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**Electricity Supply to Africa and Developing Economies –
Challenges and Opportunities**

Enabling Universal Access to electricity in developing economies

A tool for pre-feasibility techno-economic comparison of rural electrification options: grid extension and off-grid systems

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Abstract

630 million people in Sub-Saharan Africa have not access to electricity and 75% of them dwells in rural areas that are not reached by a national power system or by a local distribution grid. Providing them with adequate and reliable access to electricity means to support rural development and represents an opportunity to reach a huge amount of potential consumer from the investor point of view.

Technical solutions consist of grid extension, micro-grids or home-sized systems. Nevertheless, feasibility of such solutions is often hindered by uncertainties and differences of each targeted context. Therefore, replicable solutions can be hardly foreseen, thus requiring procedures and tools to address the design of the proper solution for each context.

In this framework, this paper describes a tool based on MS Excel to be used at the early stage of the design process in rural electrification projects. The tool has been devised with the objective of providing a quick pre-feasibility comparison between grid extension and off-grid systems (PV-storage and/or diesel micro-grid, or PV-storage home systems), on the basis of simple input data (costs, load demand, energy resource availability), and few techno-economic indicators (levelised cost of energy, loss of load). Beside the description of the tool, the paper also presents its application to a case study in rural Uganda.

Keywords: Sub-Saharan Africa, rural electrification, off-grid, feasibility, sizing, simulation

1. INTRODUCTION, MOTIVATION AND OBJECTIVE

Globally, 1.2 billion people lack electricity access; yet reliable electricity is crucial to human well-being and to a country's development [1]. If the economies of Sub Saharan Africa (SSA) continue their rapid growth rates, their citizens and businesses will need access to reliable, affordable, and clean electricity. Furthermore, 75% of about 630 million people which do not have access to electricity in SSA dwells in rural areas. This means thousands among villages and households that (a) are not reached by the national power supply grid nor by local distribution grids based on diesel generators or (b) are poorly electrified by small-scale generation systems like solar home systems and diesel generators [2].

Providing adequate and reliable power supply to these large shares of the population is mandatory to support rural development, and represents an opportunity to reach a huge amount of potential consumer. Technical solutions to this purpose consist of: (1) grid extension, (2) micro-grids (3) home-sized systems [3]. Nevertheless, economic feasibility of these solutions can be hindered by the high uncertainties of each targeted context and other socio-economic issues. Therefore, replicable solutions can be hardly foreseen and each targeted context should be analysed singularly. This means that procedures and tools are needed to address the design steps towards the best solution [4].

The paper describes a tool based on MS Excel to be used at the early stage of the design process in rural electrification project. The tool has the objective of providing a pre-feasibility techno-economic comparison between the most typical technical options on the basis of simple input data (costs, load demand, energy resource availability) and few techno-economic output indicators (levelised cost of energy – LCoE, loss of load probability – LLP). Compared to already available tools, the proposed one employs less data while preserving the capability to assess the opportunity for a rural electrification action and to provide a comparison between grid extension and typical off-grid systems. In particular, for the case of off-grid systems the following configurations are considered: PV and storage, (2) diesel, (3) diesel and PV, (4) diesel, PV and storage. For these options the tool implements pseudo-optimisation procedures that allow computing power sources and storage capacities.

In the following, the paper provides an overview of main features and design tools about off-grid systems, then it focuses on the description of the developed tool by describing the method, the implemented models and the simulation approach. Finally the application of the tool to a case study based on field collected data of a rural area in Uganda is presented.

2. OFF-GRID SYSTEMS OVERVIEW

Conventional rural electrification options consist on the extension of the national power system (transmission and distribution) or the use of small diesel generators. However, in the past 10/15 years also the option based on isolated systems (off-grid) and renewable technologies have become more and more attractive.

2.1. GENERAL ELEMENTS

The off-grid concept encompasses a large spectrum of technological solutions for generation and distribution in isolated contexts. Table 1 shows a classification of off-grid systems based on the number of users and the number of generation units.

Stand-alone systems provide electricity to a single user relying on a single energy source. In particular, they are used to serve small loads which are characterised by the absence of a distribution grid. The power generation can be based on several technologies present on the market and their possible integration with energy storage system (EES). These include PV, diesel generators, micro wind turbines and, mainly, lead-acid battery banks.

OFF-GRID SYSTEMS MATRIX			
Energy Uses	**Stand-alone**	**Micro-Grid**	**Hybrid Micro-Grid**
Household needs	Home-based Systems	Systems including a distribution grid	Systems including a distribution grid
Community services	Community-based Systems		
Productive uses	Productive-based Systems		
Consumer Number	Single	Multiple	Single OR Multiple
Generation Sources	Single		Multiple

Table 1 Off-grid systems matrix [3]

Micro-grids are intended for systems which provide energy to several users located in small areas (such as hospitals or schools), or villages. In both cases, the system requires a distribution grid (LV and possibly MV) considering the micro-grid's generation is characterised by a single, not small, energy source and supplies reaches several consumers. Moreover, the implementation of a micro-grid in a rural context requires engineering analysis and design activities.

Concerning hybrid micro-grids, they are similar to micro-grids in terms of served users and distribution grid, however they are characterised by having several energy sources. Typically, hybrid micro-grids integrate traditional system (diesel generator) with renewables and EES. The implementation of various technologies causes an increase of system complexity. A relevant share of not-dispatchable generation influences the design process, requiring specific-site solutions. Moreover, the definition of the system architecture, the sizing process, and the development of control logics are addressed without defined procedures and methodologies, but relying on almost experimental and innovative solutions [5]. A further classification (Figure 1) based on the energy sources for the electricity generation is possible.

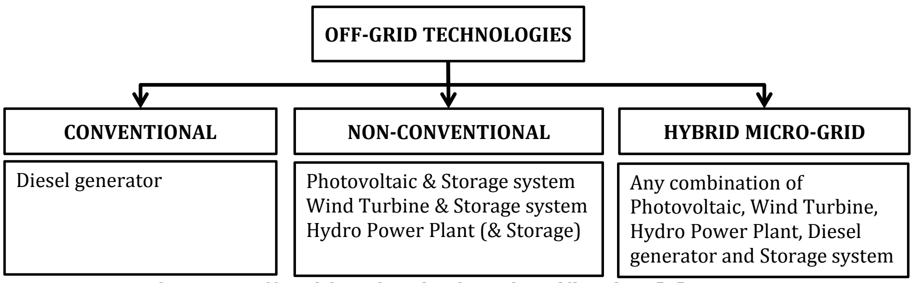


Figure 1 Off-Grid technologies classification [3]

Diesel generators are considered as *conventional* technology because of their broad historical use for rural electrification. Instead, *non-conventional* technologies as PV and wind turbines combined with EES, are recently becoming relevant due to cost reduction and to a more sustainable impact (i.e. noise and pollution very limited). Despite this cost reduction, the cost per kWh of off-grid systems can be one order of magnitude higher than traditional systems. Table 2 shows a comparison of LCoE for several power generation technologies.

In rural areas of SSA, the implementation of off-grid systems to promote local electrification face several issues. These include a difficult design process, financing constraints, local management and maintenance of the system, definition of a proper tariff scheme and the overall economic management of the system. In particular, the design process is influenced by the high uncertainty related to the assessment of the load demand and its evolution as well as of energy sources availability. These aspects together with typical local financial constraints usually led to design the system accepting a share of loss of load [6].

Technology	LCoE [€/kWh]	Technology	LCoE [€/kWh]
PV system	0.1 – 0.3	Coal	0.08
Wind turbine	0.07 – 0.18	PV off-grid	0.45 – 0.70
Hydro	0.07	Micro hydro off-grid	0.02 – 0.19
Biomass	0.085	Diesel generator off-grid	0.35 – 0.50
NGCC	0.073		

Table 2 LCoE comparison for different technologies [7-9]

2.2. SIZING METHODOLOGIES AND TOOLS

A proper pre-feasibility design procedure of off-grid systems is essential to avoid under/over sizing and to identify an optimal solution over the system life-time. The importance is not only related with economic optimisation, but also with reliability of the supply. Four main approaches in this regards can be identified [10]:

- **intuitive methods**: simplified calculations of the system components size based on daily values of required electric load and energy resource availability data;
- **numerical methods**: several combinations of system components sizes are simulated typically on a year basis, employing hourly or daily load and resource availability profiles, and one or more indicators are used to select the best components set;
- **analytical methods**: mathematical optimisation problem with one or more objective functions subjected to one or more conditions. The objective function(s) and the conditions provide the system physical modelling, and define the functional relationships between component specifications and techno-economic parameters;
- **real-time power methods**: based on short-term simulations (from few to tens of seconds), these analyses are based on circuit models of the components and on the solving of related equations within the continuous time-domain. They are carried out for short intervals to study the developments of electrical quantities and to verify the proper system functioning under particular circumstances. They do not provide elements to optimise the component sizes over their life-time, therefore they are not considered for life-cycle feasibility analyses (which is the theme of the tool proposed in this work).

According with the aforementioned methodologies, sizing procedures have been implemented in software tools [11-12]. *HOMER Energy* by NREL is probably the most used software for the numerical design optimisation of off-grid systems (stand-alone, micro-grid and hybrid micro-grid) [13]. *RETScreen* by CANMET is a renewable energy decision support tool. The model is developed in Visual Basic for Application within Microsoft Excel spread-sheets and employs intuitive-numerical method. *iHOGA* by University of Zaragoza is a C++ based tool that exploits genetic algorithm for the multi or mono-objective size optimisation of hybrid power systems (analytical method). *HYBRID2* by WEC-MIT is probabilistic/time series computer model that uses statistical methods to perform long-term performance, economic analyses on various off-grid systems (analytical method). *PVsyst* by PV syst SA is a software for the study of standalone and grid-connected solar systems. It allows the hourly simulation of the plant importing weather data form different sources as well as user-defined personal data (intuitive method). *PoliNRG* is a software tool developed by Dep. of Energy of Politecnico di Milano for pre-feasibility techno-economic design of isolated micro-grid taking into account the uncertainty of resource availability and energy requirements over the system life-time (i.e. it provides a robust design) [14-15].

The tool proposed in this paper deals with life-cycle techno-economic feasibility (as HOMER and RETScreen). In this regards, it is worthwhile to say that the economic feasibility of off-grid system implementation actions can be hindered by the high uncertainties associated by the specific features of each targeted context, for example: potential load demand and its projections, availability of local renewable energy sources, reliability of fossil fuel supplies, land acquisition issues, willingness to pay, local capabilities for O&M, etc. . Therefore, standard replicable solutions can be hardly foreseen, consequently each targeted context should be analysed singularly. Indeed, the considerable amount of data required and the related uncertainty influence the results' quality. The already available tools do not catch all these issues, thus this means that proper procedures and tools are needed to address the sequential design steps to identify the best solution and its specific features.

In the light of these elements, the proposed tool wants to contribute in developing a design procedure that counterbalance some of the aforementioned issues. In particular, compared to the already available tools, the design procedure of the new one relies on specific dedicated tools for some design aspects, and employs less data while preserving the capability to assess the opportunity for a rural electrification action in a given context and to provide a comparison between grid extension and off-grid systems.

3. THE PROPOSED TOOL

The developed tool is based on a simple algorithm that finds a sub-optimal solution for a target area. The tool is intuitive and has been developed with the aim to provide a quick pre-feasibility techno-economic comparison between different technical options, based on simple input data (costs, load demand, energy resource availability) and few techno-economic output indicators (LCoE, LLP). These indicators are computed via energy simulation of system behaviour based on hourly profiles of load demand and energy resources (*numerical method*). The technical options compared by the tool are: PV micro-grid (Scenario A), hybrid micro-grid (Scenario B), and grid extension (Scenario C). The final goal is to provide to the user a comparison of the options in terms of reliability (LLP) and cost of electricity (LCoE).

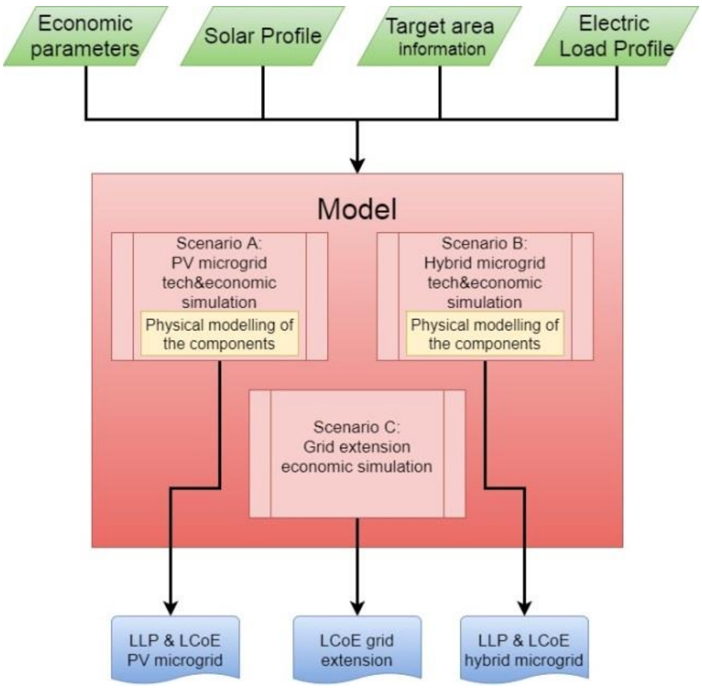


Figure 2 Model structure

Figure 2 shows the structure of the design approach which is the typical one for off-grid system sizing procedure. In detail: (i) the green blocks identify the input data required to perform the simulation of the considered scenario, (ii) three different models (light red blocks) embrace the analysis of the considered scenarios based on components' physical modelling (yellow blocks) and system simulation, (iii) simulation results (blue blocks) are compared and the optimal solution is identified.

3.1. SYSTEM MODELLING, SIMULATION AND INDICATORS

Considering the input data, the tool relies on other external dedicated tools for the solar resource and the load profiles. In particular:

- the tool relies on data available via an open source database ('Renewable.ninja' [16]) to obtain hourly power output along a year of a PV power plant given site coordinates;
- the tool relies on LoadProGen tool for the computation of daily load profiles [14, 15, 17]. This tool has been developed by the Dep. of Energy of Politecnico di Milano. Survey-based or assumed data about electrical devices and usage pattern of targeted costumers are employed by the bottom-up stochastic approach of LoadProGen to formulate load profiles. LoadProGen does not forecast the load, but rather formulates possible realistic load profiles. When survey are not available, the online tool 'Universal access to electricity' [18] is a source of input data: the "tier of access to electricity" data indicates the appliances that could be used by the local population, while the "population" data are used to scale the characteristic electric load of the targeted tier.

Physical modelling of the components are implemented to simulate the scenarios. In particular this applies for Scenario A (PV-ESS micro-grid), and Scenario B (PV-EES and genset). On the contrary, the grid extension options (Scenario C) is modeled with an intuitive approach which does not require any component physical modeling. Main features of the models are: (i) they implement basic physical behaviors of each component; (ii) they maintain a low level of complexity to guarantee the tool to be simple and easily accessible; (iii) they embrace economic elements that allow a techno-economic simulation and optimisation considering the lifespan of the components.

As regards the PV, the physical behavior is defined by 'Renewable.ninja' data. Indeed, this tool provides PV power generation data considering the effect of direct and diffuse irradiance on inclined panel, the effect of temperature on the photovoltaic cell, and generic losses due to the charge controller and inverter. The developed model only performs the data scaling up to the PV size considered in the analysis.

Concerning the diesel generator, it is modelled as a single unit, characterised by peak power and minimum power limits of operation. Moreover, depending on the size of the generator and on the load factor, hourly fuel consumption is provided by means of a typical fuel-to-consumption curve. With regards to life-cycle modelling, the maximum operating hours that the generator can operate before replacing are defined.

As regards the EES, the developed model identifies the state-of-charge (SOC) as the reference parameter. The SOC is calculated dividing the current stored energy by the maximum energy capacity. The minimum value of the state of charge (SOCmin) in which the battery is no longer capable to provide energy to the system is also defined (Equation 1).

$$SOC(t) = \begin{cases} \frac{Eb(t)}{Eb_{max}}; & Eb(t) > Eb_{min} \\ SOC_{min}; & Eb(t) = Eb_{min} \end{cases}$$

Equation 1 SOC computation – SOC(t): State of charge of the battery at the time step t; Eb(t): energy stored in the battery at the time step t; Ebmax: maximum energy storable in the battery; SOCmin: minimum state of charge level.

Moreover, the EES system is characterised by a charge and discharge efficiency that models the losses due to internal resistance and heat generation. Another factor that has been taken in consideration is the power-energy fraction limit (PE). PE is a limit to the charge/discharge power flowing to/from the battery with respect to its energy capacity. Considering the EES life-span modeling, the rain-flow cycle counting method has been implemented. This basically evaluates the equivalent number of cycles to failure, using the typical curve 'cycle to failure–depth of discharge' of lead-acid batteries .

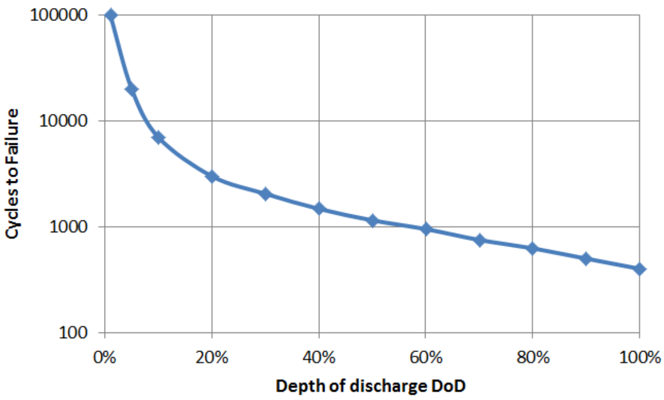


Figure 3 Typical life-time representation of lead-acid batteries according to DoD

Given the input data and the physical components of the micro-grid, in the following the procedure to identify the optimal micro-grid sizing and compare the results with the grid extension scenario is introduced. From a general perspective: (i) concerning micro-grid scenarios (hybrid and not-hybrid), the algorithm identifies the most competitive configuration (the lowest LCoE) in relation with the reliability constraint (selected LLP), (ii) regarding the grid extension scenario, the algorithm only evaluates the economic parameter. Then, the results of the three scenarios are shown and compared.

I. To identify the sub-optimal sizing of the PV micro-grid and hybrid micro-grid (scenario A and B), the developed procedure consists of:
   1. Identification of preliminary components sizes via intuitive method;
   2. Creation of several configurations (search space) characterised by different sizes of the components "around" the intuitive result;
   3. Evaluation of the system's reliability for each configuration in a quantitative manner (*numerical method*). This is based on the simulation of system behaviour throughout a year. The simulation allows calculating the reliability of the system (LLP) as:

$$LLP = \frac{\sum_{y=1}^{T} LL(y)}{E_y}$$

Equation 2 LLP: LL(y): electricity demand not fulfilled in the year (y); Ey: electricity demand over a year

   4. Assessment of the system economic indicators: the model calculates the Net Present Cost (NPC) and the LCoE which expresses the price for electricity that would equalise the sum of discounted costs throughout the lifespan of the system.

5. Identification of the best case for micro-grid scenarios: among the simulated configurations, the model identifies the most cost effective (i.e. the lowest LCoE) which respect the LLP constraint fixed by the user.

II. With regards to the grid extension scenario, the algorithm does not perform the sizing of any component, neither it evaluates the best configuration for a given context (this pertain to power system planning studies). The algorithm simulates the cash flow and calculates NPC and LCoE considering: (i) line extension and connection costs, (ii) the price of electricity in the target area and (iii) the O&M costs (assumed as a percentage of the capital per year). The 'Universal access to electricity' database provides information about the distance from the existing transmission grid and the price of electricity in the target area. These allow estimating the grid extension costs assuming a proportional relation between distance and investment cost.

III. Finally, the model compares the results obtained in the previous steps. For Scenarios A and B, the tool allows finding sub-optimal sizing configurations with related NPC, LCoE and LLP. These can be compared with the economic indicator resulting from the estimate on grid extension (Scenario C).

3.2. THE IMPLEMENTED TOOL

The models and sizing procedures previously described, have been implemented in a tool based on MS Excel and Visual Basic for Application. The tool is structured into 4 modules: (1) Command module, (2) Input modules, (3) Engine modules and (4) Result modules.

In the *command module*, the user defines the main parameters and constraints: interest rate, accepted LLP, system life-time, and location. The *input modules* are organised into dedicate spread-sheets: solar profile, geographical information, electric load, and components. The *engine modules* are the core of the tool as the macros perform the simulation of all the cases. The macros allow also developing output charts with LLP map, that exposes the system reliability of each case, and cash flows (Figure 4). The engine module also carries out the economic analysis. Considering the input data, the tool calculates the NPC and LCoE for each case analysed. Finally, the best cases of micro-grid configurations and grid-extension are presented in the *results module*.

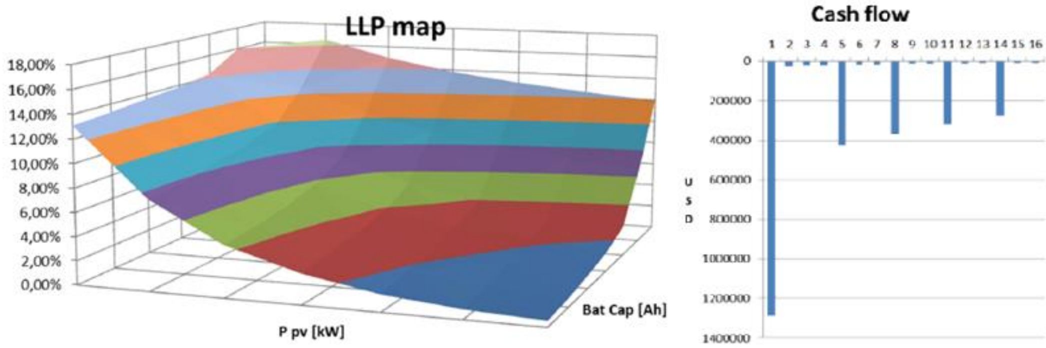
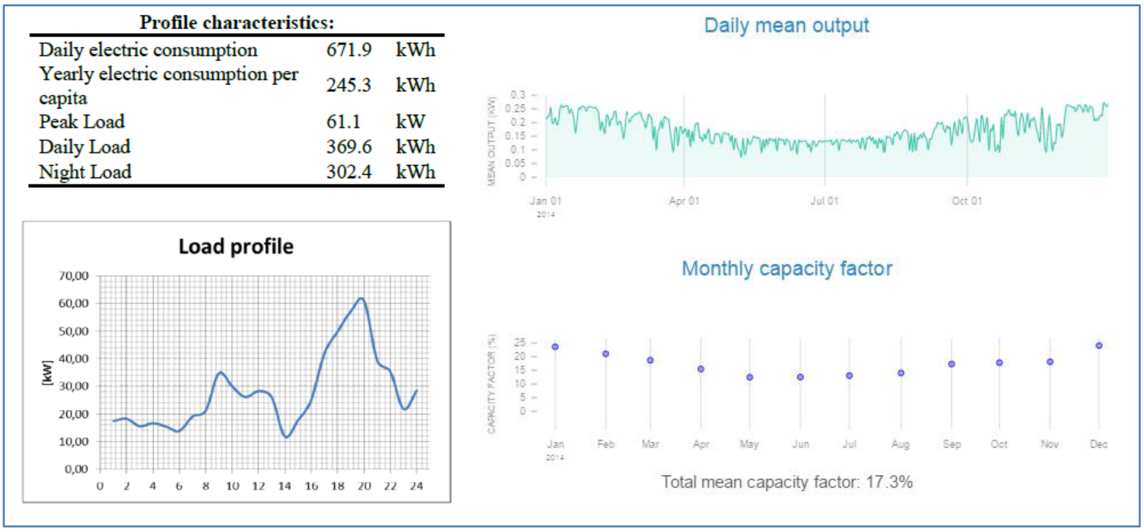


Figure 4 Example of PV micro-grid results: LLP map (left), cash flow along project duration (right)

4. CASE STUDY: SOROTI – UGANDA

The tool has been used for a case study applied to the electrification of the rural town and surroundings of Soroti in Uganda (Latitude:1,7150; Longitude: 33,6111). This site has been considered in previous studies of the authors and it is characterised by diffuse poverty and reduced access to electricity. Specifically, 1000 people (with typical households energy needs in the range 0,5 – 5 kWh/day) and related local enterprises and community services (clinics, schools, etc.) have been considered as targeted users [6, 14].

The load profile has been computed through LoadProGen in a previous study [14], while the solar profile for Soroti has been obtained from ‘Renewable.ninja’ (Figure 5). Finally, with regards to the ‘geographical information’, the tool requires the distance from the existing transmission grid and the cost of diesel. These data have been obtained via the ‘Universal access to electricity’ data. Other context data have been considered based on previous studies [6]. These includes: interest rate, accepted LLP, plant life cycle. Regarding the economic data, costs were set with values representative of the Ugandan context.



Profile characteristics:		
Daily electric consumption	671.9	kWh
Yearly electric consumption per capita	245.3	kWh
Peak Load	61.1	kW
Daily Load	369.6	kWh
Night Load	302.4	kWh

Figure 5 Input data of Soroti: load profile data (left), solar profile data (right)

Given the input data, the tool runs the simulation, thus finding the optimal component sizes for each scenario. At this stage, it is worthwhile to recall that that the results are not the final components size to be supplied. Indeed, the aim of the simulation is to identify the ideal sizing area where the optimal solution is present (sub-optimal solution). Table 3 shows the solution for the PV micro-grid, hybrid micro-grid and grid extension for the Soroti case. In the light of the results, the tool has identified the grid extension as the optimal solution. Clearly, the results depend on the short distance of the existing transmission grid (5 km).

PV micro-grid configuration		
PV	213.4	kW
Battery	960	kWh
NPC	1016	kUSD
LCoE	0.351	USD/kWhe

Hybrid micro-grid configuration		
PV	18.3	kW
Battery	87	kWh
Genset operational range		
Genset peak power	42.7	kW
Genset lower limit	19.8	kW
NPC	837	kUSD
LCoE	0.289	USD/kWhe

Grid extension scenario		
NPC	661	k$
LCoE	0.207	USD/kWhe

Table 3 Scenarios’ results for Soroti case study

Other relevant outcomes should be highlighted: (i) concerning the EES, the simulation reveals that the battery bank completes at least one full charge-discharge cycle every day, thus resulting in an average lifespan of 3 years that consistently impacts on the investment cost of the scenario, (ii) regarding the hybrid micro-grid, the presence of the generator influences cash flow with fuel costs that play a relevant role (the optimal hybrid micro-grid has fuel cost that covers 66% of the overall life cycle cost).

Lastly, to evaluate the tool validity, the results were compared with the results of a same analysis for the same area and based on PoliNRG. Table 4 displays the results for the PV micro-grid of PoliNRG model and the developed tool [19]. The results are similar (PV size and LCoE) apart the battery banks that is about 10% larger. This difference can be explained by the different simulation logics of the components (simplified in the proposed tool).

PV micro-grid configuration PoliNRG results			PV micro-grid configuration Developed tool		
PV	214	kW	PV	213.4	kW
Battery	790	kWh	Battery	960	kWh
NPC	947	kUSD	NPC	1016	kUSD
LCoE	0.382	USD/kWhe	LCoE	0.351	USD/kWhe

Table 4 Results comparison between the proposed tool and PoliNRG

5. CONCLUSION

In this paper, we presented a tool based on Microsoft Excel that can be used to perform quick pre-feasibility techno-economic analysis of typical rural electrification system options. Compared to already available tools, the proposed one employs simple input data and few techno-economic output indicators. Nevertheless it preserves the capability to assess the opportunity for electrification actions and to provide a comparison between grid extension and off-grid systems, i.e. (1) PV and storage, (2) diesel, (3) diesel and PV, (4) diesel, PV and storage. Clearly, the tool outputs cannot be considered as system design figures. Indeed, for grid extension classical power system studies are required to plan and design the network, while for micro-grids other studies are required to analyse the system architecture, the control logics, the dynamic and transient behaviour, and the protection schemes. However, as highlighted by the proposed case study in Soroti (Uganda), the tool allows addressing the essential step of pre-feasibility analysis that is a pre-requisite for the detailed design.

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