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Kontakt/Contact

ZBW – Leibniz-Informationszentrum Wirtschaft/Leibniz Information Centre for Economics
Düsternbrooker Weg 120
24105 Kiel (Germany)
E-Mail: [rights\[at\]zbw.eu](mailto:rights[at]zbw.eu)
<https://www.zbw.eu/econis-archiv/>

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Carbon Footprint Evaluation and Environmental Sustainability Improvement through Capacity Optimization

Hope Evwieroghene Orovwode^{1*}, Simeon Matthew¹, Elizabeth Amuta¹, Felix Ayoade Agbetuyi¹, Isaac Odun-Ayo²

¹Department of Electrical and Information Engineering, Covenant University, Ota, Nigeria, ²Department of Computer and Information Sciences, Covenant University, Ota Nigeria. *Email: hope.orovwode@covenantuniversity.edu.ng

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ABSTRACT

The burning of fossil fuel for power generation emits Greenhouse gases into the environment. Greenhouse Gases (GHGs) emission is the principal cause of global warming. In order to regulate the emissions of these gases, the emissions need to be assessed and quantified. Carbon footprint is the evaluation of human activities that lead to GHGs emissions. The Covenant University Electricity Network during periods when utility supply fail runs on diesel powered generators located at different centers within the campus. These generators emit carbon-based compounds into the environment. Assessing the quantity of carbon dioxide which is the principal GHGs emitted per year gives 33.14-tonnes. Analysis of the load profiles in the centers showed that all the eight generators are not supposed to be running simultaneously as it is now. This study developed a new network model where all the generators were integrated into a DC microgrid that ensured resource sharing. The model was simulated using energy management and optimization techniques resulting in reduced micro-generators engagement, Green House Gases emission and fuel consumption. Consequently, carbon dioxide emitted per year dropped to 18.44-tonnes from 33.14-tonnes. The developed model improved the carbon footprint of the campus by as much as 44.3%.

Keywords: Greenhouse Gases, Climate Change, Carbon Footprint, Optimization, Energy Management

JEL Classifications: Q5, Q430, L94

1. INTRODUCTION

Climate change is one of the worst challenges the world is facing today (Huisingh et al., 2015; Matthew et al., 2018). The contribution of greenhouse gas (GHG) emission to climate change is a serious point of concern to the developed nations who have the mandate to reduce it by 50-80% by 2050 (Mac et al., 2018). The Kyoto Protocol covered six main GHGs, including: carbon (iv) oxide (CO₂), perfluorocarbons (PFCs), hydrofluorocarbons (HFCs), methane (CH₄), nitrogen monoxide (N₂O), and Sulphur hexafluoride (SF₆) (Cirman et al., 2009, p. 7; Evandro et al., 2018). Several human activities and processes are responsible for the emission of these gases into the environment. Human activities such as burning of fossil fuels for power generation and aluminium production emit CO₂, CH₄, N₂O and PFCs into the environment

(Olivier and Peters, 2020; Rafique and Rehman, 2017). Other activities contributing to GHG emissions include: waste water treatment especially the high energy demand plants (Mamais et al., 2015), construction works through onsite electricity use and construction material production (Hong et al., 2014), livestock farming which alters the Nitrogen, carbon and phosphorus cycles (Leip et al., 2015), etc. Although the afore mentioned processes contribute greatly to climate change, the world still encourages them in order to enhance economic growth and human wellbeing (Althor et al., 2016). Amongst the human activities or processes that emits GHG, the generation/consumption of electrical power has become an essential part of human life that acts as crucial stimulus for rapid and sustainable socio-economic development of any nation (Abdallah et al., 2015). Power generation using thermal plants requires the combustion of fossil based fuels which

contribute significantly to the emission of carbon (iv) oxide (CO₂) (Chen et al., 2020). Carbon (iv) Oxide constitutes 77% of the greenhouse gases (Abdul et al., 2017). As a result of the negative effect of excess Carbon (iv) Oxide in the atmosphere, its quantity that is emitted through each activity needs to be quantified. This is the concept of carbon footprint evaluation.

The evaluation of Carbon footprint was defined as a quantitative measurement of Carbon (iv) Oxide emissions caused directly or indirectly by individuals, organizations, processes or products by the authors in (Econometrica Press, 2008; Solé et al., 2018). It is expressed in terms of the mass (in kg, t, etc.) of greenhouse gases emitted with no reference to any area unit (Galli et al., 2012). The quantization of the emissions is required in order to develop and prioritize the strategies for its reduction with special focusing on the areas of greatest savings potential with lesser hazards. Hence, this study evaluates the Carbon Footprint resulting from electrical energy generation/consumption in Covenant University, Ota, Nigeria and uses capacity optimization method for environmental sustainability improvement.

1.1. Carbon Footprint Assessment

Carbon footprint Assessment and quantification can be carried out by the identification and classification of emission-releasing event/activities into direct emissions (code named scope 1 emissions where emissions are released directly into the environment by activities/events of individuals or organizations), indirect emission ((code named scope 2 emissions which are consequences of activities occurring at sources that cannot be controlled by the individual organization) and other indirect emission (code named scope 3 Emissions which result from activities occurring at sources outside the control or ownership of the individual or organization involved and which are not classed as scope 2 (Olatunji et al., 2019; Jones and Kammen, 2011).

The evaluation of Carbon footprint can be carried out using two methodological approaches namely: bottom-up (which is Process Analysis based) or top-down (which is Environmental Input/Output analysis based) (Lin et al., 2013). Process analysis considers the impacts of individual processes or events on the environment from cradle to grave while Environmental Input/Output analysis considers all economic activities, process or event at the meso or sector level (Wiedmann and Minx, 2008).

1.2. Efficient Use of Resource as a Tool for Carbon Footprint Improvement

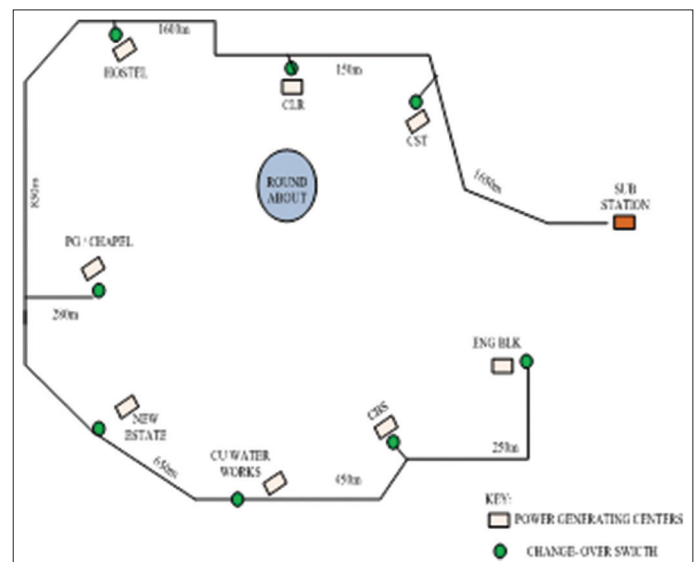
The United Nations in her conference on Climate Change has set a goal to achieve reduction in GHGs emissions to a level that would prevent unsafe emissions that will interfere with the climate system (Congregational Research Service, 2020). The GHG emissions resulting from energy-related activities increased rapidly between 1970 and 1997 in Africa, with South Africa alone accounting for almost half of the emission (Friedrich and Trois, 2016). Other significant carbon emitters include Egypt, Nigeria, Algeria, and Libya (United Nations Economic Commission for Africa African Climate Policy Centre, 2011). Consequently, various types of technologies have been suggested to assist in the reduction of carbon footprint. These technologies include: capturing and

storing of carbon; energy from waste; hydrogen production from non-fossil fuel based energy sources and fuel cells (Huisingh et al., 2015). A new method being proposed in this paper is the optimization of existing capacity which significantly mitigates carbon footprint through resource sharing and energy conservation. This is in line with the EU's 10-year economic strategy adopted in June 2010 where the issue of efficient use of resources gained further policy support. The "Europe 2020" strategy demands the transformation towards green and resource efficiency from 2011 onwards (Galli et al., 2012).

2. DESCRIPTION OF THE EXISTING COVENANT UNIVERSITY ELECTRICITY NETWORK

The Covenant University Electricity Network (CUEN) is an off-grid microgrid with installed capacity of 9750kVA. It comprises of eighteen diesel generator sets with the least rated at 250kVA and the biggest rated at 1000kVA sited in eight different locations on the campus. The generators are located at the College of Developmental Studies (CDS), Centre for Learning and Research (CLR), College of Science and Technology (CST), University Water Works, Pg Hostel/University Chapel, Undergraduate Hostel, New Estate and Engineering Block. The layout of the existing network is as shown in Figure 1. When the power supply from the Canaan Land Utility power supply fails, the eight generators will be switched on and allowed to run at the same time to supply power to the different buildings/units. With all the eight generators operating at any given time, they deliver a total output of 3750kVA at minimum units combination and 6000kVA at maximum units combination. The eighteen generators are of three different brands: 13 sets of Caterpillar, 2 sets of Perkins and 3 sets of Cummins to make a total of eighteen generating sets. The authors in (Orovwode et al., 2014) reported that while some of the generator sets are overloaded, others are operated below rated capacity. The University load profile data collected and analyzed, showed that if the resources are well harnessed, there are periods

Figure 1: The existing Covenant University Power Architecture



that some of the generators would not need to run thereby reducing fuel consumption and GHG emissions. Therefore, to reduce fuel consumption and reduce GHG emission on the campus, we need to re-engineer the power network to make it more reliable, efficient, cost effective and eco- friendly.

3. THE OPTIMIZED COVENANT UNIVERSITY ELECTRICITY NETWORK

The main idea of the proposed optimization of the Covenant University network is to ensure resources sharing. The proposed network retained the generating stations in their existing locations but with the outputs tied together to form a microgrid connected in a ring form. As a result of technical limitations including frequency, phase and terminal voltage matching, the generators cannot be synchronized on an AC bus. As a result, to effectively synchronize the outputs, the AC outputs of the generators were converted to DC outputs through rectifier units to form a DC microgrid. The power from the DC microgrid was interfaced with an inverter at each load center to convert the grid DC voltage to AC voltage required by the loads. The network consists of a central control unit that coordinates the controllers attached to each generating and loading points at the point of common coupling. The generators were dispatched economically according to the load profiles such that all the generators were not engaged at the time. The control algorithm with management strategy based on the peculiarity of the university’s load profiles was developed to fully optimize the network in order to ensure effective capacity utilization. The layout of the optimized network proposed is as shown in Figure 2.

4. SIMULATION OF THE UNIVERSITY POWER NETWORK

Hybrid System Optimization Model for Electric Renewables (HOMER 2.81), software produced by the United States National Renewable Energy Laboratory was used for sizing, simulation and optimization in this study. HOMER 2.81 has a number of in-built energy components and evaluates suitable options on the basis of availability and cost energy resources (Ani, 2014). To generate adequate results using HOMER information related to energy resources (diesel-powered internal combustion engines, in this case), economic constraints, energy storage systems and control strategies were required. Inputs such as plant size, type, capital outlay, number of units, operation, maintenance and replacement costs, efficiency and operational life were also required. The two models (the existing and the DC microgrid models) were simulated using the HOMER software. In the DC microgrid system shown in Figure 3, the AC voltages produced by the generators were tied to a DC bus using rectifier units. At the load centres, the DC voltage was re-converted to AC for the AC loads. Electronics and other loads requiring DC at the load end still retain their power supply units to convert the AC voltage to the required DC input. Such series of conversions increases losses in the system. In order to improve the efficiency of the system, direct connection of the DC loads to the DC bus is recommended.

5. ANALYSIS OF RESULTS AND DISCUSSION

The analysis and discussion in this section will be considered in two folds: Fuel consumption and carbon dioxide emission.

Figure 2: The proposed DC microgrid Architecture

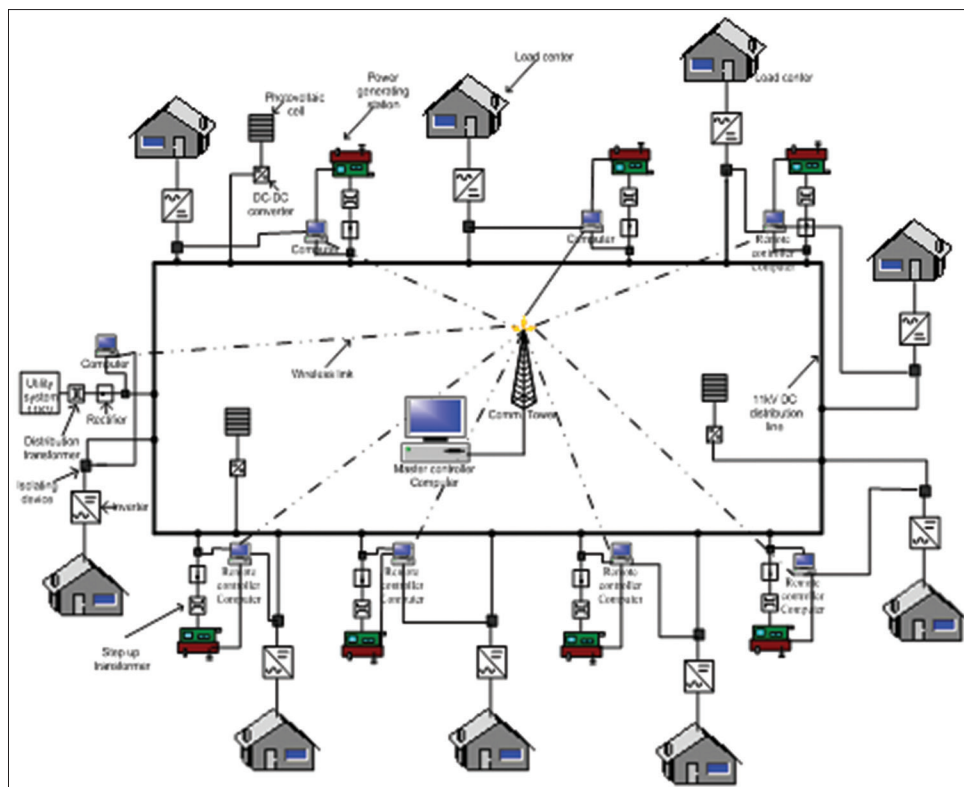


Table 1: Plants’ annual fuel consumption

	CDS	CST	CU WATER WORKS	PG/CHAPEL	CLR	HOSTEL	ENG BLK	NEW ESTATE	Total
DC Microgrid model (Litre/year)	348,315	1,346,565	1,331,715	1,247,380	1,050,303	665,610	209,880	786,720	6,986,488
Existing model (Litre/year)	1,568,040	1,568,040	1,568,040	1,568,040	1,568,040	1,568,040	1,568,040	1,568,040	12,544,320

5.1. Fuel Consumption

The results in Table 1 show the annual fuel consumption of the generating plants for the existing and the proposed optimized DC microgrid models.

The annual fuel savings resulting from the proposed model (DC microgrid model) was estimated from Table 1 using equation (1)

$$AFS = TFC_{EM} - MCTFC_{DCM} \tag{1}$$

Where:

AFS is the annual fuel saving

TFC_{EM} is the annual fuel consumed in the existing model in Litre/year = 12,544,320

TFC_{DCM} is the annual fuel consumed in the DC Microgrid in Litre/year = 6,986,488

Thus AFS=12544320 - 6986488 = 5,557,832 L

This amount to 44.3% saving in annual fuel consumption

5.2. Analysis for Carbon Dioxide Emission

The quantities of Carbon dioxide emitted by the existing network and the DC microgrid configuration were estimated using equation (2) and the quantity of fuel consumed and the result generated by HOMER® shown in Table 1.

The mass of carbon dioxide emitted during the combustion of fossil fuel is given in (United States Environmental Protection Agency, 2016) as:

$$M_{CO_2} = 3.67 dC_c \times M_{fuel} \tag{2}$$

Where;

C_c is the mass of carbon contained in the fuel

M_{fuel} is the mass of fuel consumed

The carbon content of diesel is 85.7%, density of diesel is 0.84kg/l (Meseguer et al., 2017).

Therefore, burning 1 L of diesel as fuel gives

$$M_{CO_2} = 3.67 \times 0.857 \times 0.84 \text{ kg} = 2.64 \text{ kg/l.}$$

Using the M_{CO₂} calculated for diesel and the annual fuel consumption from Table 1, the emitted carbon dioxide for both configuration were obtained as shown in Table 2.

Table 2: Carbon dioxide emission calculated for the existing and the DC microgrid models

	annual fuel consumption (L)	Carbon content of the fuel (kg/year)	carbon content of the fuel (un-emitted) (kg/year)
DC Microgrid Model	6,986,488	18,448,162	14,672,621
Existing model	12,544,320	33,114,483	0

Figure 3: The Direct Current System Network model configuration

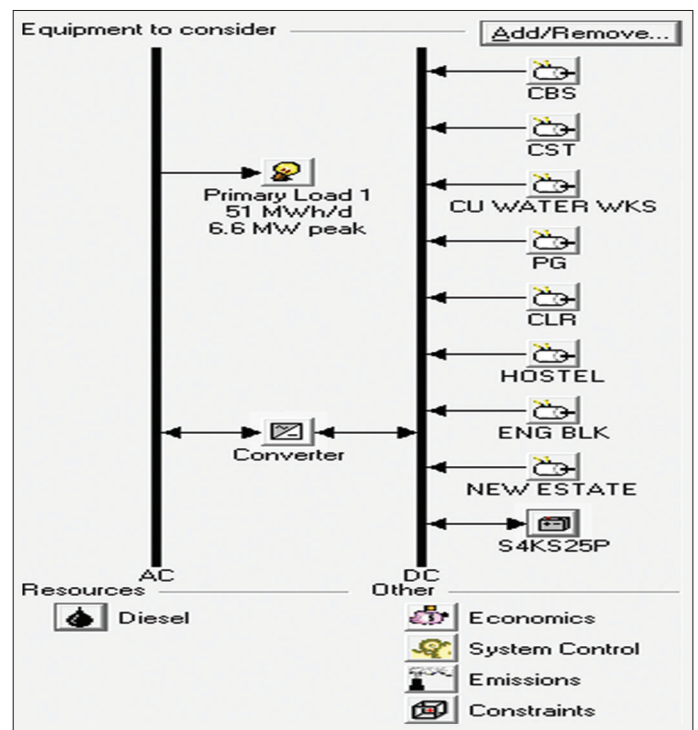


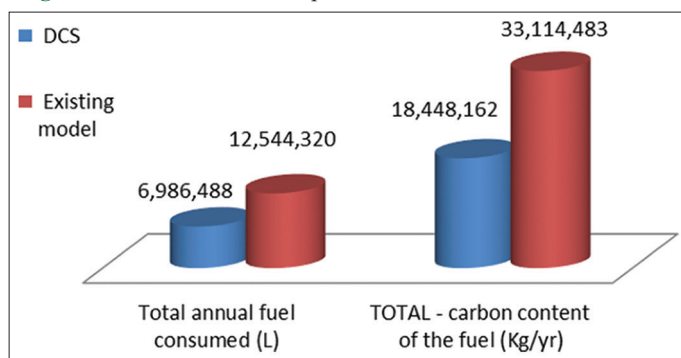
Table 2 shows that the existing network emitted 33,114,483kg of carbon dioxide/year while the optimized DC microgrid system emitted 18,448,162kg of carbon dioxide/year indicating a reduction of annual carbon dioxide reduction of 14,672,621 kg (44.3%). The plot of the total fuel consumption and emission for the existing network and the DC microgrid configuration is as shown in Figure 4.

Also, the CO₂ emission results obtained from simulation using HOMER is as shown in Table 3. The total CO₂ emitted from fossil based fuel (diesel in this case) was 33,134,483 and

Table 3: CO₂ emissions from the existing and DC microgrid models

Pollutant	Emissions from the DC Microgrid system (kg/year)	Emissions from the existing model (kg/year)
CO ₂ *	18,397,720	33,072,786
CO*	45,412	52,015
Particulate matter*	3,423	3,921
Unburned hydrocarbons*	5,030	5,761
Nitrogen oxides	405,216	464,135
Sulfur dioxide	36,946	42,318
Annual carbon content of the fuel	18,448,162	33,134,483

*Carbon-based component of the fuel burnt

Figure 4: Annual fuel consumption and emission for the two models

18,448,162 kg respectively for the existing and DC microgrid model. This validated the results obtained in Table 2.

6. CONCLUSION

In this study, an optimized DC microgrid network was proposed for carbon footprint mitigation. The covenant university power network was as a case study while HOMER software was used for the simulation. The existing covenant university power network and the proposed optimized DC microgrid system were modeled and simulated in the HOMER environment. The annual quantities of carbon dioxide emitted by the existing and the proposed models were estimated from the quantity of fuel (diesel) consumed and compared. The results showed that, with the proposed optimized DC microgrid system, the fuel consumption and emission of pollutants into the environment were reduced considerably. The quantity of fuel consumed per year was reduced from 12,544,320 to 6,986,488 L representing 44.31 percentage reductions in fuel consumption. The annual quantity of carbon dioxide emitted was also reduced from 33,114,483 kg to 18,448,162 kg. Thus the proposed model has the potential to mitigate carbon footprint.

Further works shall consider carbon footprint mitigation through the integration of renewable energy sources in the existing network.

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