Journal of Engineering Research, Volume 28, Number 1, June 2023

Life Cycle Modeling of Economic and Environment Impacts Assessments of a Three Hundred Mega Watts per Day (300MWD) Natural Gas Power Plant in Lagos, Nigeria

K.E. Abhulimen*, A.A Jadesola, and M.A Razzakk
Department of Chemical and Petroleum Engineering
University of Lagos, Lagos, Nigeria
Corresponding Author Email: kabhulimen@unilag.edu.ng

Abstract
In this paper, a life cycle model [LCM] is presented to quantify the economic value chain, green houses gases [GHG], carbon footprint and environmental impact categories of a three hundred megawatts (300MW) natural gas power plant operated in Lagos Nigeria. The LCM evolved from the linear space concept where the process flow units of the power plant are partitioned into economic and environment matrix system based on the final demand vector. The GHG footprints are based on its current technology value chain (raw materials and energy utilization) measured against environmental targets. The results shows that higher water injection rates to the cooling unit of power plant turbine tend to reduce GHG and other pollution gases from natural gas power plant to within accepted limits. The simulation results show impact categories from power plant operations to be 79% for global warming and 89% for Sulphur (IV) oxide acidification pollution. The Monte Carlo simulation run shows a strong correlation from stochastic generated values of 22% environmental impact units and 2% net impact.

Key words: Power Plants, life cycle model (LCM), Green House Gases (GHG), carbon footprints, environmental impacts categories, technology value chain

NOMENCLATURE

A	Technology matrix	
B	Intervention Matrix	
d	discrepancy factor	
f	final demand vector	
$\tilde{f}$	Final supply vector	
g	reference inventory vector	
g'	Reference Inventory Vector	
$\hat{H}$	Classification Vector	
h	Impact Vector	
V	Production Volume	bbls, gallons, m^3, liters
V_o	Initial Volume	bbls, gallons
C	Concentration	kg/m^3, mol/m^3
F	Flow Rate	bbls/day, m^3/s

$\gamma_{1a}\gamma_{1b}\mu_{1b}\mu_{2b}$ and the allocation factors which achieve an allocation of the economic flow, liter of fuel and the environment flows kg of carbon dioxide, kg of Sulphur dioxide over the two newly created unit processes.

1.0 INTRODUCTION

Life cycle assessment (LCA) of energy, technology and material resource utilization in power generation plants and its impacts in global warming offers key solutions in the assessments of carbon footprint, GHG, economic and environment value chain. The intervention categories (environment impacts) from process units of modern power plants are important targets in life cycle assessment (Alan, 1995). Several life cycle assessment models presented in technical literature (Bergerson and Lavel, 2002, Weidema *et al.,* 2008) that enables decision makers plan budgets and meet up environmental regulatory audit requirements have been used to assess the impacts of material, products, waste inventory and economic value categories derived from raw material utilization in the processing, transmission, and electricity generation units of a power plant. The LCA model shows economic value chain of materials, technology, and energy usage in relation to the intervention (environment impact categories) presented in the linear space model. The linear space model equates the (process flow) as the ratio of flow into the economic systems of energy, technology, and raw material usage A to flow into the environment system (environment, material, and energy wastes pollution impacts B) that is $P = \frac{A}{B}$. Current LCA models predict direct emissions from electricity generation plant which often could lead to wrong conclusions because of misleading data of the actual inventory in the processing units of the plant (Odeh and Cockerill, 2008; Ito et *al.,*2008). Previous studies (Meier, 2002 and Spadaro, 2000) show indirect GHG emissions represent 25% of overall emissions of carbon prints from electricity generation (Weisser, 2007; Edenhofer *et al.,* 2011). There are claims in literature (ISO EN ISO 1040, 2006, European Commission, 2010; Bolin, 1997; Ekvalland and Wedema, 2004) that discrepancies in LCA and GHG data sets from different studies of similar electricity technologies are likely attributed to the wrong perception and quantification of the GHG carbon footprint audits in the economic and environment impact categories. Therefore, we present a unifying model for LCA that enables accurate determination of environment impact categories, GHG and economic value chains from power plants in conformity with LCA guidelines (ISO 14040 and ILCD handbook) (ISO EN ISO 1040, 2006)) which are repeatedly changed to ensure comparability among LCA studies (Gagnon *et al.*, 2002; Abernath and Knode, 2001; BPSR, 2017)

2.0 MODEL DEVELOPMENT AND CONCEPT METHODOLOGY

The LCA linear space model quantifies flows in connection with each unit processes in production systems and power plants (Bulovas, 1996; Chastin, 1999; Jensen *et al.,* 1997). The basic modeling concept reduced the power plants into process flow units and assessed the technology (economic) value impact categories in relation to intervention (environmental impact categories) computed for each process using the material and energy balance method. The linear system model consists of multiple unit process as presented in eqn.1.

$$p = p_1|p_2|p_3|p_4| \dots \dots |p_n| \quad (1)$$

P is the process matrix apportioned into two distinct parts. The first part (A) represents flows in the economic system known as technology matrix and second part is flow into the environment system (B) is known as intervention matrix. The portioning leads to matrix eqn. 2.

$$p = \left(\frac{A}{B}\right) = \left(\frac{|\boldsymbol{A}| = \begin{bmatrix} a_{01} & a_{02} & a_{03} & a_{04} & a_{05} \\ a_{11} & a_{12} & a_{13} & a_{14} & a_{15} \\ a_{21} & a_{22} & a_{23} & a_{24} & a_{25} \\ a_{31} & a_{32} & a_{33} & a_{34} & a_{35} \\ a_{41} & a_{42} & a_{43} & a_{44} & a_{45} \end{bmatrix}}{|\boldsymbol{B}| = \begin{bmatrix} b_{01} & b_{02} & b_{03} & b_{04} & b_{05} \\ b_{11} & b_{12} & b_{13} & b_{14} & b_{15} \\ b_{21} & b_{22} & b_{23} & b_{24} & b_{25} \\ b_{31} & b_{32} & b_{33} & b_{34} & b_{35} \\ b_{41} & b_{42} & b_{43} & b_{44} & b_{45} \end{bmatrix}} \right) \qquad (2)$$

The first step in LCA modeling is the development of the inventory model specification of the system. In general, a reference flow Øis determined as one way of fulfilling the process functional unit (eqn. 3). For instance, a reference flow could be 1000 kWh of electricity. In general, the only non-zero element of the vector of the r[th] reference flow; process resource flow matrix for all stages is given by $PF(J) = (PF_O, PF_1, PF_2, PF_3, PF_4)$

$$p = \left(\frac{Amount\ of\ resources\ consumed}{Amount\ of\ environmnetal\ release}\right) \qquad (3)$$

Where, p is the process vector of a particular process and LCAs carried out on large systems in power plant comprises many different unit processes. The representation of a system of unit processes is given by eqn. 4.

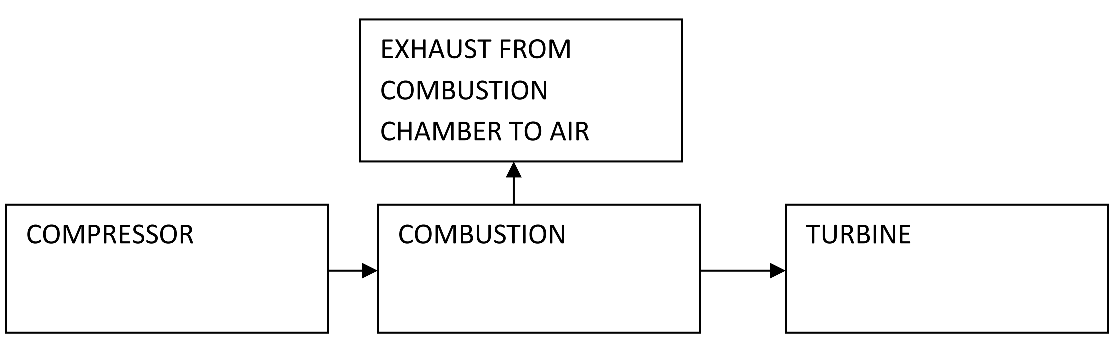
$$pi = \left(\frac{Amount\ of\ resources\ consumed\ of\ a\ particular\ unit\ i}{Amount\ of\ environmnetal\ release}\right) \qquad (4)$$

The perturbation theory and statistical analysis of inventory analysis is approximated by A and given by eqn. 5.

$$\frac{\partial s}{\partial \alpha_{ij}} = -A^{-1} \frac{\partial A}{\partial \alpha_{ij}} A^{-1} f \qquad (5)$$

2.1 Power Plant Gas Turbine Unit

The LCA linear space model was implemented on turbine process of a 300MWD power plant production system operated in Lagos Nigeria. The turbine units consist of a starting device, support systems, an axial-flow compressor, combustion system components, three-stage turbine which is apportioned process units [p_1, p_2 ....p_n]. Both compressor and turbine are directly connected with an-line, single shaft rotor supported by two pressure lubricated bearings. The inlet end of the rotor shaft is coupled to an accessory gear having integral shafts that drive the fuel pump, lubricating pump, and other system components. Figure 1 shows the block process flow diagram of gas turbine.



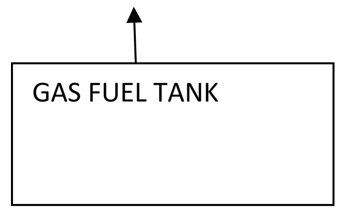


Figure 1: Gas Turbine Block Process Flow Unit

The turbine starting system is actuated and the clutch is engaged, ambient air is drawn through the inlet assembly, and filtered compressed in the 17th stage axial flow compressor.

3.0 RESULTS AND DISCUSSIONS

The final demand vector for a 300MWD power plant operated in Lagos Nigeria was evaluated for economic (technology) and environmental (intervention matrix) system that generates the minimum environmental burden. The environmental burden associated with the generation of electricity by a gas-fired power plant and life cycle data used to assess them is sensitive; therefore, a basis reference unit upon which other calculations for a 300MWD power plant has been adopted. Assumptions about the power plant are: (1) it has a power factor of 0.8; (2) It runs averagely for about 292 days in a year and 20hrs per day; (3) It has a life span of thirty years; (4) Capacity utilization is 80%.

3.1 LCA Technology and Intervention Results of Power Plant

The basis of economic linear space is presented in eqn.6 as a matrix of units.

$$\begin{pmatrix} MjofElectricty \\ CubicMeterofNaturalGas \\ KgofAluminiumm \\ KgofSteel \\ Kgofcopper \\ kgofbauxite \\ kgofIron \\ kgofgravel \\ kgofgypsum \\ kgofsand \\ capitalinvested \\ equipment \end{pmatrix} \tag{6}$$

The final demand vector simulated for is presented as eqn.7.

$$f = \begin{pmatrix} 4.0366e^{6}MJ \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \end{pmatrix} \quad (7)$$

The basis for the environmental part of the linear space is presented in eqn.8.

$$\begin{pmatrix} kgofCarbondioxidetoair \\ kgofcarbonmonoxidetoair \\ kgofmethanetoair \\ kgofnitrogenoxidetoair \\ kgofsulphurdioxidetoair \\ kgofparticulates \end{pmatrix} \quad (8)$$

The emission delivered by plant is shown in Table 1.

Table 1: Emission per Delivered Plant

Emission to Air	Value	Unit
Carbon dioxide	0.222	Kg/kg NG
Dinitrogen Monoxide	1.64 E-06	Kg/kg NG
Methane	0.0152	Kg/kg NG
Carbon dioxide	0.000479	Kg/kg NG
Nitrogen Oxide	0.00436	Kg/kg NG
Sulphur Oxide	0.00949	Kg/kg NG
VOC	0.000181	Kg/kg NG
PM	1.43 E-066	Kg/kg NG

The MATLAB and Microsoft Excel sheet simulation of the scaling vector for the system was obtained as eqn.9:

$$s = \begin{pmatrix} 3.367085325724581e^{+004} \\ 3.98763915155623e^{+002} \\ 1.895669038382939e^{+000} \\ 5.534153004942057e^{+003} \\ 4.208856657155729e^{-001} \\ 6.97606206124921e^{+000} \\ 6.492391605623236e^{+003} \\ 1.201553708095026e^{+003} \\ 1.532023823204685e^{-004} \\ 1.075783761569004e^{-002} \end{pmatrix} \quad (9)$$

The inventory vector results are presented in eqn.10:

$$g = \begin{pmatrix} 3.788788369165930e^{+004} \\ 5.483312100973606e^{+002} \\ 1.808174747223664e^{+002} \\ 8.121750793212635\ e^{+001} \\ 8.551477701287055e^{+001} \\ 2.092835962416468e^{-002} \end{pmatrix} \quad (10)$$

The impact vector h was simulated and presented in eqn.11.

$$h = \begin{pmatrix} 4.001448601456872e^{+004} \\ 1.423670325653590e^{+002} \\ 1.808174747223664e^{+002} \end{pmatrix} \quad (11)$$

Where, h_{11} has a unit of kgCO_2-equivalent, h_{12} kg-SO_2-equivalent and h_{13} kg-CFC-$_{11}$ equivalent.

The normalized impact vectors were obtained is presented in eqn.12:

$$\tilde{h}_{.} = \begin{pmatrix} 9.643485536289450e^{-010} \\ 4.427620335860492e^{-010} \\ 3.001570080163163e^{-007} \end{pmatrix} \quad (12)$$

All the elements of this vector have a unit of year. The weighted index was computed to be w=1.891152787908058e-005 yr. The outputs of electricity and heat are associated with input materials, processes, outputs emissions of energy production processes. The data was derived from report (NDC, 2016) which has a unit of kg emissions per MJ of MG of the plant. The units of technology matrix are presented in eqn.13.

$$\begin{pmatrix} Mj\ \ of\ Electricty \\ Cubic\ Meter\ of\ Natural\ Gas \\ Kg\ of\ Aluminiumm \\ Kg\ of\ Steel \\ Kg\ of\ \ copper \\ kg\ of\ bauxite \\ kg\ of\ Iron \\ kg\ of\ gravel \\ kg\ of\ gypsum \\ kg\ of\ sand \\ capital\ invested \\ equipment \end{pmatrix} \quad (13)$$

Figures 2 and 3 show results from the contribution analysis of power plant, construction and operation, raw materials extraction and production and distribution of natural gas. The pie chart results for the studied power plant in Lagos Nigeria show contribution of global warming and sulphur IV oxide SO_x acidification from the power plant construction and operations is significant with a pie chart value of 89% for So_x acidification pollution and 79% global warming from GHG.

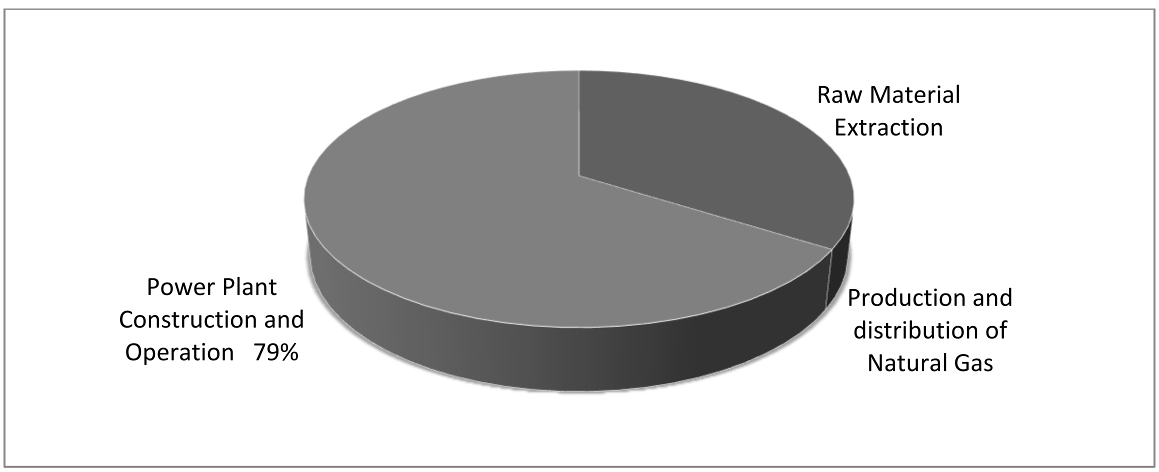


Figure 2: LCA Pie Chart of Contributions of Power Plant Processes to Global Warming (Kg /CO_2 equivalence)

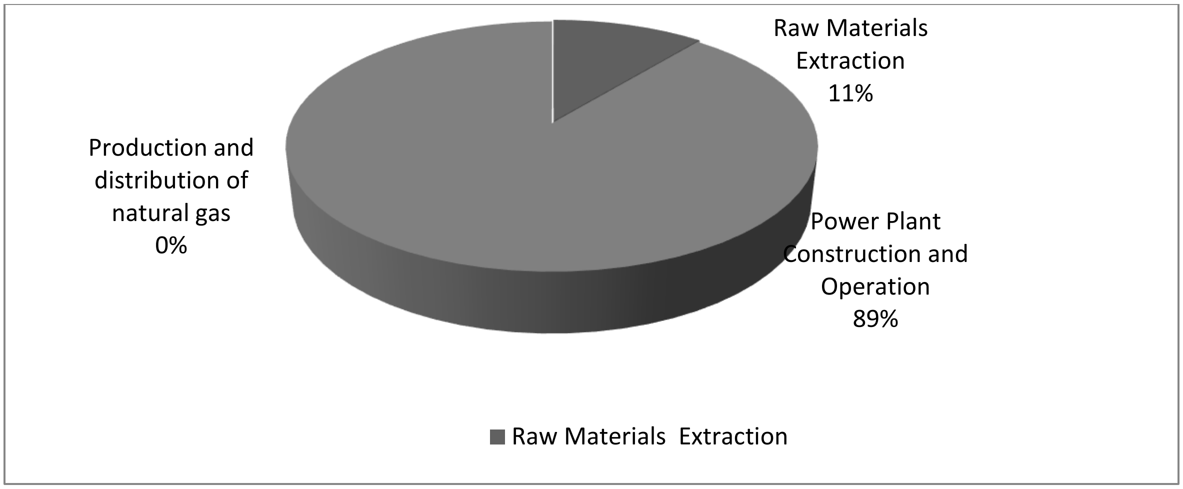


Figure 3: LCA Pie Chart Contributions of Power Plant Processes to Acidification (kg/SO_2 equivalence)

Figure 4 shows the plot of Nox, CO, CO_2 and CH_4 emission with water injection rate for the power plant. It appears that increase in the water injection rate significantly reduce the NOx emission to the atmosphere for the period observed. Figure 5 show the plots of NOx and CO plots against water injection rates. While both plots show significant decrease in concentration of pollutants of NOx and CO, the effect is experienced more in the NOx emission than CO emission. There is a relationship between water injection rates and the concentration of pollutant gases (CO_2, CH_4) and (NOx, CO) released to the environment, that higher water injection rate tends to reduce pollutants released to the environment. Therefore, adjustment in the water injector rate to the gas turbine unit cooling unit will reduce GHG and other pollutants emitted by gas plant to within accepted limits.

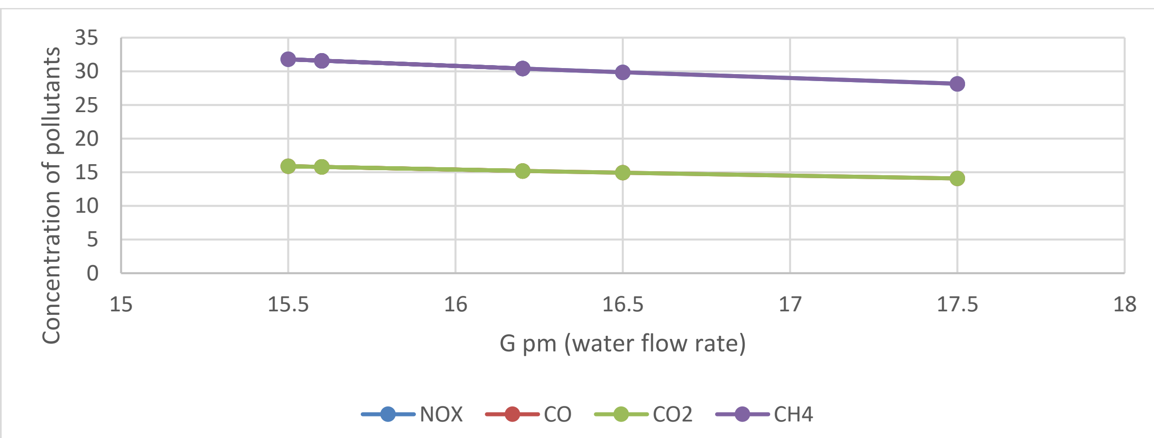


Figure 4: Plot of Concentration of Pollutants with Water Flow Rate

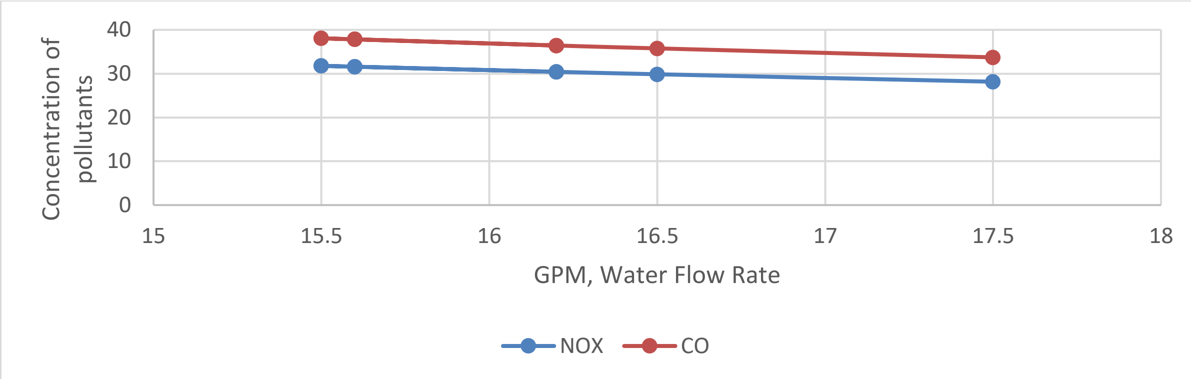


Figure 5: Plot of Nox and Cox (ppm) with water injection rate

Table 2 shows the intervention matrix B (environmental impact categories) of simulated pollutants concentrations of carbon dioxide, carbon monoxide, methane, nitrogen oxide, sulphur dioxide and particulates for each process units (P1, P2, P3, P4….P10) of gas Power Plant. The process units of gas plant were derived from Process and Instrumentation Design (PID) data supplied by the field operators. Process unit 5 has the highest concentration generated of 5.2106 ppm, and particulates of 0.0003 pp. It was observed that process unit P1 has most of the pollutants generated from the process, while process unit 8 and process unit 10 has no pollutants generated from that process unit.

Table 2: Intervention matrix for Different Process Unit Power Plant

INTERVENTION MATRIX B	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10
Carbon dioxide	0.73152	0.2011	1.26	1.6141	5.2106	0	0.653	0	0	0
Carbon Monoxide	0.00717	0.000363	0	0.029974	0.001998	0	0.0217	0	0	0
Methane	0.00737	0	0.00036	0	0.010241	0	0	0	0	0
Nitrogen dioxide	0.0022	0	0	0	0	0	0.0011	0	0	0
Sulphur Dioxide	0.00222	0.000803	0	0	0.136495	0	0.0016	0	0	0
Particulates	0	0	0	0	0.0003	0	0	0	0.001132	0

Table 3 and Table 4 are results of a Monte Carlo simulation run of the LCA of the Power Plant. For demand vector of an annual production of electricity 3,597 MJ, the environmental units were evaluated to be 22 % environmental unit, 24% economic unit and net impact of 2%. Table 4 is Monte Carlo Simulation Report and Sensitivity analysis for sample size of 10,000runs with a simulated demand vector of annual production run of a mean value of 2881.52MJ with a mean standard error of 8.46.

Table 3: Monte Carlo Simulation of LCA on Power Plant Final Demand Vector Analysis

SN	SIMULATION	Environmental Impact Unit	Economic Unit	Impact Net Impact	ANN. PROD.
		%	%	%	MJ
1	Final Demand Vector	22	24	2	3,597

Table 4: Monte Carlo Simulation Report and Sensitivity Analysis

Monte Carlo Simulation (Summary Report)	*See Monte Worksheet*

Summary Statistics	
Sample Size (*n*):	10000
MEAN:	2,881.52
STDEV:	845.56
Mean Standard Error:	8.46

Press F9 to Re-Calculate Monte Carlo simulation

Probability of Final Demand Vector greater or Less Than			
		Final Demand Vector	2,769.78
		Simulated Mean:	2881.52
Pr(x <	2769.78	**) =**	49.45%
Pr(x >	2769.78	**) =**	50.55%

6.0 CONCLUSION

A life cycle model has been developed and applied for the life cycle assessment of a power plant operated in Lagos Nigeria. The Life cycle model evolved from the linear space concept of the process flow units of the power plant partitioned into economic and environment system based on the final demand vector. The contribution of SO_x acidification and global warming from the power plant construction and operations were significant with a value of 89% for So_x acidification pollution and 79% for global warming from GHG. The results establish relationship between water injection rates and the concentration of GHG and pollution gases released to the environment; that higher water injection rate tends to reduce pollutants released to the environment. *Therefore, modification in the water injector rate to the gas turbine cooling unit will reduce GHG and other pollutants emitted by gas plant to within accepted limits.* The Monte Carlo simulation run also shows correlation between final demand vectors and environmental impact categories of stochastic generated values of 22% environmental impact units.

ACKNOWLEDGMENTS

The contributions of the Department of Chemical Engineering by providing the enabling environment and moral support to carry out the study are acknowledged. We also acknowledged the operators of 300MWD Egbin Plant Barge at Ikorodu and the Federal Government for providing data.

REFERENCES

Alan, G. (1995). Environment Impact Assessment-Cutting edge for the twenty-fist century, Cambridge University Press, pp23.

Abnernath, S.E., and Knode, T.L. (2001). "Creation of an integrated Management System" SPE 66582 presented at the SPE/EPA. Exploration and Production Environment Conference, Texas Feb 2001

Bulovas, B.J. (1996). Environmental Target Setting and Ranking. SPE 35831 International Conferences on Health, Safety and Environment, New Orleans

Bergerson, J. and Lave, L. (2002). A life cycle analysis of electricity generation technologies: Health and Environmental Implications of Alternative fuels and Technologies, Carnegie Mellon Electricity Industry Center, pp 4

Chastain, B. (1999). Environmental Performance Exploration and Production Operations. Proceedings of the 6th International Petroleum Environmental Conference, Texas

Edenhofer, O., Pichs-Madruga R., Sokona Y., Seyboth K., Matschoss P., Kadner.S, Zwickel, T., Eickemeier, P., Hansen,.G, Schlömer, S., von Stechow C. (2011). IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, 2011.

European Commission - Joint Research Centre - Institute for Environment and Sustainability, EC-JRC (2010). International Reference Life Cycle Data System (ILCD) Handbook - General guide for Life Cycle Assessment - Detailed guidance, Luxembourg, Publications Office of the European Union, 2010.

Gagnon, L., Belanger, C. and Yehiyama, Y. (2002). Life cycle assessment of electricity generation options: The status of research in year 2001, Energy policy 30, 14, 1267-1278

ISO, EN ISO 14040 (2006). Environmental management – Life cycle assessment – Principles and Framework, 2006.

Ito, M., Kato, K., Komoto, K., Kichimi, T., Kurokawa, K. (2008). A comparative study on cost and life-cycle analysis for 100 MW very large-scale PV (VLS-PV) systems in deserts using m-Si, a-Si, CdTe, and CIS modules, Progress in Photovoltaic: Research and Applications. 16, 17–30.

Jensen, A.A., Hoffman, L., Møller, B.T., Schmidt, A., Christiansen, K.S., Berendsen, Elkington, J. (1997). Life Cycle Assessment (LCA) A guide to approaches, experiences and information sources, Report by European Environmental Agency.

Odeh, N., Cockerill, T. (2008). Life cycle analysis of UK coal fired power plants, Energy Conversion and Management. 49, 212–220.

NDC, 2016. Nigeria's Draft Nationally Determined Contribution (NDC). Implementation action plan for the power sector.

Weidema, B.P., Thrane, M., Christensen, P., Schmidt, J., and Løkke, S. (2008). Carbon Footprint, Journal of Industrial Ecology. 12 ,3–6.

Meier, P.J. (2002) Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis, Dissertation, University of Wisconsin, Madison

Weisser, D. (2007) A guide to life-cycle greenhouse gas (GHG) emissions from electric supply technologies, Energy. 32, 1543–1559.