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

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Abstract

This study aimed at developing a standard procedure for the design of large-scale institutional grid-connected solar PV systems using the roofs of buildings and car parks. The standard procedure developed was validated in the design of a 1MW grid-connected solar PV system for Kwame Nkrumah University of Science and Technology (KNUST), Ghana. The performance of the 1MW grid-connected solar PV system was also simulated over the guaranteed life of the system using RETScreen Clean Energy Project Analysis software, designed by Natural Resources Canada. The project began with a prefeasibility study of a 1MW grid-conducted solar PV system using RETScreen software which has a broad database of meteorological data including global daily horizontal solar irradiance and also a database of various renewable energy systems components from different manufacturers. 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 1MW grid-connected solar PV system for KNUST-Ghana. The technical and financial performances of the 1MW grid-connected solar PV system were simulated using the RETScreen software. The preliminary analyses of the simulation results showed that the project is socially beneficial to the community in this case the university with an annual energy yield of about 1,159MWh, which is about 12% of KNUST's annual electricity consumption. The process of electricity generation from solar PV saves about 792 tonnes of CO2. The yield factor, performance ratio and capacity factor were other technical performance parameters considered. Under the prevailing tariff conditions in the country, the project is not financially viable without incentives such as grants and feed-in tariffs.

1. Introduction

This study is being conducted with the aim of developing a standard procedure for the design of large-scale institutional grid-connected solar PV (Photovoltaic) systems using the roofs of buildings and car parks. The standard procedure developed will be validated in the design of a 1MW grid-connected solar PV system for KNUST (Kwame Nkrumah University of Science and Technology)-Ghana. The performance of the 1MW grid-connected solar PV system will also be simulated over the guaranteed life of the system using solar PV planning and simulation software packages such as PVSyst and RETScreen.

The study is necessary because Ghana has experienced a number of power crises over the last two decades, mainly due to the heavy reliance on hydroelectric power which is more often than not dependent on the rain fall pattern of the country. It has been estimated that grid electricity demand would grow from about 6,900GWh to 18,000GWh between 2000 and 2015 and even up to about 24,000GWh by the year 2020 (Energy Commission, 2006). In order for Ghana to ensure secured uninterrupted electricity supply by the year 2020, the existing installed capacity of 1760MW must be doubled (Energy Commission, 2006). The economy of Ghana must grow at a GDP of between 8-10% if it is to attain the status of a middle income country and these growth rates require significant amount of electricity (Brew-Hammond et al., 2007). The government of Ghana has targeted 10% of the country's electricity generation from renewable energy and this will come mainly from solar, small and medium sized hydros, wind, biomass and municipal solid wastes (Energy Commission, 2006).

A look at the world map of mean solar radiations reveal that, Africa as a continent receives the highest amounts of solar radiation between 300 and 350 W/m2 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 globally as the Dark Continent in general; thus referred globally as the Dark Continent.

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 will be a very good way to boost the existing electricity production capacity in the country, which is mainly from hydro and thermal sources. This will contribute positively to the worsening energy situation in the country. Solar energy, being a renewable source, will also provide energy without pollutants and greenhouse gas emissions. This can go a long way to help mitigate the adverse effect of global warming as well as contribute to sustainable energy development. It will also set the pace for similar projects to be developed in other institutions thereby helping attain the target of 10% renewable energy in the electricity generation mix set by the government.

The main objective of the project is to design a 1MW grid-connected solar photovoltaic system for KNUST-Ghana using the roofs of buildings and car parks and to analyze the technical and financial performances based on the results of 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 analysis based on the software simulation results

2. Literature Review

Photovoltaic systems are solar energy supply systems, which convert sunlight directly to electricity. The chief component in PV systems 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 (DGS, 2008).

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 in the night. They are mostly used in areas where it is not possible to install an electricity supply from the mains 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).

Grid-Connected PV Systems

Grid-connected 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 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 incorporated into the building's integrated system (DGS, 2008). In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is served 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).

Solar PV is currently the fastest growing power generation technology in the world with about 38,584MW 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 75kWp. The commission is also spearheading development of a 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 both have installed 4kWp grid-connected solar PV systems each, donated by the German state of North Rhine Westphalia to aid in research into grid-connected solar PV systems (MoE, 2010; Energy Commission, 2011).

3. Methodology

The project began with a literature review of solar photovoltaic systems. This was followed by a simple prefeasibility study (using RETScreen or other suitable software) to obtain an idea of the amount of energy that will be generated by the system, estimate the total space (area) required for the installation of the system and access the economics of the whole project.
A draft procedure for the design of grid-connected systems was prepared which will be updated from time to time (in the course of the design of the 1MW grid-connected system for KNUST-Ghana) until a standard procedure is developed which can be used to replicate the design of large-scale grid-connected solar PV systems in other institutions.

The draft procedure comprises the following steps;

1. Assessment of the solar radiation data for the location from various institutions such as the American Space Agency (NASA), the Joint Research Commission (JRC) of the European Commission and UNEP which helps to estimate the amount of electricity generated. Most simulation software packages also have inbuilt solar radiation data which can be used for this same purpose.
2. Obtain a land use map of the location showing the various sites that can be used for the project.
3. Confirm the various locations on the land use map and update where necessary.
4. Identify various building roofs and car parks that can be used for the project based on a minimum roof area.
5. Identify grid access and requirement for grid connection
6. Obtain the dimensions of the roofs of the selected buildings and car parks to be used.
7. Assessment of roof properties such as roof type, roof area, roof orientation, pitch/slope, strength of roof and the effect of shading on the roofs.
8. Selection of suitable roofs and collation the total area available PV system design.
9. Obtain solar PV information from various solar dealers both locally and internationally. This information should include; type, cost, size, weight, etc
10. Design the layout of the system for each of the selected building roofs

This draft procedure was followed in the design of a 1MW grid-connected solar PV system for KNUST-Ghana and update where necessary. A Simulation of the technical and financial performance of the design was conducted using planning and simulation PC software packages; PVSyst, developed by the Group of Energy of the Institute for the Sciences of the Environment of the University of Geneva in Switzerland and RETScreen Clean Energy Project Analysis Software, developed by Natural Resources Canada. The draft procedure will be updated based with the information gathered from the various components of the design until a standard procedure which can be used to replicate the design of such grid-connected PV systems is obtained.

Design of a 1MW grid-connected PV system

The design of the 1MW solar PV systems was based on the procedure developed in the methodology. Three solar radiation datasets; Solar and Wind Resource Assessment (SWERA) which was developed by the Mechanical Engineering Department of KNUST, for

the United Nations Environment Programme (UNEP), satellite data from the American Space Agency NASA (used in the RETScreen Software) and also PVGIS-Helioclim developed by the European Commission were compared. The radiation data from SWERA was chosen for the study because it comes from actual ground measurements of the solar radiation.
In all, 54 buildings with a total area of 34,292m2 were assessed based on the criteria mentioned in the methodology out of which 24 buildings with a total roof area of about 9,120m2 facing the south were selected. South facing roofs were selected because they receive the highest amount of radiation.

An assessment of solar PV components was then conducted with information from various manufacturer out of which the most cost effective components were selected. Table 1 gives a summary of some of the basic design parameters used in the design of the 1MW grid-connected solar PV system.

Table 1: Summary of the basic design parameters for the 1MW grid-connected solar PV system

Meteo Data	
Daily horizontal irradiation	4.30kWh/m2/day
Building Orientation	
Number of Buildings selected	13
Total Roof Area	9,120m2
Roof Pitch	15^o
Roof orientation	South
Module-Inverter Details	
Module Type	Polycrystalline (Sharp ND-U235Q2)
Module capacity	240Wp
Module Efficiency	14.4%
Total Installed Module capacity	1000kWp
Number of modules	4,255
Inverter Capacity	1000kW
Inverter Efficiency	97%
Number of inverters	13

4. Analysis of Results

The analysis of the preliminary results includes the technical and financial analysis for the "Design and Analysis of a 1MW Grid-Connected Solar PV System KNUST-Ghana" and this was carried out with the help of two planning and simulation PC software packages.

Technical Analysis
The technical analysis was done with the help of PVsyst software, a PC software package for the study, sizing, simulation and data analysis of complete PV systems. The software has an extensive database of meteorological data for different locations, system components and their specifications from manufacturers and simulates the performance of the PV system, taking into consideration the various possible losses.

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 ration 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 1 shows the average monthly energy yield for the system.

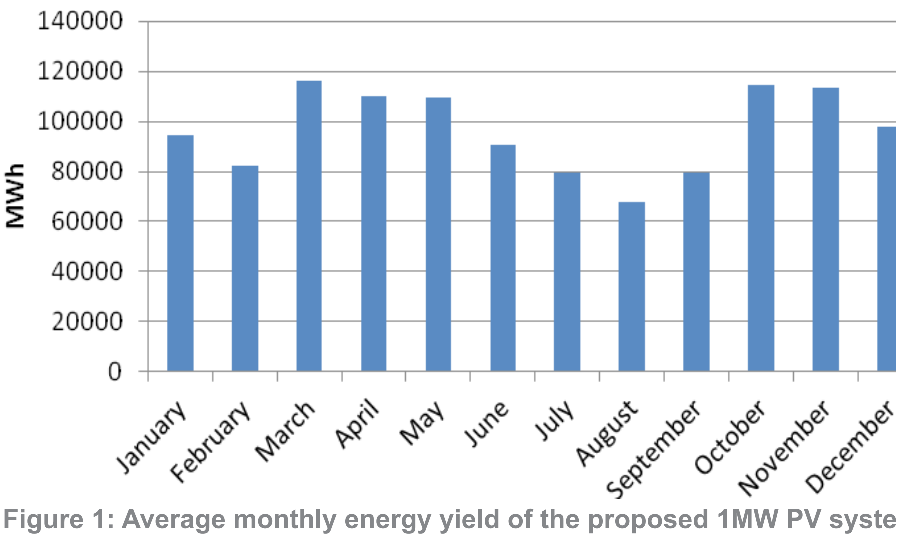

Figure 1: Average monthly energy yield of the proposed 1MW PV system

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, Yr, 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/m2 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

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 estimates taken from renowned online solar PV research firms such as Solarbuzz (solar market research and analysis), SolarServer (an online portal to solar energy) and Greentech Media Inc. The module and inverter cost alone makes up about 76% of the total investment cost. Table 3 contains 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
Engineering & Project Management	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:

Table 4: Parameter for base case scenario

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

It is interesting to note that, 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 2 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.

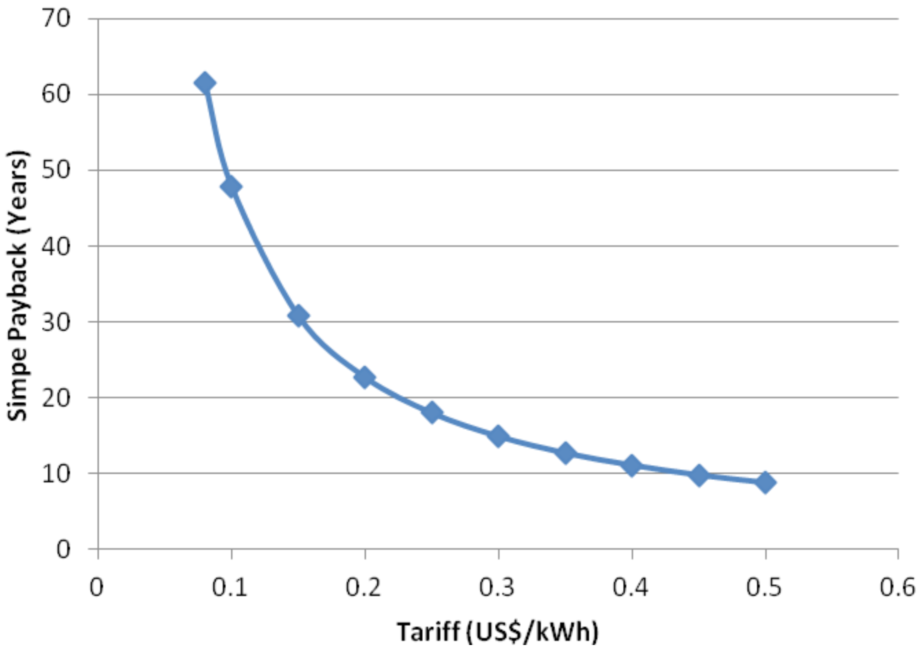

Figure 2: Feed-in tariff scenario

5. Conclusion and Recommendations

The draft procedure developed touches on some very important issues to be considered in the design of institutional large-scale grid connected solar PV systems using roofs of buildings and car parks. Notable among these design steps are the assessment of the solar radiation data for the location, the identification and assessment of the roofs of buildings as well as the subsequent selection of suitable roofs, selection of solar PV system components and finally, designing the layout of the grid-connected PV system.

In designing the 1MW grid-connected solar PV system for KNUST-Ghana, the draft procedure developed was followed critically. A practical assessment of the various items was conducted and the lessons drawn from them used to update the draft procedure. At the end of the design of the 1MW grid-connected PV system for KNUST-Ghana, a standard procedure should be developed which can be used to design large-scale grid-connected solar PV systems.

Analyses of the simulation results show that, the project when implemented will supply about 1,159MWh electricity annually, which is about 12% of KNUST's annual electricity consumption. The project also stands the chance of saving about 792 tonnes of CO2 which would have been emitted by a crude oil fired thermal power plant generating the same amount of electricity. At the prevailing tariff conditions in the country, this project can be considered as not financially viable except with feed-in tariff scheme or other incentives such as grants/ capital subsidies are applied. However, the other non-financial benefits like the greenhouse gas emissions savings can, in the long run, help mitigate the adverse effects of the climate change problem plaguing the entire earth.

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