Design and Analysis of a 1MW Grid-Connected Solar PV System in Ghana

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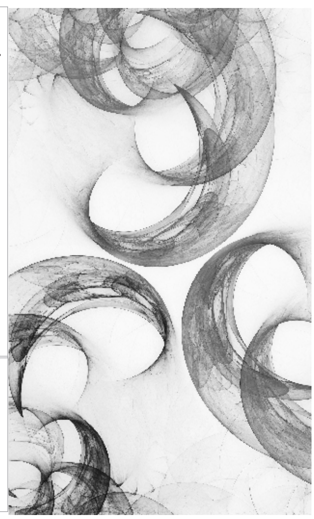

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Abstract

This study aims at developing a standard procedure for the design of large-scale institutional grid-connected solar Photovoltaic (PV) systems using the roofs of buildings and car parks. A prefeasibility study of renewable energy projects including grid-connected solar PV systems was conducted using RETScreen software, designed by Natural Resources Canada and used for. An extensive literature review of solar PV systems with a special focus on grid-connected systems was conducted after which the procedure for the design of institutional large-scale grid connected solar PV systems was developed. The developed procedure was used in the design of a 1 Megawatt (MW) grid-connected solar PV system for KNUST-Ghana. The performance of the system was simulated using RETScreen Clean Energy Project Analysis software and the results analysed. The analyses of the simulation results show that the project is socially beneficial to the community, in this case the university, with an annual energy yield of about 1,159 Megawatt hour (MWh) which is about 12% of Kwame Nkrumah University of Science and Technology (KNUST's) annual electricity consumption. The process of electricity generation from solar PV saves about 792 tonnes of CO_2. The yield factor, performance ratio and capacity factor were other technical performance parameters considered. Under the prevailing tariff conditions in the country, the project yields a very large negative net present value (NPV) and a simple payback period of about 50 years. These parameters, however, improve when higher feed-in tariffs, grants and capital subsidies are introduced into the simulation.

1. Introduction

There is a major challenge of providing reliable and continuous energy supply in Ghana, which has resulted in many power crises in the country over the past decade. Lessons from over-reliance on hydro-electric power generation have led the country to explore alternative forms of energy generation to meet the aspirations for full electrification. Solar power, one of the many renewable energy options, provides attractive benefits like environmental protection, job creation, and global potential for technology transfer and innovation. Ghana, and for that matter, the African continent in general, has the greatest potential for solar power projects with a greater part of the continent receiving about 300W/m2 of solar radiation annually.

Grid-connected solar Photovoltaic (PV) systems employ the direct conversion of sunlight into electricity which is fed directly into the electricity grid without storage in batteries. This option, like many other renewable energy options, is generally carbon free or carbon neutral and as such does not emit greenhouse gases during its operation, since global warming and climate change are mostly caused by the release of carbon dioxide and other greenhouse gases into the atmosphere.

A look at the world's map of mean solar radiations reveal that, Africa as a continent receives the highest amounts of solar radiation between 300 and 350 W/m^2 annually (Brew-Hammond et al., 2008). This makes the African continent, of which Ghana is a part, exceptionally suitable for solar energy projects. In spite of this huge potential, Africa still trails the rest of the world in terms of solar energy applications and energy services in general, thus referred to globally as the Dark Continent. The design and analysis of a 1MW grid-connected solar PV system for Kwame Nkrumah University of Science and Technology (KNUST), Ghana, will seek to reduce the amount of work involved in designing grid-connected solar PV systems, by coming out with a set of standard procedures that will make it easy for institutions to adopt. In the long run, it will help promote the use of grid-connected solar PV systems.

1.1 Problem statement

Most African countries are characterised by very poor access to electricity. The International Energy Agency in 2010 estimated Africa's electrification rate at 25%, the lowest on the globe. Yet, Africa receives the highest amount of solar radiation, which happens to be the most abundant source of energy on the globe. In spite of the huge solar radiation potential of Africa, the continent still trails the developed world when it comes to solar applications including grid-connected solar. It is for this reason that this project is being initiated to contribute to the development of grid-connected solar PV systems on the continent.

1.2 Objectives

The main objective of the project is to design a One Megawatt (MW) grid-connected solar photovoltaic system for KNUST-Ghana using roofs of buildings and car parks and to analyze its technical and financial performance using simulation software packages.

The specific objectives are as follows:

- To develop a standard procedure for the development of institutional large scale grid-connected solar PV systems. This would include; an assessment of area required; assessing the suitability of roofs of buildings and car parks for orientation, pitch, shading effects, etc.

- To test the developed procedure in the design of a 1MW grid-connected solar PV system in KNUST-Ghana.
- To simulate the performance of the 1MW grid-connected solar PV system using suitable software packages and conducting technical as well as financial analyses based on the software simulation results.

2. Literature Review

Photovoltaic systems are solar energy supply systems that convert sunlight directly to electricity. The chief component of a PV system is the solar panel which is formed by putting together several PV cells. Putting together several PV cells forms a PV module; several modules form arrays and several arrays form panels. The modular nature of PV cells makes it possible for them to be used for a wide range of power applications ranging from a few milliwatts in wrist watches and scientific calculators to several megawatts in central power stations. Solar cells are usually made of semiconductor materials such as silicon, gallium arsenide, cadmium telluride or copper indium diselenide (DGS, 2008).

Solar cells come in two major forms based on the nature of the material used in their production. The two main forms are crystalline solar cells and thin film solar cells. Crystalline solar cells, so far, have the highest conversion efficiencies when it comes to photovoltaic cells and the main types are monocrystalline and polycrystalline cells (DGS, 2008). Thin film cells, although less efficient than crystalline silicon, offer greater promise for large-scale power generation because of ease of mass-production and lower materials cost. The commonest example of thin film cells is the amorphous silicon cell (DGS, 2008).Photovoltaic systems can be grouped into two main groups; namely off-grid systems and grid-connected systems Solar Server (2010).

Solar PV is currently the fastest growing power generation technology in the world with about 38,584 megawatt (MW) capacity installed in the year 2010. In all, Europe alone contributes about 70% of the total installed capacity of PV systems with North America, Japan, China and Australia following in that order (EPIA et al 2010). Grid-connected systems make up the majority of these figures and this is as a result of favourable incentives such as feed-in tariff schemes, tax rebates and investment subsidies (EPIA et al, 2010; REN21, 2011).

The solar PV industry has also seen tremendous improvement in cell efficiencies for the various technologies available on commercial scale. This improvement in technology and the continuous growth of the PV market has led to drastic reduction in the cost of solar PV systems on the global market (EPIA et al, 2010).

The situation on the African continent is, however, not encouraging, with Africa contributing less than 1% of the world's installed solar PV systems (installed capacity of 163MW as at the end of 2010), in spite of the huge solar energy potential available to the continent (Brew-Hammond et al., 2008). This is as a result of the lack of policy instruments that help promote renewable energy technologies in general and also the very high initial capital involved in developing solar PV systems. Grid-connected solar PV systems are not that popular in Africa since most solar PV applications are employed in off-grid rural electrification projects to rural communities (for lighting, educational and health applications) that are far from the national grid (EPIA et al, 2010).

The situation in Ghana is not so different from the rest of the Africa continent with most solar PV systems employed in off-grid rural electrification projects. The Energy Commission of Ghana is, however, leading efforts to promote grid-connected solar PV in the country by partly sponsoring individuals and institutions to install grid connected solar PV and wind energy systems with capacities not less than 75 Kilowatt peak (KWp). The commission is also spearheading development of renewable energy law for the country which will provide incentives for the development of renewable energy technologies in the country including grid-connected solar PV. The Energy Commission and KNUST have each installed 4KWp grid-connected solar PV systems donated by the German state of North Rhine Westphalia to aid in research into grid-connected solar PV systems (MoE, 2010; Energy Commission, 2011).

2.1 Off-Grid Systems

Off-grid PV systems, as the name implies, are systems that are not connected to the public electricity grid. These systems require an energy storage system for the energy generated because the energy generated is not usually required at the same time as it is generated (DGS, 2008). In other words, solar energy is available during the day, but the lights in a stand-alone solar lighting system are used at night so the solar energy generated during the day must be stored for use at night. They are mostly used in areas where it is not possible to install an electricity supply from the main utility grid, or where this is not cost-effective or desirable. They are therefore preferable for developing countries where vast areas are still frequently not supplied by an electrical grid. Off-grid systems are usually employed in the following applications; consumer applications such as watches and scientific calculators, industrial applications such as telecommunications and traffic signs and remote habitations such as solar home systems and water pumping applications.

A typical off-grid system comprises the following main components:

- Solar PV Modules: these convert sunlight directly to electricity.
- Charge Controllers: manage the charging and discharging of the batteries in order to maximize their lifetimes and minimize operational problems
- Battery Or Battery Bank: Stores the energy generated by the PV modules
- Inverter: converts the DC current generated by the solar PV modules to AC current for AC consumer load (DGS, 2008).

2.2 Grid-Connected PV Systems

Grid-connected PV systems are systems connected to a large independent grid usually the public electricity grid and feed power directly into the grid. These systems are usually employed in both decentralised grid-connected PV applications and centralized grid-connected PV applications (DGS, 2008). Decentralised grid-connected PV applications include rooftop PV generators, where the PV systems are mounted on rooftops of buildings and building integrated system in which the PV systems are incorporated into the building (DGS, 2008). In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met by the PV system and the excess is fed into the grid; their capacities are usually in the lower range of kilowatts (DGS, 2008).

A typical grid-connected PV system comprises the following components:

- Solar PV Modules: these convert sunlight directly to electricity.
- Inverter: converts the DC current generated by the solar PV modules to AC current for the utility grid.
- Main disconnect/isolator Switch
- Utility Grid

Central grid-connected PV applications have capacities ranging from the higher kilowatts to the megawatt range (DGS, 2008).

3. Methodology

A prefeasibility study for the 1 MW grid-connected solar photovoltaic systems was conducted. It also included a greenhouse gas emissions analysis. The prefeasibility study was undertaken to identify the total estimated area required for the installation of the 1MW system as well as the basic economics of the project including the simple payback period and net present value for the project.

A zero-order draft procedure, which included the various steps required for the achievement of the project objectives, was prepared to aid in the project and was updated from time to time until a standard procedure was developed which could be replicated in other institutions. The zero-order draft procedure included steps such as solar resource assessment for KNUST, a study of buildings and car parks to ascertain the total area available, as well as an assessment of the structural properties of the roofs and their ability to carry the weight of the solar panels. The structural analysis carried out on the selected buildings for the PV installations was done with the help of structural engineers from the Civil Engineering Department-KNUST. The results of roof assessments and the technical specifications of the solar PV systems led to the designing of the layout of the system.

The performance of the system was then simulated using RETScreen Clean Energy Project Analysis Software; a software developed by Natural Resources Canada to undertake prefeasibility as well as full feasibility studies for most renewable energy projects. The software, which comes with inbuilt solar radiation data for various locations including KNUST-Ghana, as well as system specifications from various manufacturers, has the capability of simulating technical and financial performance of renewable energy systems over the entire project life.

4. Results and Findings

4.1 Solar Resource assessment

Solar resource assessment for the location was performed to determine the amount of solar radiation reaching the location and at what orientation and inclination a solar device will receive maximum radiation. Data used for this study was from the Solar and Wind Resource Assessment (SWERA) report for Ghana, developed by the Mechanical Engineering Department of KNUST for the United Nations Environment Programme (UNEP). This data is from actual ground measurements of solar radiation using a solar radiation measuring device. This data was compared to some satellite data from the American Space Agency (NASA) (used in the RETScreen Software), and also PVGIS-Helioclim developed by the Joint Research Commission of the European Commission and is shown in Figure 1.

The daily horizontal solar irradiance for Kumasi (KNUST) chosen for this study was 4.30kWh/m2/day based on radiation data in the Solar and Wind Resource Assessment (SWERA) database.

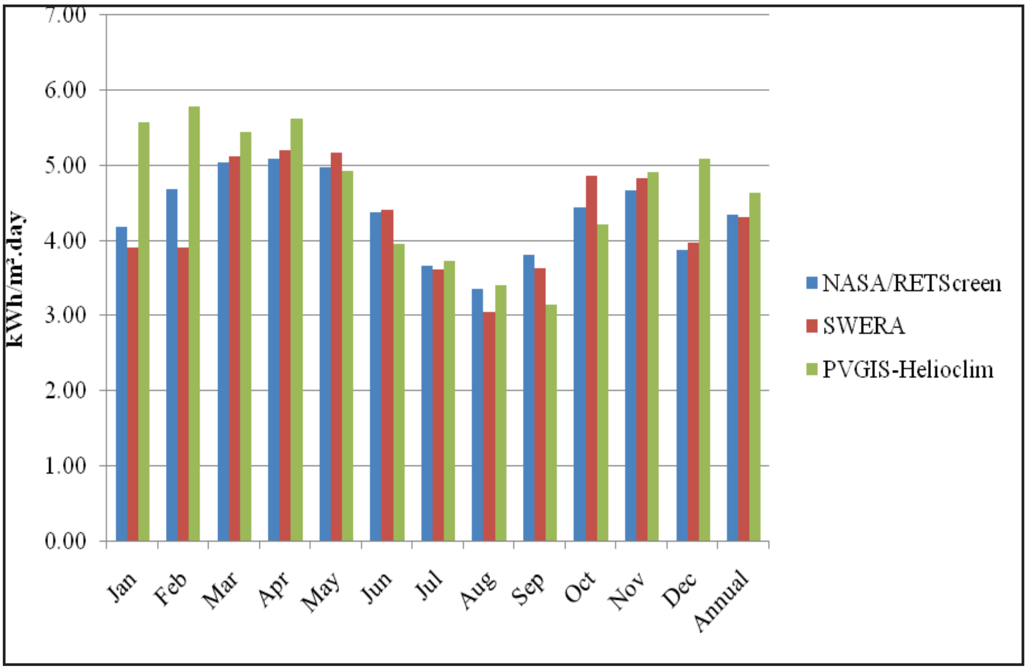

Figure 1: Comparison of solar radiation data from 3 different sources

For roof mounted systems, the maximum amount of radiation is limited by the properties of the roof such as pitch/slope and orientation which cannot be changed. Roofs in KNUST mostly have slopes of about 15^o, since the slopes are mostly to prevent rainwater from staying on the roofs. Figure 2 shows the solar radiations at the different orientations (south, north, east and west) for a 15^o, angle of inclination. It can be observed from figure 2 that, south facing roofs receive the highest amount of solar radiation for the specific location.

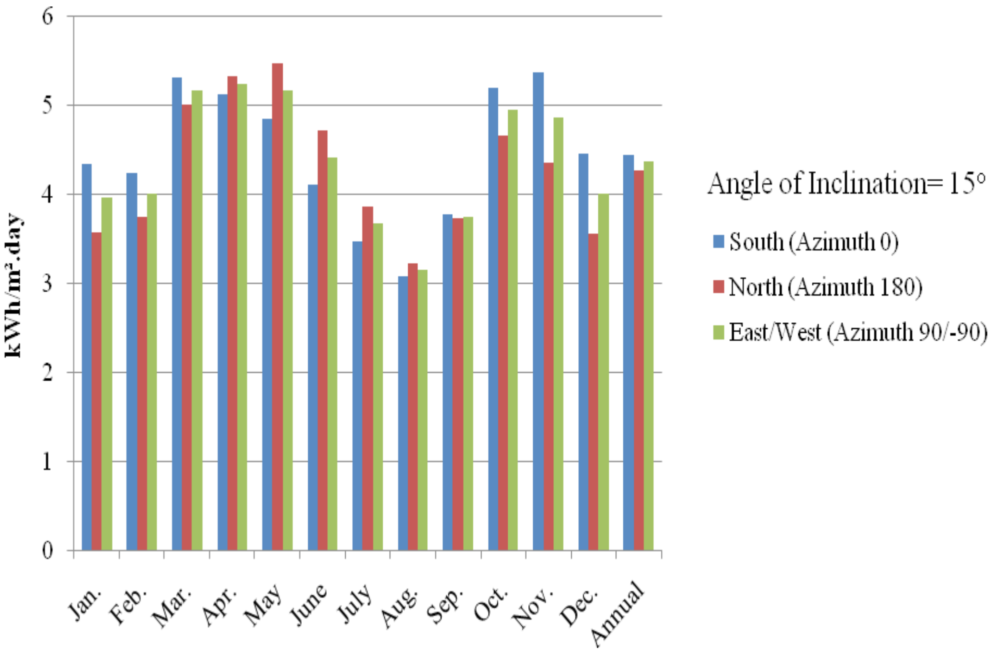

Figure 2: Solar radiation at 15°, inclination and different orientations

4.2 Building roof assessment and solar system selection

The roof assessment revealed that the total amount south-facing roof space available on the campus is about 9,434 m2 covering a total of about fifty five (55) faculty buildings on the campus which are suitable for the installation of solar panels and accessories.

The selection of the components of the solar PV system was done with the help of catalogues from various dealers both local and international. In all, polycrystalline silicon panels were selected because their performance was very good and also they are moderately priced compared to Monocrystalline (which have the highest performance but the most expensive of the three) and amorphous silicon (which has the worst performance but the cheapest of the three). The detailed specifications of the selected panels are shown in the table below:

Table 1 Specifications of selected panels

Nominal power	190W	Voltage at Nominal Power (Vmpp)	36.4V
Efficiency (ŋ)	14.1%	Current at Nominal Power (Impp)	5.22A
Area (A)	1.31m^2	Open Circuit Voltage (V_oc)	45.2V
Cell type	Mono-Si	Open Circuit Current (I_oc)	5.46A
Weight	15.5kg	No of Cells	72

4.3 Technical Performance

The international energy agency (IEA) Photovoltaic Power Systems Program outlines the parameters used to describe energy quantities for PV systems and their components. These parameters include the total energy yield, the yield factor, the performance ratio and the capacity factor and they help in the comparison of similar projects to determine which works best. The total energy yield is the total amount of energy generated by the system and in the case of grid-connected PV systems, the total amount of electricity that is injected into the utility grid. The result of the simulation shows that, the total energy to be generated by the 1MW grid-connected solar PV system is estimated at 1,159MWh/year. This is about 12% of KNUST's annual electricity consumption. Figure 3 shows the average monthly energy yield for the system.

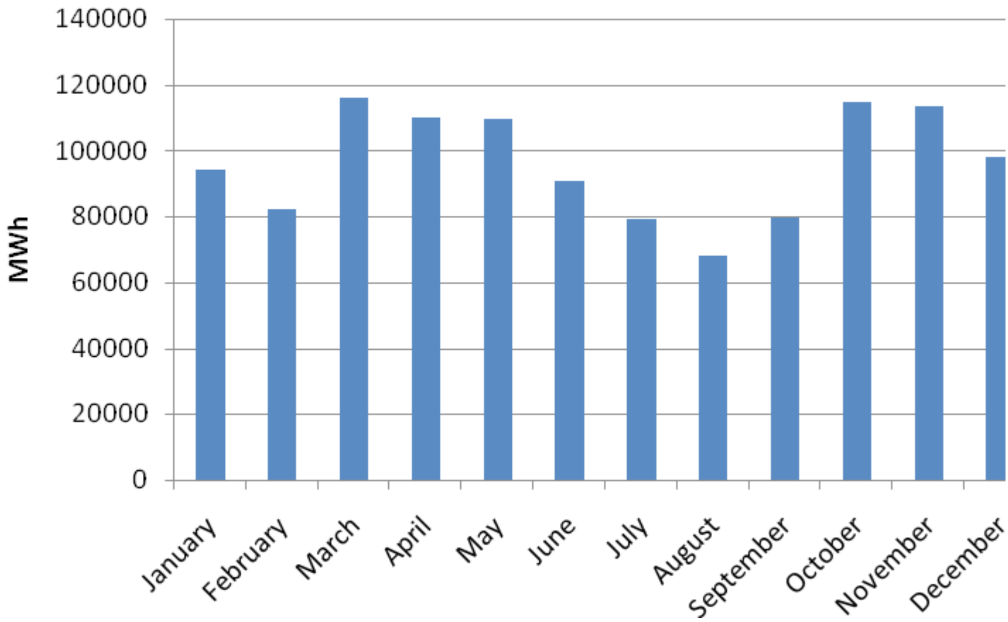

Figure 3: Average monthly energy yield of the proposed 1MW PV system

Yield factor (YF) refers to the plant's specific performance in net kWh delivered to the grid per kW of installed nominal PV module power. This is also equivalent to the number of full load hours for the plant.

The reference yield, Y_r, is the ratio of the total irradiance reaching the surface of the PV array (in-plane irradiance) to the PV array's reference irradiance (which is 1,000W/m^2 for STC). Performance ratio (PR) is defined as the actual amount of PV energy delivered to the grid in a given period, divided by the theoretical amount according to STC data of the modules.

Performance ratios of 70% and above are considered to be very good performing systems. The Capacity factor of a power plant is the ratio of the actual output of a power plant over a period of time and its potential output if it had operated at full nameplate capacity the entire time. Table 2 gives a summary of the key results.

Table 2: Summary of the key technical results for the proposed 1MW system

Performance at the inverter output		
Output	**Unit**	**Total**
Energy Yield	MWh/year	1,159

Yield Factor	kWh/Kwp/year	1,163
Reference Yield	hours	1,565
Performance Ratio	%	74.30
Capacity factor	%	13.2

4.4 Economic Analysis

The economic analysis of the 1MW grid-connected solar PV system was carried out to assess the cost and intended benefits of the project. It was carried out with the help of RETScreen software. The software is easy to use and has the capability of simulating the net present value and simple payback period as well as estimating the greenhouse gas saving potential of renewable energy projects over their entire operational life. The NPV and simple payback period will help determine how feasible the project will be. The total investment cost comprises the following components; module, inverter, cables, mounting structures, engineering and project management, labour and miscellaneous costs. The costs of the various solar PV components used for this study were international prices taken from renowned online solar PV research firms such as Solar buzz (solar market research and analysis), SolarServer (an online portal to solar energy) and Greentech Media Inc. These institutions compile price changes of solar components periodically. The module and inverter cost alone makes up about 76% of the total investment cost. Table 3 below shows a breakdown of the total investment cost. The total investment cost for the 1MW project is estimated at US$5,000,000.

Table 3: Cost breakdown for the Grid-Connected Solar PV system

Component	Cost (US$/W)
Module	3.10
Inverter	0.72
Cables	0.15
Mountings	0.25
Eng & PM	0.10
Labour	0.25
Miscellaneous	0.43
Total	5.00

The economic analysis for this work was done by first developing a base case scenario consisting of the present electricity cost and other financial parameters. Subsequent scenarios were then developed from this base case to help analyse the implications of the various financing options on the project. Some of the options considered include grants/ capital subsidies, feed-in tariffs (FiT) and carbon credit financing. The parameters used to develop the base case include;

- Solar PV system cost = US$5.00/W
- Operating and Maintenance Cost =US$0.01/kWh
- Electricity Export Rate =US$0.08/kWh(Bulk generation charge)
- Project Life =25years (solar panel guarantee period)
- Discount Rate =10%
- Inflation Rate =0%

- Grant/Capital Subsidy =0%
- GHG Credit =US$0/tonne

The base case scenario results in a simple payback period of about 62 years, which is more than twice the project life. However, applying a feed-in tariff scheme to the base case scenario as show in figure 4 indicates that it is possible for the project to be paid for within its lifetime with a feet-in tariff of about US$0.20/kWh. Figure 5, on the other hand, shows that, the project will be viable only if a feed-in tariff of about US$0.38/kWh is paid for electricity generation.

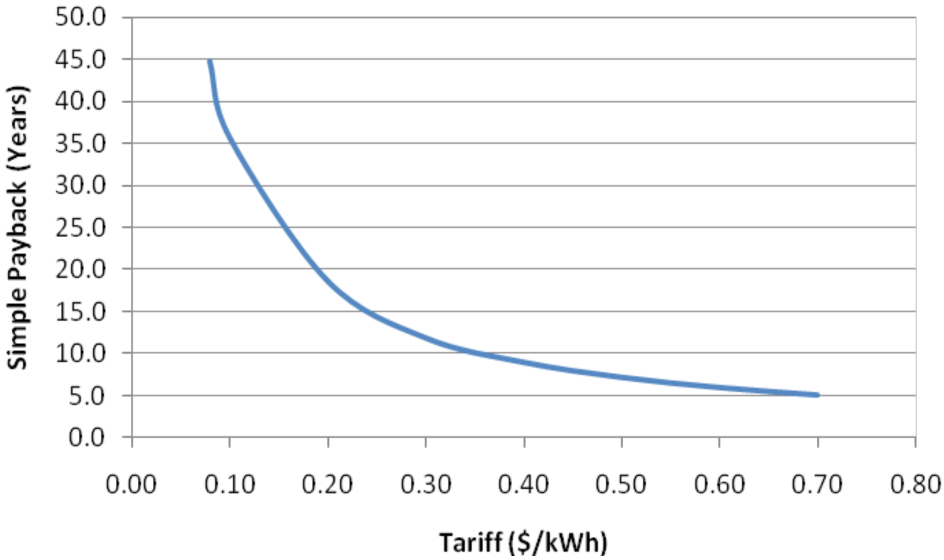

Figure 4: Feed-in tariff scenario

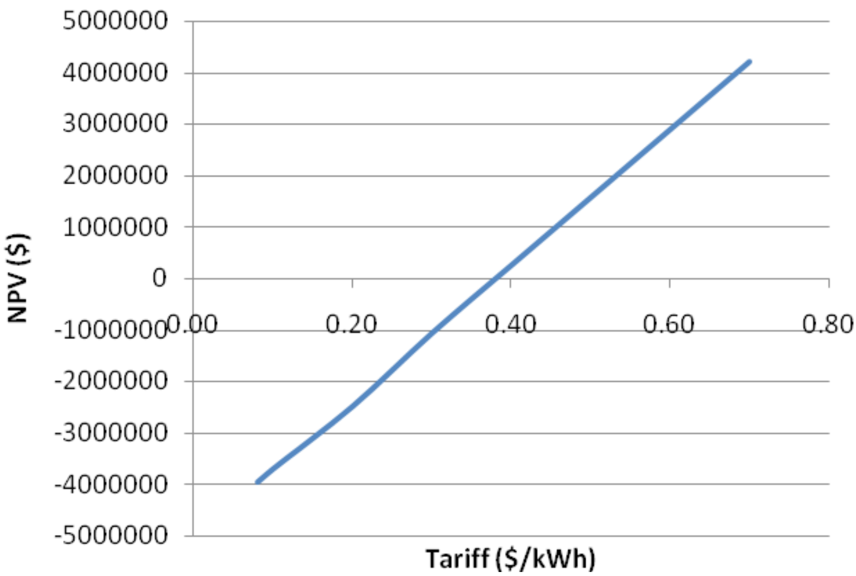

Figure 5: Net Present Value of the Project

5. Conclusion

The design of a roof-mounted grid-connected solar PV system required that a solar resource assessment be carried out for the KNUST. This revealed that, KNUST receives about 4.30kWh/m2/day according to the SWERA data for KNUST. The roof assessment also revealed that, a 1MW solar system would require a total of about 5,900m2 of total roof space for the installation. These roofs must be oriented southwards in order to receive the maximum amount of solar radiation. In selecting the solar PV components, both international and local dealers were contacted and the best in terms of performance and cost were selected. A polycrystalline PV module was selected because if combines benefits from both cost and total area required.

The analysis of the RETScreen simulation results reveal that, the system when installed will generate an average of about 1,159MWh of electricity a year; which is about 12.5% of KNUST's electricity consumption needs with a performance ratio of 73.40%. The project also stands the chance of saving about 850 tonnes of CO2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity.

The financial analysis of the simulation results indicate that, at the prevailing bulk generation charge of about US$0.08/kWh and a total system cost of about US$5/Wp, the project can be considered as not financially viable since its payback period will be about 45 years. It is important to note that, a tariff of about US$0.38/kWh will make the project more financially viable. There are also some non-financial benefits like the greenhouse gas emissions savings which can in the long run help mitigate the adverse effects of the climate change problem plaguing the entire earth.

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