Research Journal of Applied Sciences, Engineering and Technology 8(6): 778-788, 2014
DOI:10.19026/rjaset.8.1034
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: May 21, 2014 Accepted: June 18, 2014 Published: August 15, 2014

Research Article

A Methodology to Develop Design Support Tools for Stand-alone Photovoltaic Systems in Developing Countries

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Abstract: As pointed out in several analyses, Stand-Alone Photovoltaic systems may be a relevant option for rural electrification in Developing Countries. In this context, Micro and Small Enterprises which supply customized Stand-Alone Photovoltaic systems play a pivotal role in the last-mile-distribution of this technology. Nevertheless, a number of issues limit the development of these enterprises curbing also potential spinoff benefits. A common business bottleneck is the lack of technical skills since usually few people have the expertise to design and formulate estimates for customers. The long-term solution to tackle this issue implies the implementation of a capacity building process, but this solution rarely matches with time-to-market urgency of local enterprises. Therefore, we propose in this study a simple, but general methodology which can be used to set up Design Support Tools for Micro and Small Enterprises that supply Stand-Alone Photovoltaic systems in rural areas of Developing Countries. After a brief review of the techniques and commercial software available to design the targeted technology, we describe the methodology highlighting the structure, the sizing equations and the main features that should be considered in developing a Design Support Tool. Then, we apply the methodology to set up a tool for use in Uganda and we compare the results with two commercial codes (NSolVx and HOMER). The results show that the implemented Design Support Tool develops correct system designs and presents some advantages for being disseminated in rural areas. Indeed it supports the user in providing the input data, selecting the main system components and delivering estimates to customers.

Keywords: Design techniques, micro and small enterprises, off-grid systems, rural electrification, solar photovoltaic, Uganda

INTRODUCTION

Stand-alone photovoltaics for rural electrification and micro and small enterprises: Providing access to modern energy services is at the root of Developing Countries (DCs) growth. Nevertheless, despite the efforts made, especially in the last decade, by international organizations, trust funds, NGOs and others (ESMAP, 2001; EU, 2002; FEMA, 2006; UN Foundation, 2010; United Nations, 2010), data still show a poor situation. Indeed, according to the most recent estimates more than 2.6 billion people rely on traditional biomass for cooking and about 1.3 billion people do not have access to electricity (IEA, 2013). The population of rural areas is most affected by poor access to energy services (UNDP and WHO, 2009). Those areas generally have a scattered population which is isolated and characterized by a high illiteracy rate, lack of access to health care and clean water supply (Lahimer *et al*., 2013; Mainali and Silveira, 2013) that result in "standards of living" that "almost universally lag far behind urban areas" (Sahn and Stifel, 2003).This situation has been also determined by a limited progress in access to electricity. Indeed, addressing the process of electrification, governments of DCs have directed their resources mostly towards urban areas where economic activities are more significant. In addition, rural electrification is generally the most expensive element within the centralized electrification process and hence utilities have been reluctant to extend the service to rural areas (Mostert, 2008; Turkson and Wohlgemuth, 2001; Zomers, 2003).

Nowadays, the high costs and complexity of centralized grid extension approach and the growing consideration towards the target of universal access to energy, have been drawing attention towards the off-grid systems option (Colombo *et al*., 2013). Off-grid systems are defined as power systems that operate detached from the centralized grid with a maximum rate of 5 MW (Mandelli and Mereu, 2013). They can run either on fossil fuels, on renewables, or with a mix of renewables and fossil fuels (i.e., hybrid systems). Moreover they often require storage in order to provide continuity of service. At local level, several analyses show that renewable off-grid systems are the most

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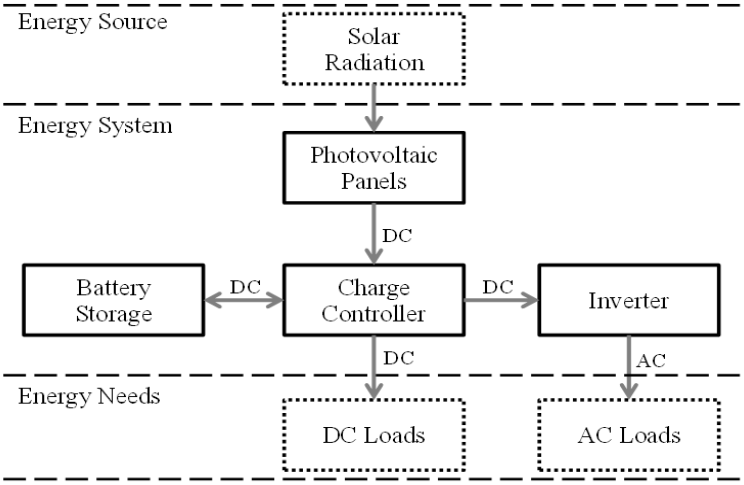

Fig. 1: SAPV building-block layout

appropriate options for rural electrification (Kaundinya *et al*., 2009; Nguyen, 2007; Nouni *et al*., 2008), while, at global level, the International Energy Agency (IEA) estimated that 55% of the additional generation required to achieve the Energy for All Case in 2030 is expected to be generated through off-grid solutions. This scenario also supposes that off-grid systems are totally employed for rural electrification with more than 90% of the generation provided by renewable and hybrid technologies (IEA, 2010b, 2011). In addition, the IEA study highlights the role of stand-alone systems which contribute 20% of the total off-grid share.

Stand-alone systems are systems made by autonomous units where production, conversion and distribution have no interaction with other units, which are tailored to specific needs of single consumers and are usually based on renewable energy sources (Mandelli and Mereu, 2013). The importance of stand-alone systems within the Energy for All Case results from the fact that they can fit with the conditions of the remotest areas of DCs:

- They are located close to the consumers thus avoiding transmission and distribution costs and limiting power losses.
- They can achieve small power rates and they are often modular, hence they easily suit different electric requirements.
- Being based on renewables, they enable total reliance on local sources, reducing dependence on fossil fuels and limiting local and global emissions.

Among renewable sources, solar energy is the most available energy source in DCs (Hoogwijk and Graus, 2008), consequently Stand-Alone Photovoltaic (SAPV) systems turn out to be often the most proper solution for rural electrification (Al-Smairan *et al*., 2012; Attachie and Amuzuvi, 2013; Cloutier and Rowley, 2011; Diouf and Pode, 2013; Mahmoud and Ibrik, 2006).

SAPV systems are made up of four main components (Fig. 1).

The photovoltaic panels: PV panels range between 5 and 240 W. For the smallest SAPV (i.e., PV power lower than about 50 W), the panel is often not located on a fixed structure, like a roof or a ground support, but instead it is portable (plug-and-play) and is placed in the sun manually when battery charging is needed.

The battery storage: A single battery ranges between 5 and 200 Ah with typical voltage of 12 V. Among the different options, lead-acid batteries are preferred in rural areas of DCs due to more affordable costs and plentiful supply. Like PV panels, when capacity is lower than about 50 Ah, the battery can be plug-and-play and often it is placed in a case together with the charge controller, the switches and the connectors.

The charge controller: Despite lower performances, the Pulse Width Modulator is preferred to the Maximum Power Point Tracking due to its lower cost; in order to optimize energy stored in the batteries, charge controller usually adopts Maximum Power Point Tracking functions and, moreover, acts in order to regulate the DC the unable.

The inverter: It is required when the SAPV system has to supply power to AC Loads and, especially for smaller systems, it noticeably contributes to increasing the cost.

Typical applications of SAPV are solar lanterns (ESMAP, 2005), solar home systems (Rahman and Ahmad, 2013), solar pumps (Caton, 2014) and battery charging stations (Dung *et al*., 2003). These technologies are ever increasing in rural areas of DCsdriven by a growing market that benefit from:

- Appreciable decreasing in PV panels and batteries costs
- Integration of SAPV systems in the rural electrification programs
- Increasing commitment of Multinational Corporations due to the huge potential market (IEA, 2010a; IFC and World Bank, 2012; Ondraczek, 2013)

Within this frame and both in market-pull and donor-push strategies, a relevant role is played by local entrepreneurs who, by mean of Micro and Small Enterprises (MSEs), contribute greatly to the last-mile-distribution of SAPV systems (Chaurey and Kandpal, 2010; GIZ, IFC and DOE, 2013).

In this study, we want to address such MSEs and specifically those that supply customized SAPV systems: i.e., businesses which design, install and maintain SAPV systems for single consumers of different typologies (e.g., households, schools, small productive activities, dispensaries, etc.). We made this choice since, in our opinion, they can contribute at different levels to the process of local development.

Appropriate rural electrification level: They can reach remote rural areas and dealing one-to-one with customer, they can best design SAPV systems.

Capacity building level: Off-grid systems being a growing market where international donors, rural energy agencies, NGOs and others act, local entrepreneurs need to develop strategies to exploit the market potentialities through multiple stakeholders. Moreover, such strategies can also be replicated for other business activities.

Income generation level: They are often ventures established locally by individuals who then employ local workers. Hence, they contribute to generating local income and also to the possible development of new businesses.

Nevertheless, besides these positive features, a number of issues limits the development of these enterprises: the difficult access to capital for small-scale and early-stage investments, the weak public support schemes and regulatory framework, the lack of consumer awareness and the lack of local technical skills (GIZ, IFC and DOE, 2013; IFC and World Bank, 2012).

This study seeks to contribute to addressing the last issue in particular. Indeed the lack of technical skills is often a bottleneck in the activity of local MSEs since design and component selection in SAPV systems are not straightforward and usually within these enter prises very few people have the technical expertise to develop the design and the estimate for the customers. Therefore we propose a simple, but general methodology which can be used to develop and set up appropriate SAPV Design Support Tools (DST) for MSEs that work in rural areas of DCs.

METHODOLOGY

Motivations and features of the design support tool: The lack of technical know-how within MSEs that supply customized SAPV systems in rural areas of DCs is an obstacle to the business development. The issue arises because often very few people, within an MSE, have the expertise needed to collect the proper data, to size the main system components, to select the most suitable ones in the local market and to provide an estimate to the customers. Furthermore, such expertise is often the result of practical experience with limited theoretical background and due to the poor access to Internet, even commercial and free available software is seldom utilized. Consequently, the business activity has a limited capacity and slowness in dealing with potential customers. Indeed, in the absence of expert staff the business activity is unable to deal with customers' requests and hence design and estimate formulation takes a very long time (even some months) which can discourage the clientele.

This issue can be solved by introducing and employing a Design Support Tool that enables, even inexpert staff, to be lead along the process of design and estimate formulation. Moreover, employing an automatic procedure can speed up the design process enabling quick cost comparisons among different system options in accordance with customer requirements.

Summarizing, the main structure of the DST should follow the system building-block layout as shown in Fig. 1 and it has to be capable, given the energy source (solar radiation) and the energy needs (DC and/or AC Loads), of defining the technical specifications of the energy system components (i.e., PV panels, batteries, charge controller and in case the inverter) and of formulating an estimate (i.e., to select the components among those available on the local market). Furthermore, in order to fit with the conditions of typical MSEs of DCs, the DTS should be.

Simple: Everyone should understand its capabilities and be able to use it properly.

Fast: Employees should be able to provide the customers the requested quotes in a few minutes, following some simple steps.

Market-based: The system design and estimate should refer to components that are available on the local market.

Flexible: It should adapt to different SAPV customer requests.

Editable in the future: The DST elements (i.e., databases, sizing equations, economic assumptions, etc.) should be modifiable according to new business needs.

Overview of SAPV design techniques and software tools: Several techniques and different kind of software are available for the design and analysis of SAPV systems. The purpose of all these techniques and software is to provide technical specifications of the system components in order to match solar radiation and electric loads according to one or more objective functions: meeting the electric loads, limiting costs, maximizing performances, etc. The essential specifications are the size of the PV panels (peak power (W)) and the battery capacity (Ampere hour (Ah) at a reference voltage, or Watt hour (Wh)); then according to the level of detail of the design process also the specifications of the other system components can be computed (e.g., inverter rated power, charge controller maximum current, etc.).

All the design techniques available in the scientific literature are based on the solving of the balance between solar radiation and electric loads while also considering the features of the system components. Differences mainly result from the length of the time-step the balance is solved for and from the approach employed to look for the optimal solution: a higher degree of detail in the load and solar data and in the mathematical modeling of the system components occurs as a consequence of a shorter time-step and greater complexity of the solver. The techniques can be classified into three categories: intuitive, numerical and analytical (Khatib *et al*., 2013). The intuitive methods can be defined as simplified calculations of the system components size based on daily values of required electric load and solar radiation. Therefore these methods provide design results for an average system that match average values (monthly or yearly) of solar resource and energy needs. They are mostly chosen for simple calculations which make them intelligible and replicable by an inexpert designer. Nevertheless they may cause over/under sizing of the design (Sharma *et al*., 1995; Sidrach-de-Cardona and Mora Lopez, 1998). In the numerical methods several combinations of system components sizes are simulated on a year basis, employing hourly or daily load and solar profiles and one or more objective functions are used to select the best component set. During the simulation, the energy balance of the system and the state of charge of the battery are calculated for each time-step considered. Moreover, also performance and economic parameters (e.g., loss of load, loss of energy, O&M costs, replacement cost, etc.) are calculated. Such parameters are employed at the end of the simulation to compute the objective function(s) (e.g., Loss of Load Probability, Net Present Cost, Levelized Cost of Energy, etc.) which enable identification of the best component set among the simulated ones. Numerical methods enable consideration of the uncertainty in solar radiation and electric load by simulating hourly solar and load data series, thus leading to more accurate results. The drawbacks are the long calculation time required and the difficulty of finding reliable data series (Ibrahim, 1995; Shen, 2009). In analytical methods, the design process is developed as a mathematical optimization problem with one or more objective functions subjected to one or more conditions. The objective function and the conditions are the physical modeling elements of the system and they are defined by means of functional relationships between the component specifications and the economic and technical parameters. The main advantage of analytical methods is that the simulations are simple and fast. On the other hand it is very difficult to find the coefficients for the functional relationships proper for each specific context (Barra *et al*., 1984; Mellit *et al*., 2005).

Several software tools are also available for the analysis, simulation and design of SAPV systems (Silvestre, 2012). Among the tools available, we introduce NSolVx and HOMER which we later employ for a comparison with our DST. NSolVx (Danley, 2012) is an intuitive- and market-based tool to be used in design and analysis of SAPV systems (and also PV-diesel generator hybrid systems). Given monthly solar radiations and daily electric loads, it computes PV and battery bank sizes using an intuitive technique based on the Array-to-Load-Ratio and Battery Days parameters. It includes also databases for the system components which can be adapted to the local market products. The design process is simple and made up of different steps which lead the user through the data input, component sizing and selection and system analysis. This tool does not consider system costs, but enables a statistical analysis of the Loss-of-Load-Probability parameter. HOMER (HOMER Energy LLC, 2014) is a numerical- and market-based tool that simulates and optimizes off-grid hybrid power systems. It can consider any combination of wind turbines, PV panels, small hydro plants, generators, batteries and others. The simulations are based on hourly load data as well as on technical specification of components available on the market. During the simulations HOMER tests any combinations of the system components considered by the user for different dispatch and load management strategies. The design optimization determines, among the simulated system combinations, the best one according to the minimum life-cycle Net Present Cost given a maximum Loss-of-Load-Probability value. Despite HOMER being based on numerical technique, the design process is simple and user friendly. It has been applied also for SAPV system design and analysis (Johnson *et al*., 2012).

A methodology to develop SAPV design support tools: Hereafter we describe a simple, but general methodology that enables the development of Design Support Tools for SAPV systems. Our purpose is to provide suggestions about the general structure, the equations and the features that should be considered in setting up DSTs that are appropriate for MSEs working in rural areas of DCs. The DST has to lead any user to develop an estimate by employing information about solar radiation, electric loads and technical specifications of the system components. In order to be simple to understand and fast when computing the results, the DST is based on the intuitive sizing technique. Moreover, developing databases of local available system components is mandatory to render the DST market-based. Finally, the DST can be set up in Microsoft Excel in order to be flexible and because it is a well-known spreadsheet application also in Developing Countries, thus allowing it also to be editable in the future. Figure 2 shows the logical block structure of the SAPV design and estimate process: it highlights the five blocks where input information is required, the output data elaborated throughout the process and the steps where the user can review the system design.

The process starts by getting data about the customer's electric needs (block 1) and by setting solar radiation data (block 2) and storage assumptions (block 3). Moreover, databases with technical specifications and costs (block 4) for each system component must be built. While electric needs are specific to each customer and storage assumptions can vary according to the required service, on the contrary solar radiation data and databases are fixed for a specific context (the databases should be updated from time to time). The information gathered within these blocks is elaborated in order to provide data in the proper form for the intuitive sizing technique; hence each block has its own specific outputs that are employed to compute the sizing results. At this point the system has been sized, but further cost information is required to define the final cost (block 5). Once the pricing results are obtained and if the customer is not satisfied, the user can review the design and estimate process at two levels:

- By modifying the selected components (and probably reducing the quality) thus changing the final cost without affecting the sizing results
- By modifying the electric needs thus affecting the sizing results. Once the customer is satisfied the estimate can be delivered

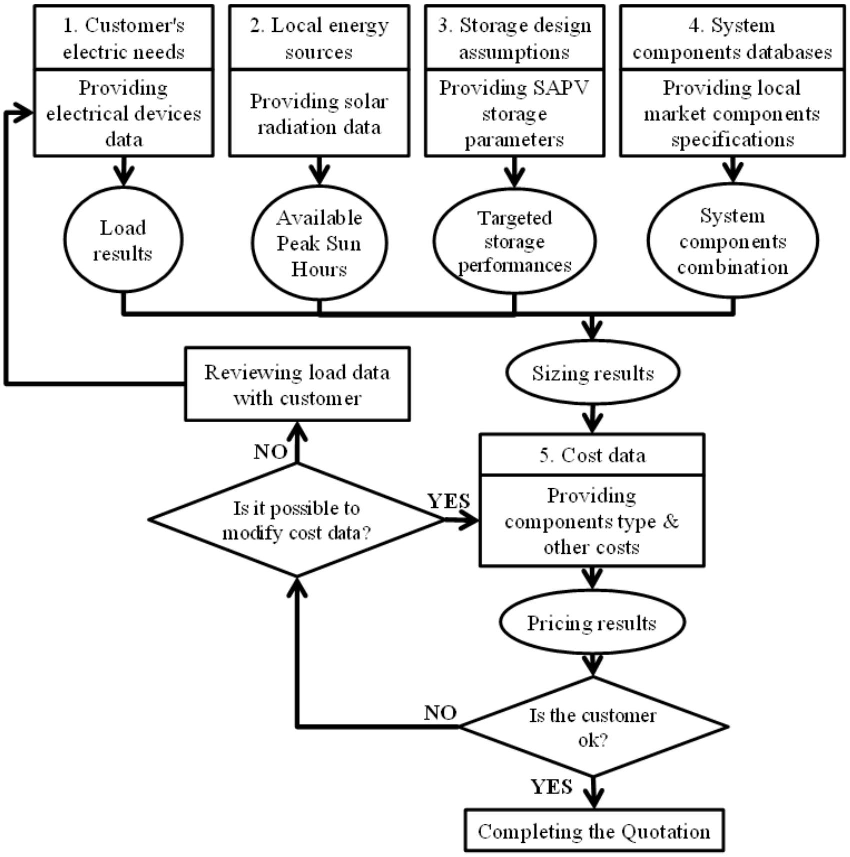

Fig. 2: Logical block structure of the SAPV design and estimate process

Table 1: PV database

Array power (W)	Panel rated power (W)	N	Array power (W)	Panel rated power (W)	N
50	50	1	140	70	2
65	65	1	150	75	2
70	70	1	160	80	2
75	75	1	200	100	2
80	80	1	240	240	1
100	100	1	300	100	3
120	120	1	360	120	3
130	65	2	400	100	4

Now we describe each input information block with the related data elaboration and we provide details about the sizing equations.

For each load devices *i*, the required data are the rate Power (P_i), the AC or DC feature, the Number of devices (N_i) and daylight ($h_{d,i}$) and night hours ($h_{n,i}$) of utilization. The *load results* consist in daylight (E_d) and night load (E_n), total daily load (E_L) and maximum power of all the devices ($P_{L,max}$). They are calculated as follows:

$$E_{d(n)} = \sum_{i=1}^{n} P_i \cdot N_i \cdot h_{d(n),i} \ [Wh] \tag{1}$$

$$E_L = E_d + E_n \ [Wh] \tag{2}$$

The maximum power is the maximum value of the total power required during the daylight hours and the night hours.

The required solar radiation data are the values of monthly and yearly averaged irradiation incident on a horizontal surface (Wh/m^2/day); these data are available in a number of websites (NASA, 2013). Nevertheless, the input data for the sizing process are the Peak Sun Hours (PSH) that are given by the ratio of the averaged irradiation and the standard irradiance of the PV panels (i.e., 1000 W/m^2).

The storage assumptions are required to set the storage capability of the system. They are the percentages of daylight and night load the battery bank should be able to provide every day (we refer to them as coverage factors, f_d and f_n) and the number of storage days (n_{sd}). These parameters define the *targeted performance* in terms of energy storage (E_{st}):

$$E_{st} = (E_d \cdot f_d + E_n \cdot f_n) \cdot n_{sd} \ [Wh] \tag{3}$$

Databases are required for the four main system components: panels, batteries, charge controllers and inverters. Databases for panels and batteries are built differently from the controllers and inverters. Indeed, while the design assumption for the SAPV systems is to employ always only one charge controller and (if needed) one inverter, the panels and batteries can be assembled in arrays and banks; consequently their databases have to consider the possible combinations of available single panels and batteries. Specifically, the inverter database has to report for each product the rated power, the working voltage and the cost, while the charge controller database has to report the rated current and the cost. As for panels and batteries, first the common products available should be identified with the required technical specifications: namely the panels rated powers and the batteries rated capacities. Then, panels and batteries should be combined to form further possible array sizes and battery bank capacities. As an example we show a section of the panels' database from the Uganda case in Table 1: the array powers are obtained by assembling N panels with the same rated powers.

If the considered electrical devices comprise AC loads, the sizing process begins with the inverter rated power that is computed on the maximum power required by the load taking into account the inverter efficiency (η_{inv}):

$$P_{inv,min} = \frac{P_{L,max}}{\eta_{Inv}} \ [W] \tag{4}$$

Then, among all the inverters in the data base, the smallest one among those which have a rated power greater than $P_{inv,min}$ is selected for the system. Moreover, the working voltage of the selected inverter becomes the reference voltage of the DC bus (V_{ref}).

The next step is to size the power of the PV array. The peak power is given by:

$$P_{PV,min} = \frac{E_L}{PSH \cdot BOS} \ [W] \tag{5}$$

where, *BOS* is the Balance of System efficiency which takes into account all the losses not accounted for the components considered (i.e., wiring, switches, shading, etc.) and the value of Peak Sun Hours (PSH) is either the minimum available monthly irradiation value or the average yearly irradiation value. The selected PV Power within the database (P_{PV}) is the smallest one among those which have a power greater than $P_{PV,min.}$ Nevertheless, noting that the majority of PV panels on the market are made to work in 12 V systems, generally more panels need to be put in series to reach the DC bus voltage imposed by the inverter. Consequently, the PV array power selected should be modified, typically by increasing the number of panels in order to have the proper voltage in each string.

The charge controller is selected according to the imposed maximum current, which derives from the PV power and the DC bus voltage as follows:

$$I_{CC,min} = \frac{P_{PV}}{V_{ref}} \ [A] \tag{6}$$

Equation (6) is an approximation of the close circuit current of the PV array and it is conservative for the charge controller selection. Then, the value of the computed rated value $I_{cc,min}$ is compared with those recorded in the database to select the proper available charge controller.

The value of the Energy storage (E_{st}) computed with Eq. (1) provides the battery bank capacity. Nevertheless the final capacity should be computed as follows considering the value of the minimum permitted State of Charge (*SOCmin*) which preserves batteries from over-discharging:

$$C_{B,min} = \frac{E_{st}}{(1-SOC_{min})\cdot V_{ref}} \text{ [Ah]} \qquad (7)$$

Note that no battery charge/discharge efficiencies are employed since the related losses can be accounted for by a conservative assumption on the daylight coverage factors f_n. The battery bank capacity selected within the database is the smallest one among those which have a capacity greater than $C_{B,min}$. Moreover, similarly to the PV array sizing, the DC bus voltage has to be respected; therefore, since typical lead-acid batteries for SAPV systems are developed to work in 12 V systems, the battery number should be increased in order to match the proper voltage in each string.

In DC systems (typically below 100 W), the design process does not comprise the inverter, while the other components are sized with the same equations considering 12 V as the reference voltage.

Once the sizing results are obtained the pricing results can be computed by selecting the brand of the component among those available in the databases which match the required technical specifications and by adding labor and other system costs related to cables, switches, sockets, etc. If the customer expectations in terms of final cost is not satisfied even selecting the cheapest components available on the market, a reduction of the estimate can be accomplished by reducing the size of the components and hence by reducing, in agreement with the customer, the devices data input (i.e., reducing value of the total daily load (E_L) and Energy storage (E_{st})).

VILLAGE ENERGY SIZING AND PRICING TOOL

The described methodology has been applied to set up a DST that is now employed at Village Energy Ltd, a micro enterprise that supplies customized SAPV systems in the urban area of Kampala and in the rural areas of Soroti (Uganda). The DST, named VE Sizing and Pricing, is a user friendly tool that capitalizes on the expertise of local technicians and formalizes it within a tool that improves the business activity by enabling anyone at Village Energy to formulate an estimate for the clientele.

VE Sizing and Pricing supports the design of DC and AC SAPV systems with a maximum PV power of about 3.5 kW, it is set up in Microsoft Excel and it is made up by nine spreadsheets: five *data bases* (i.e., PV panels, batteries, inverters, charge controllers and other electrical components), the *device sheet* which computes the load results given the electrical device data, the *sizing sheet* which provides the sizing results according to the proposed intuitive technique, databases, storage assumptions and DC bus voltage, the *price sheet* which computes the pricing results given the components own brand and other charged costs and the *quote sheet* which generates the estimate to be delivered to the customers. In Table 2 we report key information for the local available components while typical storage assumptions and components parameters are reported in Table 3. The daylight and night coverage factors and the number of storage days in particular, are imposed (and should be imposed) on the basis of the experience of local technicians according to a compromise between costs, customer expectations as regard the provided service and system performances.

Table 2: Local components information

	Size range	Costs range
PV panel (12 V)	5-240 W	1-4.3 €/W_p
Battery (12 V)	5-200 Ah	1.2-1.9 €/Ah
Inverters	300 and 600 W →12 V	€ 30-170
	1000 W → 24 V	€ 290
	2500 W → 32 V	€ 800
Charge controller	5-80 A	€ 10-430

Table 3: Village energy storage assumptions and components parameters

Sizing assumption			
Daylight coverage factors	f_d	20	%
Night coverage factors	f_d	100	%
Storage days	n_{sd}	1 2 if power >1 kW	
Components parameters			
Balance of system efficiency	BOS	90	%
Minimum state of charge of battery	SOC_{min}	40	%
Peak sun hours	PSH	6.0	h
Inverter efficiency	η_{inv}	90	%

Now we describe the application of VE Sizing and Pricing. We consider a reasonably large system in order to carry out the comparison with the commercial software as regards a more significant case rather than a small lighting SAPV system used for basic rural electrification. The case study is located in Soroti, a small but expanding town in the central-east of Uganda where the national electric grid reaches only the main town, while several households in the periphery employ small diesel generators. Nowadays, thanks to the favorable climatic conditions and to the increase of activities like Village Energy, people have been taking the opportunity to shift towards SAPV systems. The customer considered is a householder who lives in the periphery of the town, whose aim is to power the appliances already present in his house. The household is made up of 8 people who need to light the rooms, to have security night lights, to charge 2 mobile phones and 2 laptops and to power one television, one small fridge and one standing fan. In Table 4 we report the electrical device data while Table 5 shows the load

Table 4: Case study electrical devices data

Device	Power (W)	N	Daylight hours of utilization (h)	Night hours of utilization (h)
LED indoor lights	5	8	0	6
LED security lights	5	4	0	12
Laptops	50	2	3	2
Phone charging	5	2	2	2
20" TV	100	1	0	4
Fridge	300	1	4	3
Standing fan	50	1	4	0

Table 5: Case study load results

Total daily load	E_L	3720	Wh
Daylight load	E_d	1720	Wh
Night load	E_n	2000	Wh
Maximum power required	$P_{L,max}$	570	W

Table 6: Case study sizing results

Inverter sizing			
Inverter		1000	W
DC bus voltage		24	V
PV array sizing			
Minimum nominal power required	$P_{PV,min}$	689	W
Single panel peak power		240	W
Number of installed panels		4	
PV array power	P_{PV}	960	W
Battery bank sizing			
Energy storage	E_{st}	2.34	kWh
Batteries minimum capacity	$C_{B,min}$	163	Ah
Single battery capacity		200	Ah
Number of installed batteries		2	
Battery bank capacity	C_B	200	Ah
Charge controller sizing			
Maximum current	$I_{CC,min}$	40	A
Charge controller		40	A

results: the total daily load is about 4 kWh and the maximum power required is about 600 W.

The sizing results are shown in Table 6. Owing to the 1000 W inverter, the voltage of the DC bus is 24 V. The PV power is approximately 690 W, which can be met by 3 modules of 240 W. However, this solution does not respect the DC voltage and hence the PV array should be made up of 4 modules with a final power of 960 W. As for the storage, owing to the imposed 24 V, two batteries of 200 Ah are required. The total cost of the system is about €2100 with 88% of the cost related to the four main components. Administrative and labor costs are not considered in order to render the analysis independent of the corporate strategy.

A COMPARISON WITH TWO COMMERCIAL SOFTWARE TOOLS

Hereafter we compare NSolVx and HOMER with VE Sizing and Pricing in addressing our targeted MSEs issue. We select these applications since in our opinion they would be the most suitable among all those available to support business activities similar to Village Energy.

First of all, NSolVx and HOMER should be set up in such a way as to be operational within the Village Energy context. Therefore the input fields (e.g., components' database, sizing assumptions, etc.) have to be filled in with coherent data. However, we noticed that both tools have some limitations in this respect. Concerning NSolVx, despite its structure being quite similar to VE Sizing and Pricing, we noticed three critical points:

Table 7: NSolVx results

System voltage	24	V	Charge controller	40	A
PV array	1200	W	Array-to-load-ratio	1.32	
Battery bank	400	Ah	Battery days	1.20	
Inverter	1	kW	LLP	3.20	%

- No support in computing the load data: The user is required to provide the total daily load, but there is no support for collecting information about the custumer's devices.
- The array-to-load-ratio and battery days values need to be set: These parameters are not in current use in SAPV design and may be difficult to understand for local designers.
- The components within the databases at the beginning of the sizing process need to be selected. This choice is not assisted, but it requires expertise as regards relationships among the components.

Concerning HOMER, four limitations make it inappropriate for DCs real-context use:

- The value of Loss-of-Load-Probability (LLP) needs to be se: This parameter cannot be estimated by inexpert user because it requires competence to analyze the load data.
- Hourly load profile needs to be provided: This information can deeply affect the sizing results, but customers are often unable to provide proper information and in any case it is difficult to estimate also for expert technicians.
- The user has to provide the size ranges for each component to be simulated: This aspect requires a good practical sense to detect the correct ranges to be simulated.
- Databases are available only for batteries and not for PV array and inverters, moreover charge controllers are not considered in the sizing process.

Now we present the results obtained with HOMER and NSolVx. Considering NSolVx (Table 7), we have found consistency regarding inverter and charge controller sizing and discordances about PV power and battery bank capacity. These differences result from the fact that the NSolVx intuitive method is based on the Array-to-Load-Ratio and Battery Days parameters. In particular, given a set of components, the design process always suggests:

Table 8: HOMER results

PV (W)	Batt (Ah)	n° batt	Batt (Ah)	Inverter (kW)	Investment (€)	Net present cost (€)	LLP (%)
480	100	2	100	1	1312	1766	50
600	100	2	100	1	1432	1886	40
720	150	2	150	1	1761	2557	30
960	150	2	150	1	2001	2797	20
960	200	2	200	1	2092	3050	10
960	300	4	150	1	2452	4045	5
960	800	8	200	1	3721	7551	1

- An Array-to-Load-Ratio greater than 1 in order to excess the array capacity to optimize batteries charging thus leading to higher PV array power.
- Battery Days at least equal to 1 thus sizing the storage to the entire daily load (in VE Sizing and Pricing we propose to cover the night load and a fraction of the daylight load).

Therefore NSolVx produces PV and battery over sizing and hence greater system reliability. Nevertheless, since a cost analysis is not available, it is not possible to balance the over sizing with the resulting high costs.

Considering HOMER results (Table 8) and remembering that it provides the best systems that address the load at different LLP, we found that the resulting VE Sizing and Pricing system is the best system that meets the customer needs with 10% of LLP, which is a reasonable and absolutely acceptable value for SAPV systems in Developing Countries. A further consideration is that, in order to increase reliability an increase in the battery capacity is required instead of the PV array power. The design and economic results provided by HOMER are more accurate than NSolVx and VE Sizing and Pricing due to the numerical design technique and the advanced modeling of the components. Nevertheless the required component details, the need to set the LLP value and the analysis capability requested to evaluate the results, make HOMER complex and inefficient for our purpose.

CONCLUSION

This study describes a general, but simple methodology that enables the development and setting up of Design Support Tools for Stand-Alone Photovoltaic Systems. Our main purpose is to contribute, in the short run, to improving the current business activities of Micro and Small Enterprises that work in Developing Countries by supplying off-grid PV systems. Indeed such systems are considered as one of the main options in addressing the process of rural electrification. By means of the methodology, we introduce the structure, the sizing equations and the main features that should be considered in developing an SAPV Design Support Tool. In particular it is needed to employ an intuitive design technique and to develop databases of local available system components. We employ the methodology to set up a DST, called VE Sizing and Pricing, in Uganda. This DST is now utilized by a local micro-enterprise named Village Energy Ltd. We compare the application of VE Sizing and Pricing to a case study of a local household with the commercial software NSolVx and HOMER. The results show that VE Sizing and Pricing best matches our targeted purpose while also developing a correct system design. Indeed, it supports the user in providing the input data (devices information and component databases), selecting the main system components (PV panels, battery bank, charge controller and inverters) and formulating an estimate to the customer. The methodology introduced represents a very important step to overcome an urgent bottleneck of local MSEs and may also represent a non-marginal and short-term contribution to the needed long-term process of capacity and competence building which is strongly required at local level in Developing Countries.

ACKNOWLEDGMENT

The authors would like to thank the CEO of Village Energy, Abu Musuuza and the CTO, Paola De Cecco, for the support in collecting all the information and in developing the VE Sizing and Pricing tool during the stay in Uganda.

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