Microgrid design: sensitivity on models and parameters

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***Abstract*— Designing off-grid systems in developing countries is not a trivial task; unpredictable energy sources and uncertain load demands have to match in a seamless solution, providing the most favourable conditions in terms of adequacy with respect to the energy needs and costs. The challenge is to define which parameters/assumptions could have a strong impact on the results in order to properly model them.**

This paper is based on a peculiar study case: a microgrid deployed by the Politecnico di Milano team in Tanzania, load and generator power profiles have been sampled each second over many months. Given such a large amount of data, it is proposed a sensitivity analysis devoted to quantifying the impact that different assumptions could have in the design of a theoretical new microgrid that could optimally feed the loads. Numerical analysis is based on a tool, named PoliNRG, developed by a research team of Politecnico di Milano.

***Keywords*— Developing countries, Electrification Processes, Microgrid Design, Renewables, Energy Storage.**

I. INTRODUCTION

Worldwide Energy access is more and more one of the major concerns: climate change, energy security, renewables and energy efficiency, energy economics, are regularly in the agenda of Policymakers. New problems ask for new solutions; in such a perspective microgrids are under investigation in order to develop an effective decentralized approach to energy access. Both industrialized countries and developing countries are looking for proper models and tools asked to point out (cfr. quantify) where and when decentralized microgrid could be economically viable, reliable and feasible from a social impact point of view.

Focusing on the emerging countries perspective, it is mandatory to stress out how much energy is important for a socioeconomic development. Quality of life for the people, global security and environmental protection are directly linked to access to energy. Energy is the basis for most economic activities: food production, transport, education, commerce, agriculture, or simply the production of commodities to elaborate other products or supply services. Energy is also essential for protecting human health and environment: access to electricity and to clean cooking facilities can help to avoid premature deaths, diseases, local air and water pollution, indoor pollution, deforestation, ecosystem damages, CO_2 emissions, etc. Moreover, it is today universally accepted that there is a direct link between access to energy and income, access to energy and quality of life, access to energy and development, access to energy and education.

Recently IEA reported [1] that over 120 million people worldwide gained access to electricity in 2017. Nevertheless, despite the positive outcome, 600 million people in sub-Saharan Africa and 350 million in Asia lack access to electricity, moreover 2.7 billion people worldwide do not have clean cooking facilities. Nevertheless, the problem is far from being solved and, in particular, developing countries depict critical peculiarities. Energy needs are very intermittent and not regular, electric grids are hardly reliable and power quality is a critical issue, there is typically a rapid growing demand for energy and, at the same time, final users' capacity to pay cannot be taken for granted [2]. On top of that, in developing countries one of the major concerns is in a chronic lack of data (both for the consumption and for the production side). Such peculiarities ask for tailored tools, designed in order to properly manage the developing countries problem.

The main goal of this paper is to propose an effective approach for designing microgrid in developing countries and to detail a sensitivity analysis on a real-life study case in order to evaluate how each single parameter (cfr. input) could affect the optimal sizing of each component (generation portfolio, energy storage, etc.).

II. TOOLS FOR MICROGRID DESIGN

Capacity generation planning is a quite well-known problem, actually several tools are proposed in the literature [3]:

- HOMER is the most used software for the simulation and optimization of off-grid hybrid power systems. It determines the configuration that minimizes life-cycle costs. The tool can perform optimization and sensitivity analysis of both off-grid and grid connected power systems [4][5][6].

- iHOGA looks to the minimization of total system costs (or maximization of profits) over the system lifetime, transferred or updated to the initial moment of the investment (Net Present Cost, NPC). The program also allows multi-objective optimization [7][8][9].
- OSeMOSYS is an open source modelling system for long-run integrated assessment and energy planning; the tool has been employed to develop energy systems models from the scale of continents down to the scale of countries, regions and villages. It can cover all energy sectors, including heat, electricity and transport and has a user-defined spatial and temporal domain and scale [10][11][12].
- The Distributed Energy Resources Customer Adoption Model (DER-CAM) is an economic and environmental model, a decision support tool for investment and planning of decentralized energy resources in buildings or micro-grids [13][14].
- LREM (Local Reference Electrification Model) is a tool aimed to produce detailed micro-grid designs suitable for the rural context. The network design is done with the Reference Network Model (RNM), based on two different models: the brownfield model, which attempts to build the new distribution network into the existing infrastructure, and the greenfield version, which is used for scratch design of rural micro-grid [15][16].
- PVsyst is a quite well-known software for the study of stand-alone and grid-connected solar systems. It can be adopted to support microgrid design processes, even though it not focused on rural area electrification purposes [17].

When dealing with rural electrification, information about loads are typically not available, i.e., they are characterized by significant uncertainty. Moreover, even if realistically estimated for the current conditions, as an off-grid power system operates for several years, usually a static picture of users' demand is not suitable. Underestimating the energy needs would cause critical value of Loss of Load Probability (LLP); vice versa, too conservative assumptions would cause an insane growth of the microgrid costs, hindering its economic viability. Moreover, to provide an environmentally sustainable solution, off-grid systems have to rely on renewable energy sources. This requires dealing with the energy resource data availability. Sensible energy models have to be developed in the design phase in order to properly evaluate the impact of the power fluctuations on each microgrid component.

In order to manage such issues, authors developed a suited procedure named PoliNRG, specifically designed to manage electrification processes in developing countries [18][20]. For sake of clarity, authors do not pretend to propose a universal tool, capable to fully tackle the electrification problem, vice-versa the goal is to provide a contribution on a procedure specifically designed for developing countries. In particular, the main goal of this paper is to exploit such a procedure in order to discuss the impact of uncertainties and models on microgrid design.

III. PROPOSED METHODOLOGY

PoliNRG has been proposed to optimally design components in a microgrid based on PV and Battery Energy Storage System (BESS). A detailed description is reported in [18][20]; the tool has been coded in a Matlab procedure that is freely available [19]. The tool solves the Capacity Generation Planning in a given microgrid looking for the minimization of the Net Present Cost (*NPC*).

$$NPC = Inv + \sum_{y=1}^{T} \frac{CF(y)}{(1+r)^{y}} - RV(T) \quad [€] \qquad (1)$$

where Inv is used to account for investment cost, *CF*(y) is the net cash flow during the year y actualized with the discount factor r, *RV*(T) represents the residual value of the assets (i.e. BESS) at the end of the investment term T. Cash flows can be computed by accounting for penalties and replacement costs:

$$CF(y) = O\&M(y) + C_R(y) \qquad (2)$$

where *O&M*(y) are the operation and maintenance costs, *CR*(y) accounts for replacement costs of BESS by taking into account the projected BESS cost at a specific year y.

$$C_R(y) = c_{BESS}(y_P) * BESS_{size} \qquad (3)$$

Moreover, a constraint is added in order to check the adequacy of the solution proposed in satisfying at least a percentage of the energy required by the load. This constraint is defined as a maximum limit in the Loss of Load Probability (*LLP*).

$$LLP = \frac{\sum_{k=1}^{LT} LL(k)}{\sum_{k=1}^{LT} \mathrm{LC}(k)} \qquad (4)$$

where Loss of Load (*LL*, the amount of unsupplied energy required by the load) is computed as the loads consumption *LC*(k) unsatisfied due to saturation of the BESS:

$$LL(k) = LC(k)\Big|_{(BESS\ limits)\ V\ \left(\frac{\Delta E}{\Delta t} \geq \frac{BESS_{size}}{EPR_{max}}\right)} \qquad (5)$$

Given a combination of sizes for PV and BESS, the operation of the microgrid is simulated for the expected lifetime in order to find the values of *NPC* and *LLP*. A heuristic technique is used for iterating among different combinations of sizes until the global optimal point is found.

In order to verify and quantify the importance of a detailed model of the components of the microgrid, the tool has been used for a sensitivity analysis of the microgrid sizing problem. The main components of the microgrid can be assumed to be the load, the PV plant and the BESS; in this paper several models of such equipment are proposed and compared with each other. In the following, investigated models are shortly introduced.

A. Energy Storage modeling

PoliNRG tool is provided with different BESS models [21]; in the present study two different approaches have been compared.

- The first model evaluated, named B1, is based on a very simple representation of the BESS performances: just a constant overall efficiency is considered whilst no capacity fade or other non-linearities are simulated.
- The second model, named B2, aims to a more accurate evaluation of the BESS behaviour. State of Health

(SOH) degradation due to equivalent cycle Eq_cycles of each time step t is calculated as:

$$SOH(t) = SOH(t-1) - Eq_{cycle(t)} \cdot C_{fade}(t) \quad (6)$$

where c_fade is the capacity fade of the battery defined as a function of the C-rate in case of lithium ion batteries, while it is a function of the Depth of Discharge (DOD) for lead acid batteries. Similarly, efficiency is properly evaluated as a cubic function decreasing with the C-rate where parameters are defined according to the electrochemical technology [21]:

$$\eta = a \cdot C_{rate}^3 + b \cdot C_{rate}^2 + c \cdot C_{rate} + d \quad (7)$$

B. Modeling of Load and PV production power profiles

The proposed procedure requires as input the load profile during the entire lifetime of the microgrid. It is possible to model it in different ways depending on the availability of information about the consumption. When limited information is available (typical case of first electrification), a standard or typical daily consumption profile can be defined and repeated to create the whole year load profile. If more information is available it is possible to take into account the typical behaviour of the future user (e.g. difference between work days and holidays, weekly behaviours, seasonality variations…). Moreover, another degree of freedom is related to the time resolution adopted in the power profile simulation (one hour, quarter of hour, one minute, etc.). Finally, a variable that could have an impact on the sizing process can be the expected growth of the load over the years.

In this paper different models have been adopted and compared with each other, as listed in the following:

- Hourly-simple (Model **L1**): One single daily profile is generated and replicated throughout each day of the year with hourly time resolution;

- Hourly-complex (Model **L2**): A yearly power profile is generated, taking into account changes in the energy needs over different weeks and seasons. An hourly time resolution is adopted;

- Minute-simple (Model **L3**): The model is similar to L1 but detailed in a one-minute time resolution;

- Minute-complex (Model **L4**): The model is similar to L2 but detailed in a one-minute time resolution.

Obviously, models **L2** and **L4** drive to a more accurate evaluation of the load fluctuations over the year, whilst models **L1** and **L3** lead unavoidably to the loss of some information. Vice-versa, in real life applications, models **L1** and **L3** better fit with the (limited) information that are generally available for the microgrid design.

To evaluate the energy balance for each time step within the microgrid, a solar power production profile has also to be modelled. The procedure requires as an input the per unit power profile with respect to the rated power of the plant; as long as the nominal power of the PV plant is provided once solved the optimization problem. To define the PV p.u. profile, the procedure adopts external databases of historical irradiation profiles. A PV panel model, parametrized in the Power Plant geometry, external temperature, and derating factor (yearly reduction of the Panel efficiency), convert irradiation profiles in power production profiles.

With respect to the procedure proposed in this paper, as for the load profile, four different models have been adopted.

- Hourly-simple (**S1**) - One PV daily profile is generated and replicated throughout each day of the year with hourly time resolution.

- Hourly complex (**S2**) - A yearly PV profile is generated, taking into account changes in the energy production over different days. An hourly time resolution is adopted.

- Minute-simple (**S3**) - The model is similar to S1 but detailed in a one-minute time resolution;

- Minute-complex (**S4**) - The model is similar to S2 but detailed in a one-minute time resolution.

Simplified models **S1** and **S3**, has been obtained normalizing the yearly profile, i.e. keeping the same yearly energy production of the complete models **S2** and **S4**.

IV. CASE STUDY

The methodology proposed has been applied to a real-life case study: the secondary school of Ngarenanyuki, located in a rural area of Arusha region, in the North-eastern part of Tanzania. In 2003, from wood and soil dilapidated buildings, a restructuring process started and today the school hosts about 500 students. In 2014, the research team of Politecnico di Milano started a collaboration with the school; the first task was related to a quantitative monitoring of the energy needs and of the power profiles (generation and consumption). The energy consumption of the school has been monitored by Politecnico of Milan since 2015, energy flows (consumption, production, BESS) are sampled each second and stored in a cloud repository. The microgrid combined power systems already available on site, diesel generators and a hydro turbine, with new installations, PV panels and batteries. Data collected through field survey, together with measured data, were used to generate realistic load profiles given as input to Poli.NRG procedure. The availability of realistic data regarding load consumption has been crucial for performing the analysis described in the following paragraph. Simulations in fact consider the high load variability of the real-life scenario that represents a typical case in rural areas of emerging countries. The load consumption profile for the month of October 2017 is reported in Figure 2; the sampled trend clearly demonstrates the high fluctuating behaviour of the energy need in a rural area microgrid.

Figure 1 Ngarenanyuki school in 2016 (about 500 students)

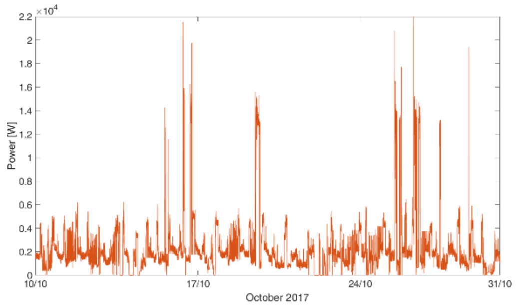

Figure 2 Measured load consumption in Nagrenanyuki school

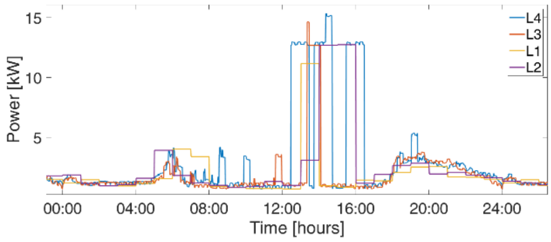

Figure 3 Load profiles comparison

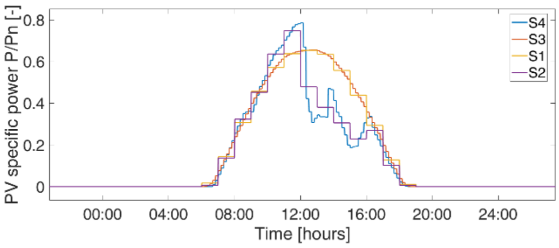

Figure 4 PV power profiles comparison

Given the four load models introduced in Section III data gathered in Ngarenanyuki have been elaborated in order to obtain accurate yearly power profiles detailed in minute samples (L4) or hourly samples (L2), similarly simplified profile have been defined replicating a standard daily profile identically over the year (L1, hourly samples, & L3, minute samples). Solar irradiation data for Ngarenanyuki were taken from public databases [22]; whilst the photovoltaic power profile was computed considering an average efficiency of the panels. As for the load profile, four different power profiles were generated: hourly-simple (S1), hourly complex (S2), minute-simple (S3), minute-complex (S4) (Figure 4). As concerns BESS modelling, the technology that has been chosen is the Li-ion, due to the high performance and the promising future in developing countries. The two different models described in Section III, simplified (B1) and complete (B2) have been compared. PV modules, inverters and batteries costs have been estimated by several Tanzanian suppliers, whereas other costs such as operation and maintenance cost have been defined through experience. In particular, two different assumptions for PV modules have been considered: 2500€/kW and 850€/kW. The higher cost corresponds to the value found in Ngarenanyuki, caused by the high transportation and installation costs of the remote locality. The second value is instead related to the average literature price of PV panels.

TABLE 1 SIMULATIONS SET-UP

Model adopted for load and simulation time resolution	**Simple Battery Model B1**	**Complete Battery Model B2**
L1 & S1	Sim 1	Sim 5
L1 & S2	Sim 2	Sim 6
L2 & S1	Sim 3	Sim 7
L2 & S2	Sim 4	Sim 8
L3 & S3	Sim 9	Sim 13
L3 & S4	Sim 10	Sim 14
L4 & S3	Sim 11	Sim 15
L4 & S4	Sim 12	Sim 16

TABLE 2 SIMULATIONS OF LOAD GROWTH SCENARIOS

Model adopted for load, battery and simulation time resolution	**Scen 1**	**Scen 2**	**Scen 3**
L4&S4&B2	Sim 17	Sim 18	Sim 19

The comparison has been useful to understand the sizing trends in two different likely conditions.

Sixteen simulations have been performed to assess results with all the different model/assumption combinations, as shown in Table 1. In addition, it is likely that the school consumption will rise over time, due to the growing energy needs of teachers and students. It becomes hence relevant to understand how the size of the microgrid would change when considering different load growth scenarios:

- Scenario 1: linear load increase of 1% each year;
- Scenario 2: linear load increase of 2% each year;
- Scenario 3: linear load increase of 5% each year.

Therefore, three additional simulations have been performed (Table 2). The simulations have been performed on a i7-4790 16gb workstation, in windows10-Matlab.

V. RESULTS AND DISCUSSION

The sixteen-mentioned combinations in Table 1 have been simulated (adopting Poli.NRG tool) and they have been compared in terms of sizing results, costs and simulation time. Numerical results are reported in Table 3 and the percentage error with respect to the most accurate case (Sim 16) are represented in Table 4. The results related to the different lifetime scenarios and the percentage increase of the components' size are shown in Table 5 and table 6 respectively. The most accurate model has been classified as L4&S4&B2: load is detailed for each single day of the year, similarly for pv production. Power profiles are simulated with a high time resolution (one minute) and a complex model for the bess is adopted. In the following, such model is adopted as a reference case, i.e. the case correspondent to the optimal design of the microgrid. The sensitivity analysis on the model demonstrates that the parameters that mostly affect PV size are the load and PV power profiles. As can be seen in Table 4, 2500€/kW case, simulations 4, 8 and 12 have the smallest percentage error with respect to the reference case. These simulations all consider high variability both in load and PV profile and are closer to real life scenario. The results are slightly different for the 850€/kW case where PV panels are under dimensioned in simulations 4 and 12. However, the error committed in sizing the panels is acceptable (less than 25% in the first case and a bit higher in the second case) even when using simplified assumptions. BESS modelling has a higher influence in the simulations of case 2 (seen e.g. by the difference of sim 4 with 8) while the time step duration has only a small effect on PV size as it can be seen by the small error difference from simulations 1 to 8 with respect to simulations 9 to 16. As opposed to the PV size, simplifications lead to relevant percentage errors and to inaccurate results related to BESS size. From Table 4 it can be noticed that BESS size defined by simulations 1, 5, 9 and 13 is half the correct value. Moreover, according to simulations 6 and 14, load simplification is the parameter that mostly affects the dimensioning. The battery size differs according to the considered battery model, but the error results acceptable if the parameters of the simple model are chosen in the correct manner. Once more, time step duration does not have a big influence on results' uncertainties. The uncertainty on LCOE value varies from a minimum of 1% to a maximum of 30%, i.e. models have a strong impact on the LCOE estimation. Considering load growth scenarios, Table 6 shows that PV and BESS size increase almost linearly with the increase in load consumption. It is hence of significant importance to consider realistic assumptions related to the increase of energy consumption in the area.

TABLE 3 SIMULATIONS' RESULTS (CONSTANT LOAD OVER LIFETIME)

Sim	2500€/kW			850€/kW			Comp. Time s
	PV kW	BESS kWh	LCOE €/kWh	PV kW	BESS kWh	LCOE €/kWh	
1	12,4	26,4	0,54	12,4	26,4	0,41	116
2	13,3	58,1	0,62	16,1	36,5	0,46	87
3	13	49,1	0,65	15,7	37,4	0,51	116
4	14,9	57,1	0,70	14,9	57,1	0,54	87
5	12,3	28,2	0,49	12,3	28,2	0,36	293
6	14,2	45,1	0,59	16	37	0,43	116
7	12,9	48,9	0,62	16,1	36,3	0,47	176
8	15,1	54,2	0,69	17,4	44,1	0,52	90
9	12,4	26,8	0,58	12,4	26,8	0,45	1.600
10	14,1	47,5	0,66	15,9	38,3	0,50	1.800
11	13	52,2	0,67	16,2	38,5	0,52	2.400
12	15,4	58,5	0,72	15,4	58,5	0,55	2.000
13	12,3	28,6	0,52	12,3	28,6	0,39	5.000
14	14,2	45,9	0,63	15,9	38,4	0,47	7.000
15	12,9	52	0,64	17,3	34,8	0,49	7.000
16	15,8	54,6	0,71	18,1	45,1	0,53	7.000

TABLE 4 PERCENTAGE RELATIVE ERROR (SIM16, IN RED, IS THE REFERENCE CASE, I.E. THE MORE ACCURATE MODEL)

	2500€/kW			850€/kW		
Sim	**PV**	**BESS**	**LCOE**	**PV**	**BESS**	**LCOE**
1	22%	52%	24%	31%	41%	23%
2	16%	6%	13%	11%	19%	13%
3	18%	10%	8%	13%	17%	5%
4	6%	5%	2%	18%	27%	1%
5	22%	48%	32%	32%	37%	33%
6	10%	17%	17%	12%	18%	19%
7	18%	10%	12%	11%	20%	11%
8	4%	1%	3%	4%	2%	3%
9	22%	51%	19%	31%	41%	17%
10	11%	13%	7%	12%	15%	6%
11	18%	4%	6%	10%	15%	2%
12	3%	7%	1%	15%	30%	4%
13	22%	48%	27%	32%	37%	27%
14	10%	16%	12%	12%	15%	12%
15	18%	5%	10%	4%	23%	9%
16	0%	0%	0%	0%	0%	0%

TABLE 5 SIMULATIONS' RESULTS (LOAD GROWTH SCENARIOS)

	PV (kW)	BESS (kWh)	Computational Time (s)	LCOE (€/kWh)
Sim 17	17,6	60,4	6.230	0,7368
Sim 18	19	70,4	6.230	0,7645
Sim 19	26,2	88,9	9.000	0,8463

TABLE 6 PERCENTAGE INCREASE OF RESULTS (LOAD GROWTH SCENARIOS)

	Average load increase	PV	BESS
Sim 17	11%	11%	11%
Sim 18	21%	20%	29%
Sim 19	53%	66%	63%

Overall results are also shown in Figure 5 and Figure 6 which allow to have a broader perspective on the topic. The four subplots represent the solutions obtained in the sixteen different simulations. In the four plots the dots are coloured in different ways according to the parameter that is analysed; they are blue when the parameter is simplified and red when it is more complete. To see its relevance, time step is also considered as a parameter, simple when hourly profiles are used and complex when the resolution is of one minute. What can be clearly noticed is that there is a priority order in the way parameters should be improved. When the models are simple, solutions tend to be under dimensioned (bottom left corner of the graphs) and the change in BESS model and time step do not lead to significant improvements. The first factors to be considered are instead the accuracy in load and PV power profile determination. When these two aspects are improved, errors are reduced significantly (e.g. from sim 1 to sim 2). PV and BESS optimal size tends to increase

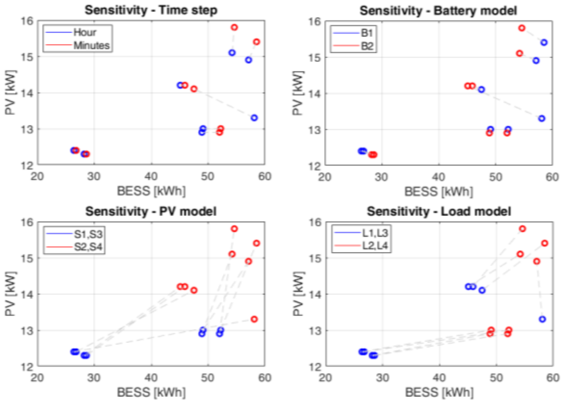

Figure 5 Sensitivity analysis-PV Panels quoted 2500€/kW

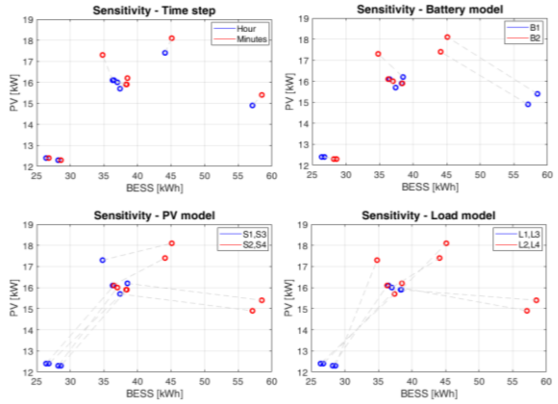

Figure 6 Sensitivity analysis- PV panels quoted 850 €/kW

because of the peaks of load consumption and of the low irradiance of cloudy days considered in the realistic profiles. As a second step, battery model can be improved to further reduce the error and finally, also the time step reduction is useful to arrive to the most accurate results (sim 16). The trends are similar in both the analysed cases, with 2500€/kW and 850€/kW for PV price. When choosing the better approach, it is anyway necessary to consider also the computational burden. The most simplified procedure is two orders of magnitude faster with respect to the most complex one (computation time rise from 80 to 7000 seconds). The major difference concerning computational time is caused by the length of the time step: using hourly profiles reduces significantly the computational burden.

Final remarks should be made by looking at the influence of the battery modelling approach. The simplified model, in fact, in some cases leads to significant over dimensioning of the battery causing a relevant error. It would be important to investigate which of the parameters of the simplified model are causing the shift in results. As an example, if the maximum number of cycles the battery can withstand before replacement is too low with respect to the real operating conditions, the resulting optimal size will be greater than the one determined with a complex model.

VI. CONCLUSION

The paper presented a sensitivity analysis on models and parameters adopted to design a microgrid for rural area electrification. Results clearly indicate that different assumptions, to simplify the model, both with respect to the data gathering tasks and for the computational effort required to solve mathematical models, could have a strong impact on the microgrid design.

The study motivates the proposal for new procedures devoted to pre-process data in order to evaluate which are the parameters that mostly affect the output and that must be most accurately determined. As a second step, already available tools could be adopted in order to optimally design microgrids.

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