Comparative design of a stand-alone solar energy system with socioeconomic factors

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***Abstract*—New energy policies encourage the supply of electricity through renewable energy sources in rural areas of South Africa to improve the living conditions of locals. Solar energy is of particular interest for designing sustainable energy systems, thanks to the geographical location with its high potential of solar radiation. To optimally integrate the solar energy systems in future smart grid applications, specific design methodologies are required to size the solar production considering techno-economical constraints. This paper presents a comparative design of a stand-alone solar energy system for a school located in Mamelodi East, Pretoria, by using PVsyst and HOMER Pro software. Considering the socioeconomic aspects, two methodologies are proposed that contribute to ensure the energy needed for supplying an entire classroom thus facilitating the integration of additional learners to education.**

Keywords—optimal design, solar energy system, socioeconomic criteria, PVsyst, HOMER Pro

I. Introduction

Sustainable systems based on renewable energy are considered to be an extremely efficient solution for developing countries in order to help them meet their policy goals for secure, reliable and affordable energy [1]. This implies the electricity access for all by reducing price volatility and the promotion of social and economic development. An interesting scenario regards the rural areas of South Africa. First, because of their high potential in solar radiation and secondly, because of the social impact of new energy policies which reclaim the supply of 50 kWh/month electricity through renewable energy sources [2,3]. In addition, more than 80% of children in Sub-Saharan Africa attend primary schools that lack electricity, thus engaging the emerging energy leaders to determine diverse financing streams enabling planners, investors and policymakers to ensure that schools can provide students with the light, heat and modern tools of teaching they deserve [4].

Several projects were concerned with the implementation of grid-connected or remote sustainable energy systems in developing countries. For the economic analysis and optimal design of renewable power systems different simulation software are used. PVsyst software was frequently used for sizing self-supported solar power plants, such as the grid-connected solar system in Daikundi province of Afghanistan [5]. HOMER which stands for Hybrid Optimization Model for Electric Renewables, was used for the design of various microgrids configurations like the hybrid system of the Baluchistan's Seashore, in which the designing of grid deals with wind, solar and converters installation which decreases amount payable to the grid [6]. To achieve electrification of primary and secondary school, a system design and performance evaluation is conducted with HOMER Pro in [7], on a solar battery-based energy system with diesel back-up generator for a remote school area in Bangladesh. Comparative studies of different optimization software were lead in [8,9,10] for grid-connected or stand-alone photovoltaic (PV) systems in Brazil, Bangladesh and India, particularly for communities of few houses in peripheral areas.

This paper studies the installation of a stand-alone PV system to provide electricity for light, heat and modern tools of teaching for the learners of a school located in Mamelodi East, Pretoria, by using PVsyst and HOMER Pro software. Further sections explain the context of the proposed study case, with the two methodologies used for enabling the software's use for the design of the proposed system. The system modelling specifications are also detailed and simulation results are confronted. Finally, relevant conclusions regarding the comparative design of the proposed system are presented with suggested improvements.

II. Study Case Background

The study of several reports about the South African education situation revealed that not only the access to electricity is very unequal, but the equipment using this energy are also outdated [4].

The proposed study case concerns the Mahube Valley[1] primary school in Mamelodi East, Pretoria, where more than 1000 learners are dispatched in dozen crammed mobile classrooms without electricity. One mobile classroom is represented by a container designed to accommodate 40 learners.

In the last years, this school is battling with overcrowding thus being in desperate need for more classrooms. Fig. 1 presents the configuration of a stand-alone PV system to be installed on a container in order to provide electricity for

[1] https://www.thesouthafrican.com

light, heat, air conditioning and modern tools of teaching for the learners during a whole day.

III. METHODOLOGY

The study case model is built upon energy load specifications for the use of electricity for a whole day including seasonal constraints. A comparative analysis of two methodologies enabling the use of PVsyst and Homer Pro software are conducted and simulations are performed to examine the system performance with regard to technical indicators and economic constraints.

A. *System modelling*

To analyze the optimal dispatched energy to the Mahube Valley primary school, the following steps were considered:

- The definition of the energy consumption according to user needs;
- The solar irradiance potential according to different meteorological sources;
- The integration of PV and battery systems according to the available technologies.

B. *Solar GHI potential*

The region of Mamelodi East, Pretoria is situated in South Africa. From Fig. 2 it can be noticed that the country has an average theoretical potential of 5.63 Global Horizontal Irradiation (GHI, kWh/m^2) [11]. This fact is insufficiently exploited to increase the 67.9 % amount of rural population having access to electricity in 2016 as shown in Fig. 3. New energy policies search however to reclaim legal supply of monthly electricity consumption through renewable energy sources. Based on the social impact and considering government fundings, PV systems configurations are extremely suitable for investors in this area.

C. *Energy consumption*

To evaluate the energy consumption of the installation, an estimation of the user's energy needs was proposed. The final purpose is to provide electricity for light, heat, air conditioning and modern tools of teaching for the learners. Lights and computers contribute to better conditions for learners in their studies, while heating and air conditioning installations ensure their thermal comfort.

The load demand is sized based on standard ratings of the used components and typical daily power consumption by the learners as shown in Table 1. According to seasonal constraints, during the summer months, a constant power of standing fans is used for the ventilation. This is not the case during the winter months for the heating system since the necessary power consumption of a container is calculated according to Heating Degree Days (HDD).

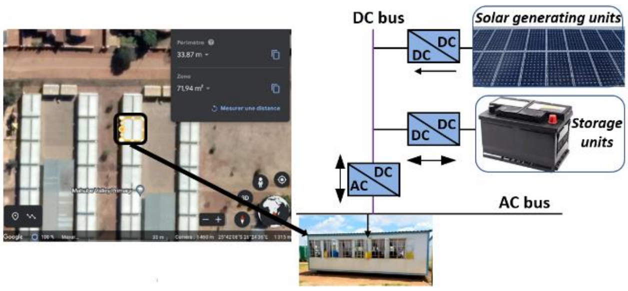

Fig. 1. Stand-alone PV system for the Mahube Valley school's classroom

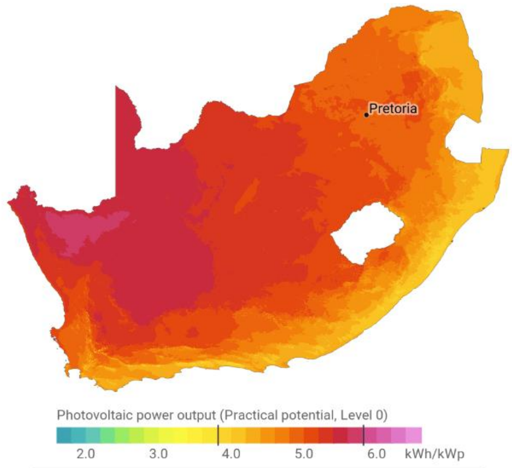

Fig. 2. PV output power according to solar potential for Pretoria [11]

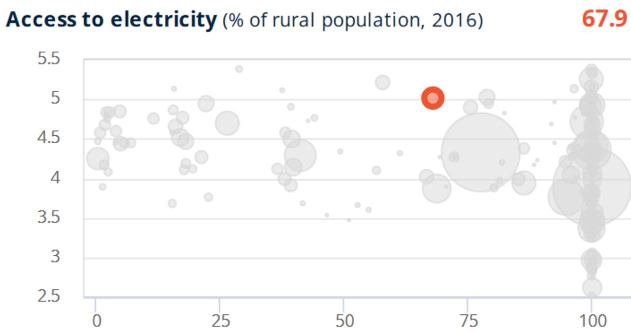

Fig. 3. Electricity acces of rural population in South Africa [11]

The HDD provide a simple metric for quantifying the amount of heating that buildings in a particular location need over a certain period. When HDD value is zero or negative, it means that there is no need for using the heating systems. A standby power consumption is considered for the week-end days when the school is closed, thus maintaining the building structure and preventing the accelerated aging of installations.

TABLE I. ENERGY LOAD DEMAND

Load	**Use 8h/day**		
	Quantity	***Power (W)***	***Energy (Wh/day)***
Lighting	9	36	2592
Computer/PC	20	100	16 000
Standing fan	4	40	1280
Heating	April	49.5	396
	May	1460.25	11 682
	June	2796.75	22374
	July	2945.25	23562
	August	1410.75	11286

D. *Storage system in off grid configuration*

The Mahube Valley primary school lacks electricity and no feasible grid-connection is available in the area. Thus, storage systems such as batteries need to be considered in the proposed off grid configuration [17]. This will allow to benefit of the whole capacity of the PV output production. The saved energy could be used during the night or off-peak periods for standby consumers. This energy could later bring future incomes if shared with nearby consumers.

E. PVsyst methodology

PVsyst is a simulation software developed in Europe and dedicated to the design of PV systems in off grid or grid-connected configuration. It is particularly designed to calculate the functioning and operating mode of the PV system and to evaluate the amount of energy produced [13].

A generic methodology is proposed in Fig. 4 for the system's sizing. According to the geographical location of the selected site for the PV system implementation, an off-grid configuration with battery technologies is defined. The project's definition takes into account the site location of the Mahube Valley in Mamelodi East, Pretoria with meteorological data from the Meteonorm data base [14]. The module orientation takes into account a transposition factor of 1 which correspond to the ratio between the incident irradiation on the plane and the horizontal one. Fig. 5 shows the horizon portion where the blue line corresponds to the auto-shading of the photovoltaic modules. Fig. 6 details the specification related to field parameters and a tilt angle of 10° is chosen for the module orientation to illustrate how accessible the sun is.

In PVsyst, the output is founded on measurement system simulation including loss parameters. The typical layout of the stand-alone system in PVsyst is illustrated in Fig. 7. The optimal results analysis can be performed within an iterative process by changing different parameters in a new configuration of the project design. The PV type is a LongiSolar model from the PVsyst database with 390 Wp nominal power per module. As for the storage system, Power Brick Lithium-ion batteries are used with a nominal voltage of 12.8 V and a nominal storage capacity of 101 Ah.

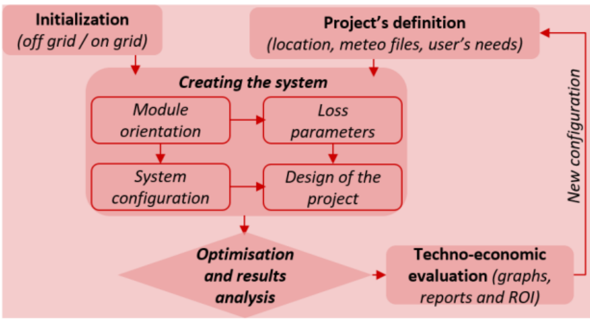

Fig. 4. Methodology designed to enable the use of PVsyst

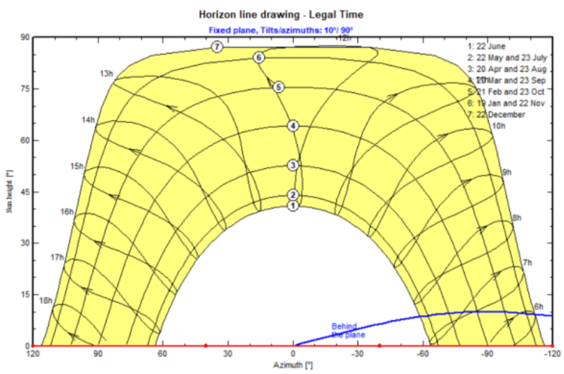

Fig. 5. Solar horizon line at Mahube Valley

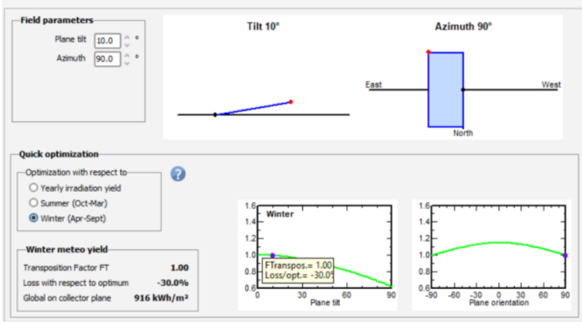

Fig. 6. Solar horizon line at Mahube Valley

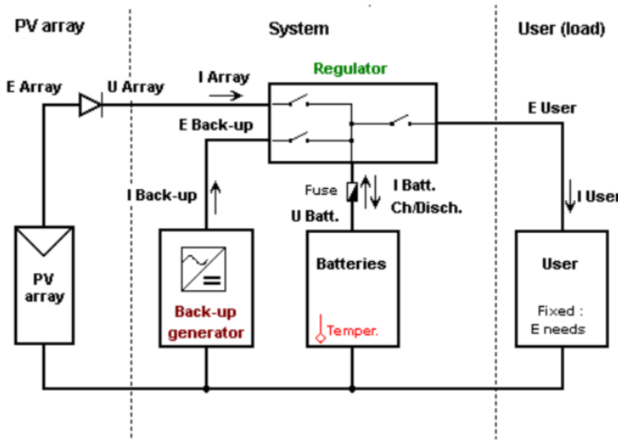

Fig. 7. Typical layout of the stand-alone system with PVsyst

F. Homer Pro methodology

Homer environment is an optimization design tool initially developed by the National Renewable Energy Laboratory (NREL) in the United States for microgrids operating in isolating mode or grid-connected.

The generic methodology proposed for enabling the use of Homer Pro latest version is shown in Fig. 8. To initialize the system parameters, the location coordinates for Mamelodi East, Pretoria are selected. This enables the use of solar resources from the NASA Prediction of Worldwide Energy Resource meteorological database. For an annual average of 5.65 kWh/m^2/day, the monthly average solar GHI is show in Fig. 9.

As for the PVsyst model, the project lifetime is 25 years with a discount rate of 6%. The system is simulated for 8760 hours per year. Thus, the electrical load of the specific classroom is updated accordingly and the schematic configuration of the hybrid power system is presented in Fig. 10. To build the hybrid power system configuration, similar PV technology was retrieved in the software's complete catalog for a nominal power of 300 W. An equivalent idealized battery model with a nominal voltage of 12.8 V was selected for a nominal capacity of 100 Ah.

Initially economic constraints are considered for defining the capital, the replacement and the operation and maintenance (O&M) cost of each technology. This enables the optimization process for minimizing the installation net present cost (NPC).

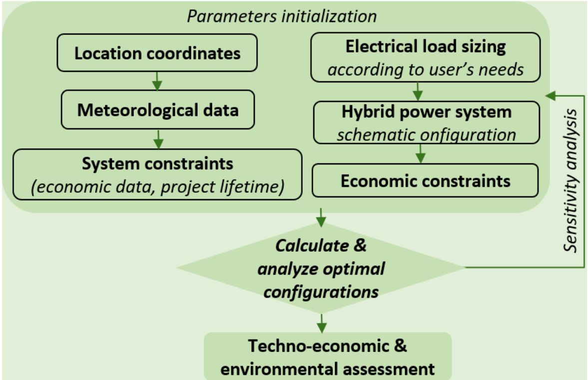

Fig. 8. Methodology designed to enable the use of Homer Pro

Fig. 9. Monthly average solar GHI for Pretoria region

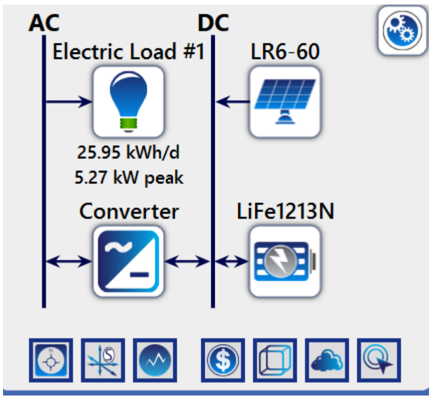

Fig. 10. Schematic configuration of the hybrid system with Homer Pro

Homer Pro identifies the optimal configuration related to the characteristics of the components and estimates different costs such as the life cycle cost and the levelized energy cost. Besides the economic evaluation, the software gives valuable information regarding the renewable penetration and the dispatched energy in the system, the storage State-of-Charge (SOC) or environmental aspects such as the CO_2 emissions. Additionally, sensitivity analysis cases can be studied to analyze how the outputs change to different sensitivity inputs.

IV. SIMULATION RESULTS

The design and analysis of the photovoltaic plant were done using PVsyst and Homer Pro tools. A series of simulations were performed to examine the system performance with regard to technical indicators and economic constraints including the levelized cost of energy (LCOE).

Table 2 shows the comparison of simulation results with PVsyst and Homer Pro software. For approximately the same of used energy, a number of 16 PV panels and 18 batteries are proposed for the PVsyst optimal sizing and 24 PV panels and 21 batteries with Homer Pro environment. It can be seen that for similar characteristic of PV system and battery technology, the NPC is lower within PVsyst simulation, whereas the LCOE is more interesting according to Homer optimization results.

The normalized generation and performance ratio (PR) of the proposed system using PVsyst are shown in Fig. 11 and Fig. 12. The useful energy production in the figure is 3.35 kWh/kWp/day and the performance rate is 55.8 %. These two parameters show that the system is working in good condition, however the PR could be slightly improved. The monthly generated energy of the system analyzed by Homer Pro is shown in Fig. 13. The results obtained from the analysis of the system show that the annual energy produced using Homer software is calculated as approximately 40677 kWh with an excess electricity of 76 %.

TABLE II. COMPARISON OF SIMULATION RESULTS

	PV panel number	***Batteries number***	***Used energy (kWh/year)***	***NPC ($)***	***LCOE ($/kWh)***
PVsyst	16	18	9486	28616	0,38
Homer Pro	24	21	9196	32537	0,27

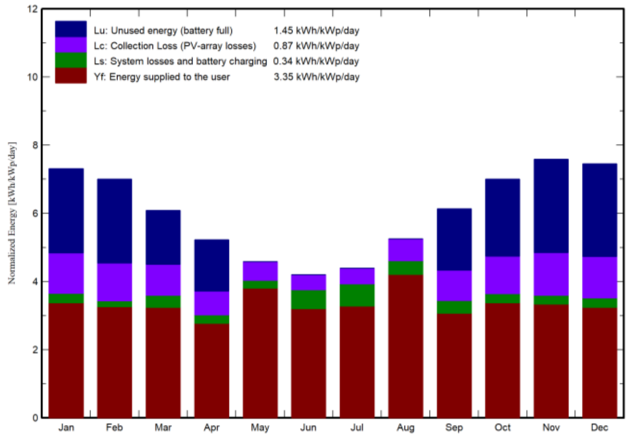

Fig. 11. Normalized production per installed kWp with PVsyst

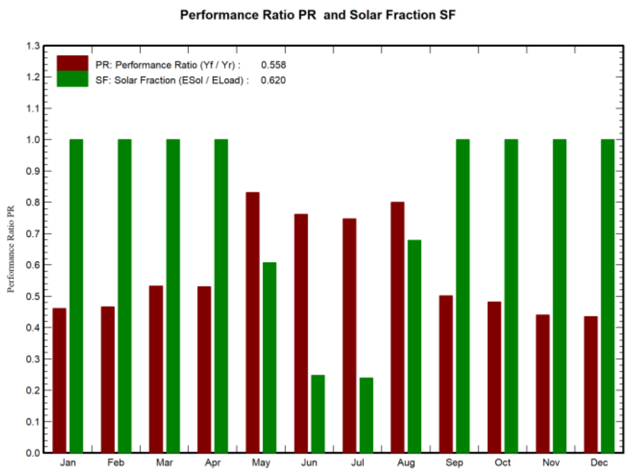

Fig. 12. Performance ration with PVsyst

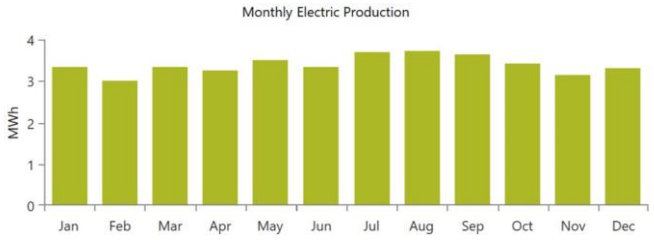

Fig. 13. Monthly energy produced by the PV system analyzed in Homer

The GHI, the Effective Global, corr. for IAM and shadings (GlobEff), the Available Solar Energy (E_Avail), the Unused Energy (EUnused), the Missing Energy (E_Miss), The Energy supplied to the user (E_user) and the Solar fraction (SolFra representing EuUsed/Eload) of the system analyzed with PVSYST are given in Table 3.

The loss diagram of the proposed system with PVsyst tool can be analyzed in Fig. 14. As depicted in the figure, with 17, 75 % efficiency, the array nominal energy at standard test condition is 10299 kWh/year. Due to effects of field losses and system components, the available energy at the inverter output is decreased to 9486 kWh/year and shows that the losses are about 7.89%.

TABLE III. COMPARISON OF SIMULATION RESULTS

	GlobHor kWh/m²	GlobEff kWh/m²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	234.2	222.4	887.8	367.6	0	502.5	503	1.000
February	198.2	192.7	770.7	329.8	0	439.0	439	1.000
March	189.6	184.6	748.1	235.5	0	483.3	483	1.000
April	159.8	152.6	633.0	216.6	0	399.6	400	1.000
May	143.4	137.4	577.8	0.0	366	566.6	932	0.608
June	126.7	121.2	520.4	0.0	1408	449.8	1858	0.242
July	137.6	131.5	562.2	0.0	1553	485.9	2039	0.238
August	165.5	158.6	658.6	0.0	296	626.1	922	0.679
September	187.2	180.2	733.8	259.7	0	443.1	443	1.000
October	220.2	212.9	856.0	336.9	0	502.5	503	1.000
November	228.9	223.4	891.0	394.6	0	481.5	481	1.000
December	234.3	226.9	906.1	405.4	0	483.3	483	1.000
Year	2225.7	2144.5	8745.4	2546.1	3623	5863.2	9486	0.618

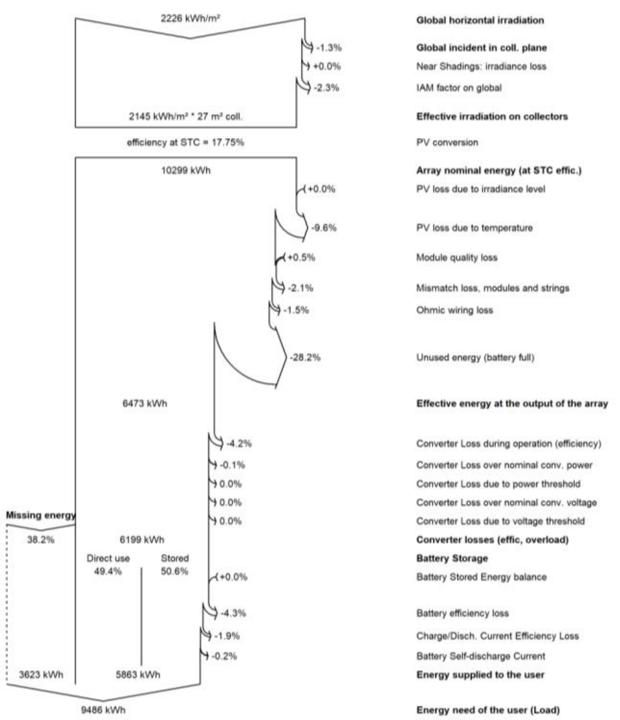

Fig. 14. Loss Diagram analyzed in PVsyst

V. CONCLUSION

The proposed work investigates the design of a stand-alone solar PV energy system that takes into consideration the energy load specifications to enhance the energy access for a school in Mamelodi East, Pretoria.

Two different methodologies are implemented to compare the system's performance using PVsyst and Homer Pro software regarding techno-economical constraints. The objective is to provide the optimal design within suitable configurations for the considered study case. 16 PV panels and 18 batteries were found with PVsyst sizing tool as well as 24 PV panels and 21 batteries with Homer Pro environment for a similar used energy of approximately 9500 kWh/year.

It has been shown that for similar technical specifications of PV system and battery technology, the net present cost is more interesting within PVsyst simulation. However, the levelized cost of energy is lower by using the configuration proposed by Homer Pro designing tool. In addition, an excess electricity production is found within Homer simulation results. Thus, a sensitivity analysis should be performed in future work to improve the system configuration optimal design. For this study case PVsyst shows better optimal configuration requiring however a careful analysis of parameters that could improve the performance rate of the system.

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