – s1)

h1 = ((((((((2.788 *10 ** (-19) * T1 – 3.987 * 10 ** (-16)) * T1 + 2.39894 * 10 ** (-13)) * T1 -7.857 * 10 ** (-11) * T1 + 1.521311 * 10 **(-8)) * T1 – 1.76274 * 10 ** (-6)) * T1 + 1.208711 * 10 ** (-4)) * T1 – 4.45397 * 10 (-3)) * T1 + 4.25348) * T1

h2 = ((((((((2.788 *10 ** (-19) * T2 – 3.987 * 10 ** (-16)) * T2 + 2.39894 * 10 ** (-13)) * T2 -7.857 * 10 ** (-11) * T2 + 1.521311 * 10 **(-8)) * T2 – 1.76274 * 10 ** (-6)) * T2 + 1.208711 * 10 ** (-4)) * T2 – 4.45397 * 10 (-3)) * T2 + 4.25348) * T2

h3 = ((-7.35167 * 10 **(-6) *T5 – 0.00233298) * T3 + 2.43725) * T3 + 2491.595 + 6349.4 / (T3 – 387.449)

```
h4 = (0.000304331 * T4 + 1.81687) * T4 + 2503.63 – 21492.63 * w * (0.0193115 / (v **3) + w**2 / v**(14.7866)*(0.013956+0.00406747*w**2))

h5=h1+x5*(((-7.35167*10**(-6)*T5-0.00233298)*T5+2.43725)*T5+2491.695+6349.4/(T5-387.449)-h1)

h6=h4-Turbineefficiency*(h4-h5)

Tstack=Exitgastemperature-(s4-s1)*((Exitgastemperature-(T2K-Pinchpoint/(s4-S2))

Qtransmitted=(Massflow*1150*(Exitgastemperature-Tstack)*0.8/10**6

Q=Fuelflow*45.45

Steammassflow=Qtransmitted*1000/(h4-h2)

Steampower=Steammassflow*(h4-h6/1000

nominalThermalefficiency=(Steampower+Power)/Q

txtefficiency=nominalThermalefficiency

endprogram
```

Appendix C

Biofuel Property generated by Daniel Ihiabe June 2012.

FAR 0.000 WAR 0.00000 P 0.020

# t	h_abs	s_abs	R_spec	cp	gam	vis
1.9400E+02	-1.0449E+05	6.8810E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3284E-01
1.9500E+02	-1.0348E+05	6.9330E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3341E-01
1.9600E+02	-1.0248E+05	6.9840E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3398E-01
1.9700E+02	-1.0148E+05	7.0350E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3455E-01
1.9800E+02	-1.0048E+05	7.0860E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3512E-01
1.9900E+02	-9.9466E+04	7.1360E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3569E-01
2.0000E+02	-9.8466E+04	7.1860E+02	2.8705E+02	1.0024E+03	1.4013E+00	1.3625E-01
2.5000E+02	-4.8333E+04	9.4240E+02	2.8705E+02	1.0031E+03	1.4009E+00	1.6302E-01
3.0000E+02	1.8588E+03	1.1254E+03	2.8705E+02	1.0048E+03	1.3999E+00	1.8746E-01
3.5000E+02	5.2176E+04	1.2805E+03	2.8705E+02	1.0082E+03	1.3981E+00	2.1020E-01
4.0000E+02	1.0271E+05	1.4155E+03	2.8705E+02	1.0135E+03	1.3952E+00	2.3163E-01
4.5000E+02	1.5355E+05	1.5352E+03	2.8705E+02	1.0206E+03	1.3913E+00	2.5199E-01
5.0000E+02	2.0480E+05	1.6432E+03	2.8705E+02	1.0295E+03	1.3866E+00	2.7148E-01
5.5000E+02	2.5653E+05	1.7418E+03	2.8705E+02	1.0398E+03	1.3814E+00	2.9023E-01
6.0000E+02	3.0879E+05	1.8328E+03	2.8705E+02	1.0510E+03	1.3757E+00	3.0832E-01
6.5000E+02	3.6164E+05	1.9173E+03	2.8705E+02	1.0628E+03	1.3700E+00	3.2585E-01
7.0000E+02	4.1508E+05	1.9965E+03	2.8705E+02	1.0749E+03	1.3643E+00	3.4288E-01
7.5000E+02	4.6913E+05	2.0711E+03	2.8705E+02	1.0870E+03	1.3588E+00	3.5946E-01
8.0000E+02	5.2378E+05	2.1417E+03	2.8705E+02	1.0988E+03	1.3536E+00	3.7563E-01
8.5000E+02	5.7901E+05	2.2086E+03	2.8705E+02	1.1103E+03	1.3487E+00	3.9142E-01
9.0000E+02	6.3480E+05	2.2724E+03	2.8705E+02	1.1213E+03	1.3441E+00	4.0688E-01

Extracts of Fuel Property Tables

Natural Gas

	FAR = 0.000 WAR =0.00000 p = 0.020						
~~Nt~~	Density	h_abs	S_abs	R_spec	cp	gam	Vis
1.98E+02	3.57E-02	-1.0E+05	7.09E+02	2.87E+02	1.00E+03	1.40E+E00	1.35E-05
1.99E+02	3.55E-02	-9.9E+04	7.14E+02	2.87E+02	1.00E+03	1.40E+E00	1.35E-05
2.00E+02	3.53E-02	-9.7E+04	7.19E+02	2.87E+02	1.00E+03	1.40E+E00	1.36E-05
2.25E+02	3.14E-02	-7.3E+04	8.37E+02	2.87E+02	1.00E+03	1.40E+E00	1.36E-05
2.50E+02	2.82E-02	-4.8E+04	9.42E+02	2.87E+02	1.00E+03	1.40E+E00	1.50E-05
2.75E+02	2.57E-02	-2.3E+04	1.03E+03	2.87E+02	1.00E+03	1.40E+E00	1.63E-05
3.00E+02	2.35E-02	1.9E+03	1.14E+03	2.87E+02	1.00E+03	1.40E+E00	1.75E-05
3.25E+02	2.17E-02	2.7E+04	1.21E+03	2.87E+02	1.01E+03	1.40E+E00	1.87E-05
3.50E+02	2.02E-02	5.2E+04	1.28E+03	2.87E+02	1.01E+03	1.40E+E00	1.99E-05
3.75E+02	1.88E-02	7.7E+04	1.35E+03	2.87E+02	1.02E+03	1.40E+E00	2.08E-05
4.00E+02	1.76E-02	1.03E+05	1.42E+03	2.87E+02	1.03E+03	1.40E+E00	2. 12E-05
4.25E+02	1.57E-02	1.54E+05	1.48E+03	2.87E+02	1.05E+03	1.39E+E00	2.32E-05
4.50E+02	1.41E-02	2.054E+05	1.54E+03	2.87E+02	1.07E+03	1.39E+E00	2.52E-05
5.00E+02	1.18E-02	3.09E+05	1.64E+03	2.87E+02	1.10E+03	1.38E+E00	2.71E-05
6.00E+02	1.01E-02	4.15E+05	1.83E+03	2.87E+02	1.12E+03	1.36E+E00	3.08E-05
7.00E+02	8.82E-03	5.24E+05	2.00E+03	2.87E+02	1.14E+03	1.35E+E00	3.43E-05
8.00E+02	7.78E-03	6.34E+05	2.14E+03	2.87E+02	1.16E+03	1.34E+E00	3.75E-05

Wood

Temp	N2	O2	Ar	Ne	H2O	CO2	CO	SO2	Stoich FAR
200	0.72729	0	0.00872	0	0.13716	0.12682	0	0	0.066578
300	0.72729	0	0.00872	0	0.13716	0.12682	0	0	0.066578
400	0.72729	0	0.00872	0	0.13716	0.12682	0	0	0.066578
500	0.72729	0	0.00872	0	0.13716	0.12682	0	0	0.066578
600	0.72729	0	0.00872	0	0.13716	0.12682	0	0	0.066578

Bagasse

Temp	N2	O2	Ar	Ne	H2O	CO2	CO	SO2	Stoic FAR
200	0.73065	0	0.00876	0	0.12857	0.13203	0	0	0.06802
300	0.73065	0	0.00876	0	0.12857	0.13203	0	0	0.06802
400	0.73065	0	0.00876	0	0.12857	0.13203	0	0	0.06802
500	0.73065	0	0.00876	0	0.12857	0.13203	0	0	0.06802
600	0.73065	0	0.00876	0	0.12857	0.13203	0	0	0.06802

Appendix D

Thermodynamic coefficients of selected species used in the calculation of specific heat, enthalpy and the entropy.

It is obtained from the NASA CEA and [89]

Black values for lower temperatures of 200≤T≤1000 and the Red ones of 1000≤T≤6000

```
O
 2.56942078E+00-8.59741137E-05 4.19484589E-08-1.00177799E-11
1.22833691E-15    2
 2.92175791E+04 4.78433864E+00 3.16826710E+00-3.27931884E-03
6.64306396E-06    3
-6.12806624E-09 2.11265971E-12 2.91222592E+04 2.05193346E+00
4
O2                TPIS89O   2               G   200.000  3500.000
1000.000    1
 3.28253784E+00 1.48308754E-03-7.57966669E-07 2.09470555E-10-
2.16717794E-14    2
-1.08845772E+03 5.45323129E+00 3.78245636E+00-2.99673416E-03
9.84730201E-06    3
-9.68129509E-09 3.24372837E-12-1.06394356E+03 3.65767573E+00
4
H                 L 7/88H   1               G   200.000  3500.000
1000.000    1
 2.50000001E+00-2.30842973E-11 1.61561948E-14-4.73515235E-18
4.98197357E-22    2
 2.54736599E+04-4.46682914E-01 2.50000000E+00 7.05332819E-13-
1.99591964E-15    3
 2.30081632E-18-9.27732332E-22 2.54736599E+04-4.46682853E-01
4
H2                TPIS78H   2               G   200.000  3500.000
1000.000    1
 3.33727920E+00-4.94024731E-05 4.99456778E-07-1.79566394E-10
2.00255376E-14    2
-9.50158922E+02-3.20502331E+00 2.34433112E+00 7.98052075E-03-
1.94781510E-05    3
 2.01572094E-08-7.37611761E-12-9.17935173E+02 6.83010238E-01
4
OH                RUS 78O   1H   1          G   200.000  3500.000
1000.000    1
 3.09288767E+00 5.48429716E-04 1.26505228E-07-8.79461556E-11
1.17412376E-14    2
 3.85865700E+03 4.47669610E+00 3.99201543E+00-2.40131752E-03
4.61793841E-06    3
```

-3.88113333E-09 1.36411470E-12 3.61508056E+03-1.03925458E-01
4
H_2O L 8/89H 2O 1 G 200.000 3500.000
1000.000 1
3.03399249E+00 2.17691804E-03-1.64072518E-07-9.70419870E-11
1.68200992E-14 2
-3.00042971E+04 4.96677010E+00 4.19864056E+00-2.03643410E-03
6.52040211E-06 3
-5.48797062E-09 1.77197817E-12-3.02937267E+04-8.49032208E-01
4
HO_2 L 5/89H 1O 2 G 200.000 3500.000
1000.000 1
4.01721090E+00 2.23982013E-03-6.33658150E-07 1.14246370E-10-
1.07908535E-14 2
1.11856713E+02 3.78510215E+00 4.30179801E+00-4.74912051E-03
2.11582891E-05 3
-2.42763894E-08 9.29225124E-12 2.94808040E+02 3.71666245E+00
4
H_2O_2 L 7/88H 2O 2 G 200.000 3500.000
1000.000 1
4.16500285E+00 4.90831694E-03-1.90139225E-06 3.71185986E-10-
2.87908305E-14 2
-1.78617877E+04 2.91615662E+00 4.27611269E+00-5.42822417E-04
1.67335701E-05 3
-2.15770813E-08 8.62454363E-12-1.77025821E+04 3.43505074E+00
4
C L11/88C 1 G 200.000 3500.000
1000.000 1
2.49266888E+00 4.79889284E-05-7.24335020E-08 3.74291029E-11-
4.87277893E-15 2
8.54512953E+04 4.80150373E+00 2.55423955E+00-3.21537724E-04
7.33792245E-07 3
-7.32234889E-10 2.66521446E-13 8.54438832E+04 4.53130848E+00
4
CH TPIS79C 1H 1 G 200.000 3500.000
1000.000 1
2.87846473E+00 9.70913681E-04 1.44445655E-07-1.30687849E-10
1.76079383E-14 2
7.10124364E+04 5.48497999E+00 3.48981665E+00 3.23835541E-04-
1.68899065E-06 3
3.16217327E-09-1.40609067E-12 7.07972934E+04 2.08401108E+00
4
CH_2 L S/93C 1H 2 G 200.000 3500.000
1000.000 1
2.87410113E+00 3.65639292E-03-1.40894597E-06 2.60179549E-10-
1.87727567E-14 2
4.62636040E+04 6.17119324E+00 3.76267867E+00 9.68872143E-04
2.79489841E-06 3
-3.85091153E-09 1.68741719E-12 4.60040401E+04 1.56253185E+00
4
$CH_2(S)$ L S/93C 1H 2 G 200.000 3500.000
1000.000 1
2.29203842E+00 4.65588637E-03-2.01191947E-06 4.17906000E-10-
3.39716365E-14 2

```
 5.09259997E+04 8.62650169E+00 4.19860411E+00-2.36661419E-03
8.23296220E-06    3
-6.68815981E-09 1.94314737E-12 5.04968163E+04-7.69118967E-01
4
```

CH_3 L11/89C 1H 3 G 200.000 3500.000

```
1000.000    1
 2.28571772E+00 7.23990037E-03-2.98714348E-06 5.95684644E-10-
4.67154394E-14    2
 1.67755843E+04 8.48007179E+00 3.67359040E+00 2.01095175E-03
5.73021856E-06    3
-6.87117425E-09 2.54385734E-12 1.64449988E+04 1.60456433E+00
4
```

CH_4 L 8/88C 1H 4 G 200.000 3500.000

```
1000.000    1
 7.48514950E-02 1.33909467E-02-5.73285809E-06 1.22292535E-09-
1.01815230E-13    2
-9.46834459E+03 1.84373180E+01 5.14987613E+00-1.36709788E-02
4.91800599E-05   3
 -4.84743026E-08 1.66693956E-11-1.02466476E+04 4.64130376E+00
```

Appendix E

Other Scatter diagrams of the other variable factors in the risk assessment

Aero-derivatives

(a)

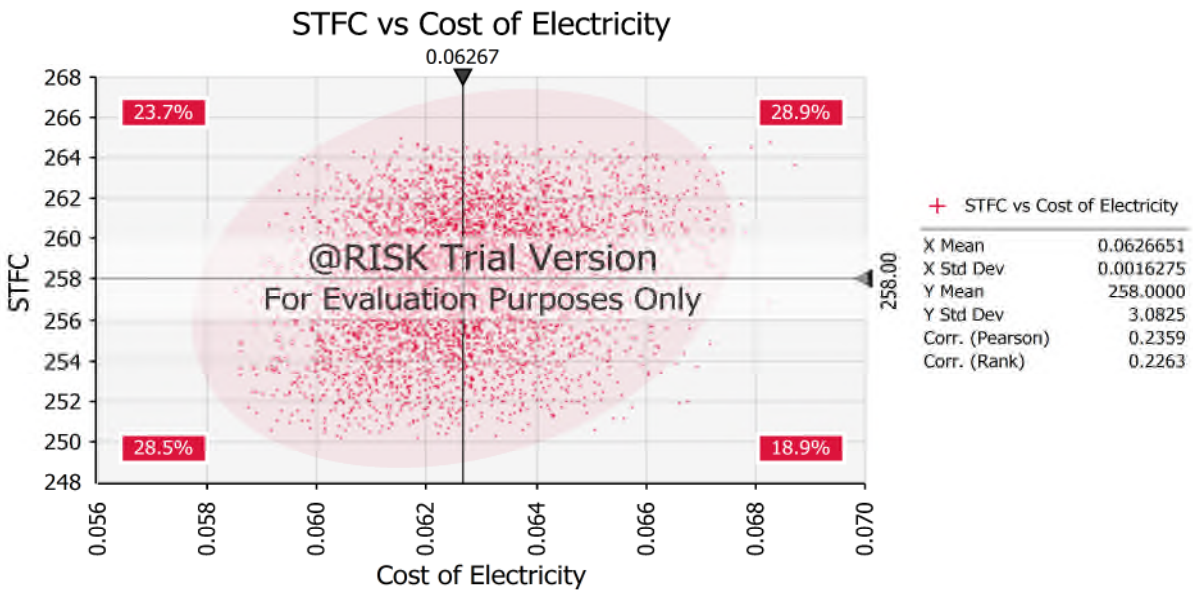

Figure A5.1 Response of CoE to Specific Total Fixed Cost for all Iterations

(b)

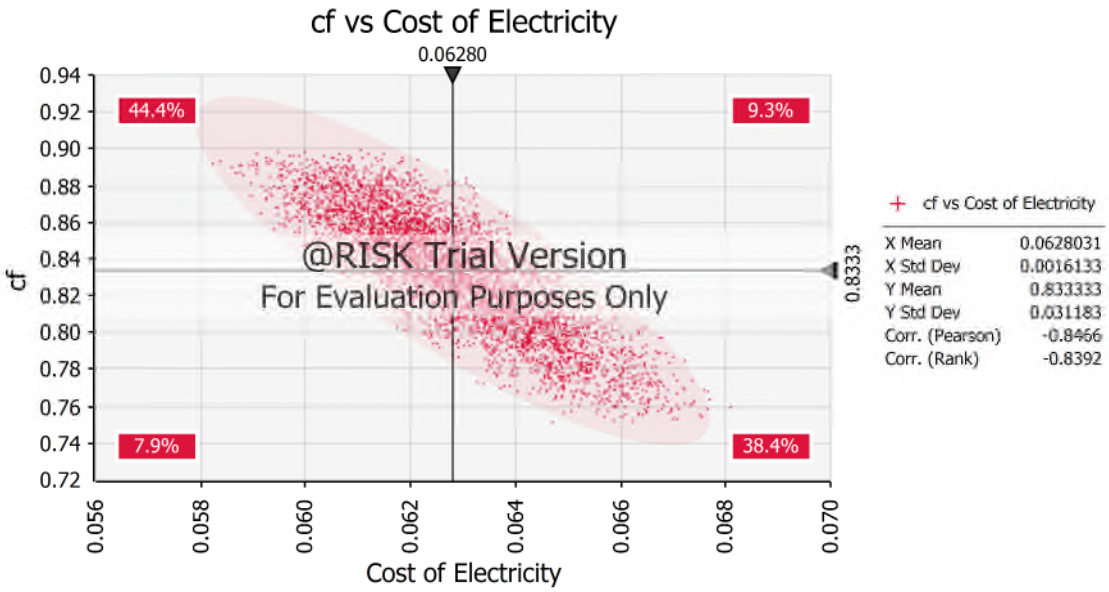

Figure A5.2 Response of CoE to Capacity Factor for all Iterations

(c)

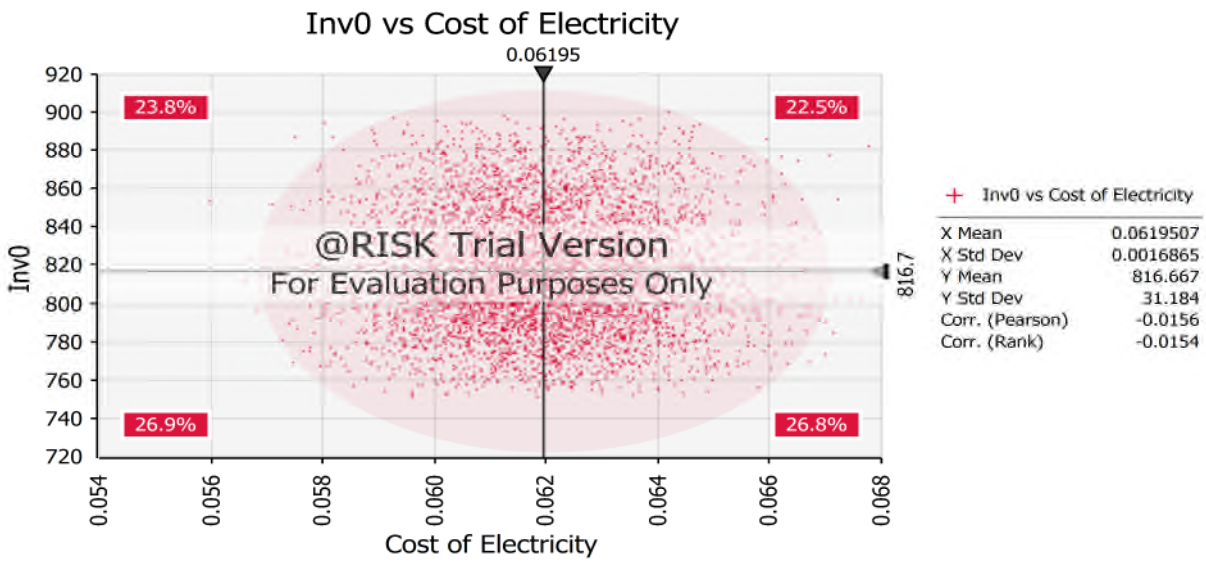

Figure A5.3 Response of CoE to First Year Investment for all Iterations

Industrial

(d)

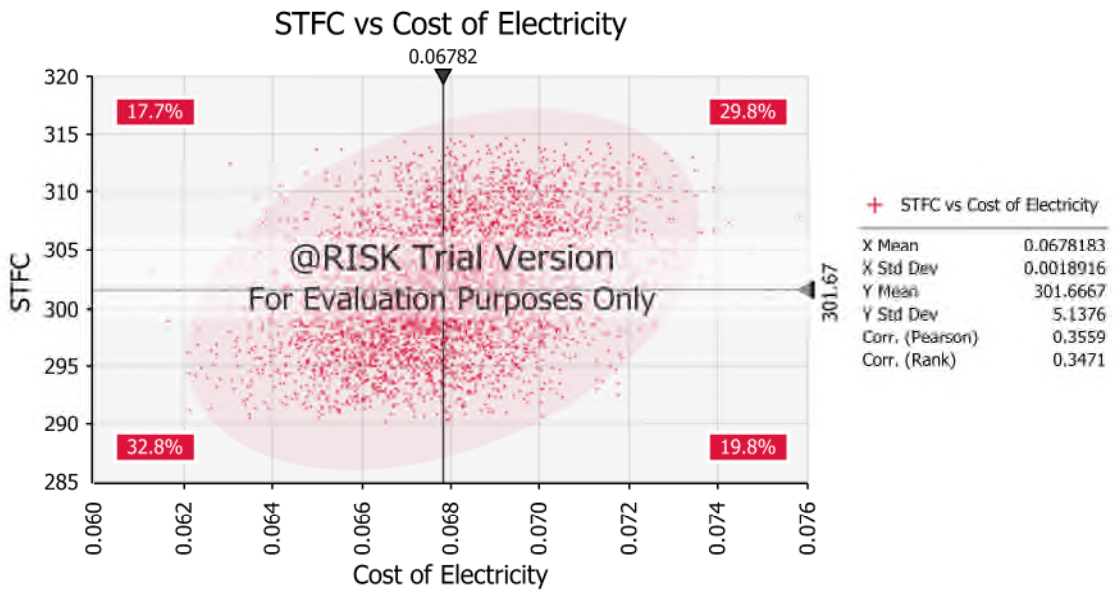

Figure A5.4 Response of CoE to Specific Total Fixed Cost for all Iterations

(e)

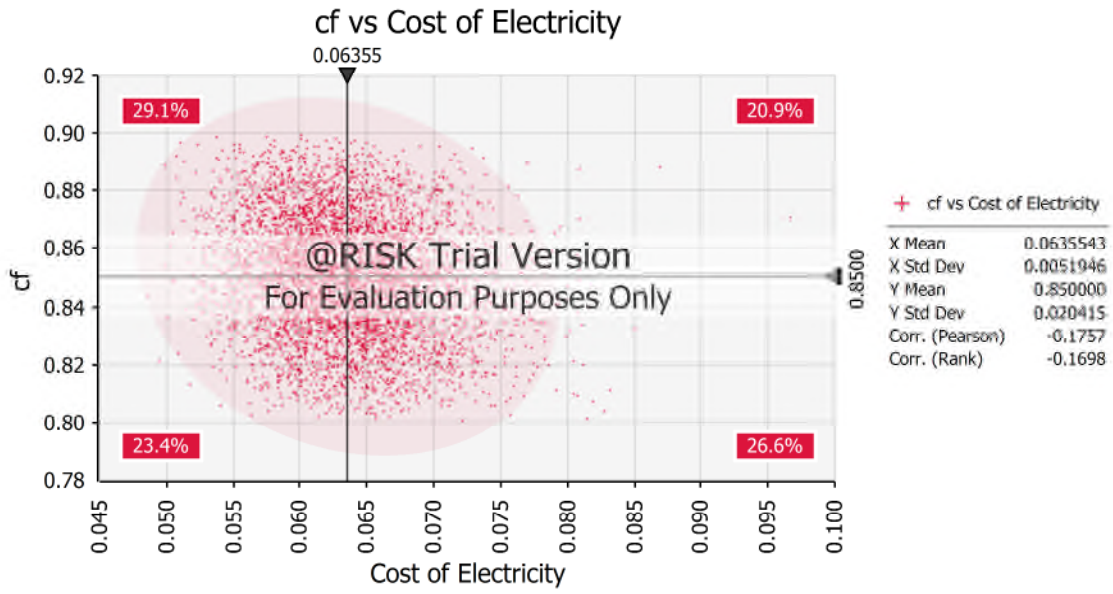

Figure A5.5 Response of CoE to Capacity Factor for all Iterations

(f)

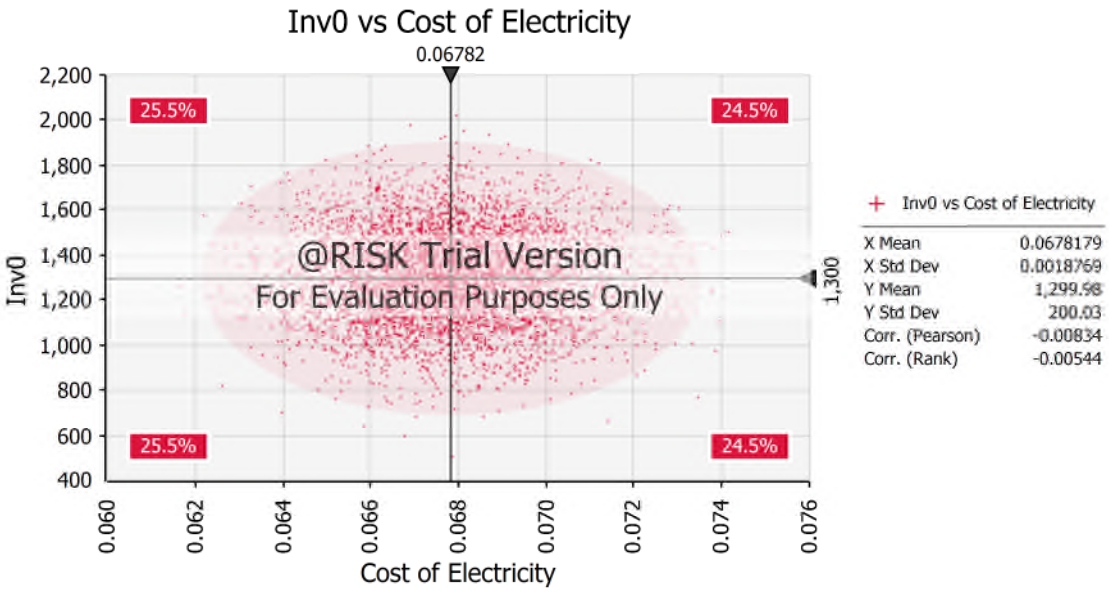

Figure A5.6 Response of CoE to First Year Investment for all Iterations