Feasibility Study of Cafeteria Energy Demand with Integration of a Downdraft Bio-digester System

E. O. B. Ogedengbe[1, a], E. Kingsley[a], R.U Eteure[a] and M. A Rosen[b]

[a] *Energhx Research Group, Department of Mechanical Engineering*
University of Lagos, Akoka-Yaba, Lagos, Nigeria

[b] *Faculty of Engineering and Applied Science*
University of Ontario Institute of Technology, Oshawa, Ontario, L4J 7S5, Canada

Energy demand load analysis of the 2001 Cafeteria complex, at the University of Lagos, with the audit of a feasible supply of biogas from a bio-degradable food waste using a downdraft bio-digester, is conducted. A walk-through energy audit of all the appliances that are installed or operated within the complex and its building envelope for maintaining the thermal comfort, indoor air quality, and cooking and lighting equipment is considered. The design and optimization of the process of collection, storage and management of the food waste from about twenty vendors operating inside the complex is proposed. Using a standardized performance index for a conventional downdraft bio-digester, the energy-saving advantage of developing and integrating a biogas production system with the 2001 Cafeteria is presented. The results of this study are desirable for the estimation of the economical and environmental impact assessment of a proposed development of a compact solar bio-reactor for independent generation and storage of hydrogen.

I. Introduction

RECENT developments in Nigeria's electricity sector underscore a significant paradigm shift in the nation's energy policy. The Electric Power Sector Reform Act, 2005 attempts to obtain a solution to the problem of energy sustainability and the promotion of clean energy. The resulting change is a shift of focus to the generation of power from renewable energy such as the use of a bio-digester. With the enormous availability of renewable resources, in addition to being one of the largest oil producing countries in the world, it is difficult to explain the fact that Nigeria's power production capacity still stands at about 4,000 MW for a population of more than 150 million. However, the power reform plan of the current administration, among other initiatives, proposes a Feed-In-Tariff (FIT) program (to be administered by the National Electricity Regulation Commission) for the generation of power with renewable energy sources. If this proposal is adopted by the major stakeholders, and launched by January, 2012, power rated with installed capacity above 1 MW and fed into the national grid will be paid based on the technology of the renewable power project (₦34.8/kWh for solar photovoltaic; ₦12.0/kWh for wind; and ₦20.4/kWh for small hydro).

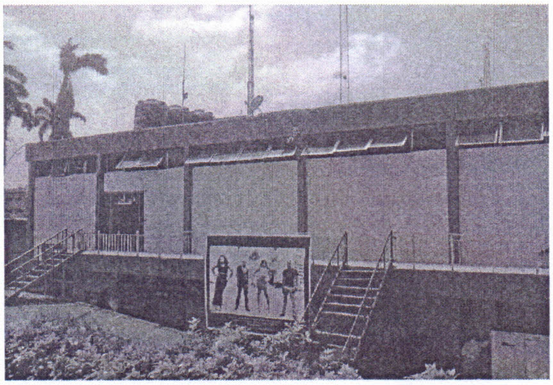

Figure 1. View of the 2001 Cafeteria Complex, University of Lagos

[1] Consultant & Senior Lecturer, Energhx Research Group, 353 Faculty of Engineering, University of Lagos, Akoka-Yaba, Lagos, Nigeria. AIAA Member. (Corresponding E-mail: ogedengbe@energhx.com)

-Clean energy practice starts with effective conservation of the available electricity in the local grid. However, there is little incentive for energy audits and conservation practices for most buildings in Nigeria, resulting in poor understanding of the recommended standard for indoor air quality and thermal comfort. Some of these concerns arise from observable effects on, for instance, human health, while others stem from actual or perceived environmental risks such as possible accidental release of hazardous materials. Renewable energies include wind, ocean wave and tides, solar, biomass, rivers, geothermal (heat of the earth), etc. They are 'renewable' because they are regularly replenished by natural processes and are therefore in almost endless supply. They also can operate without polluting the environment. Technologies have been developed to harness these energies and such technologies are called renewable energy technologies (RETs) or "clean energy technologies" or "green energy technologies". Because renewable energy resources are constantly being replenished from natural sources, they have security of supply, unlike fossil fuels, which are negotiated on the international market and subject to international competition, sometimes resulting in conflicts and shortages. A global effort towards demand side management has been reported by the International Energy Agency[1]. Figure 2 shows three basic models for improving building energy efficiency, including Solar Energy Supply Contracting (Solar-ESC), Energy Supply Contracting (ESC) and Energy Performance Contracting (EPC). While the basic models have some challenges, a search for a suitable "tool" to execute energy conservation potentials has led to the recommendation of an integrated Energy-Contracting model[2].

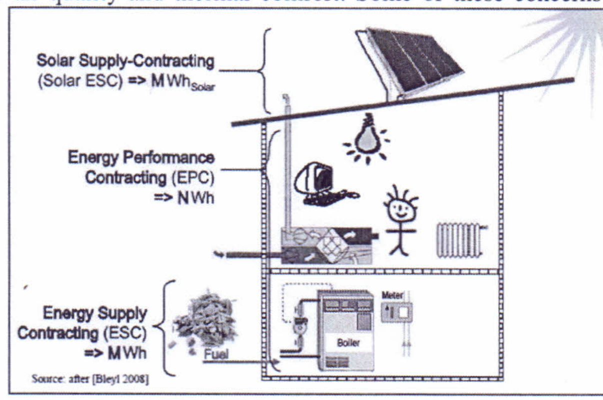

Figure 2. Schematic showing the three-mode Energy Contracting Models

The University of Lagos, Akoka-Yaba, Lagos (UNILAG) is one of the foremost federal universities located in the western part of Nigeria and was founded in 1962. The presence of the university in Lagos, which is the commercial nerve centre of Nigeria, has caused the institution to grow notably. The student population has continued to increase with a corresponding increase in teaching and non–teaching staff. Banks and agro-allied industries are now scattered within and outside the university. A fraction of the electrical power supplied to the University of Lagos is distributed to staff quarters, hostels, offices, lecture halls, faculty blocks, laboratories and workshops, shopping malls, etc., and subsequently used to power lighting systems, sound systems, kitchens, fridges, air conditioners, fans, electric kettles, computers and other house-hold/office devices. This fraction of power does not meet the 8 MW power demand of the university community. The university administration continuously spends millions of Naira each year to supplement power from the Power Holding Company of Nigeria, PHCN. This study audits the feasibility of developing and demonstrating a bio-digester system, by using food waste from the operation of vendors at the 2001 Cafeteria complex, conducting a comprehensive energy audit of the complex; and estimating the loads for the management of the indoor air quality, electrical appliances, thermal comfort demand of the building, while monitoring and characterizing the food waste that will be fed into the proposed bio-digester system.

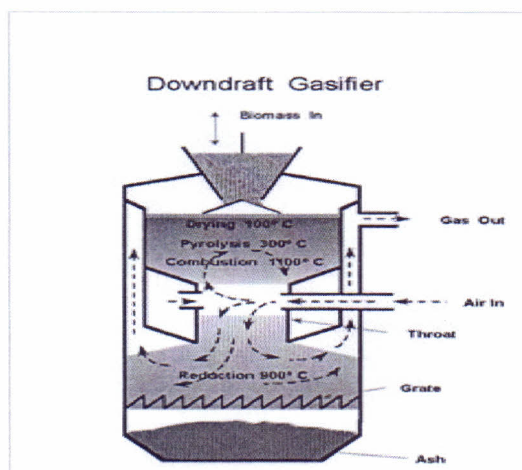

Figure 3. Schematic of a Downdraft Gasifier

II. Description of the Energy System

In classical thermodynamics, domestic and non-domestic facilities, like the 2001 Cafeteria complex in Figure 1, are considered as energy systems. The demand for energy includes lighting, ventilation and air-conditioning, and appliances. Without energy storage, renewable power supply from solar photovoltaic technology will depend on the national grid for consistent power supply. Therefore, accurate energy planning requires an analysis of the demand for power. An energy system control volume comprises the external boundary of a building envelope. Figure 3 shows the schematic of a bio-digester with various compartments for drying, pyrolysis, and gasification of the food waste. The design and integration of the bio-digester depend on an accurate analysis of the demand for energy to maintain a smooth running of the cafeteria complex. These activities include space cooling, cooking, entertainment, and processing of goods and services, depending on the nature of business of the vendors. The boundary of this building envelope encloses a mass of fluid, representing transport of heat and fluid transport with significant energy conversion mechanisms. Assuming incompressible flows, these scalar transport variables can be predicted based on the following three-dimensional form of continuity, momentum, CO_2 concentration, and energy equations: [3]

$$\frac{\partial(\rho)}{\partial t}+\frac{\partial(\rho U)}{\partial x}+\frac{\partial(\rho V)}{\partial y}+\frac{\partial(\rho W)}{\partial z}=0 \tag{1}$$

$$\frac{\partial(\rho U)}{\partial t}+\nabla.(\rho \upsilon U)=-\frac{\partial P}{\partial x}+\nabla.(\mu\nabla U)+\dot{S}_U \tag{2}$$

$$\frac{\partial(\rho V)}{\partial t}+\nabla.(\rho \upsilon V)=-\frac{\partial P}{\partial y}+\nabla.(\mu\nabla V)+\dot{S}_V \tag{3}$$

$$\frac{\partial(\rho W)}{\partial t}+\nabla.(\rho \upsilon W)=-\frac{\partial P}{\partial z}+\nabla.(\mu\nabla W)+\dot{S}_W \tag{4}$$

$$\frac{\partial(\rho c_p T)}{\partial t}+\nabla.\left(\rho c_p \upsilon T\right)=\nabla.(k\nabla T) \tag{5}$$

$$\frac{\partial(\rho c_p C)}{\partial t}+\nabla.\left(\rho c_p \upsilon C\right)=\nabla.(k\nabla C) \tag{6}$$

The energy system has a volume whose boundary encloses the mass contained, within the system there is variation in the indoor air concentration and the temperature. The density of the system is constant since it is assumed to be incompressible. The source terms in Eqns. 2-4 represent the various heat sources within the complex, including the heat releases from cooking appliances and human activities.

Fig. 4 shows a schematic of the renewable supply of bio-fuel for the bio-digester system. The heat of combustion is also proposed to be supplied by a renewable source, i.e., a photocatalytic reactor. However, a good estimation of the quantity of available food waste is essential in order to ascertain the effectiveness of the proposed renewable energy system. The method of collection and processing of food waste can be a significant design criteria. For instance, the moisture content of the feedstock plays a vital role in the design of the drying chamber configuration and all the heat transfer components of the system.

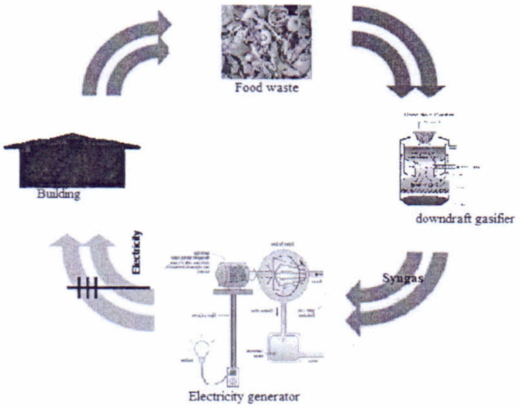

Figure 4. Schematic showing the Integration of a Bio-digester system with the Cafeteria Complex

The thermophysical properties of the complex are shown in Table 1. There are ten vendors providing various goods and services within the complex, including cybercafe, restaurant, supermarket, processing of consumables and the production of entertainment services. As observed in Figs. 5-14, the indoor air quality and thermal comfort level of these various compartments differ.

III. Discussions of Results

Proposing a three-predictor-variable regression analysis, including the indoor concentration of CO_2, occupancy, and indoor temperature, the thermal comfort of the energy stocks can be captured, using the relative humidity data; while a one-predictor model, based on the number of electrical appliances is used for the forecast of electrical power consumption. The forecast of electricity consumption and thermal comfort for the cafeteria complex represents a significant planning tool for the proposed independent power generation in order to mitigate the problem of erratic power supply from the grid. The generalized polynomial regression analysis suggests that either the relative humidity or electrical power consumption is the criterion variable, Q_i, for each of the energy stocks.

Table 1. Thermo-physical Properties of Building Envelope Elements

Element	Quantity	Orientation	Area [m^2]	Thickness [m]	R-value [m^{2}k/W]
			Husky Foods		
Wall	4	N	67.07	0.3	0.208
		E	17.15		0.208
		S	52.56		0.208
		W	34.3		0.208
Ceiling	1		176.5		0.153
Door	1	N	1.49		0.347
	1	E	3.4		0.009
	4	W	1.49		0.347
Window	11	N	9.68		0.009
	5	E	3.71		0.009
			Unilag Water		
Wall	4	N	29.4	0.3	0.208
		E	59.7		0.208
		S	26.4		0.208
		W	59.7		0.208
Ceiling	1		195.02		0.153
Door	2	W	7.16		0.347
Window	20	E	10.91		0.009
Wall	4	N	29.4	0.3	0.208
		E	59.7		0.208
		S	26.4		0.208
		W	59.7		0.208
			Hommies Bakery		
Wall	4	N	29.4	0.3	0.208
		E	24.78		0.208
		S	44.55		0.208
		W	29.4		0.208
Ceiling	1		176.5		0.153
Window	1	S	1.87		0.009
	5	E	2.73		0.009
			Eatery Hall		
Roof	1		571.11		0.008
Wall	3	E	89.55	0.3	0.208
		S	103		0.208
		W	89.55		0.208
Ceiling	1		455.51		0.125
Door	3	N	7.72		0.347
Window	2	W	18.05		0.009
		E	18.05		0.009
			Wisdom Café		
Roof	1		102.22		0.008
Wall	2	N	73.49	0.3	0.208

		S	73.49		0.208
Ceiling	1		77.57		0.125
Door	1	E	4.47		0.347
Window	6	E	8.69		0.009
		Pinto Lounge			
Roof	1		102.22		0.008
Wall	2	N	77.04	0.3	0.208
		S	77.04		0.208
Ceiling	1		81.32		0.125
Door	1	E	4.47		0.347
Window	6	E	8.69		0.009
		Oriental Cuisine			
Roof	1		102.22		0.008
Wall	2	N	77.18	0.3	0.208
		S	77.18		0.208
Ceiling	1		81.46		0.125
Door	1	E	4.47		0.347
Window	6	E	8.69		0.009
		PMG Supermarket			
Roof	1		102.22		
Wall	1	S	73.82	0.3	0.208
Ceiling	1		77.92		0.125
Door	1	N	3.73		0.019
Window	4	S	2.16		0.019
		PMG Food			
Roof	1		102.22		
Wall	2	N	45	0.1	0.069
		S	45	0.3	0.208
Ceiling	1		71.25		0.125
Door	2	E	3.83		0.009
		S	1.76		0.347
		PMG Café			
Roof	1		102.22		0.008
Wall	2	N	77.04	0.3	0.208
		S	77.04		0.208
Ceiling	1		76		0.125
Door	1	S	1.97		0.347

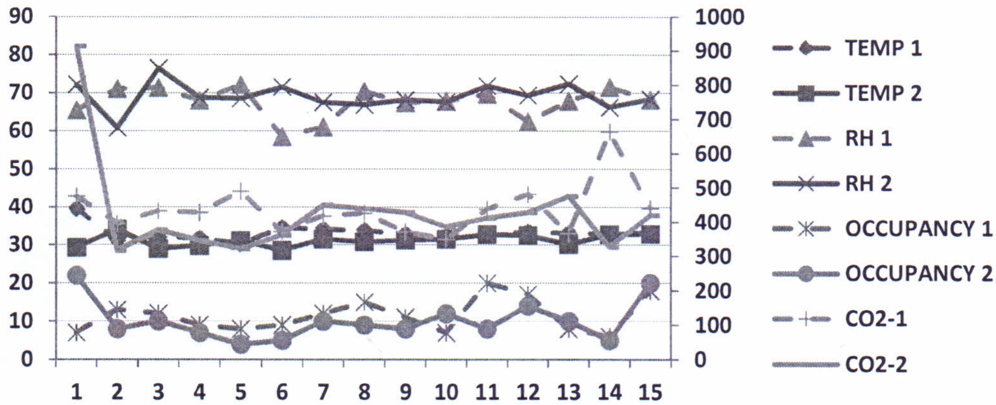

Figure 5. Indoor RH, Temperature, Occupancy and CO_2 concentration for Husky Foods (The primary axis depicts temperature in degree Celsius, relative humidity and occupancy; while the secondary axis shows the CO_2 concentration in PPM)

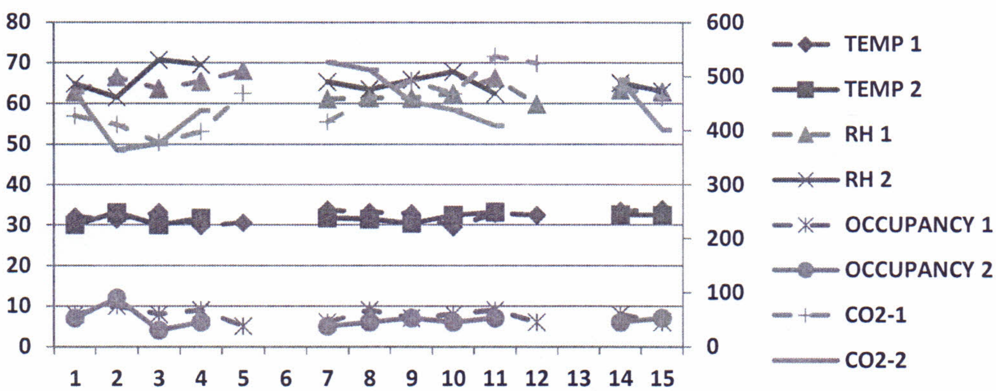

Figure 6. Indoor RH, Temperature, Occupancy and CO_2 concentration for Unilag Water

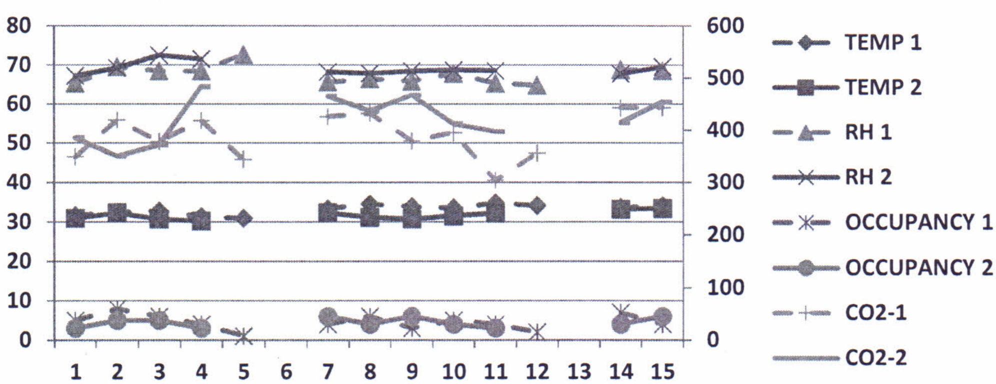

Figure 7. Indoor RH, Temperature, Occupancy and CO_2 concentration for Hommies Bakery

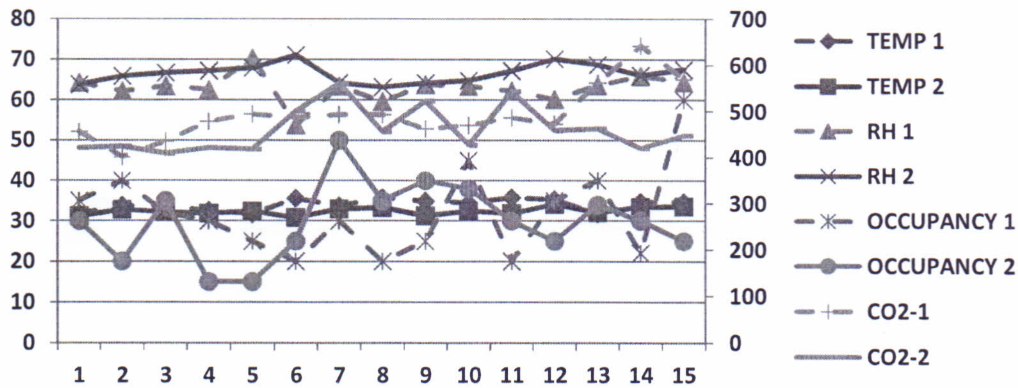

Figure 8. Indoor RH, Temperature, Occupancy and CO_2 concentration for Eatery Hall

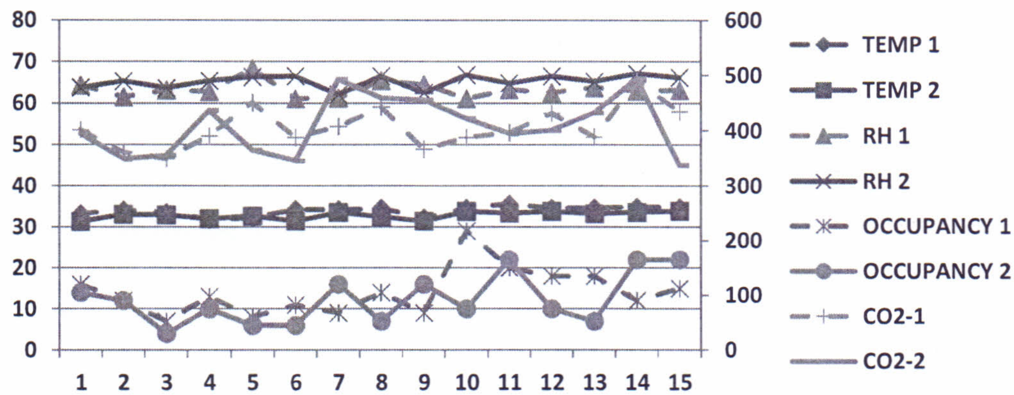

Figure 9. Indoor RH, Temperature, Occupancy and CO_2 concentration for Wisdom Cafe

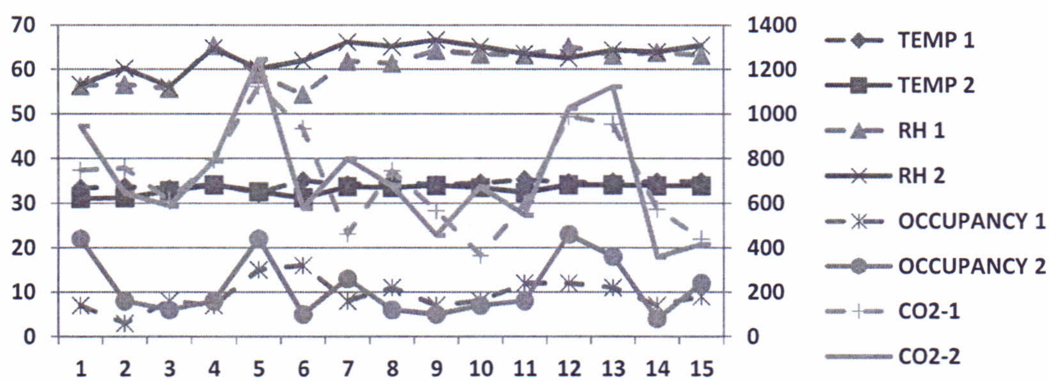

Figure 10. Indoor RH, Temperature, Occupancy and CO_2 concentration for Pinto Lounge

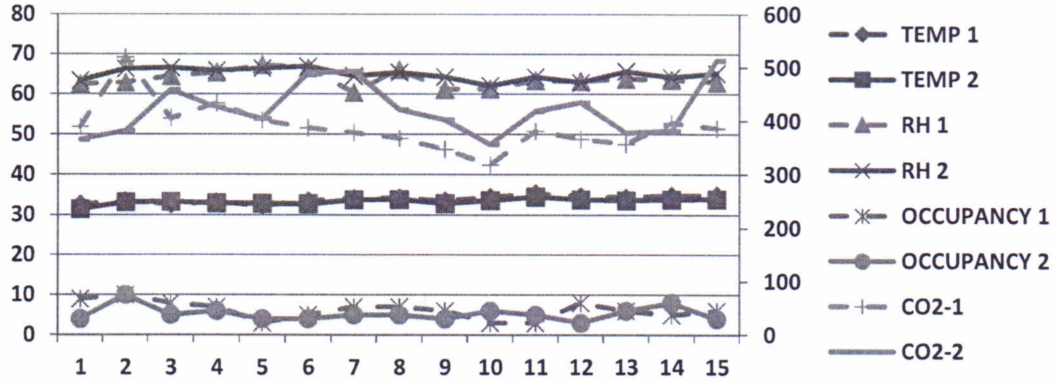

Figure 11. Indoor RH, Temperature, Occupancy and CO_2 concentration for Oriental Cuisine

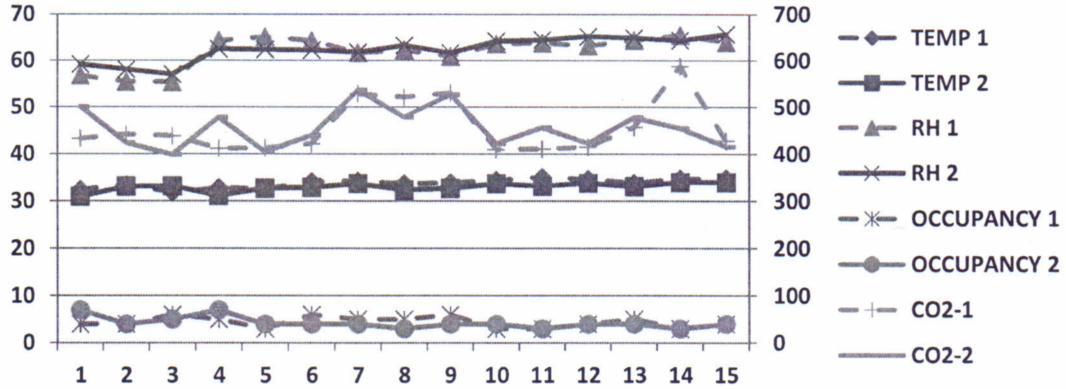

Figure 12. Indoor RH, Temperature, Occupancy and CO_2 concentration for PMG Supermarket

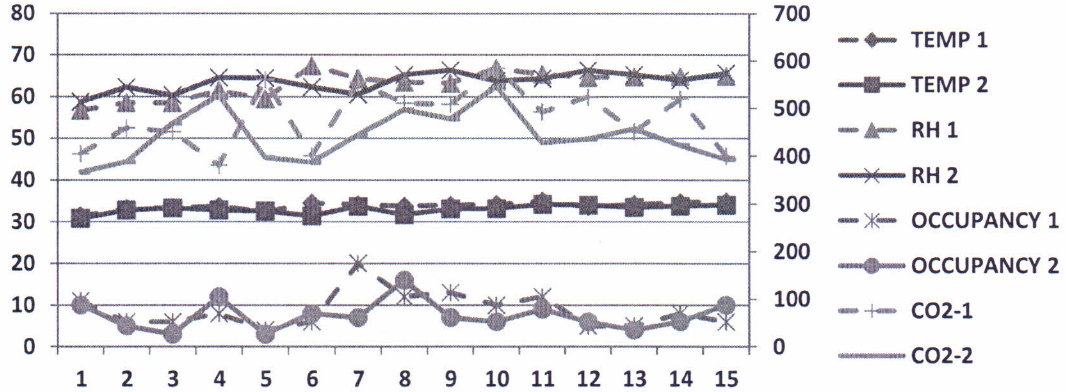

Figure 13. Indoor RH, Temperature, Occupancy and CO_2 concentration for PMG Food

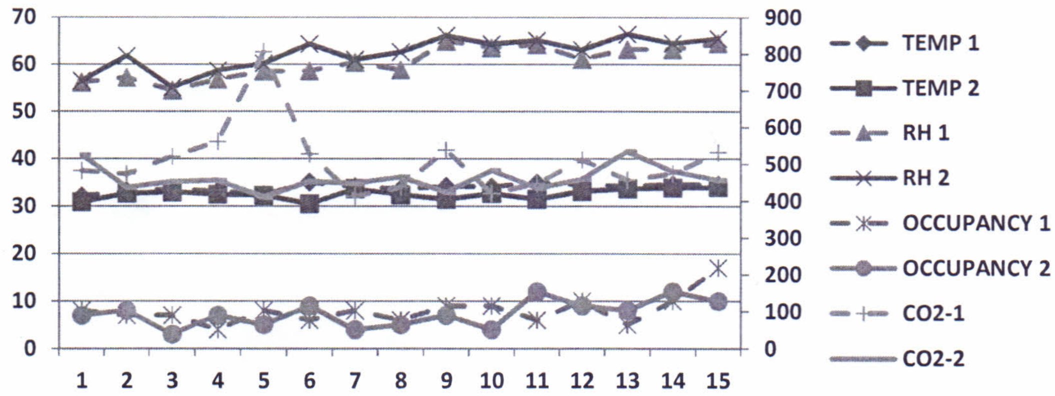

Figure 14. Indoor RH, Temperature, Occupancy and CO_2 concentration for PMG Café

Figures 5 to 14 show the CO_2 concentration of the energy stock on the secondary axis, while the other data are plotted on the primary axis. It shows that the CO_2 concentration increases as the occupancy of the energy stock rises. However, as the indoor temperature of the energy stock increases, the relative humidity of the energy stock decreases. Equation 7 captures the relative humidity, RH_i, for all the energy stocks within the complex, including Husky foods, Unilag water, Hommies bakery, Eatery hall, Wisdom cafe, Pinto lounge, Oriental cuisine and PMG.

$$Q_i = a_{i0} + \sum_{j=1}^{m} a_{ij} X_{ij} \quad , i = 1,2,3, \dots n \tag{7}$$

where n represents total number of energy stocks, X_{ij} denotes the predictor variables, and the regression coefficients are denoted by a_{ij}. For instance in the case of thermal comfort analysis, the following are the predictor variables: X_1 is the indoor temperature, X_2 is the CO_2 concentration and X_3 is the occupancy of the energy stock, and the criterion variable is the relative humidity of the energy stock.

Table 2. Regression Coefficients of the Cafetaria's Energy Stocks

Energy Stocks	*Regression Coefficients*							
i	a_0		a_1		a_2		a_3	
Husky	67.53	119.23	0.00044	-1.63	-0.000014	-0.0034	-0.0036	0.21
Unilag water	11.08	0.27	0.0049	2.32	0.00032	0.0012	6.61	-1.39
Homes bakery	32.28	0.19	0.011	1.9	0.001	0.025	6.49	-0.396
Eatery hall	60.81	58.91	0.00019	0.14	-0.000011	0.0185	0.065	-0.18
Wisdom cafe	64.66	48.22	0.00013	0.61	-0.000002	-0.0058	-0.108	-0.0435
Pintos lounge	62.12	-0.70	-0.0004	1.97	0.0000036	-0.00043	-0.113	-0.12
Oriental cuisine	64.68	78.36	0.00015	-0.727	-0000037	0.02	-0.16	0.417
PMG super	66.15	43.77	0.00008	0.56	0.0000067	0.0068	-0.93	-0.68
PMG food	61.99	21.05	0.00017	1.15	0.0000106	0.00699	0.1056	0.186
PMG cafe	56.33	43.83	-0.0003	0.516	0.0000065	-0.00715	0.506	0.684

Figures 15 and 16 compare the level of energy consumption with various vendors operating within the complex. The main eatery hall is being served by a collection of food vendors; allowing the hall to atttract a higher patronage of customers. While the relationship between all the predictor variables is sufficiently non-linear, additional complexity (due the fact that the ASHRAE standard for indoor air quality must be factored in the forecast of the aggregate power consumption) is characterized by the proposed model.

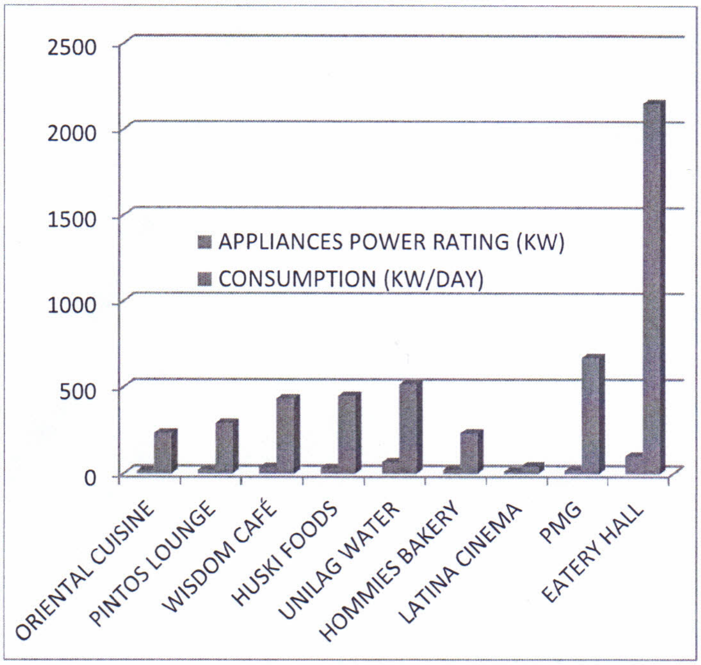

Figure 15. Power Rating of all Appliances within the Complex

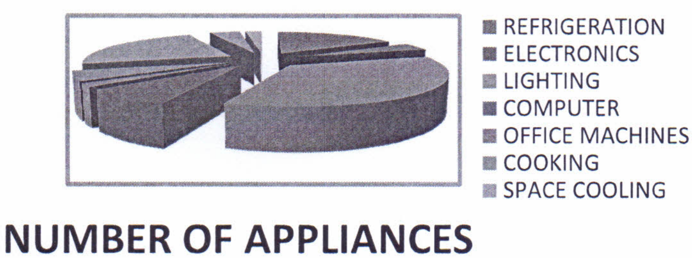

Figure 16. Distribution of Energy Supply by Demand Load

The average food waste produced daily from the cafeteria is given below:

- The Eatery hall produces 244.53 kg of food waste daily
- Other shops produce 75.24 kg of food waste daily

The total food waste produced from the cafeteria is as follows:

- From Monday to Saturday, it produces 319.77 kg of food waste daily
- Sunday, it produces150.48 kg of food waste daily

Mansour[4] estimated that 10 kg of kitchen waste produces 1.5m^3 of biogas, which consists of 1m^3 of methane. It is therefore estimated that 319.77 kg of the food waste daily will produce 31.97m^3 of methane daily from Monday to Saturday, while on Sunday 150.48 kg of food waste will produce 15.48m^3 of methane, resulting in an estimated monthly methane production of 200 m^3.

IV. CONCLUSIONS

Brief analyses are presented of the energy demand in Nigeria's emerging electricity market and the potential is described of not using fossil fuels, but rather using renewable energy sources of high potential. A multivariate energy consumption model is proposed as a significant criteria for the design of subsystems, including a bio-digester, a waste food collector and a mixer, a bio-reactor, and a hydrogen storage system. The proposed biogester will produce an esimated 200 m^3 of methane gas monthly from food waste collected from the cafetaria. With adequate monitoring of the characteristics of each energy stock, through the analysis of the regression variables, demand monitoring of the energy needs and thermal comfort of all the clients is possible. Future work will calibrate the client's energy demand with the coefficients of the regression analysis.

References

[1] IEA DSM Task XVI – Competitive Energy Services (Energy-Contracting, ESCo Services), Final Task Report, Phase 1, 2006-2009, Graz, 2010.

[2] Integrated Energy Contracting. A new ESCo Model to Combine Energy Efficiency and Renewable Supply in Large Building and Industry, Final Task Report, Phase 1, 2006-2009, Graz, 2010.

[3] E.O.B Ogedengbe and G.F Naterer, "*Convective Flux Dependence on Upstream Flow Directionality in Finite Volume Computations*", *Numerical Heat Transfer A*, Vol. 51, n. 7, pp. 617 – 633, 2007

[4] Mansour-Al Sadi,"Design and Building of Biogas Digester for Organic Materials Gained from Solid Waste" , M.Sc Thesis, Ah-Najah National University, Nablus-Palestine, 2010