Planning of sustainable and stable micro grids for Ghanaian hospitals with photovoltaics

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ABSTRACT

Despite good solar irradiation conditions, power supply by photovoltaics (PV) in Ghana is still underdeveloped. Due to frequent blackouts, the power supply of Ghanaian hospitals by the national grid is mainly backed up by individual diesel generators. But the tremendous decrease of the prices of solar power and rising costs of diesel makes photovoltaics an attractive substitute for diesel generation, lowering power costs and environmental impact. In combination with batteries, photovoltaics may even fully substitute existing generator systems.

At the Cologne University of Applied Sciences already gathered experience in modelling such systems based on real-world experiments. Unlike common tools like e.g. HOMER, a self-created tool for the planning and implementation of microgrid systems include more precise models to depict the behavior of the different system components like photovoltaics (PV), battery energy storage systems (BESS) and diesel generators. For PV and BESS professional opensource models can be used. For the behavior of a diesel generator in case of higher load fluctuations an own model was developed based on real-world experiments.

In addition, the Cologne University of Applied Sciences installed several PV power plants at the St. Dominic’s Hospital in Akwatia in Ghana. These projects deliver valuable insights into the planning and operation of such PV systems. As a continuation, the EnerSHelF project (Energy Self-sufficiency for Health Facilities in Ghana) initiated and coordinated by the University of Applied Sciences Bonn-Rhein-Sieg aims to close gaps in available load and meteorological data. Thus, more precise potentials of sustainable improvement of the power supply of the Ghanaian health sector shall be analyzed. For this purpose, the Cologne University of Applied Sciences carries out several measurements of the power consumption of the sector-specific loads together with Ghanaian partners. The real-world measurements help to apply the self-created tool to Ghanaian circumstances.

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This paper presents a first approach to apply the self-created tool to design micro grid power systems to a Ghanaian health facility micro grid with load data from 2015 and only back-up by a diesel generator. Local measured PV profiles from 2016 could be used to simulate an even more realistic behavior of scalable PV. Calculations show a maximum improvement of Levelized Cost of Electricity by 2.4 ¢/kWh and 29 tons of CO_2 emission savings by adding 150 kWp of PV and no BESS. However, there are also profitable solutions with a BESS which can even save up to 60 tons of CO_2 emissions.
The authors know of no comparable study that has applied such an analysis of microgrid design to health facilities in sub-Saharan countries.

KEYWORDS

micro grid, planning tool, Ghana, renewable energy, diesel generator, health facilities

INTRODUCTION

Ghana is a country with a high solar energy potential. The yearly sum of Global Horizontal Irradiance in ranges from 1600 to 2050 kWh/m^{2}a [1]. However, the energy supply by photovoltaics (PV) is still underdeveloped with a supply share of less than 1% of the yearly demand [2]. Since 2014 hydro power generation decreased in Ghana, while fossil thermal power generation increased although there is a high solar energy potential [3]. Furthermore, the quality of supply in the electricity distribution grid is low, since often outages occur.
Given the above-mentioned facts, the supply of a critical infrastructure, such as health facilities, is a challenge. To ensure the power supply of such facilities, their micro grids are usually backed up by diesel generators. However, due to the price decrease of PV power plants, they can help to lower the levelized cost of electricity (LCOE), to improve in combination with Battery Energy Storage Systems (BESS) supply security and to transform the energy supply system towards 100% renewable energy.
To plan and initiate such renewable based micro grids in the health sector of Ghana the existing local structure of electricity consumption, generation and transmission has to be known. However, often only few or insufficient information is available yet.
Within the scope of the EnerSHelF project (Energy Self-sufficiency for Health Facilities in Ghana) data about the structure of electricity demand, supply and power quality are collected in collaboration with the Kwame Nkrumah University of Science and Technology (KNUST) in Kumasi, Ghana [4].
A common and widespread tool to design such micro grid systems is HOMER [5]. However, it computes its operational energy dispatch strategies and technical component behavior with simplified models and methods.
However, more and more valuable and realistic simulation models for individual components are available with an open-source-license within the Python-universe [6]. PVLIB [7] is a library with simulation tools for the behavior and yields of PV plants including a number of precise models like e.g. different single diode models [8]. BESS including the thermal behavior and aging processes can be simulated in SimSES [9]. Wind power plants and their energy yield can be calculated by windpowerlib [10]. The simulation of energy systems and its infrastructure can be done by means of oemof [11] or more detailed in pandapower [12].

The authors already have a lot of experience in modelling and optimally design renewable based micro grids under varying atmospheric conditions and for context specific energy demand-patterns A self-created tool by the Universities of Applied Sciences in Cologne to design and plan such micro grid energy systems works with realistic models [13]. This tool is expanded by a load model for Ghanaian health facilities during EnerSHelF. Furthermore, guidelines for the implementation of such sector- and country-specific micro grids will be created.

This paper applies the planning and design tool including analyzes of the profitability and CO_2 emission savings to a health facility in Ghana. Such an analysis is not yet known to the authors.

MICRO GRIDS IN GHANA

Renewable energy represents 0.2% of the electricity generation mix in Ghana as of 2018. The generation is dominated by thermal (62.76%) and hydro (37%) [2]. Though, the electricity access rate (84.3% in 2018) is one of the highest in Sub-Saharan Africa, the reliability of the supply is a major problem which affects all sectors of the economy including the health sector. Within hospitals, sensitive units such as surgical operating theatres require a reliable supply of electricity for safe and effective health care delivery. Some health care facilities are using backup diesel generators to complement the national grid.

Studies were conducted in other parts of the world but for different sectors, different climatic conditions and different macro-economic indicators. Usman et al. in 2018, in Indian, compared the coal-based grid system with PV hybrid grid connected and PV hybrid diesel generator systems. They concluded that the grid had the lowest LCOE followed by PV grid connected and by the standalone PV diesel system [14]. Similarly, in Cambodia, a techno-economic analysis of hybrid PV system for rural electrification was performed by Lao et al, (2017) [15]. They found that the combination of PV, storage battery and gensets had the least cost of energy and was more environmentally friendly than other options.

Ghana having different prevailing conditions than the above-mentioned countries, it is worth investigating the potential of solar PV systems in supplying reliable, affordable and sustainable energy but limiting the scope to healthcare facilities. First assessments were done in Northern Ghana. By examining several scenarios with Generator, PV and/or BESS estimations of the LCOE resulted in between 0.12 (only PV & BESS) and 0.81 US$/kWh (only Generator). PV with battery storage and hybrid PV-Diesel with battery storage are financially advantageous compared to using the national grid as health facilities fall under commercial customers. The tiered rate structure is used in Ghana where the more electricity is consumed, the higher the price per kilowatt-hour [16]. Health facilities who consume more than 600 kwh/month pay as high as US$ 0.290/kWh.

Although solutions with BESS may result in best LCOE and lowest CO_2-emissions, they demand a much higher investment. Since the monetary inflation in Ghana ranges at least between 10 and 20 %, it is difficult to get lending rates below 20% for further investments [17]. Thus, it would be useful to identify feasible system solutions with low investment at the implementation start and with possible small-step improvements towards an optimum of system costs and environmental impacts.

PLANNING TOOL

The planning tool is developed at the University of Applied Sciences in Cologne and is based on the Python programming language [6].
The tool consists of several layers. The overall structure is shown in Figure 1.

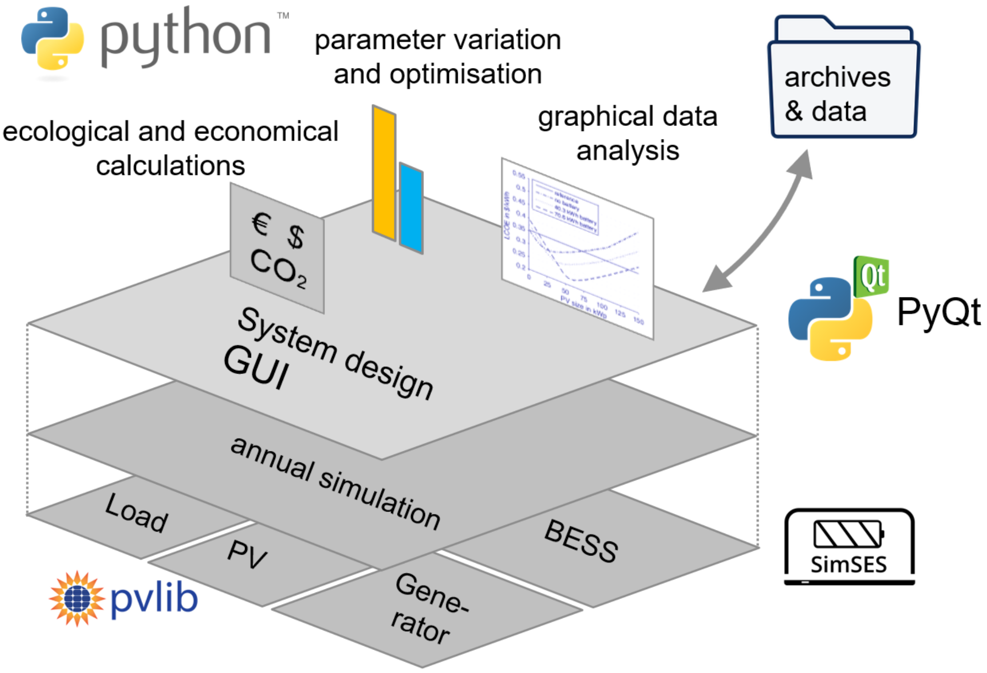

Figure 1: Layer-structure of the tool by the University of Applied Sciences in Cologne

According to Figure 1, the lowest program layer consists of models to simulate the single component behaviour in a preferably realistic manner. Table 1 gives an overview of the models in use within the planning tool.

Table 1: Models in use within the planning tool

Component	*Model in use*	*Open source*
PV	single diode model by PVLIB [7]	yes
BESS	SimSES [9] for Li-Ion battery systems **or**	yes
	Shepherd model [18] for Lead-Acid battery systems	not yet, in progress
Diesel Generator	Self-created dynamic loading model based on the generator Break Specific Fuel Consumption (BSFC)	not yet, in progress

Especially the model of the diesel generator is based on empirical real-world studies of dynamical loading of diesel generators. Such dynamic load steps can more and more occur in micro grid systems with PV, since PV power may fluctuate due to weather conditions.

These models are included in an annual system simulation (layer 2, cf. Figure 1). In this program layer several energy dispatch strategies can be chosen to be conducted within a time series analysis over one year. The strategy used in this paper is described in [13] and is used to find a compromise between loading of the battery and generator which both cause ageing respectively wear and tear of the components.
The annual system simulation is embedded into techno-economic analyses including calculation of the LCOE over a certain period (default over 20 years of lifetime) and CO_2-emissions. Further, there are options like parameter variation, parameter optimization and multi-objective pareto-optimizations to find the optimal system design with individual planning objectives [19].
Moreover, the whole tool with its settings can be controlled by means of a graphical user interface using TkInter [20]. For simulating an individual new system, it can access to an own archive with data for of over 400 diesel generators, 700 PV modules and 70 BESS.

APPLICATION

The planning tool is applied to an exemplary Ghanaian health facility. The known electricity supply and demand infrastructure is shown in Table 2.

Table 2: reference electricity supply infrastructure of an exemplary Ghanaian health facility

Component	*Size*
Grid Transformer	200 kVA
Back-up Diesel Generator (2x)	250 kVA
Total installed Loads	700 kVA
Common maximum load	180 kVA

The tool is applied to a given real measured load profile (15 min. resolution) of the overall hospital in an area of the Köppen-Geiger climate classification of tropical savanna [21]. For PV yield calculations a real measured profile of a new PV plant at the given site can be used. Here, the PV profile of 2016 is applied to the load profile in 2015 (without PV generation), assuming the load did not change during that year. Further assumptions are a fuel price of 0,9 $/l and an electricity charge of 0.24 $/kWh, what usual values are for the region. Furthermore, investment costs of PV are assumed as 2500 $/kWp, of the BESS 760 $/kW and of one 250 kW diesel generator overall 70.000 $. The system lifetime is assumed to be 20 years.
The reference case of the system is a power supply by the public power grid only and in case of an outage a supply by the diesel generator only. This case is compared with scenarios adding PV and BESS of different sizes. For the component behaviour simulation, the dispatch strategy described in [13] is applied. According to this strategy, PV energy is primarily used, followed by BESS charging or discharging (power following). Missing gaps are supplied by the diesel generator.

Figure 2 shows the power supply of the exemplary Ghanaian health facility of three weeks of different seasons by adding a PV of 210 kWp and a BESS of 50 kW to the system.

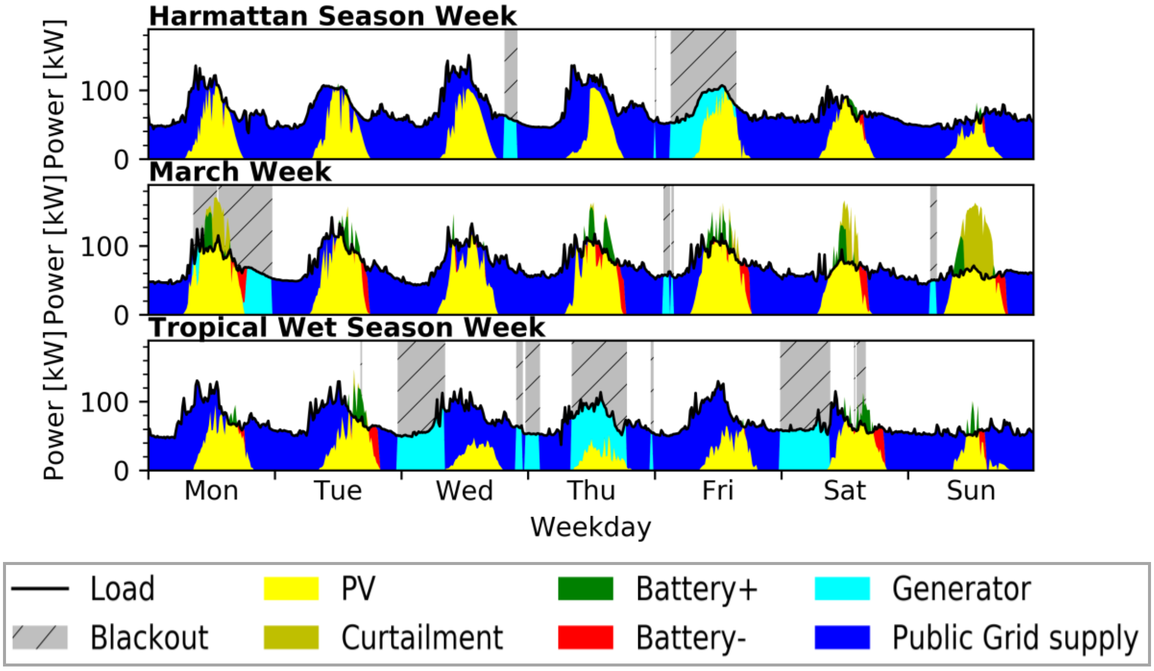

Figure 2: Supply of an exemplary Ghanaian hospital compared for three weeks of different seasons in year 2016 with a 210 kWp PV plant and a 50 kW BESS.

Blackouts occur regularly (several times a day, once a day or once in a few days). During that observed year (2015) 234 power outages with a mean duration of 3,4 hours occurred (total 795,75 hours that year). The back-up diesel generator only supplies the facility during these outages. As shown in Figure 2, PV yield is diminished in the Harmattan season and in the tropical rainy season, so that PV production hardly ever exceeds the load. Between these seasons (shown here as an example for a week in March), the yield regularly exceeds the load, with the result that much excess energy even has to be curtailed, as the battery cannot store all of it.

In general, by means of the PV plant a lot of public grid supply can be saved. Additionally, the BESS can enlarge the usage of PV energy. However, this system still mainly depends on the backup diesel generator.

Without any PV and BESS, the annual fuel consumption is about 52.889 l diesel which corresponds to approximately 139 tons of annual CO_2-emissions. With the system shown in Figure 2, 17.016 l of diesel respectively 45 tons of annual CO_2 emissions can already be saved.

To get an overview of feasible solutions to improve the microgrid system by adding PV and BESS a parameter variation can be done. The results of a parameter variation of 12 PV sizes (30 to 360 kWp) and 4 BESS sizes (0 to 200 kW) is shown in **Figure 3**.

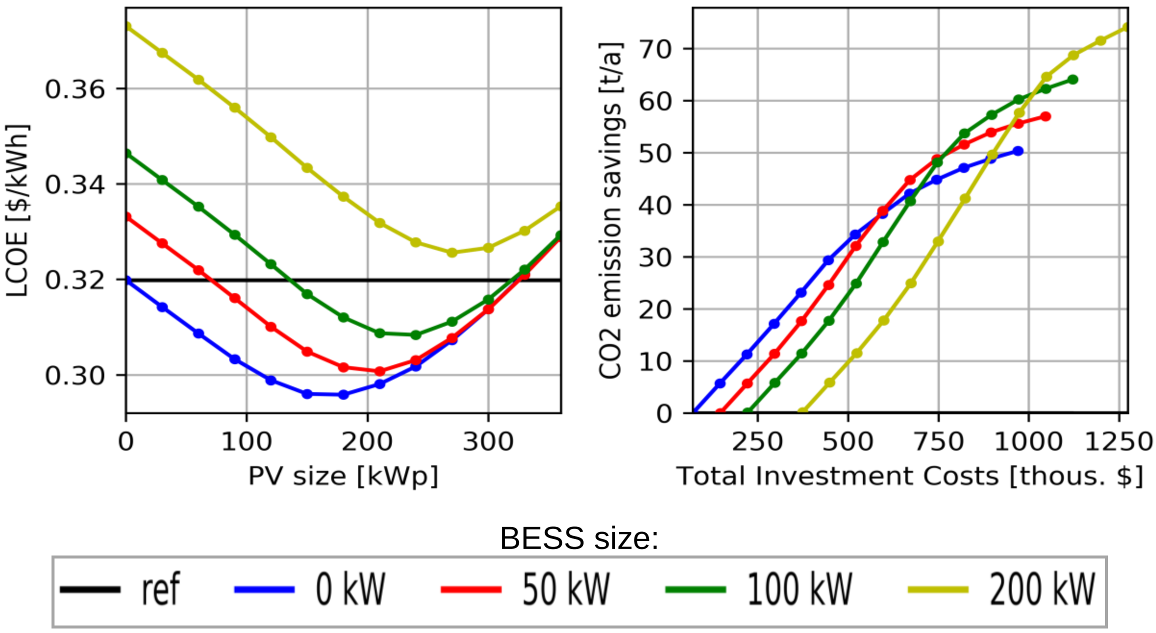

Figure 3: Sensitivity analysis of the PV and BESS sizes. Right: LCOE with different PV and BESS sizes compared to the reference case. Left: Comparison CO_2 emission savings and Investment costs with different PV and BESS sizes.

According to , an implementation of a PV system is profitable, since the LCOE can get reduced by 2.4 ¢/kWh compared to the reference case with diesel generator supply only. The most profitable solution would be a without BESS and with a PV of 150 kWp capacity.
This solution annually saves besides 29 tons of CO_2 emissions 36 thousand $ of electricity charges and 10 thousand $ of fuel costs. However, the system requires 375 thousand $ of adding investment costs. By means of an additional BESS the profitability of the system reduces. However, if CO_2 emission savings of more than 40 t/a are to be achieved, a system with BESS is more cost-effective than a system without BESS. There are still profitable system solutions with BESSs of 50 or 100 kW nominal power. With a BESS of 200 kW the highest CO_2 emissions can be saved, but it cannot be more profitable than the reference case. The scenario with the largest BESS, which system LCOE is still under the reference case is a system with a 300 kWp PV plant and a 100 kW BESS. That system can save 60 t/a of CO2, while saving 75 thousand $ electricity charges, 20 thousand $ of fuel costs, but demanding an investment of 972 thousand $.

CONCLUSION

For the first time, the design and planning of a Ghanaian health facility has been analysed by means of a component size variation. The study showed the most profitable system solution by adding a 150 kWp PV plant and no BESS which result in a LCOE 2.4 ¢/kWh lower than the reference case (0,32$/kWh) and CO_2 emission savings of 29 tons. However, systems with BESS of 50 kW or 100 kW with PV sizes between 90-300 kWp respectively 150-300 kWp resulted in lower LCOE than the reference, too. With these systems even higher CO2 emissions up to 60 tons can be saved.

To invest such an amount often is a challenge because there are no attractive lending rates in Ghana. Therefore, it would be expedient first to implement a solar system only and then invest in a BESS in addition to that in a second planning iteration.

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NOMENCLATURE

BESS	Battery Energy Storage System
BSFC	Break Specific Fuel Consumption
EnerSHelF	Project: Energy Self-sufficiency for Health Facilities in Ghana
GHI	Global Horizontal Irradiance
HOMER	Hybrid Optimization of Multiple Energy Resources
KNUST	Kwame Nkrumah University of Science and Technology, Kumasi, Ghana
LCOE	Levelized Cost of Electricity
Oemof	Open Energy System Modelling Framework
PV	Photovoltaics
PVLIB	A set of functions and classes for simulating the performance of photovoltaic energy systems
SimSES	Software for techno-economic simulation of stationary energy storage systems

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