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DESIGN OF A MODEL FOR MICRO-GRID SIMULATIONS: THE CASE OF ST. MARY'S LACOR HOSPITAL

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FONDAZIONE ONLUS
PIERO E LUCILLE CORTI
IN UGANDA, PER LA CURA E LO SVILUPPO

ST MARY'S HOSPITAL
LACOR

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There is a crack in everything
That’s how the light gets in.

Leonard Cohen

Extended Summary

Nomenclature

Acronym	Description	Symbol	Description
BESS	Battery Energy Storage System	E_{bal}	Energy that is really satisfied by the batteries
DG	Diesel Generator	$E_{bal,teo}$	Energy that should be satisfied by the batteries
CF	Cycles to Failure	E_{gen}	Energy that is satisfied by diesel generator
DoD	Depth of Discharge	$E_{gen,max}$	Maximum energy that generator can provide
LCoE	Levelized Cost of Energy	$E_{gen,min}$	Minimum energy that generator can provide
LL	Loss of Load	E_{load}	Energy demand
LLP	Loss of Load Probability	E_{loss}	Energy not satisfied
LT	Lifetime	$Energy\ max$	Maximum input/output energy of the batteries
NPC	Net Present Cost	E_{NG}	Energy provided by the national grid
Poli.NRG	Politecnico di Milano eNergy Robust desiGn	E_{PV}	Energy supplied by photovoltaic panels
PQA	Power Quality Analyser	E_{UNMET}	Energy that batteries are not able to provide due to their capacity
PV	Photovoltaic panels	SOC_{max}	Maximum value at which batteries can be considered fully charged
r	interest of rate	SOC_{min}	Maximum rate of discharge
rbt	Robust solution	t_{gen}	Duration of generator functioning
SOC	State Of Charge	$t_{gen,min}$	Minimum duration of generator functioning

Introduction

In the last decade, the role of rural electrification as an engine for social and economic development has acquired more and more relevance. Ensuring a good electric service means improving people life quality and giving them the opportunity to increase labour productivity. According to the World Bank, in 2016 around 1.2 billion people were still affected by lack of electricity access, and 2.7 relied on traditional use of biomass for heating and cooking [1].

Latest energy access projects entail the usage of innovative models centred on employment of renewable energy sources, gain in energy efficiency and distributed generation. The latter can overcome the problem of grid extension in areas where it does not exist, promoting rural electrification according to local needs and relying on local resources [2].

One of the most well-established solution is given by micro-grid, namely a combination of Photovoltaic panels (PV), Diesel generator (DG) and Battery Energy Storage Systems (BESS). In particular, it has the characteristic of being able to operate also if disconnected from the national electricity grid and operate autonomously, ensuring energy supply and continuity of services on site. Disconnection from the public grid may occur either in the event of a power failure, scheduled maintenance or for purely economic reasons [3].

Typical micro-grid applications are hospitals, factories and schools, which cannot rely only on the poor service provided by the national grid. This way, in case of power outages, their activities are not interrupted.

The goal of the thesis is to develop a tool capable to effectively manage rural area scenarios, in particular dealing with PV, storage and diesel technologies, ensuring the possibility of disconnection from the national electricity grid with the integration of a power outage identification control logic. For such a goal, a specific procedure has been elaborated and coded within the Poli.NRG package, a problem-solving software designed by Politecnico di Milano – Energy Department aimed to the optimal design of a PV+BESS system for off-grid applications, according to a bottom-up approach [4].

The methodology has been developed on the basis of a real study case: St. Mary's Lacor Hospital in Uganda. The authors spent two months (from April to June 2017) to monitor power consumption, to make an assessment of the distribution network and all the installed technologies.

The proposed methodology is used to dimension the new micro-grid system of the hospital, according to different generator sizes and power outages lasting. Several simulations are carried out and discussed from the technical and the economical point of view, evaluating the most effective solution.

Model

Starting from the concept of micro-grid, the following architecture scheme has been used to formulate the control logic of the model (Figure 1):

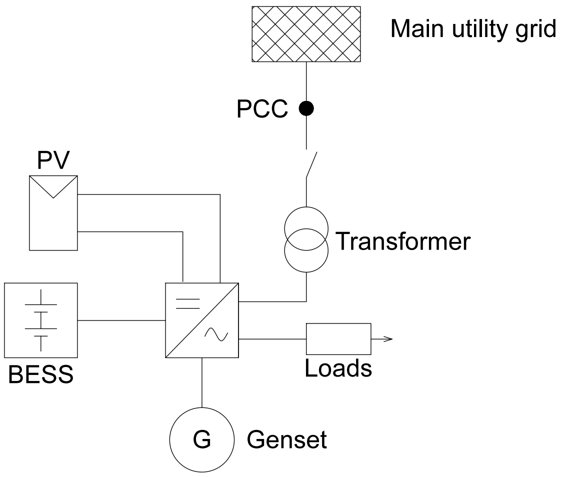

Figure 1: Architecture of the micro-grid system implemented in Poli.NRG, authors' elaboration

PV, BESS and DG are introduced as an alternative to the national grid. Each of them is modelled considering its characteristic parameter, below discussed. All the energy sources have been modelled as D.C. generators connected to a unique inverter, which is characterized by a conversion efficiency.

The proposed logic evaluates energy balances every minute (k), allowing for a better assessment of energy balances and the possible need for battery replacement before reaching the end of their useful life.

In the following, the modelled technologies are listed.

National grid

In normal operating conditions, it compensates the energy demand not satisfied by the photovoltaic panels, and eventually charges the batteries. The hypothesis to sell back solar electricity excess to the national grid is neglected. It is considered an infinite power busbar. The yearly cost is calculated as follows:

$$YC_{NG}(y) = \frac{c_{ele} * E_{NG}(y)}{(1+r)^y} \tag{1}$$

- c_{ele}: specific cost of electricity from the national grid [€/kWh].
- *r:* interest of rate.
- $E_{NG}(y)$: energy satisfied by the main grid during a year y.

Photovoltaic panels

The PV energy output for every k time step is formulated as follow:

$$E_{PV}(k) = \frac{PV_{size} * \eta_{BOS} * \left(1 - \eta_{derating}(y-1)\right) * H_\beta(k)}{h} \tag{2}$$

- PV_{size}: rated power of the panels
- $H_\beta(k)$: specific solar irradiation on the tilt panel surface according to the chosen time step.
- η_{BOS}: percentage of energy losses due to various factors (coupling between the various PV modules, the connections with the converter/converters, losses in the switchboards, conductors, wirings etc.).
- $\eta_{derating}$: decay rate of panel performance over the years.

From the economic point of view, photovoltaic panels are characterized by an initial investment cost IC_{PV} and by annual operative and maintenance fixed costs ($YC\_O\&M_{PV}$):

$$IC_{PV} = PV_{size} * PV_{cost} \tag{3}$$

$$YC\_O\&M_{PV}(y) = \frac{PV_{size} * O\&M_{PV}}{(1+r)^y} \tag{4}$$

- PV_{cost}: specific cost associated to the size of the photovoltaic panel $\left[\frac{€}{kW}\right]$.
- $O\&M_{PV}$: operative and maintenance costs $\left[\frac{€}{kW\_peak}\right]$.

BESS

The operating mechanism that regulates the functioning of the lead acid batteries is modelled according to an ideal storage system hypothesis using some characteristic parameters:

- State of charge (*SOC*), used to describe battery remaining capacity.
- SOC_{min}: maximum battery state of discharge, below which the storage bank is never used.
- $SOC_{initial}$, SOC at time of batteries activation.
- y_{BESS}, maximum years before replacement.
- k_{BESS}: power to energy ratio for which maximum power output is limited as regard the rated capacity.

$$k_{BESS} = \frac{P_{BESS}}{BESS_{size}} \tag{5}$$

- η_{charge} and $\eta_{discharge}$: charge and discharge efficiencies.

The lifecycle of the batteries is calculated through a *"rainflow function"* capable of tracking the number of cycles Z_i occurred during the year and the corresponding Depth of Discharge (*DoD*). Knowing the DoD of the batteries, the number of Cycles to Failures (CF) is computed according to Figure 2. The knowledge of the CF allows to check hour per hour (h) if batteries are going to fail and need to be replaced. According to that logic, the initial investment cost IC_{BESS} and the yearly cost of the batteries (YC_{BESS}) are:

$$IC_{BESS} = BESS_{cost} * BESS_{size} \tag{6}$$

$$YC_{BESS}(y) = \sum_m \frac{BESS_{cost} * BESS_{size}}{(1+r)^{\frac{h}{y*8760}}} \tag{7}$$

- *m*: number of battery replacements occurred during a year.

- h: hour of the year at which replacement takes place.
- $BESSsize$: size of the batteries.
- $BESScost$: battery cost $[\frac{€}{\text{kWh}}]$.

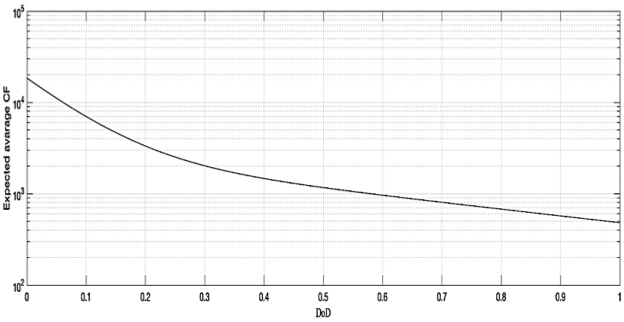

Figure 2: DoD and CF plot for lead acid batteries

The maximum energy input/output linked to the batteries is equal to the maximum deliverable power, depending on their capacity, multiplied by the correction factor k_{BESS}:

$$Energy\ max = \frac{k_{BESS} * Power\_\max}{60} \tag{8}$$

Inverter

The inverter size is function of the maximum power peak of the load during the whole plant lifetime, and it is characterized by its own efficiency:

$$\eta_{INV} = \frac{P_{AC}}{P_{DC}} \tag{9}$$

where P_{AC} is the power output and P_{DC} is the power input.

For simplicity η_{INV} is considered constant, neglecting the correlation between η_{INV} and the power output. From the economical point of view the investment cost (IC_{inv}) is calculated as follow:

$$IC_{INV} = \frac{INV_{cost} * P_{max}}{\eta_{inv}} \tag{10}$$

Diesel generator

Also known as Gen-set, it consists of a combination of a diesel engine and an electric generator for electricity generation.

Diesel generator is scheduled to work only when a power outage occurs and energy production from batteries and solar panel is not enough to satisfy the load.

The parameters introduced to describe the diesel generator are:

- c_{gen}: cost of electricity associated to the diesel generator $\left[\frac{€}{kWh}\right]$. For sake of simplicity and partial lack of information, it is taken as constant.
- P_{gen}: rated power [kW].
- LT_{gen}: lifetime of the generator.
- t_{min_gen}: minimum time of functioning for which damages to diesel generator linked to its continuous starts and stops are neglected.
- η_{up}: efficiency which considers that a small part of the rate power it is auto-consumed by the generator for internal regulator components functioning:

$$P_{gen\_max} = P_{gen} * \eta_{up} \tag{11}$$

- η_{down}: efficiency which evaluates minimum power output of the generator:

$$P_{gen\_min} = P_{gen} * \eta_{down} \tag{12}$$

The yearly energy expenditure linked to the genset is evaluated as follow:

$$YC_{gen}(y) = \frac{c_{gen} * E_{gen}(y)}{(1+r)^y} \tag{13}$$

As regards the evaluation of the specific investment and O&M costs (Figure 3), reference was made to report [5], where several Gen-sets were tested:

$$IC_{gen} = 766.09 * P_{gen}^{0.876} \tag{14}$$

$$O\&M_{gen} = 0.0653 * P_{gen} + 0.399 \tag{15}$$

$$YC_{O\&M\ gen} = h_{y,gen} * O\&M_{gen} \tag{16}$$

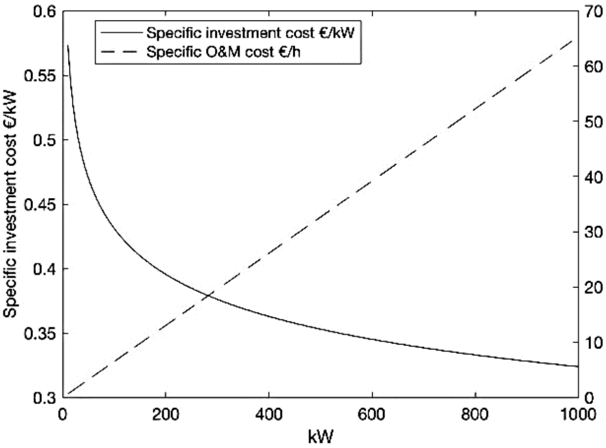

Figure 3: Specific investment cost and O&M cost curves

- $h_{y,gen}$: yearly (y) operating hours of the Gen-set,
- $O\&M_{gen}$: specific cost per yearly hour of Gen-set operation.

Dispatching strategy

The implemented logic checks the status of the main network minute by minute, so that the tool is routed into the right solution algorithm. In the event of a blackout, the system highlights its start and simulates it, assessing whether or not it is necessary to use the diesel generator. For the formulation of the energy balances Table 1 is the baseline for the formulation of the energy balances. In addition, the energy flux related to BESS can be either positive or negative: positive if charging, negative if discharging. For the other technologies, since the energy is only an output, it is positive. The proposed dispatching strategy results in a decision tree detailed in the following and reported in the flow chart depicted in Figure 11. Such a decision tree logic has been designed in order to be compliant with commercial equipment, i.e the goal of this procedure is to provide solutions to be directly deployable in emerging countries.

CASE 1: National grid is available

In this case, the public grid has to meet the energy demand, less than the energy produced by photovoltaic panels, and to eventually charge BESS after their usage due to power outage.
Four different subcases have been investigated:

1.a *$SOC(k)<SOC_{max}$* and photovoltaic production is able to both charge the batteries and satisfy the load demand:

$$E_{bal}(k) = Energy\,max \tag{17}$$

$$E_{NG}(k) = 0 \tag{18}$$

1.b *$SOC(k)<SOC_{max}$* and energy produced by photovoltaic panels is not enough to either charge the batteries or satisfy the load demand. In this case national grid will charge the batteries and, if necessary, satisfy the unmet load:

$$E_{NG}(k) = \frac{E_{load}(k)}{INV.eff} - E_{PV}(k) + Energy\,max \tag{19}$$

$$E_{bal}(k) = Energy\,max \tag{20}$$

1.c *$SOC(k) \geq SOC_{max}$* and energy produced by photovoltaic panels is not enough to satisfy the load demand. The load not fulfilled by PV is supplied by the national grid:

$$E_{NG}(k) = \frac{E_{load}(k)}{INV.eff} - E_{PV}(k) \tag{21}$$

1.d *$SOC(k) \geq (k)SOC_{max}$* and energy produced by photovoltaic panels is enough to satisfy the load demand. No energy is required from the national grid:

$$E_{NG}(k) = 0 \tag{22}$$

Excess solar energy is considered to be dissipated.

CASE 2: Power outage

In case of supply interruptions from the national grid, it is necessary to provide the unmet demand whenever the batteries and/or solar panels are not sufficient. For this purpose, a logic has been implemented to ensure that the load is satisfied anytime and to assess whether certain plant configurations lead to losses that cannot be avoided in any way.
The first step is to evaluate the energy that should be satisfied by the BESS in case solar production is not able to meet the demand ($E_{bal\,teo}(k)$). If photovoltaic production is even higher than the request it charges the batteries, complying with their capacity constraint.

$$E_{bal}(k) = E_{PV}(k) - \frac{E_{load}(k)}{INV_{eff}} \tag{23}$$

$$E_{bal}(k)(E_{bal}(k) > Energy_{max}) = Energy_{max} \tag{24}$$

$$E_{bal\,teo}(k) = E_{bal}(k) \tag{25}$$

Then the real energy that BESS is capable to provide is assessed:

$$E_{bal}(k)(E_{bal}(k) < -Energy_{max}) = -Energy_{max} \tag{26}$$

Comparing $E_{bal\,teo}(k)$ with the $E_{bal}(k)$, the eventual unmet load is calculated ($E_{UNMET}(k)$):

$$E_{UNMET}(k) = E_{bal\,teo}(k) - E_{bal}(k) \tag{27}$$

Afterwards, two main situations can arise:
2.a Batteries are not charging and can be used in case of necessity,
2.b Batteries are charging and cannot be used until they have reached their SOC_{max}.
In the following, a deep explanation of both is reported:

2.a SOC(k)>SOC$_{min}$

When batteries are available, and $E_{UNMET}(k)$ is positive, the generator has to provide this energy. In case of null $E_{UNMET}(k)$ and gen-set previously turned on, it continues to be operative only if its minimum working time ($t_{gen\,min}$) has not been reached yet.

At this point three checks are examined to guarantee the correct functioning of the generator, by meeting the constrains on maximum and minimum power capacity ($E_{gen,min}$, $E_{gen,max}$):

$$Check1_1(k) = E_{gen}(k) - E_{gen,min} \tag{28}$$

$$Check1_2(k) = E_{bal}(k) - Check1_1(k) \tag{29}$$

$$Check1_3(k) = E_{gen}(k) - E_{gen,max} \tag{30}$$

Every time $E_{gen,min} \leq E_{gen}(k) \leq E_{gen,max}$, no further control logics are introduced. On the contrary, two possible situations can occur:

2.a.1 $E_{gen}(k) < E_{gen\,min}$, *so:*

$$Check1_1(k) < 0 \tag{31}$$

If $SOC(k)<SOC_{max}$, the energy provided by the batteries is reduced, in certain circumstances even making them recharge, to enable the generator to reach at least its minimum.

$$Check1_2(k) \leq Energy\,max \tag{32}$$

$$E_{bal}(k) = Check1_2(k) \tag{33}$$

$$E_{gen}(k) = E_{gen,min} \tag{34}$$

It can happen that, by forcing the gen-set to work at its minimum, the batteries would receive a higher energy input than the acceptable one (*Energy max*). In this instance, the generator is not turned on or is forced to stop to protect itself and the batteries, inducing a loss of load only related to unmet demand:

$$E_{gen}(k) = 0 \quad (35)$$

$$E_{loss}(k) = E_{UNMET}(k) \quad (36)$$

If $SOC(k) \geq SOC_{max}$, the BESS are prevented to recharge, because they have already reached their maximum state of charge:

$$Check1_2(k) \leq 0 \quad (37)$$

$$E_{bal}(k) = Check1_2(\mathrm{k}) \quad (38)$$

$$E_{gen}(k) = E_{gen,min} \quad (39)$$

As stated above, if this constrain is not satisfied, the diesel generator is forced to stop.

$$E_{gen}(k) = 0 \quad (40)$$

$$E_{loss}(k) = E_{UNMET}(k) \quad (41)$$

***2.a.2** The energy supplied by the generator should be higher than its acceptable maximum*

$$Check1_3(k) > 0 \quad (42)$$

The generator is limited to its maximum rated power ($E_{gen\ max}$) and consequently part of the load is not satisfied:

$$E_{gen}(k) = E_{gen,max} \quad (43)$$

$$E_{loss}(k) = Check1_3(k) \quad (44)$$

2.b SOC(k)<SOC$_{min}$

BESS has to be recharged up to SOC_{max} to ensure the availability of this technology for the next power outage and to avoid unstable behaviour in the surroundings of SOC_{min} (the instability could be caused by using the BESS when exceeds SOC_{min} instead of fully recharge it).

$$Check2_1(k) = \frac{E_{load}(k)}{INV_{eff}} - E_{PV}(k) \quad (45)$$

If the energy produced by PV is equal or higher than the demand, the eventual surplus is used to charge the BESS and the generator is not turned on, unless previously it was on: if the latter condition is true ($0 < t_{gen} < t_{gen\ min}$) it is forced to run at its minimum power rate.

$$Check2_1(k) < 0 \quad (46)$$

$$E_{bal}(k) = -Check2\_1(k) \quad (47)$$

In the event of positive unbalance, the generator has to compensate it:

$$E_{gen}(k) = Check2_1(k) \quad (48)$$

Since the batteries need to be recharged, three checks on the hypothetical operating outputs of the generator are carried out:

$$Check2_2(k) = E_{gen}(k) + Energy_{max} \quad (49)$$

$$Check2_3(k) = E_{gen}(k) - E_{gen,max} \quad (50)$$

***2.b.1** The generator is capable to satisfy the demand and charge the BESS at their Energy$_{max}$.*

$$E_{gen,min} \leq Check2_2(k) \leq E_{gen,max} \quad (51)$$

$$E_{gen}(k) = Check2_2(k) \quad (52)$$

$$E_{bal}(k) = Energy_{max} \quad (53)$$

***2.b.2** Even though the gen-set is forced to charge the BESS at Energy$_{max}$, it is not capable to go beyond $E_{gen,min}$*

$$Check2_2(k) \leq E_{gen,min} \quad (54)$$

In this case the generator requires to be turned off, inducing a loss of load demand

$$E_{gen}(k) = 0 \quad (55)$$

$$E_{bal}(k) = 0 \quad (56)$$

$$E_{loss}(k) = Check2_1(k) \quad (57)$$

***2.b.3** The generator is supposed to overcome its maximum, either if it recharges the BESS at Energy$_{max}$ as well, or not.*

If the gen-set is supposed to work above $E_{gen,max}$ without taking into account the recharge of the batteries, the exceeding energy will be lost:

$$Check2_3(k) > 0 \quad (58)$$

$$E_{gen}(k) = E_{gen,max} \quad (59)$$

$$E_{bal}(k) = 0 \quad (60)$$

$$E_{loss}(k) = Check2_3(k) \quad (61)$$

It could happen that the generator can provide some energy to charge the BESS, but not at Energy$_{max}$ in order to comply with the constrain on the maximum rated power:

$$\begin{gathered} E_{gen}(k) < E_{gen\ max} \\ \cup \\ Check2_2(k) > E_{gen\ max} \end{gathered} \quad (62)$$

$$E_{gen}(k) = E_{gen\ max} \quad (63)$$

$$E_{bal}(k) = Check2_3(k) \quad (64)$$

This procedure is carried out every minute for the entire lifetime and provides the energy dispatching from every technological combination. In this way, it is possible to know the per minute contribution of every technology to the energy supply.

The per minute obtained results are updated taking into account the various technologic efficiencies.

Techno-economic optimization

During the lifetime simulation of the plant, several combinations of BESS and PV are tested.

For each combination, every time $E_{gen}(k)$>0, the tool evaluates the cumulative operating time ($Operatinghours$) at the end of the year and for the entire lifetime.

According to the per minute energy contribution from each technology, following the dispatching strategy explained above, it is possible to evaluate the eventual loss of load (*LL*) for the entire lifetime (*LT*):

$$LL_{LT} = \sum_{k=1}^{LT} E_{loss}(k) \qquad (65)$$

Reminding that the batteries have both charging and discharging efficiencies, the effective input/output energy is calculated:

$$E_{batt}(k) = E_{bal}(k) * \eta_{charge} \qquad (66)$$

$$E_{batt}\,(k) = \frac{E_{bal}(k)}{\eta_{discharge}} \qquad (67)$$

After this step, SOC(k) can be updated:

$$SOC\,(k) = SOC(k-1) + \frac{E_{batt}(k)}{BESS_{size}} \qquad (68)$$

Every hour the number of batteries cycles is evaluated, to estimate their remaining lifetime and the eventual necessity of BESS substitution. In this preliminary phase, the yearly costs related to the possible BESS replacement, lifetime expenditures linked to the main grid and Gen-set usage are computed. This information is then integrated with the assessment of all operating and maintenance costs for the final calculation of the Net Present Cost (*NPC*) for the whole lifetime of the plant LT. The NPC is defined as sum of the present value of all the costs over the period of interest:

$$NPC = IC_{LT} + YC_{LT} \qquad (69)$$

$$IC_{LT} = IC_{PV} + IC_{gen} + IC_{BESS} + IC_{INV} \qquad (70)$$

$$YC_{LT} = \sum_{y=1}^{LT} YC_{NG}(y) + YC_{gen}(y) + YC_{BESS}(y) + YC_{PV,O\&M}(y) \qquad (71)$$

A further indicator to evaluate the final specific expenditure that consumer would face for load supply is introduced under the name of Levelized Cost of Energy (*LCoE*). It is calculated through a "discounting" method, for which satisfied energy during the LT is discounted back to a present value:

$$LCoE = \frac{NPC}{\sum_{y=1}^{LT} \frac{E(y) - LL(y)}{(1+r)^{y}}} \qquad (72)$$

This indicator takes into account only the energy really satisfied, removing the possible energy losses. At this point, Loss of Load Probability (*LLP*), defined as amount of energy demand not satisfied during the LT over the total energy demand during power outages ($E_{power\ outages}$), is assessed as following:

$$LLP = \sum_{y=1}^{LT} \frac{LossOfLoad(y)}{E_{power\ outage}(y)} \qquad (73)$$

The definition of LLP is crucial for the operation of the model, as the user will be asked to define an acceptable value according to his needs. Under this rule certain solutions will be excluded.

Simulation and results

Case study

A real-life case study has been taken into consideration: authors spent a two months internship in Lacor Hospital, Uganda, from April to June 2017 for data acquisition. After the assessment of energy facilities and internal distribution network of the hospital, which required several weeks, load demand during the working and the weekend days was recorded by means of Power Quality Analyser (PQA 824). Since part of the load is satisfied by photovoltaic panels, their contribution was evaluated as well by connecting a laptop to inverters via Bluetooth. In addition, as a result of the instrumentation provided, only a limited and detailed set of data was collected. Poor equipment memory, depending on the selected sampling interval, influenced the amount of information that could be acquired in the two months of stay, allowing the record of just 26 days out of 60. The data collected, often incomplete due to power failures, were statistically revised and used to generate 200 possible annual load profiles of the hospital, so that the micro-grid dimensioning procedure could subsequently take place (Figure 5). Furthermore, according to the low reliability of the national grid, a power outage estimation matrix was created. It is based on the information provided by the hospital, which address 10% annual unreliability of the public grid [6]. Since the average duration of a power interruption is not certain, many power failure lasting have been compared.

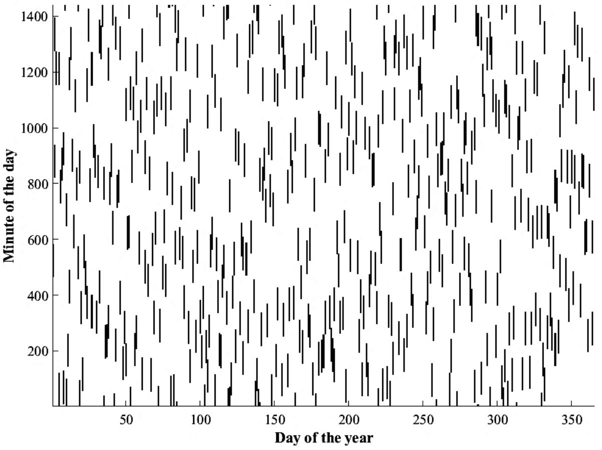

Figure 4: Power outages during a year, mean hour duration 2h

As regards the blackout matrix, an example of a generated matrix is shown in Figure 4, illustrating how randomly distributed power outages can occur throughout the whole year. The abscissa represents the day of the year and the ordinate shows the minutes of each day. The black lines correspond to the power outages.

The previously described dispatching strategy was implemented in Poli.NRG, modifying the former structure to switch from off-grid to micro-grid.

Simulations' setup

The created 200 annual load profiles, together with the blackout estimation matrix and the solar radiation are the main inputs of Poli.NRG. Due to the lack of tools for the applications into evaluation and the impossibility of measuring solar intensity radiation throughout the year

Input Data					
η_{inv}	90	%	*LLP target*	0.4	%
η_{BOS}	85	%	*Pvcost*	1200	€/kWp
$\eta_{derating}$	2	%	$Inverter_{cost}$	300	€/kW
η_{charge}	85	%	$BESS_{cost}$	200	€/kWh
$\eta_{discharge}$	90	%	$O\&M_{PV}$	20	€/kWp
SOC_{min}	42	%	$mean_{requirement}$	0.5	%
SOC_{max}	95	%	$std_{requirement}$	1	%
y_{BESS}	5	years	*LT*	20	years
k_{BESS}	0.5	kW/kWh	*r*	6	%
c_{ele}	0.13	€/kWh	c_{gen}	0.34	€/kWh
P_{gen}	150/200/250	kW	t_{mingen}	30	min
η_{up}	95	%	η_{down}	25	%

Table 1: List of input data used for all the simulations

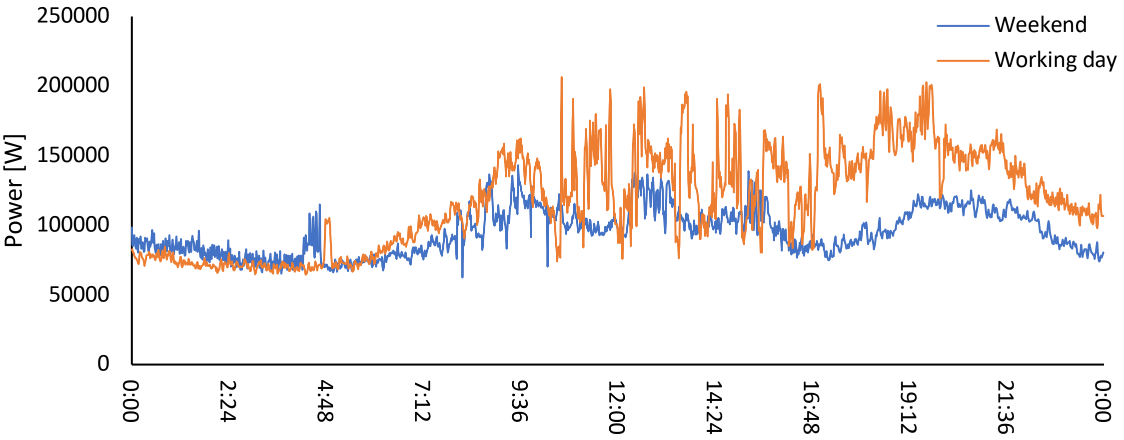

Figure 5: Example of load trend during a working day and a weekend day

at the study site, online meteorological databases have been acquired [7] and processed, as shown in Figure 6. The input shown in Table 1 complete the framework to start up simulations of the micro-grid. They have been chosen based on personal experience and data provided by the hospital administration.

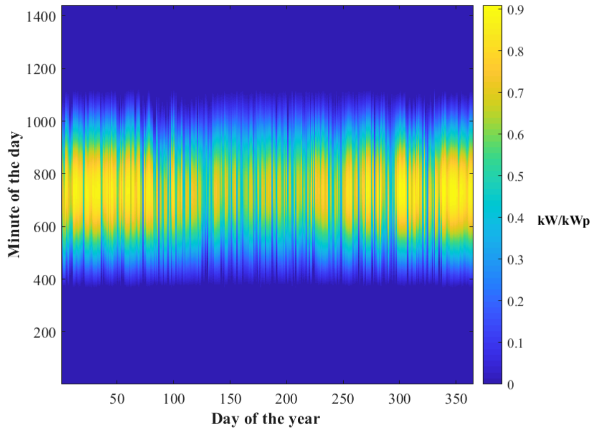

Figure 6: Solar radiation output for the whole year, Gulu, Uganda

Results and discussion

To establish a benchmark between an ideal off-grid solution and a micro-grid one, a first simulation has been developed assuming to feed the whole Hospital with a PV and storage micro-grid, using the previous inputs (Table 2). In the table the details of the mean robust solutions is reported.

Yearly increase in the loads [%]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]
0	1170	2865	4726977	0.0498	0.4581
1	1355	3065	5213660	0.0500	0.4679

Table 2: Results off- grid case for two scenarios

A possible yearly increase in the load of 1% will affect the optimal technology mix with respect to the baseline case (0%), bringing the PV size to increase by 15%, while the BESS one by only 7%. Comparison with the results obtained in the micro-grid configuration shows how economically disadvantageous off-grid solution is, leading to prefer the adoption of micro-grid systems (Table 3 and Table 4). Afterwards, the simulations were carried out in micro-grid configuration, testing two generator sizes, 200 and 250 kW, chosen according to the hospital' peak demand. For each size, different average power outage durations were compared (1, 2, 3, 4, 6, 8, 10 hours). Figure 7, Figure 8, Figure 9 and Figure 10 show the obtained *area of solutions* for the two gensets, according to the different power outages lasting, represented by different colors. Table 3 and Table 4 summarize the details of the mean robust solutions for each generator size, reporting also the *NPC, LLP, LCoE*, annual operating hours of the generator and number of battery replacement over the lifetime (LT), corresponding to different blackout durations. Each robust solution (PV_{rbt} and $BESS_{rbt}$) is computed as the weighted average (given the frequencies of the optimum points) within the related *area of solutions*.

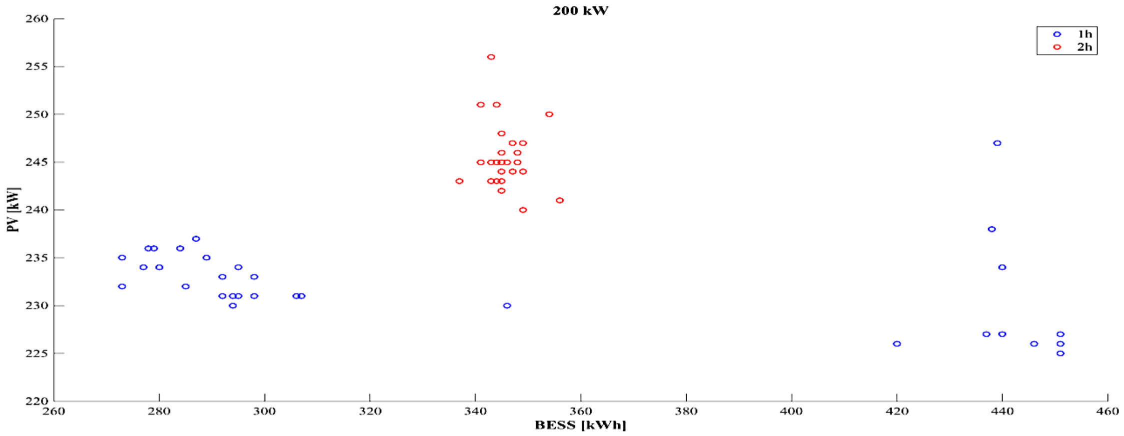

Figure 7: Area of robust solutions for short power outage durations, 200 kW diesel generator

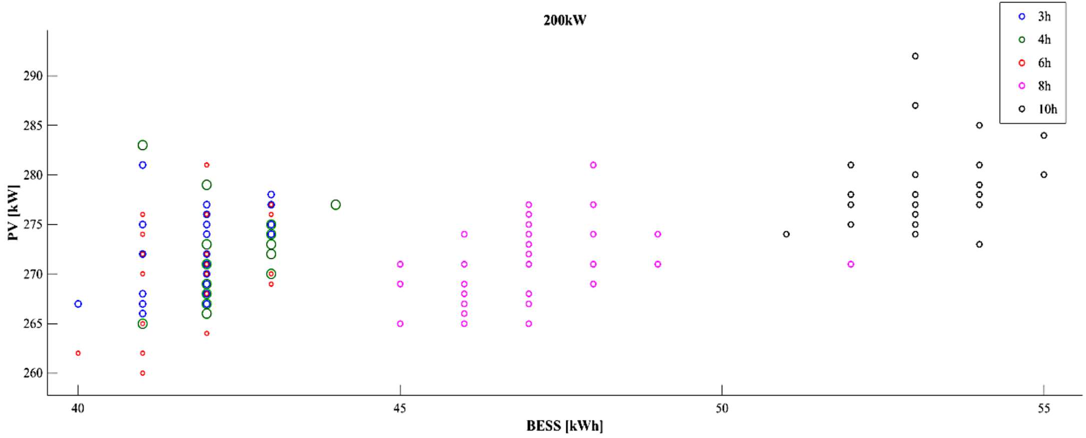

Figure 8: Area of robust solutions for long power outage durations, 200 kW diesel generator

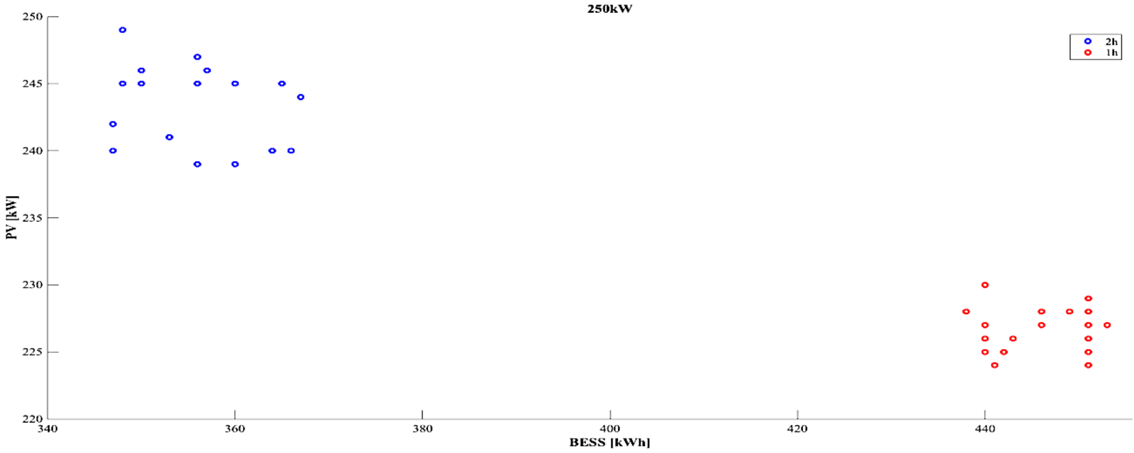

Figure 9: Area of robust solutions for short power outage durations, 250 kW diesel generator

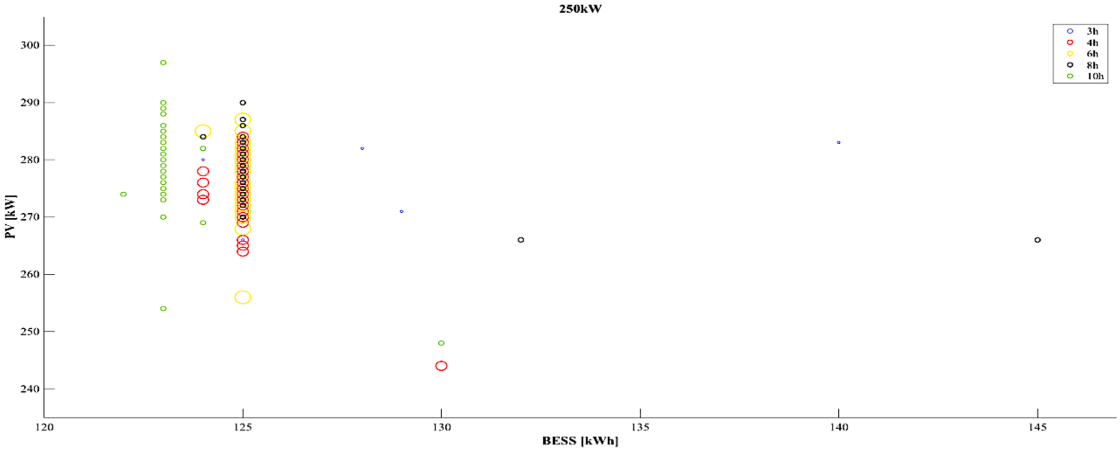

Figure 10: Area of robust solutions for long power outage durations, 250 kW diesel generator

Avarage power outage duration [h]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]	Annual generator operating hours	N° of replacements per LT
1	232	340	1946597	0	0.1809	71	4
2	245	345	2005176	4.565E-05	0.1863	92	4
3	272	42	2037659	1.863E-03	0.1894	807	4
4	271	43	2042873	1.878E-03	0.1900	808	4
6	270	42	2047497	2.379E-03	0.1903	816	4
8	272	47	2048523	1.179E-03	0.1904	808	4
10	279	53	2097214	3.876E-03	0.1950	798	4

Table 3: robust design results 200 kW genset

Avarage power outage duration [h]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]	Annual generator operating hours	N° of replacements per LT
1	227	448	1939249	0	0.18022	0	4
2	243	356	2032266	0	0.1889	82	4
3	276	126	2105371	0	0.1956	696	4
4	275	125	2116784	0	0.1967	710	4
6	277	125	2126237	0	0.1976	722	4
8	279	126	2127355	0	0.1977	717	4
10	278	123	2129273	0	0.1979	722	4

Table 4: robust design results 250 kW genset

The obtained solutions for each of evaluated load profile are robust, since the dispersion of the optimum around the identified design is very limited. It is noted, however, that during short power outages, the micro-grid system is optimized with big BESS capacities, minimizing the use of the generator, regardless its size.

For long lasting power failures, on the other hand, the use of the gen-set is essential to satisfy the hospital demand, covering the continuous task of helping batteries and PV. Having imposed as initial hypothesis that 10% of the year is affected by a detachment of the micro-grid from the public grid, power outages correspond to 876 hours per year. On average, the 200 kW generator is working for 807 hours, while the 250 kW generator for 713 hours, covering 92% and 81% of the 876 hours respectively.

Taking a generator into consideration, it is visible how the *LCoE* increases with the increase of the average interruption. This is justifiable since the Ugandan electricity grid is cheaper (0.13 €/kWh) than the other considered technologies, so reducing its availability for prolonged periods increases the probability to affect more likely time frames with high load demand.

	Yearly Blackout Energy Loss [kWh]	
	200 kW	**250 kW**
Hours	**0%**	**0%**
1	0	0
2	4	0
3	176	0
4	177	0
6	223	0
8	111	0
10	366	0

Table 5: LLP in terms of energy per year

Looking at the LLP, it is noticeable how a smaller gen-set size implies a higher loss than the one linked to the 250 kW, that in terms of energy translates into about 366 kWh per year in the worst case (Table 5).

Since the reliability of the service is the main concern for a hospital micro-grid, the 200 kW generator related solutions are excluded. Even though the economic parameter (*LCoE*) is pivotal as well, it is higher only by 0.01€/kWh in case of 250 kW generator. Moreover, in the remote event that PV and BESS would not be available, the gen-set could supply the entire demand by itself.

The final configuration has been selected according to the fact that, during the authors' stay, the blackouts were often longer than two hours and that the average robust solutions for longer power outages are quite similar among each other. In the light of the above, the selected solution corresponds to the 4 hours power failure lasting, which represents a good compromise between the obtained results and the size of PV and BESS available on the market.

So far, it is interesting to evaluate the effectiveness of the investment with respect to the current expenditure in Lacor Hospital: the financial statement for the year 2016 points out that 180,000 € is the related energy expenditure [3].

Year	Capital cost	Replacement cost	National Grid Bills	Fuel Cost	O&M Cost	Overall annual cost	Current Expenditure	Cash Flow	Cumulative Cash Flow
0	-633838	0	0	0	0	0	180000	-453838	-453838
1	0	0	-74665	-19807	-16391	-110863	169811	58948	-394890
2	0	0	-70899	-18818	-15463	-105180	160199	55019	-339871
3	0	0	-67344	-17878	-14588	-99810	151131	51321	-288550
4	0	0	-63978	-16980	-13762	-94720	142577	47856	-240693
5	0	-22418	-60798	-16104	-12983	-112303	134506	22203	-218490
6	0	0	-57793	-15282	-12248	-85323	126893	41569	-176920
7	0	0	-54933	-14567	-11555	-81055	119710	38655	-138265
8	0	0	-52243	-13834	-10901	-76978	112934	35956	-102309
9	0	0	-49688	-13152	-10284	-73124	106542	33418	-68891
10	0	-16752	-36263	-12537	-9702	-75254	100511	25257	-43634
11	0	0	-55973	-11939	-9153	-77065	94822	17757	-25877
12	0	0	-42804	-11361	-8635	-62800	89454	26655	778
13	0	0	-40745	-10825	-8146	-59716	84391	24675	25453
14	0	0	-38804	-10282	-7685	-56771	79614	22843	48296
15	0	-12518	-36953	-9793	-7250	-66514	75108	8594	56890
16	0	0	-35199	-9317	-6839	-51355	70856	19501	76391
17	0	0	-33512	-8917	-6452	-48881	66846	17964	94355
18	0	0	-31912	-8528	-6087	-46527	63062	16535	110890
19	0	0	-30395	-8155	-5743	-44293	59492	15200	126090
20	0	-9354	-28967	-18753	-5418	-62492	56125	-6367	119723

Table 6: Cash flow

Table 7 shows the details of the discounted to year zero cash flows over the expected lifetime of the micro-grid (6% interest rate), under the hypothesis of installing a completely new micro-grid. The payback time is of 12 years. Considering that the hospital owns already 150 kW of PV, the actual investment is reduced by 300,000 € and the payback time for that specific case would be only of 3.3 years.

Year	Capital cost	Replacement cost	National Grid Bills	Fuel Cost	O&M Cost	Overall annual cost	Current Expenditure	Cash Flow	Cumulative Cash Flow
0	-357838	0	0	0	0	0	180000	-177838	-177838
1	0	0	-74665	-19807	-16391	-110863	169811	58948	-118890
2	0	0	-70899	-18818	-15463	-105180	160199	55019	-63871
3	0	0	-67344	-17878	-14588	-99810	151131	51321	-12550
4	0	0	-63978	-16980	-13762	-94720	142577	47856	35307
5	0	-22418	-60798	-16104	-12983	-112303	134506	22203	57510
6	0	0	-57793	-15282	-12248	-85323	126893	41569	99080
7	0	0	-54933	-14567	-11555	-81055	119710	38655	137735
8	0	0	-52243	-13834	-10901	-76978	112934	35956	173691
9	0	0	-49688	-13152	-10284	-73124	106542	33418	207109
10	0	-16752	-36263	-12537	-9702	-75254	100511	25257	232366
11	0	0	-55973	-11939	-9153	-77065	94822	17757	250123
12	0	0	-42804	-11361	-8635	-62800	89454	26655	276778
13	0	0	-40745	-10825	-8146	-59716	84391	24675	301453
14	0	0	-38804	-10282	-7685	-56771	79614	22843	324296
15	0	-12518	-36953	-9793	-7250	-66514	75108	8594	332890
16	0	0	-35199	-9317	-6839	-51355	70856	19501	352391
17	0	0	-33512	-8917	-6452	-48881	66846	17964	370355
18	0	0	-31912	-8528	-6087	-46527	63062	16535	386890
19	0	0	-30395	-8155	-5743	-44293	59492	15200	402090
20	0	-9354	-28967	-18753	-5418	-62492	56125	-6367	395723

Table 7: Cash flow, specific to Lacor Hospital

Conclusions

The aim of this work is to provide a methodology capable of replicating national grid connected micro-grid systems, mainly made of photovoltaic panels, battery energy storage systems and diesel generators.

Since micro-grid application is widely acknowledged by the international community as the best solution for rural electrification, the focus shifted to the investigation about its state of the art and possible related issues in its design (minimum generator power output, total harmonic distortion).

A model able to combine the technological and economic aspects of a micro-grid system has been developed. The proposed methodology can simulate either the presence or the absence of the national grid and the relative dispatching strategy of the technological combination.

When the national grid is available, it contributes to the residual energy demand which is not satisfied by PV panels and eventually recharge the batteries if they were discharged during a previous blackout. Every time a power outage occurs, the only energy sources are PV, BESS and diesel generator. PV plays a pivotal role and, whenever it is not sufficient, BESS intervene. Generator task is to supply the eventual unmet load and to charge the batteries, if necessary.

The dimensioning and optimizing tool chosen to implement the described model is Poli.NRG, developed by Politecnico of Milan for off-grid systems made of PV and BESS. It has been adapted and integrated for the new micro-grid dispatching strategy, adding the national grid, its reliability and diesel generator.

To test the effectiveness of the proposed model, the case of St. Mary's Lacor Hospital, Gulu, Uganda has been chosen. A data collection campaign on the field has been undergone by the authors during an internship of two months, from April to June 2017.

According to the average hospital demand and load peak two generator sizes have been chosen, 200 and 250kW. In addition, being unable to predict the average duration of the power failures, for each generator size different outage periods have been simulated.

Results showed that short interruptions (1-2 hours) favour large BESS size and low usage of diesel generator, as BESS can almost always meet the total load demand for the entire blackout and to be recharged by PV and national grid. On the other hand, long interruptions (3-4-6-8-10 hours) adopt technical solutions which are quite similar among each other and strongly rely on genset instead than batteries. As compared to the previous situation, BESS and diesel generator work always in parallel, finding a trade-off between batteries discharge and fuel consumption.

The advantage of a smaller generator is the lower NPC given by lower battery size, although this implies the presence of significant energy losses for healthcare facilities. The evaluation of the robustness of the solutions and LCoE would lead to choose a 200 kW generator. However, the willingness to make the system as reliable as possible prompted authors to opt for the 250 kW solution, also because the variation of LCoE between the two genset for the same blackout lasting is almost negligible.

Finally, the solutions related to short power outages have been skimmed according to personal experience on the field. Since the remaining solutions do not differ significantly among each other, an average size of PV and BESS have been chosen, which corresponds to the technological results of the 4 h power failure lasting.

The cash flow analysis for the selected option (250 kW genset, 275 kW PV and 125 kWh BESS) shows a payback time of 12 years, comparing the current hospital status (under the hypothesis to pay 180,000 €/y for energy expenditure) with the proposed new configuration.

Considering that the hospital already owns a 150 kW PV plant, the incremental investment cost is substantially reduced, bringing the payback time to only 3.3 years. Such a short payback time can be addressed to the current not optimized energy mix of the Hospital: being the present generators oversized with respect to the Hospital load trend, they run far from their optimal range, increasing their specific consumptions (€/kWh). Furthermore, the measured specific generator consumptions (0.40 €/kWh) are higher than the assumed one (0.34 €/kWh) for the simulations.

The evident economic benefit and system reliability of the proposed micro-grid make such an investment very attractive.

The simulations allowed to validate the implemented model which proved to be solid and effective in supporting decision making about the best techno-economic solution. The latter is strongly influenced by the operative range constraints of diesel generator, tending to exclude the most harmful combinations for its proper functioning. All the obtained results show the effectiveness of the proposed micro-grid model and its associated potentials. It can be used by investors as a means to correctly dimension future micro-grid applications for rural electrification.

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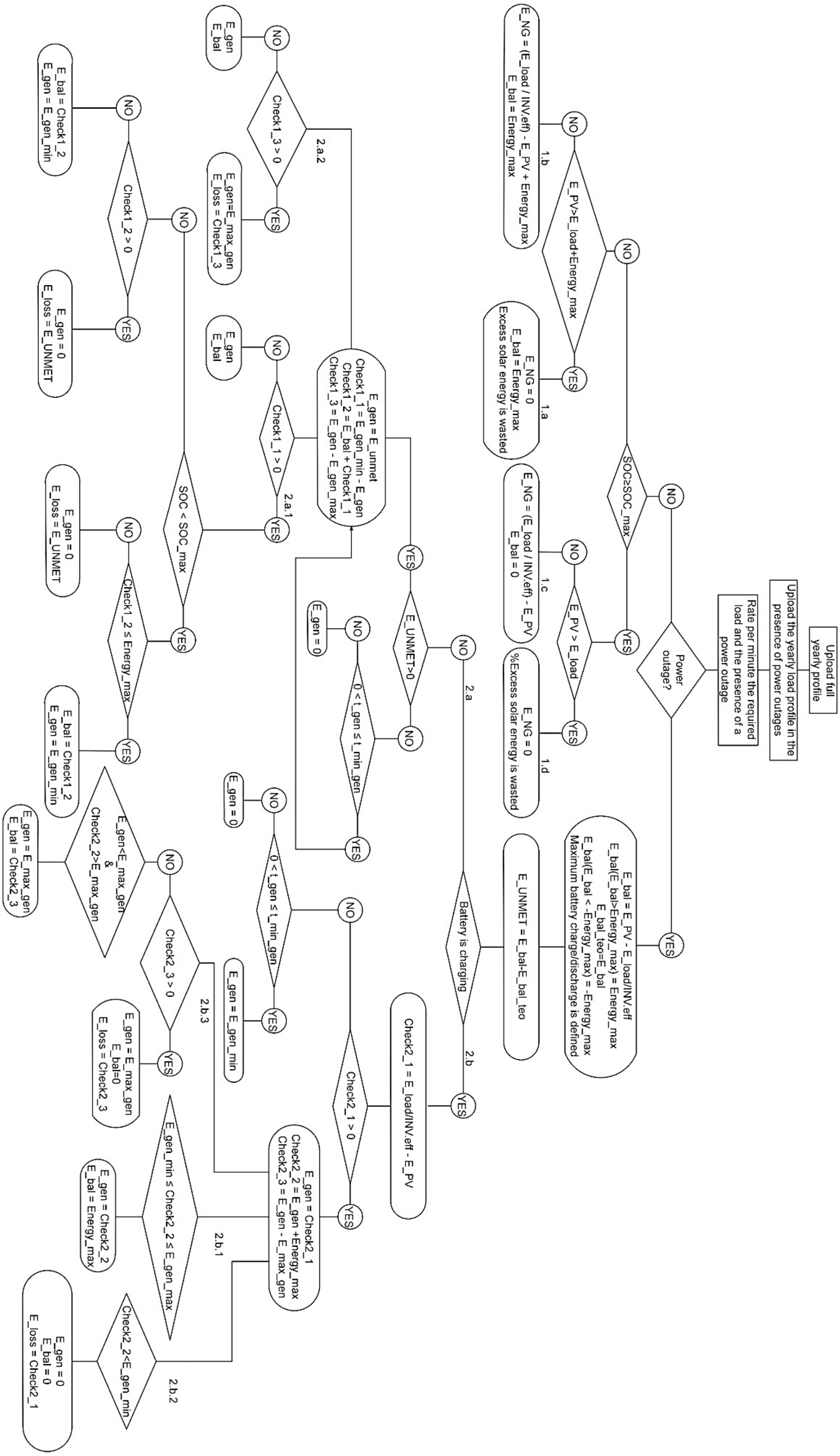

Figure 11: Flow chart of the control logic implemented in Poli.NRG

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Table of contents

List of acronyms and symbols

α	Significance level
AC	Alternate current
β	Probability to make a second kind error
BESS	Battery Energy Storage System
DC	Direct current
DG	Distributed generation
EDI	Energy Development Index
ERA	Electricity Regulatory Authority
$f(x)$	Density function
FAO	Food and Agriculture Organization
G	Gen-set
GDP	Gross Domestic Power
GNI	Gross National Income
H_0	Null hypothesis
H_1	Alternative hypothesis
HDI	Human Development Index
ICU	Intensive Care Unit
IEA	International Energy Agency
IPP	Independent Power Provider
LCOE	Levelized Cost of Energy
LLP	Loss of Load Probability
μ	Mean value of the distribution
MEMD	Ministry of Energy and Mineral Development
MPI	Multidimensional Poverty Index
n	Size of the sample
$\mathcal{N}$	Normal distribution
NEP	National Energy Policy
NPC	Net Present Cost
OECD	Organization for Economic Cooperation and Development
OPD	Out Patient Department
P	Probability
PCC	Point of Common Coupling
PCMS	Power Control & Monitoring System
PPP	Purchasing Power Parity
PQA	Power Quality Analysers

PV	Photovoltaic panel
rbt	Robust Solutions
REP	Renewable Energy Policy
RES	Integrated Renewable Energy Systems
RESP	Rural Electrification Strategy & Plan
σ	Standard deviation
SE4All	Sustainable Energy for All
SOC	State of Charge
THD	Total harmonic distortion
TPES	Total Primary Energy Supply
UEB	Uganda Electricity Board
UEDCL	Uganda Electricity Distribution Company Limited
UEGCL	Uganda Electricity Generation Company Limited
UETCL	Uganda Electricity Transmission Company Limited
UNDP	United Nations Development Programme
UNICEF	United Nations International's Children Emergency Fund
UNSDG	United Nations Sustainable Development Goals
UPS	Uninterruptable Power Supply
WB	World Bank
WHO	World Health Organization
χ	Continuous aleatory variable

Abstract

In recent decades, the link between access to energy and development has been studied in greater depth, showing that currently about 1.186 billion people still do not have access to it. Either the difficulty of expanding existing centralised generation systems due to excessive investment costs, or the low quality of service provided by the national system, have highlighted the primary role that distributed systems could play in solving the problem. Among these, micro-grid systems stand out, consisting of different energy sources, especially renewable energy ones, and storage systems. Their peculiarity consists in being able to operate in parallel with the national electricity grid and, in case of interruption of the distribution service, they are able to work autonomously, using the technologies installed on site. Generally, they rely on internal combustion generators, being easily available on the market and having reduced investment costs, and on photovoltaic panels in areas with high solar radiation. However, diesel generators have the disadvantage of depending on the availability of fuel at the place of installation, making operating costs high and consequently disadvantageous in certain situations.

The aim of this thesis is to implement a model capable of designing at best a micro-grid system connected to the national electricity grid, based on the implementation of diesel generators, photovoltaic panels and lead storage systems. To this end, all technologies have been characterized by their characteristic parameters, both at technical and economic level, and different availability profiles of the national service have been taken into consideration to verify how they can impact on the assessment of the best technological mix.

The proposed methodology has been implemented in Poli.NRG, a software coded by the Politecnico di Milano able to simulate off-grid networks. As case study to validate the model, St. Mary's Lacor Hospital was considered, whose daily energy demand profiles were acquired by the authors directly on the field. Finally, the results obtained according to the different sensitivities taken into consideration were analysed and discussed.

Key words: Micro-grid, Modelling, Rural electrification, Developing countries, Uganda, Simulation, Optimization.

Sommario

Negli ultimi decenni è stato studiato sempre più a fondo il legame che sussiste tra accesso all'energia e sviluppo, dimostrando come allo stato attuale circa 1,186 miliardi di persone non ne abbiano ancora accesso. La difficoltà di ampliare gli esistenti sistemi centralizzati di generazione a causa degli eccessivi costi d'investimento, o la bassa qualità dei servizi di rete forniti a livello nazionale, ha fatto emergere il ruolo primario che i sistemi distribuiti potrebbero avere nella risoluzione del problema. Tra questi emergono le micro-grid, costituite da diverse fonti energetiche, in particolar modo quelle rinnovabili e sistemi di accumulo. La loro peculiarità consiste nel poter operare anche in sincronia con la rete elettrica nazionale e, in caso di interruzione del servizio di distribuzione, nella capacità di operare autonomamente, utilizzando le tecnologie installate in loco. Generalmente, fanno affidamento su gruppi elettrogeni a combustione interna, essendo facilmente reperibili sul mercato e avendo costi d'investimento ridotti, e nelle zone ad elevata radiazione solare anche sui pannelli fotovoltaici. Tuttavia, i generatori diesel hanno lo svantaggio di dipendere dalla disponibilità di carburante nel luogo d'installazione, rendendo i costi operativi elevati e di conseguenza svantaggiosi in certe situazioni.

Lo scopo di questa tesi è quello di implementare un modello capace di simulare al meglio un sistema micro-grid allacciato alla rete elettrica nazionale, basato sull'installazione di generatori diesel, pannelli fotovoltaici e sistemi di accumulo al piombo. A tale fine tutte le tecnologie sono state caratterizzate dai loro parametri caratteristici, sia a livello tecnico che a livello economico e differenti profili di disponibilità del servizio nazionale sono stati presi in considerazione per verificare come possono impattare sulla valutazione del miglior mix tecnologico.

La metodologia proposta è stata implementata in Poli.NRG, un software creato dal Politecnico di Milano capace di simulare reti off-grid. Come caso studio per validare il modello è stato considerato il St. Mary's Lacor Hospital, i cui profili giornalieri di domanda energetica sono stati acquisiti dagli autori direttamente sul campo. Infine, i risultati ottenuti in funzione delle diverse sensitività prese in considerazione sono stati analizzati e discussi.

Parole chiave: Micro-grid, Modellazione, Elettrificazione rurale, Paesi in via di sviluppo, Uganda, Simulazione, Ottimizzazione

Introduction

St. Mary’s Lacor Hospital is nowadays one of the largest private and non-profit Hospitals in Equatorial Africa, receiving patients referred from all the districts of northern Uganda and beyond. Founded in 1959 in north Uganda by Combonian missionaries under the direction of Piero Corti and Lucille Teasdale, is one of the few structures to offer hope for healing and care in one of the poorest countries in the world. In Uganda (163rd country out of 187 according to the 2016 Human Development Index [1]), 34.6% of its population lives in extreme poverty (World Bank 2012), counting on less than 1.9 US$ a day. Added to this is a high infant mortality rate, 53 out of 1000 children born do not reach 5 years of age due to malaria, pneumonia, diarrhoea and malnutrition (World Bank 2016). Finally, the lack of adequate and accessible health care facilities with a ratio of 0.117 doctor per 1000 inhabitants (World Bank 2010) explains an average life expectancy of 60 years (World Bank 2015), among the lowest in the world (72 average years worldwide). Therefore the mission of St. Mary’s Lacor Hospital is to promote the access to health care of the weakest social groups, like women, children, people in destitute financial conditions, and people affected by chronic diseases who are unable to provide for themselves, offering to all of them a quality medical service [2]. The Hospital is a complex with 482 bed capacity (without taking into account the other associated peripheral health centers of Opit, Amuru and Pabo, which bring the bed capacity to 554), a medical university, a nurse and laboratory training school. It accommodates every day on average 600 inpatients plus their attendants and receives on average 600 outpatients (totalling about 2000 people each day) [3].

Hospital care services often undergo the effects of a discontinued electricity supply of the national electricity grid. Owing to frequent power outages for about the 10% of time on average (data of 2015-2016) (**Table 1**), the basic services delivered by the Hospital have risked being interrupted, thus compromising their effectiveness and the health of the patients themselves.

Year	National grid consumption (kWh)	Generator consumption (kWh)	Solar consumption (kWh)	Total consumption (kWh)	% UMEME	% Poweroutages
2015/2016	644436	84600	106468	835504	77%	10%

Table 1 *Energy partition and approximatively estimation of the percentage of power outages*

Over the years, the Politecnico di Milano has collaborated with the Hospital in order to identify plant solutions capable of minimizing the costs associated with energy demand and power outages, detecting the critical issues of the current system and possible areas for improvement [4], [5]. Not only the technical components were studied, but also an accurate analysis of the loads required by the Hospital during the year was carried out. Moreover, the collection and disposal system of waste, both domestic and medical, was examined to contain the risks associated with improper waste management.

For many years, the work of the Foundation has enticed the interest of many private companies, leading them to donate any kind of devices. Beyond the medical equipment, also generators, batteries and solar panels were provided.

It became apparent that the availability of a growing number of photovoltaic panels over the years due to external donations, and the presence of multiple generators of different sizes, caused challenges on their management and control logic.

The installation of solar panels was one of the most touched upon and discussed topics, showing how their easy availability at minimal cost pushed the responsible technicians to install them without taking into account the possible related disadvantages. As will be explained in next chapters, excessive solar penetration in a main-grid risks destabilizing the grid frequency and power quality, generating current and voltage harmonics, which could be harmful for devices connected to the Hospital distribution network. Over time, the quality management of the energy distribution service within the Hospital has therefore become increasingly complex, requiring in 2017 the installation of a Power Control Management System (PCMS) for monitoring, power quality, control and automation.

The PCMS allows the control of all existing systems available for energy production, processing input information to ensure the best possible output, both in terms of quality of current, voltage and frequency supplied, and to limit dissipation and reverse flows of power to utilities to improve power quality. The willingness to install a PCMS has brought to light how the logic of energy resources management was mainly regulated by the desire to satisfy the energy needs, not fully taking into account the complicated logic of control necessary for a perfect functioning of the distribution network in the event of a power failure.

In this portfolio, a step backwards has been taken, looking for a tool capable of designing the best resources to install to make a micro-grid system as efficient as possible.

Nowadays, millions of people all over the world do not have access to basic services and live in precarious conditions. Over the years, the increasing willingness to ensure better conditions for all has led to a better analysis of the problem of energy poverty. Energy is a promoter of economic, social and environmental growth: ensures continuity of work activities and the use of increasingly advanced technological systems, promotes social development through access to basic education and public health services, helping the meet of basic human needs for food and shelter. In addition, more efficient energy services reduce pollutants, thanks to a better management of resources, and slow down deforestation, especially in developing countries.

The aim of the thesis is to create a new universal model to simulate micro-grid systems in the presence of instability of the national electricity grid. At present, there are not yet tools capable of accurately simulating, both technically and economically, the effects of power interruptions and consequently to identify the best fit technologies, minimizing the load losses and the sustained costs. The developed model will be able to show how, in the event of an untimely or erroneous intervention, inadequate management of the power supply undermines the stability and reliability of the electrical service provided, thereby increasing costs and in some cases interrupting the essential services of the complex under study [6].

The work is divided in 7 Chapters. The first one is an overview of the current worldwide situation on access to energy, emphasising its links with development through well-structured multidimensional indicators. Chapter 2 finds the implementation of distributed generation systems, in particular micro-grid ones, as a solution to the problem, able to make the best possible use of local resources, ensuring access to affordable, reliable, sustainable and modern energy for all. Moreover, it focuses on all the considerations to do when designing a micro-grid and on the importance of a tool for its modelling. Chapter 3 frames the country situation, with a particular focus on energy policies, and the Hospital energy system. Chapter 4 describes the work on the field carried out at the Hospital, such as data collection regarding structure energy demand. These data are used as input for the actual modelling in Chapter 5. The latter includes the description of the implemented technologies in the model and the strategy used for energy despatching. Chapter 6 describes the methodology to create load profiles and the blackout matrixes, with a particular focus on the tool used for the implementation of the new micro-grid proposed logic. Chapter 7 discusses the results related to the case study, identifying the best fit plant solution for the Hospital, validating the effectiveness of the model under consideration.

Chapter 1

The issue of energy poverty and the key role of energy access

In recent years the central role of energy services in achieving broader development objectives has seen incredible progress. That's why one of the countless aims of the United Nation Sustainable Development Goals (UNSDG) is to reach the universal access by 2030 with the support of the global community [7].

Even if in the last decade the opportunity to use modern energy services has been strongly promoted, part of the humanity is still not able to rely on them and is affected by energy poverty. Currently, energy poverty has not a unique definition. The most used approaches to define it are below summarized:

- Minimum amount of physical energy needed for basic needs, such as cooking and lighting. [8]
- Form and quantity of energy that is used for those at the poverty line [8].
- Households that spend more than a certain percent of their expenditure on energy [9].
- Lack of access or lack of affordability to modern energy services [10].

Being clear the complexity involved defining it, several organizations such as International Energy Agency (IEA), United Nation agencies, World Health Organization have identified two major criteria for this scope: electricity access and dependence on traditional fuels.

A consensus regarding how to measure energy poverty has yet to emerge: most international agencies and organizations tends to think of it as an output and not an outcome [11]. Compared to other elements like income poverty, it lacks a robust theoretical thesis.

Access to energy can be considered a necessary condition for development but still not sufficient: experience has shown that electrification and the use of more modern technologies alone are unable to implement change.

In 2002 the IEA's World Energy Outlook estimated that people with no access to electricity were 1.6 billion. In the following years several factors like urbanization, economic development in several developing countries, policies promoting energy access have led to some progress. Despite this, in 2016 around 1.2 billion people (2016 World Bank), corresponding to 16% of global population, were still affected by lack of electricity access, and 2.7 relied on traditional use of biomass for heating and cooking. The most critic countries concerning electricity access are Sub-Saharan Africa and developing Asia, accounting for more than 95% of the global population without electricity (**Table 2**).

Region	**Population without electricity**	**Electrification rate**	**Urban electrification rate**	**Rural electrification rate**	**Population relying on traditional use of biomass**	**% of population relying on traditional use of biomass**
	millions	%	%	%	millions	%
Developing countries	1,185	79	92	63.7	2,742	49
Africa	634	45	71	24	793	69
North Africa	1	99	100	99	1	0
Sub-Saharan Africa	632	35	63	13	792	81
Developing Asia	512	86	96	74	1,875	50
China	0	100	100	100	453	33
Southeast Asia	102	84	94	74	1,098	69
India	244	81	96	74	819	63
Latin America	22	95	98	85	65	14
Middle East	18	92	98	78	10	5
Transition economies and OECD	1	100	100	100	-	-
World	1,186	84	95	71	2,742	38

Table 2 *Electricity access and population relying on traditional use of biomass for cooking in 2014 - Regional aggregates*

Regarding the specific case of Sub-Saharan Africa, rural (87%) and urban areas (36%) are differently affected from energy lack.

Latest energy access projects entail the usage of innovative models centred on employment of renewable energy sources, gain in energy efficiency and distributed generation.

In developed countries electrification is usually related to grid extension and centralized power generation, distribution and transmission systems. This kind of approach shows weaknesses related to high capital costs, especially in remote regions, compromising the possibility to achieve predefined targets of complete electrification by 2030. On the other side, distributed generation seems to fit better this necessity, overcoming the problem of grid extension in areas where it does not exist: micro-grid/off-grid plants are capable to promote rural electrification according to local needs, relying on local resources [12].

1.1 Correlation between access to energy and development

International organizations, such as the IEA, FAO, Health World Organization, UNDP, UNICEF etc., all agree to define access to energy as a promoter of a country development. The growing evidence of economic-environment-socio benefits due to electricity, motivates programs to improve the usage of cleaner and more reliable forms of energy (**Figure 1**).

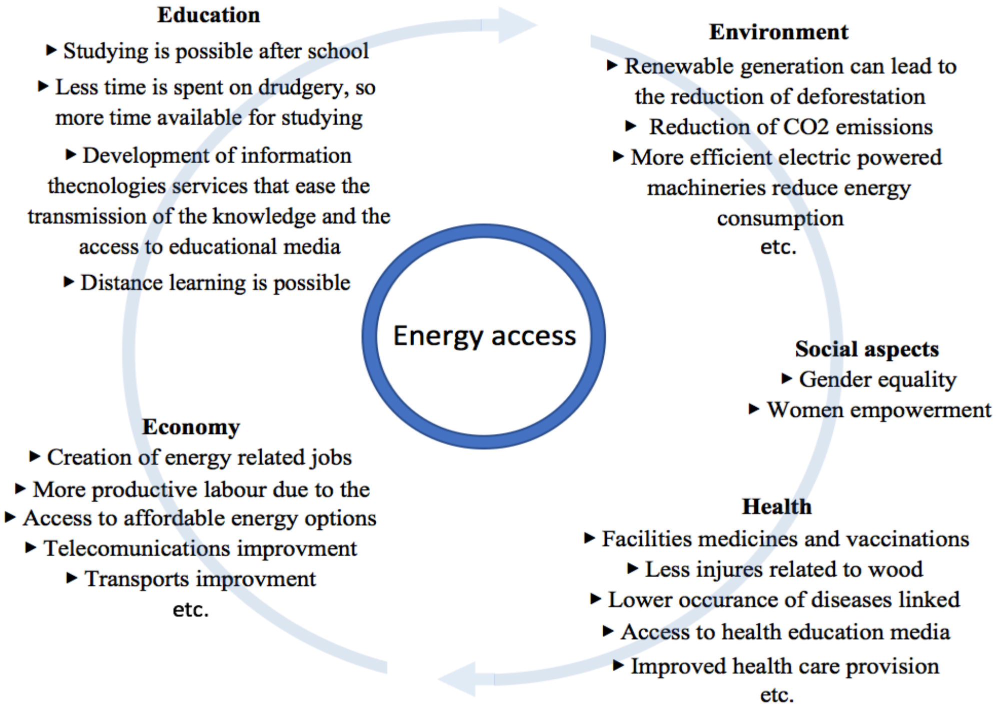


Figure 1 *Multidimensionality of energy access, authors' elaboration*

At household level, for example, electricity guarantees the extension of working hours, reading and studying, as well as the use of new technologies such as radio and television. In addition, cleaner fuel access decreases the child mortality rate, increases overall health, reduces the time that women and children use to collect wood and coal, avoids exposure to smoke from bad fuels. Rural electrification influences agriculture and small industries, raising their income and productivity using new tools and machines. Another effect is to reduce transport and communication costs, thus expanding the size and accessibility of the market.

One of the major issues encountered over the years, especially in developing countries, is the accessibility of data, which are often missing or difficult to measure. This precludes the possibility of tracking down many of the negative aspects that can affect a country's growth, making more difficult to identify an adequate action plan.

Many studies confirmed that there is a clear linkage between energy and economic growth: looking at the comparison between the countries' Gross National Income (GNI) and their total primary energy supply (TPES) in **Figure 2**, developing countries tend to have low values of both, focusing at the bottom left of the chart. Indeed, since they are behind in the various sectors (industry, services, exchanges), they do not fully exploit their potential, remaining dependent on expensive and inefficient processes. Other issues such as blackouts may dramatically affect the country's economy, forcing it to stop [13].

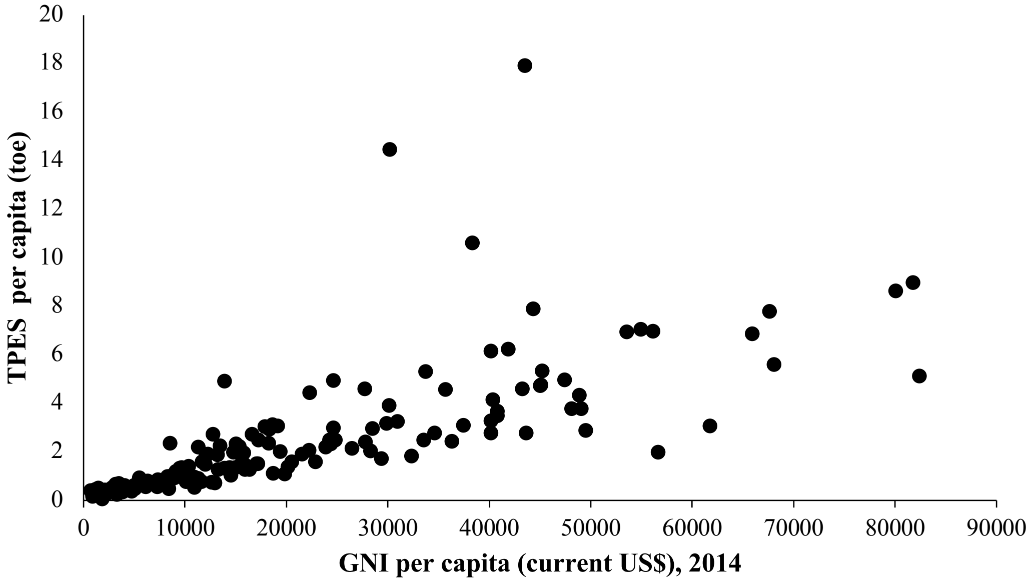


Figure 2 *Linkage between GNI(PPP) and TPES (kg of oil equivalent per capita)*

Some of the other benefits of energy access are shown in Appendix A, where it is highlighted that an increase in consumption guarantees, for example, longer life expectancy and the reduction of infant mortality rate.

However, it is necessary to ask how reliable these results are. An immediate comparison can be made, for example, on access to water services: the linkage between energy consumption and percentage of population with access to improved water sources emphasizes a possible correlation as said before (**Figure 3**).

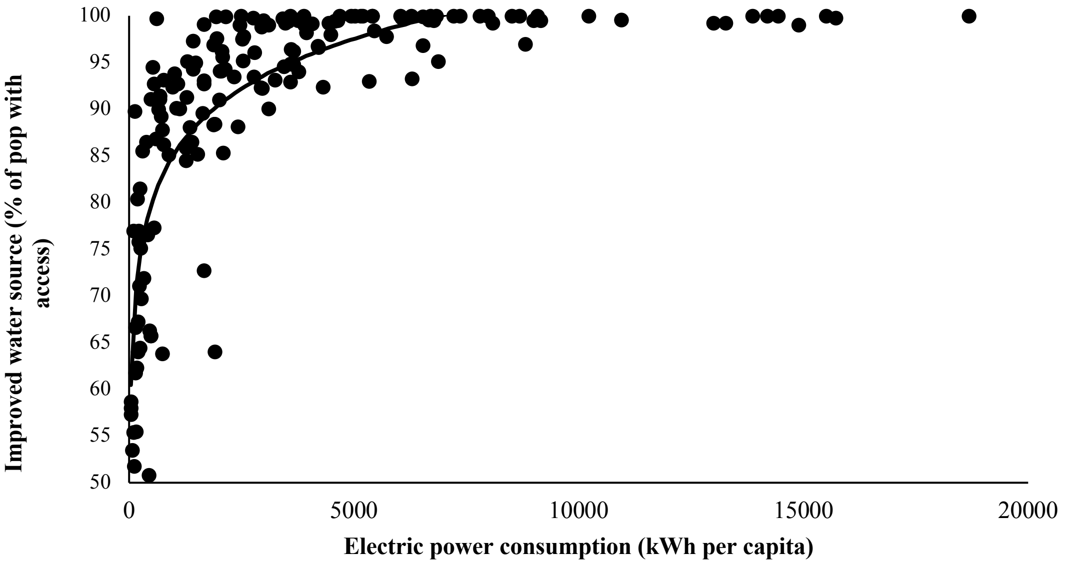


Figure 3 *Correlation between electric power consumption (kWh per capita) and improved water sources (%pop), 2014*

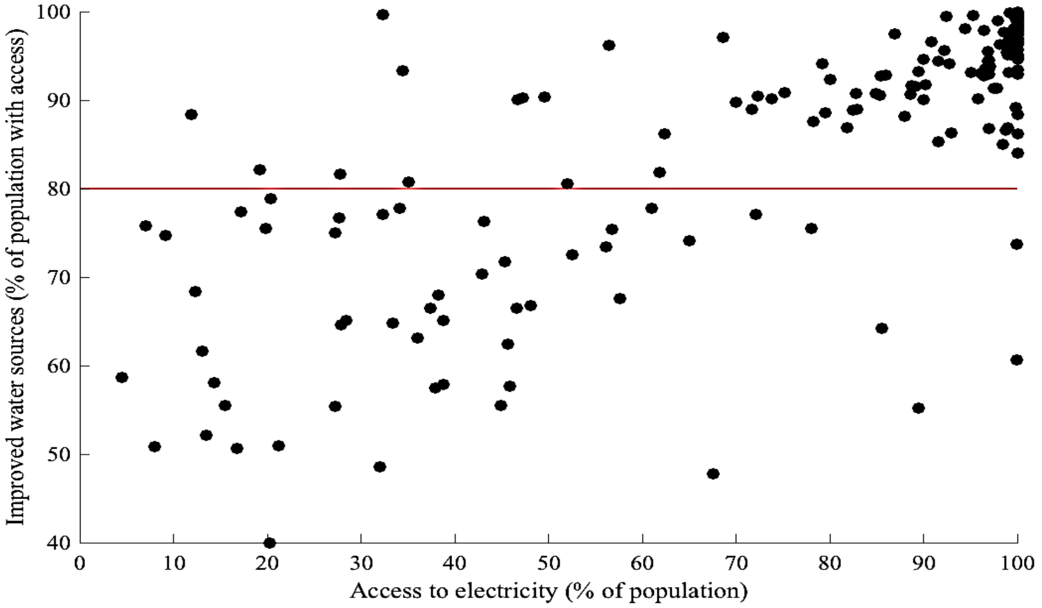


Figure 4 *Correlation between access to electricity (%pop) and improved water sources (%pop), 2014*

Despite this, representing the percentage of population with access to electricity on x-axis and the percentage of population with access to improved water services on the y-axis, it is shown that above (and in its surroundings) a hypothetical red line, identified at y=80%, no correlation exists (**Figure 4**). Elements such as the geography of a country, its availability of natural water sources, its internal structure, unequal distribution within the country etc. are crucial to give a truer picture of the reality.

1.2 How to measure progress

Energy is a key element in achieving the primary needs of people, but at present there is no measure that can fully explain this link, being a very structured and complex problem.
The correlation between energy and development is undeniable, but in the international community there is still an open debate on how to go beyond the purely energy and economic aspect: study models and complex indicators should be implemented to emphasize the multiple links between access to energy and social, economic and human development.
The identification of the various problems that prevent the growth of a country in its multidimensionality allows to understand how distinctive issues weigh in different ways on the final result: governments understand where to intervene and margins of improvement. A good indicator must be robust, well structured, able to take into account the weight of all those factors that could affect it. In this regard, the Human Development Index (HDI), the Energy Development Index (EDI) and the Multidimensional Poverty Index (MPI) are reported below.
In 1990, HDI put people and their capabilities for the first time as a pillar for a country's sustainable development, moving away from the purely economic growth vision (**Figure 5**).

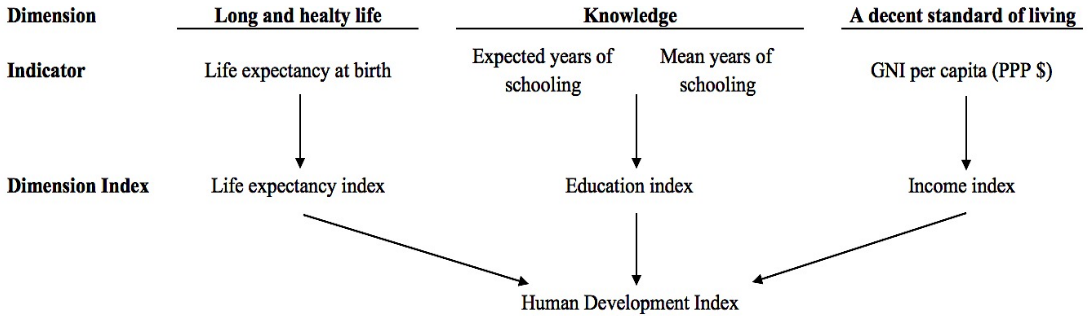


Figure 5 *Human Development Index structure*

Its contribution is integrated using the logarithm of income, enhancing the importance of energy access for low GNI countries, and showing how this correlation decreases beyond certain GNI per capita (PPP) values.
Despite the more complex structure, this indicator tends to capture only certain aspects of human development without considering such elements as inequality, gender disparity, poverty, etc.
In 2004, the IEA published an Energy Development Index capable of tracking a country's energy development during the growth process. Just like HDI, it is structured to highlight

the multidimensionality of the indicator, enabling it to trace the process towards new fuels and modern energy services at country and community level (**Figure 6**) [14]. Because of lack of data, the indicator fails to give the right weight to the use of fuels such as wood, coal and biofuels.

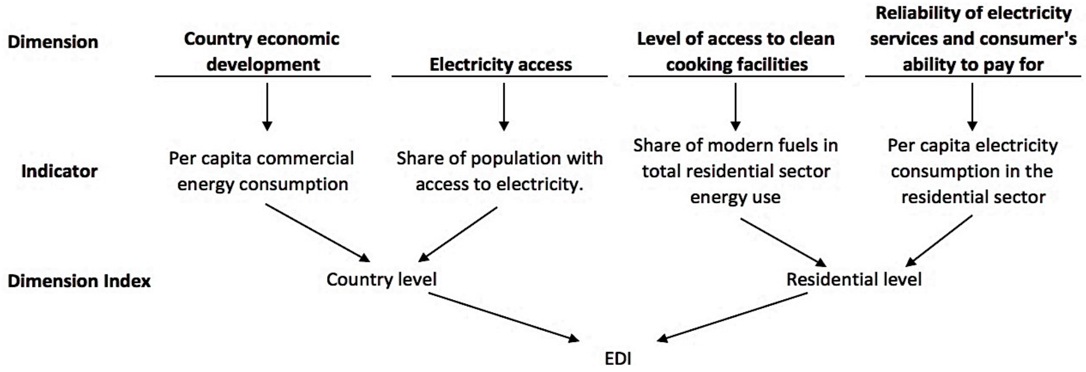


Figure 6 *Energy Development Index structure*

The correlation between EDI and HDI is not linear: the two indicators tend to decouple at high levels of human development and wealth (**Figure 7**).

The country's ranking with respect to the two indicators is similar, though a more detailed analysis highlights how:

- Countries that can rely on oil show EDI's higher than those of HDI's due to the abundance of the resource, its affordable price and the possibility of ensuring energy access to all industries and businesses.
- Many Sub-Saharan countries have low values of both, regardless of the abundance of resources.
- South American countries have low EDI values despite low biomass dependence and a good electrification rate.

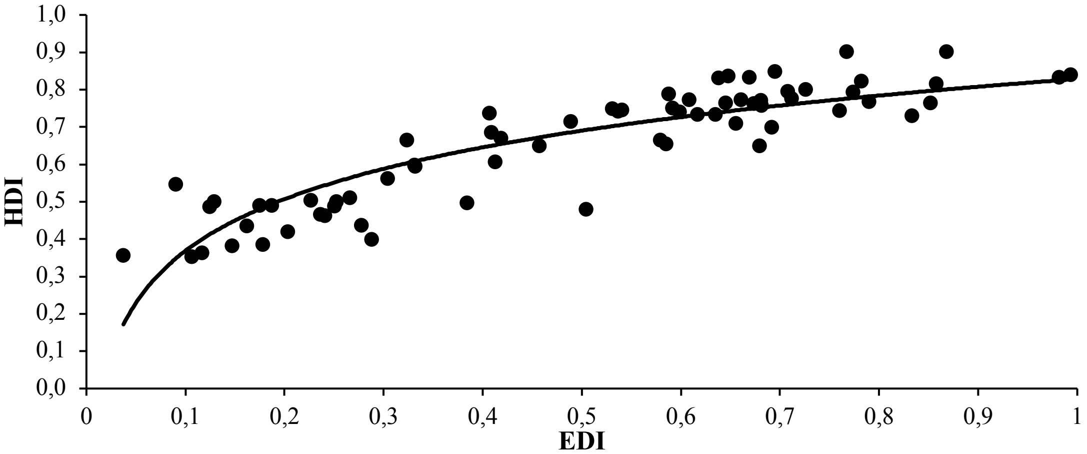


Figure 7 *Correlation between EDI and HDI, 2010* [15]

To make the HDI more complete, the Oxford Poverty & Human Development Initiative and the United Nation Development Program proposed in 2010 the Multidimensional Poverty Index (MPI).

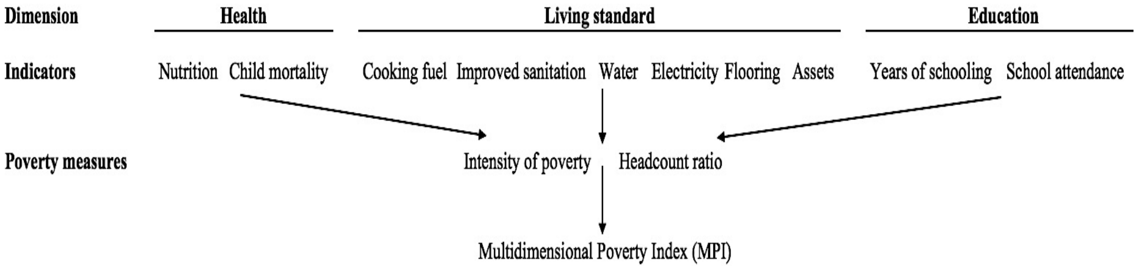


Figure 8 *Multidimensional Poverty Index structure*

This indicator goes beyond income or consumption definition of poverty, showing how an individual can be affected at the same time by different deprivations. Like HDI, it is structured on three levels (health, education, standard of living), but it uses 10 different indicators to have a more truthful view of the problem (**Figure 8**). The MPI is an index designed to measure acute poverty. Acute poverty refers to two main characteristics: first, it includes people living under conditions where they do not reach the minimum internationally agreed standards in indicators of basic functioning, such as being well nourished, being educated or drinking clean water. Second, it refers to people living under conditions where they do not reach the minimum standards in several aspects at the same time [9,10].

The 2016 Human Development Report has shown that over a sample of 102 countries (5.2 billion people, 72% of the global population) about 1.5 billion people live in multidimensional poverty. The inability to have a complete view of the world situation is due to the lack of data: MPI is forced to use datasets from 2005-2015, according to their availability.

1.3 Modern Energy access and health

Access to modern energy sources is a powerful promoter for a country's welfare, guarantees the proper and continued functioning of Hospitals and clinics, as well as making the home environment safer and cleaner.

The lack of a reliable power grid and services reduces the functionality of healthcare facilities and their ability to offer optimal services, indirectly affecting people's health. Access to energy allows storage of vaccines and blood by using refrigerators, the use of sophisticated patient care equipment, light to ensure operations at any time of the day, incubators, mechanical fans, X-ray machines, ultrasounds, and much more.

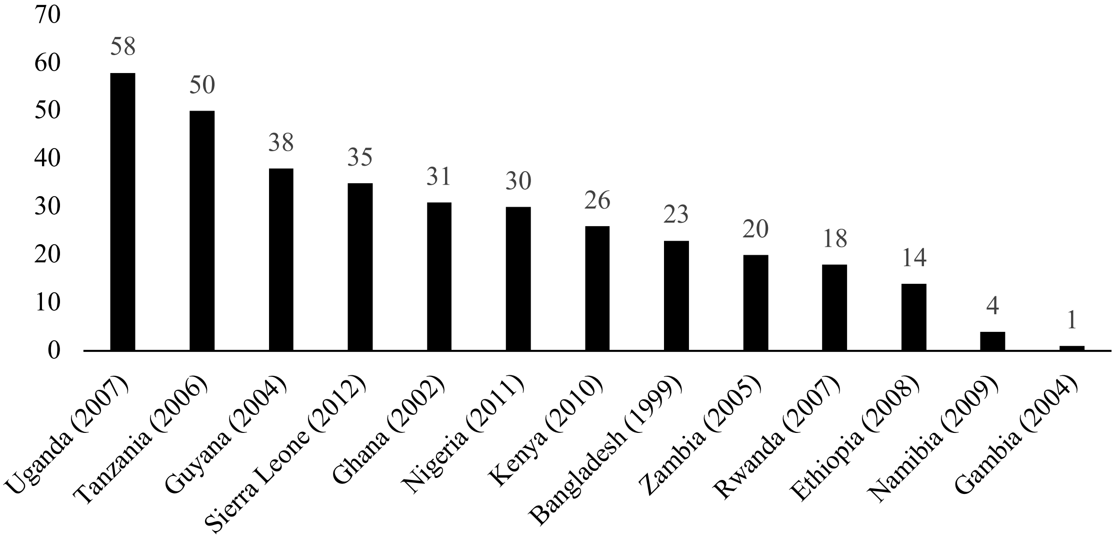


Figure 9 *Percentage of health care facilities with no energy access*

A recent analysis on a sample restricted to 11 sub-Saharan countries found that more than 25% of healthcare facilities encountered problems with access to electricity [18]. In particular, according to data collected from World Health Organization (WHO), countries like Uganda and Tanzania are more affected by this problem, accounting respectively for 58% and 50% of energy lack in health structures (**Figure 9**).

Reliance in non-reliable energy services, characterized by power outages and continuous frequency oscillation, compromises the good functioning of the medical machines and interrupts medical services. In developing countries, almost 70% of healthcare devices fails due to bad power quality (WHO 2010). World Energy Outlook 2017 estimated that power interruptions damage vaccine conservation causing the loss of almost half of them. Moreover, bad sterilization of surgery tools due to malfunctioning and interruption of the machines, endangers the lives of 50 million people (Practical Action 2013).

Several factors can be identified as obstacles to health facilities:

- Lack of specific policies for health structure electrification.
- Inability to understand the primary role of health on countries development.
- Insufficient human capacity and institutional support structures.
- Affordability of energy services and lack of financing sources in the long term for their implementation.
- Lack of data for implementation of off-grid strategies.

- Long term maintenance lack.
- Lack of qualified technicians.
- Lack of clean water supply.
- Unclear ownership of off-grid electric systems.

Chapter 2

Micro-grid as part of the solution

Centralized distribution systems of electricity generation, storage, and distribution have always played a major role in energy supply. However, despite the implementation of centralized generation systems is particularly effective, it is not fully applicable to all countries or territories: the high capital costs linked to the expansion of the electricity grid, the lack of funding and low population density in certain regions made it sometimes economically unprofitable. In addition, the current model of centralized energy production requires major investments in the construction and maintenance of distribution networks and creates a strong power of control by a few producers over the security and continuity of energy supply to consumers.

Small scale and localized distributed generation (DG) seems to be available and interesting solution in stimulating electrification and reducing energy poverty, especially in developing countries. DG is generally defined as the production of electricity in small, self-production electric power units dispersed or located in several parts of the territory and connected directly to the distribution grid. Being located in remote locations or close to the end user, these kinds of plants are generally connected to the low voltage distribution grid: energy consumption at the place of production itself results in a zero loss of energy, which is therefore cheaper in absolute terms than distribution over long distances resulting from production at large plants.

Within the distributed generation systems, micro-grid concept is included: in particular, it has the characteristic of being able to operate autonomously even if disconnected from the national electricity grid, ensuring energy supply and continuity of services on site. Disconnection from the national grid may occur either in the event of a power failure, scheduled maintenance or for purely economic reasons [19].

Featuring a capacity to meet loads of less than 10 MW, micro-grids can rely on various power generation and storage devices, making preferential use of integrated renewable energy systems (RES): the latter refers to hydroelectric, wind, geothermal, solar, biogas etc. The use of RES can also have positive effects on the environment, reducing overall CO_2 emissions. Diesel based micro-grids are by far the most common throughout the world, given the relatively low upfront capital cost of the generator and its widespread availability [20].

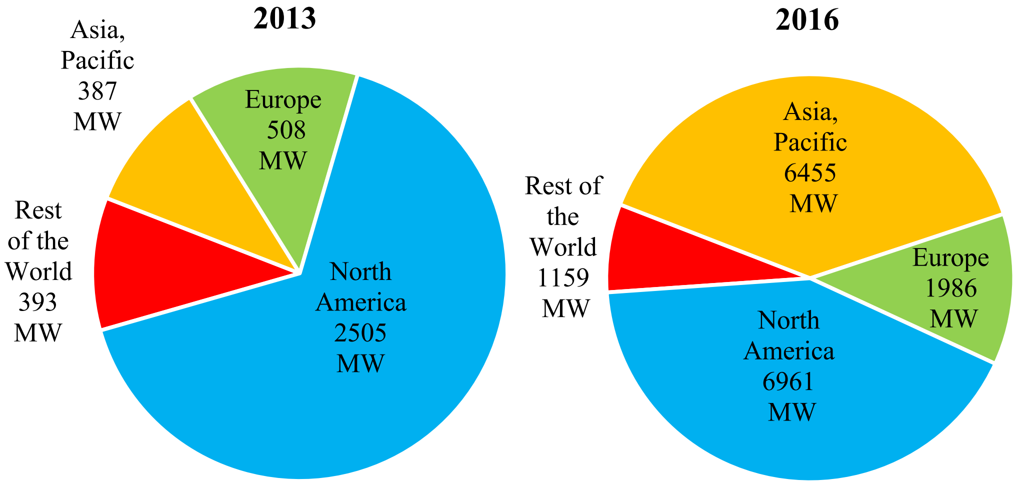


Figure 10 *MW of micro-grid installations in 2013 and 2016*

According to an assessment made by Navigant Research, 3793 MW of micro-grids were installed worldwide in 2013, which increased considerably over the years to reach 16552 MW in 2016 (**Figure 10**). In addition, recognizing the different areas of application of micro-grids (commercial-industrial, military, institutional, community and remote areas), installations in remote areas for rural electrification has increased from 20% in 2013 to 45% [20], [21].

The benefits associated with the installation of micro-grid systems in rural areas are, for example, the replacement of obsolete energy resources (coal and wood) with more energy-efficient fuels, as well as the use of better technologies, ensuring better services, reducing people's exposure to harmful fumes from conventional fuels, in addition to all the benefits of rural electrification previously introduced.

2.1 Micro-grid modelling and design

A micro-grid can be defined as a discrete energy system characterized by different distributed energy sources and loads, capable to operate either in parallel with the main power grid or independently from it (**Figure 11**).

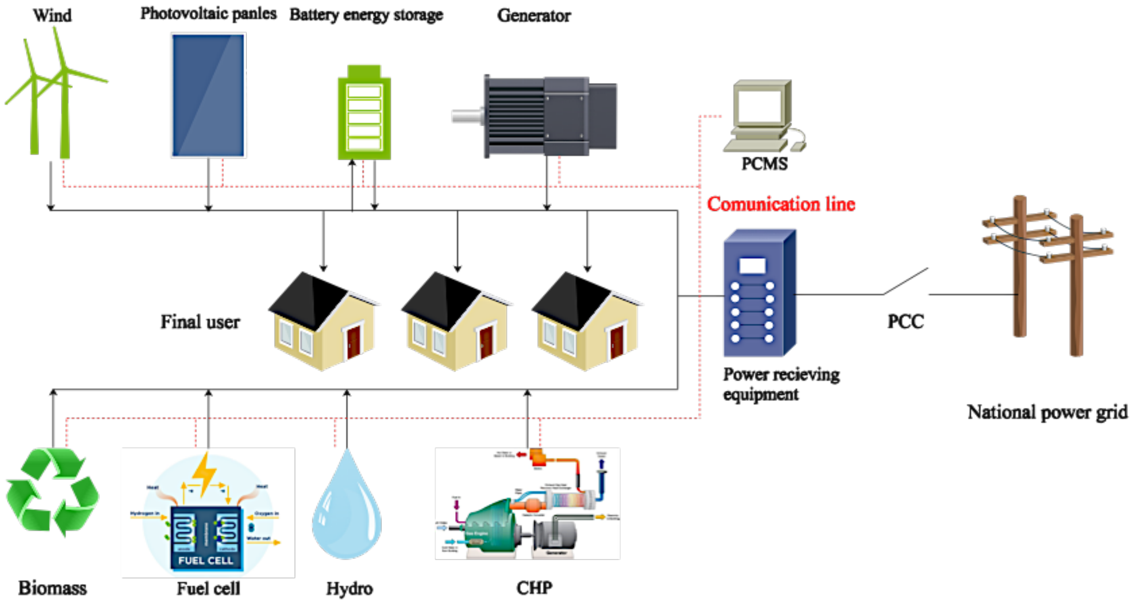


Figure 11 *Micro-grid scheme, authors elaboration*

Combined heat and power (CHP) integration in the distributed grid allows to enhance the overall energy efficiency of the power system; the usage of renewable sources could guarantee access to electricity in remote areas; distributed generators can supply load peaks (peak shaving) or priority loads during extended periods of outage or failure of the main utility grid. Moreover, distributed generators can improve power quality of the grid in terms of frequency and voltage and service reliability, thanks to their integrated power electronics interfaces.

Micro-grids structure includes different aspects related to the interface between sources and the network (including power electronics application and control systems), providing power quality, reliability, and security for end users and operators of the grid.

An increase in economic efficiency and optimization of the use of resources are the basic advantages of using micro-grids: reduction in energy transport costs (the consumption takes place where it is produced), the control and management of energy sources and loads is improved for an ever-better quality and continuity of service.

Electricity consumers are combined under a single Point of Common Coupling (PCC) with the network electrical distribution electric grid.

There are four key components of a micro-grid:

- Local distributed generation.

- Control of power loads.
- Interface to the main network.
- Power control and monitoring system (PCMS).

The necessary control and operational strategies of a micro-grid can be significantly different from those of conventional power supply systems, depending on the level of penetration of renewable energy sources, load and power quality constraints, and the strategies imposed by participation in the electricity market, if permitted.

The main reasons are the following:

- Contribution of aleatory renewable sources.
- Sources obliging the use of static converters.
- Need to manage energy storage.
- Maintaining or improving the level of power quality.
- Control of connections/disconnections of sources in the event of failure or low performance.

The introduction of the micro-grids also requires the re-evaluation of the entire structure and the protections of the distribution systems. In addition, the disconnection-reconnection of the micro-grid from/to the system requires the introduction of smart switches.

2.2 Power quality: troubles linked to micro-grid systems

The use of different technologies and their interaction in the distribution system results in temporal variations in the characteristics of power supplied to final user. These problems can occur in different ways, including sudden power outages or uncontrolled frequency f and voltage V fluctuations. The power quality is strictly connected to these factors, while reliability of the distribution system is function of frequency of services interruptions due to power outages. The energy utilities provide power in the form of alternating current (AC) and voltage, with specific voltage and frequency ranges, different from country to country. Even the costumer electric devices themselves work with clearly defined frequency and voltage bands, any deviation from this operating bands will cause the device to malfunction and subsequently deteriorate in time. It is therefore necessary to identify what could hinder the quality of the system and which equipment is most affected by these distortions.

The main disturbances affecting the power quality are identified as follows:

- Harmonic distortion.

- Electrical noise.
- Transients.
- Over-voltages and under-voltages.
- Voltage sags and swells.
- Outages.
- Voltage notching;
- Flicker.
- Back-feeding.
- Interference between different technologies.

Attention will be focused on the study of harmonics, which have a predominant influence on power quality, and possible interferences between solar energy and gen-sets.

2.3 Issues with coupling of photovoltaic systems and diesel generator

One of the most common and performing system in rural electrification is the couple diesel-photovoltaic. This technological combination is widely known as a reliable, feasible, and environment-friendly solution to supply power to remote locations. Generally, solar is preferred to wind both for its investment costs and for its ease in maintenance, but also because the mean daily solar radiation exceeds 5.5 kWh/m^2/day in equatorial regions.

The unpredictability or the unavailability of PV systems during night needs them to be combined with diesel generators as backup devices, especially when no energy storage is present. This way it is possible to reach a good reliability of the grid and to reduce the investment and the variable costs of the diesel generator. Since PV doesn’t involve any moving parts, it is possible to obtain lower maintenance and operating costs, with respect to unique employment of diesel generator.

In case of unavailability of diesel generator, the absence of energy storage system and the intermittency of PV may lead to excessive energy losses: namely, a portion of energy that cannot be delivered to the grid which is proportional to PV penetration [22]. The latter is defined as the ratio between the nominal installed power of PV [W_p] and the maximum load required by the system [23].

Typically, rural electrification systems in developing countries do not employ only Battery Energy Storage Systems (*BESS*), because of many issues, such as their short lifetime, their high investment cost and the environmental issues related to incorrect disposal [23]. The design of a system without energy storage must be done carefully, since the diesel must not be sized with respect to the peak load neither does the photovoltaic system. Otherwise, the risk is that during a particularly sunny day, PV is able to feed big part of the load and the diesel generator has to run far from its optimal range. For technical reasons, it is not advisable to run the generator below 30-40% of its rated power [24]. Fuel consumption of a diesel engine increases by about 23% for operation at 25% loading in comparison to the rated load. This may be identified as an important factor in the evaluation of the minimum loading constraint of the gen-set. However, the determinant factor is that operation under light-load conditions significantly increases the risk of engine failure and can cause its premature ageing. Working at light load also reduces the load following capability of the generator, although its response time is highly dependent on the type of controls and the load characteristic. According to these considerations, the minimum loading constraint is normally set between 30-50% [22].

Lack of batteries employment may also lead, in case of high PV penetration, unacceptable power quality conditions for the grid. As the PV penetration increase, it is more difficult for a diesel generator to stand behind quick changes in PV production [25]; typical consequences are related to harmonic distortion, voltage and frequency fluctuations and reverse power. PV inverters are the main source of injecting current harmonics into the distribution system. In turn, they can bring about voltage harmonics, making the total harmonic distortion and the distribution losses increase. The maximum Total Harmonic Distortion (THD) produced by the inverters should be less than 5%, otherwise overheating, malfunctions, and damages to both utility distribution and customer load equipment [23].

For what concerns the voltage fluctuations, they prove to be problematic if oscillate by more than 10% around the nominal voltage value. A long-lasting undervoltage can cause inability to use some appliances, while overvoltage can damage them. PV inverters can induce both voltage imbalance and voltage rise. Voltage unbalances occur when phase voltages are different among each other and can have a harmful effect on motors and power electronic devices. Voltage rise is the increase of voltage at the loads with respect to the normal value at the supply side, due to strong presence of distributed generation, which can cause reverse power flow [23]. The latter may occur when the load capacity is less than the maximally tracked PV output power and so there is an excessive power production. In this case, power would be supplied to the diesel generator which acts as a motor and the speed would overcome the accepted limits. An excessive speed implies two main consequences: voltage and frequency rise, whose effects have been already explained. Not only the power quality is detracted, but also tear and wear in the diesel engine can increase deteriorating it.

As the backup source, diesel generator must ensure the stable operation of the system, therefore it has to be kept safe. Working at a low loading rate means working at low efficiency and causing premature aging and increasing the risk of engine failure [26]. That's why a control system is necessary to prevent any of these situations, assuring a secure and high-quality power from the proposed PV-diesel system under all operating conditions and without switching off/on the diesel generator [27].

An optimal mini-grid design must take into account not only the solar photovoltaic penetration, but it has to relate it to the minimum operational load at which the generator can run without irreparable damages. The lower diesel generators can run, the greater PV penetration can be accepted, and the lower the investment costs. That's why most of the times the best solution is to use two or more generators in parallel, allowing a higher flexibility without running at too low levels. The excess PV energy has to be dumped when the diesel plant operates at the minimum loading.

To choose the optimal diesel size to install the following objective must be accomplished:

- Maximization of fuel savings by efficiency optimization.
- Maximization of PV use minimizing the dumped quantity.
- Implementing a good management strategy for diesel operation to minimize the ON/OFF cycles [22].

2.4 Choice of an appropriate tool for micro-grid design

The increasingly willingness to reduce energy poverty over the world and to ensure better living conditions, has led over the years to the creation of numerous tools for the correct dimensioning of distribution networks and for the optimal use of available local resources. However, lack of up-to-date and exhaustive databases, the impossibility in many cases to collect data on the field and the difficulty in understanding the daily needs of users, made it more difficult to implement them effectively. Despite this, none of existing tools can be defined exhaustive, showing weaknesses or inability to simulate totally truthful conditions on the field, or even focus the attention on purely technical or economic aspects without being able to integrate them. The design of the micro-grid, indeed, is a complicated multiobjective problem between environmental impact, technical solutions and economic point of view.

Below are reported some of the most popular software tools for off-grid/micro-grid systems:

- The Hybrid Optimization Model for Electric Renewables, best known as Homer, developed by the US National Renewable Energy Laboratory, is capable of simulating micro-grid electricity grids, analysing their reliability, and optimizing the technical and economic aspects to ensure the best service at minimum price, as well as being able to perform sensibility analysis. It integrates many technological solutions like gen-sets, batteries, fuel cells, PV, wind turbines etc. [28];
- The improved Hybrid Optimization by Genetic Algorithms iHOGA is a simulation and optimization program developed in C++. It is capable of handling the excess energy production by selling it to the national electricity grid. The search for optimum is done by minimizing only the Net Present Cost of the system, with constraints on CO_2 emissions or unmet load, imposed by the user [29];
- Distributed Energy Resources Customer Adoption Model, also called DER-CAM is an environmental and economic optimization model, with the integration of combined heat and power systems. It finds the most cost-effective mix of generation and storage and dispatch that minimizes costs and CO2 emissions [30];
- RETScreen is a renewable energy awareness for energy efficiency assessment, decision support, and capacity building tool developed by the CANMET Energy Diversification Research Laboratory (CEDRL) in Canada. It integrates RES and other technologies, measuring for every possible combination the energy produced, lifetime costs and greenhouse emissions [31].

Despite the potentials that has just been shown, these tools are not yet able to provide an overview of the problem of rural electrification as a whole. One of the main problems is the estimation of load demand, as it is not always possible to predict the real needs of users over time, especially those who have never had access to energy services. In addition, previous tools provide invariability of the load through the years, thus under-dimensioning the possible solutions: in real cases, knowing that access to energy is a promoter of development, over time the provision of new services requires greater amounts of energy.

The goal of the thesis is to develop a tool capable to effectively manage rural area scenarios, in particular dealing with PV, storage and diesel technologies, ensuring the possibility of disconnection from the national electricity grid with the integration of a power outage identification control logic. For such a goal, a specific procedure has been elaborated and coded within the Poli.NRG package.

Actually, Poli.NRG is a problem-solving software developed by Politecnico di Milano – Energy Department aimed to the optimal design of a PV+BESS system for off-grid applications, according to a bottom-up approach.

The procedure worked out in the thesis portfolio has been designed in order to properly manage both the grid, the operative conditions and the power outage occurrences, i.e the time slots when the public grid is unreliable and, consequently, the micro-grid is asked to operate stand alone.

Chapter 3

Energy system of St. Mary's Lacor Hospital

Before going into the details of the Hospital energy system, it is necessary to give some background info. Starting from an overview of the country, focusing mainly on energy, the analysis moves to the assessment of St. Mary's Lacor Hospital.

3.1 Context analysis: Uganda

The Republic of Uganda, with a population of 41.49 million people (World Bank 2016), is the second most populous landlocked country and remains one of the poorest countries in the world. Even though its income per capita has doubled in the last 20 years, as shown in **Figure 12**, the 34% of the population still lives on less than \$1.90 a day and the average per capita GDP is of US\$ 1848.79 (PPP-World Bank 2016).

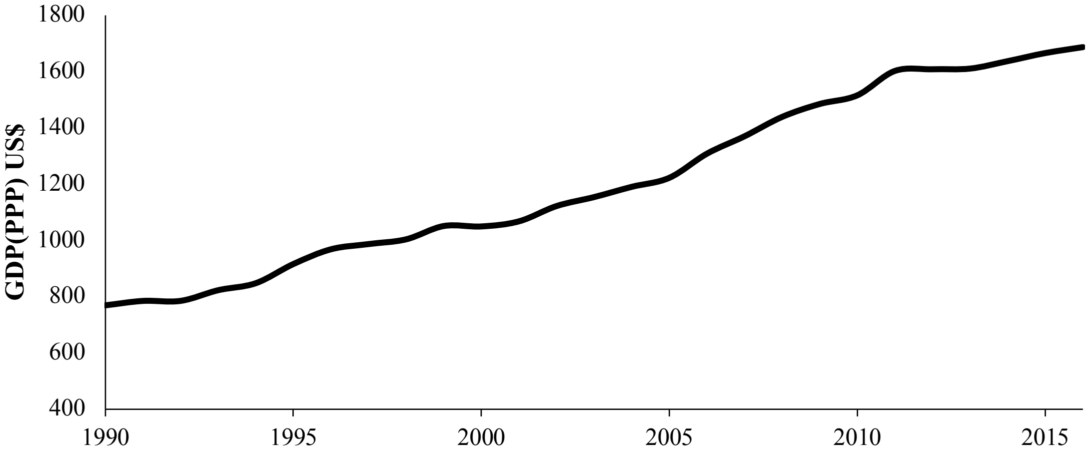


Figure 12 Uganda GDP per capita, PPP (constant 2011 international \$), source World Bank

Compared to the various indicators previously introduced, according to the UNDP Human Development Records, Uganda shows very low values for each of them (HDI 0.493 in 2016, MPI 0.367 in 2008), highlighting how Uganda occupies the last places in the world rankings. The country has many obstacles to overcome, despite the efforts undertaken by the government, the international agencies and foreign countries focused on:

- Currency reform.
- Raising producer prices on export crops.
- Increasing prices of petroleum products.
- Improving civil service wages.
- Market liberalization.
- Investments in infrastructures.

Primarily, Uganda is facing a massive migratory flow from South Sudan in which a bloody civil war made more than a million people to move. Moreover, as it occurs in many developing countries, Uganda experiences:

- Low urbanization rates.
- Non-tradable activities.
- Strong reliability on export.
- Inadequate transportation and energy infrastructures.
- Corruption.
- Insufficient budgetary discipline.

3.1.1 Economy sectors

Today the most important sector of the economy is agriculture, employing over 70% of the work force (World Bank 2017), however it exhibits one of the lowest productivity level in the world due to the high agriculture employment per hectare of arable land and to the lack of appropriate tools [32]. Neither fertilizers nor machineries are used, so the productivity per worker remains low and economies of scale is prevented. On the other hand, the industrial sector, that includes mining and construction, has doubled its share of GDP, but it holds still at 22% (**Figure 13**). Manufacturing sector shows very low share in value added to GDP and is particularly affected by low capacity utilization, mainly due to credit rationing, limited skills and inadequate infrastructures. Hence the level of export of manufacturing products cannot be boosted and export remains related to primary products, such as coffee, fish, tobacco, gold and flowers. However, reliance on these assets has made export sector vulnerable to fluctuation in world market prices and on the variability of weather. Indeed, Uganda has faced a significant long run decline in its term of trade, but the discovery of oil reservoir near the lake Albert bodes well for energy and export perspective. The World Bank estimated that oil revenues would constitute approximately 10-15% of GDP at peak production, which is expected being in 2020. Anyway, the process of setting up the production capacity and the pipelines will be slow, also because of current oil price [32].

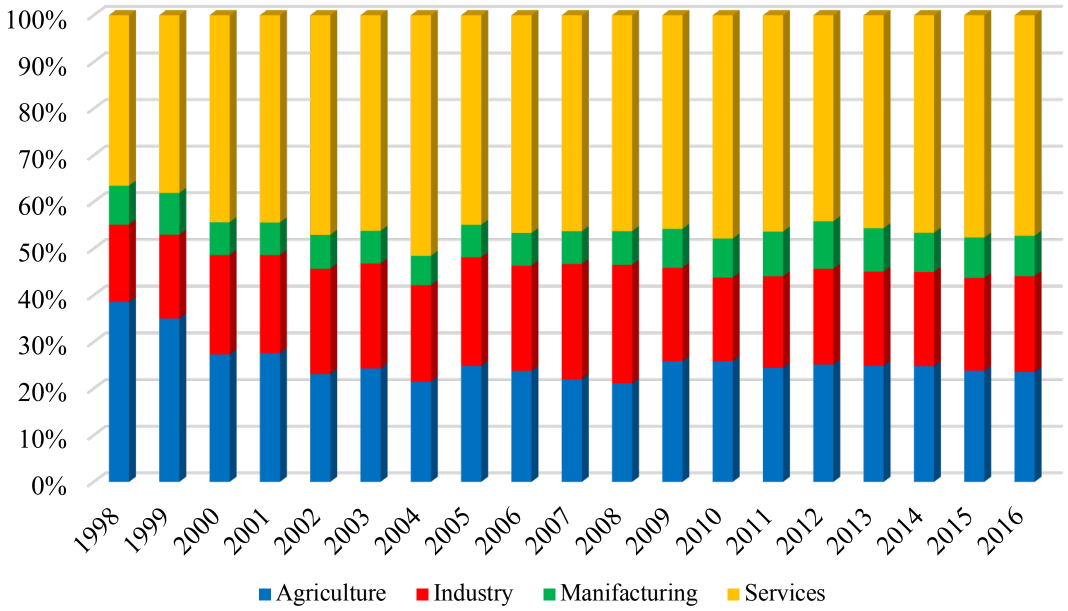


Figure 13 *Value added on GDP by sector, Source World Bank*

3.1.2 Energy assessment

Beyond the oil, Uganda is plenty of energy resources, equally scattered all over the country. These include mainly renewables (hydropower, biomass, solar, geothermal, peat), but also fossil fuels. Wind is not considered because of the moderated wind speed, which is not enough for electric energy conversion. Mean wind speed ranges between 1.8 to 4 m/s, that would be suitable only for water pumping, especially in the Karamoja region, or by small industries. According to SE4All, the country has an energy potential of 2000 MW of hydro power, 450 MW of geothermal, 1650 MW of biomass cogeneration, 50 million tons equivalent of sustainable biomass stock, 5.1 kWh/m^2 of solar energy and about 250 Mtoe of peat (800 MW) [33]. It has also been estimated 6.5 billion barrels of oil in place, but recoverable oil is estimated to be between 1.8 and 2.2 billion barrels. Oil production is expected to reach heights of between 200,000 and 250,000 barrels per day based on recent discoveries.

The total primary energy consumption is of 1.76 Mtoe (2014), of which about 90% is non-sustainable biomass. The remaining 10% is split between electricity, which contributes by only 1.4%, and oil products, mainly used for vehicles and thermal power plants.

The latter represents the highest single commodity import expenditure, but the Government of Uganda is supporting establishment of both production wells, likewise the construction of oil refinery, to make the country switch from being an importer to an exporter for about 30 years. This will be essential to supply the continuous expansion of vehicles use in tandem to the economic growth [34].

Diesel is also used for off-grid power generation by Uganda Electricity Generation Company Limited (UEGCL) for peak generation and for remote rural mini-grids, while industry and commercial groups use generators for back-up power and off-grid base load. Households employ kerosene for lighting, whose usage dropped by 13% between 2012 and 2013 [35].

Even though Uganda is endowed with a lot of energy resources, it has one of the lowest electricity penetration level, with only 20% of the total population having electricity access; the rural access to electricity lies at 10%, while the urban one at 51% (World Bank 2016). This limited service is also poor, with 19% (2015) of electricity distribution losses and 4% of transmission ones, due to inadequate and insufficient connections [36]. At the same time, the electricity consumption is one of the lowest in the World and in the Sub-Saharan Africa, around 80 kWh per capita, and it is estimated to grow at an average of 10% annually [33].

According to the Ministry of Energy and Mineral Development (MEMD), the total installed generation capacity has increased from 595 MW in 2011 to more than 900 MW in 2017, but the available generation remains around 600MW. The upgraded generation capacity allowed the reduction of suffering long-standing supply side constraints, resulted in suppressed demand and outages. In fact, the current peak electricity demand lies around 550 MW, sorted as follows: large industry for 44%, medium industry for 18%, commercial sector for 12%, households for 22% and export for 4%.

As it is possible to see from **Table 3**, the majority of the existing plants are hydroelectric ones, thanks to the presence of many water reservoirs and flows, thus implying the dependence on meteorological conditions. The capacity expansion is going to keep on, thanks to the Government of Uganda’s projects to build additional large hydropower facilities (such as the 600 MW Karuma plant and the 183 MW Isimba Falls plant), and to the private interest, given that Ugandan electricity sector is managed also by private companies. Uganda is one of the few sub-Saharan countries to have liberalized its energy market; generation, transmission and supply were unbundled in 1999, with the enactment of the Electricity Act.

Power stations	Type	Subtype	Capacity [MW]	Year completed
Adekokwok	Hydroelectric	Run of river	8	2014
Bugoye	Hydroelectric	Run of river	13	2009
Bujagali	Hydroelectric	Run of river	250	2012
Kabalega	Hydroelectric	Reservoir	9	2013
Kanungu	Hydroelectric	Run of river	6.6	2011
Kiira	Hydroelectric	Reservoir	200	2000
Mpanga	Hydroelectric	Run of river	18	2011
Mubuku I	Hydroelectric	Run of river	5	1950
Mubuku III	Hydroelectric	Run of river	10	2009
Nalubaale	Hydroelectric	Reservoir	180	1954
Nyagak	Hydroelectric	Run of river	3.5	2012
Kisiizi	Hydroelectric	Run of river	0.3	2008
Gwere-Luzira	Hydroelectric	Run of river	0.0005	2009
Siti I	Hydroelectric	Run of river	5	2017
Muvumbe	Hydroelectric	Run of river	6.5	2017
Bugala	Thermal	Biodiesel	1.5	2010
Namanve	Thermal	Fuel oil	50 (reserve)	2008
Tororo	Thermal	Biodiesel, fuel oil, crude oil	80	2010
Kakira	Thermal	Bagasse	52	2005
Kinyara	Thermal	Bagasse	40	2009
Kaliro	Thermal	Bagasse	12	2014
Lugazi	Thermal	Bagasse	14	2017
Mayuge	Thermal	Bagasse	1.6	2005
Bukuzindu	Hybrid	Photovoltaic & Diesel	1.6	2014
Soroti	Solar	Photovoltaic	10	2016

Table 3 *List of current power plants, Source UEGCL*

3.1.3 Energy policies

The former Uganda Electricity Board (UEB) was dismantled and the Electricity Regulatory Authority (ERA) was created. The general idea behind the reforms in the electricity sectors across many countries, including Sub- Saharan Africa, was that private sector participation would enable increased supply of reasonably price and reliable electricity, to follow the increasing demand. The result of this reform was the creation of three operational entities: Uganda Electricity Generation Company Limited (UEGCL); Uganda Electricity Transmission Company Limited (UETCL) and Uganda Electricity Distribution Company Limited (UEDCL) [37]. Generation and distribution assets were subsequently transferred to concessions through a competitive bidding process. Distribution is dominated by UMEME, which in 2015 supplied 98% of Uganda’s electricity consumption. The near-monopoly is a publicly traded company with a 20-year concession for distribution and retail in Kampala and several other territories. The provision that brought about such a structure was aimed to rectify UEB's poor management performance, to make the power sector financially viable without subsidies, to increase its efficiency, to improve commercial performances, to meet the growing demand for electricity and increase the coverage area, to attract private capital and to take advantage of opportunities to export electricity. To achieve these goals, some proposals related to generation, transmission, distribution, rural electrification and regulation were outlined. For what concerns the generation, the development of new generation facilities would be facilitated through international competitive bidding by the private sector on an independent power provider (IPP). On the other side, a separated transmission company would be established and be responsible for network maintenance, system operations and dispatch, planning and bulk purchase, and the supply of electricity. To improve the distribution, the restructuring of its system (to make it financially viable and to improve its commercial performance) was seen as the key to the success of the reform programme. But it was, and it is not still enough to think of the three processes of the electricity service. This is proven by the fact that in 1999, only 1% of the population in the rural areas had access to electricity. The Government sought to encourage the private sector to take part in rural electrification by simple and non-bureaucratic licensing framework for IPPs and by retail tariffs set at the levels required to ensure the financial viability of the local electricity service providers. To manage all of these adjustments, a strong regulation was needed, to rebuild confidence of the private sector and consumers in the electricity sector. For these purposes, an independent of political influence authority (ERA) was established to carry out the regulatory function.

Over the last years, performance of the Ugandan power system has improved since the onset of reforms, resulting in a reduction in the extent of load-shedding.

The Electricity Act was the first of many measures that have been issued by the Ministry of Energy and Minerals Development to pursue a sustainable development, according to the Uganda's Sustainable Energy for All (SE4All) initiative action agenda. Indeed, only three years later, the *National Energy Policy (NEP 2002)* was approved with the aim of incentivizing the customer side as well. The main objectives were the establishment of the availability, potential and demand of the different energy sources; the increase of access to modern affordable and reliable energy; the reduction of poverty eradication; the improvement of energy governance and administration; the stimulation of economic development and the management of energy related environmental impacts. Aiming to reach these objectives, the government created incentives:

- To make electricity and modern fuels more easily accessible in rural areas.
- For the industries and for the commercial sector to adopt more efficient energy end-use technologies.
- To increase competition in the power sector.
- To operate and expand the existing system at minimum cost and price.

As a natural result of the *NEP*, the *Renewable Energy Policy (REP2007)* was born, pushing the spread of environmental friendly energy technologies to pass from 4% to 61%. Moreover, the introduction of renewable energies have increased the energy access in the rural areas, compensated the supply deficit due to the fall in Lake Victoria water levels, reduced the use of oil whose price was rising, fulfilled the Government's commitment related to greenhouse gases emissions reduction [38]. In 2010, with the *National Development Plan (2010),* Ugandan government targeted to reach the status of middle income countries by 2030 and among all the objectives there were bringing the poverty headcount ratio at national level below 24.5% and bringing the per capita GDP (constant 2010 US$) from 506 to 850 at an average growth rate of 7.2%. For these purposes, energy role was considered crucial: the main strategy to improve country's competitiveness and foster accelerated socio-economic transformation, to make the electricity consumption raise from 75 kWh to 674 kWh, set out to add 3500 MW of generation capacity [39]. Actually, only the poverty reduction target and the generation capacity one were reached, and in 2015 the *Second National Development Plan* was launched. One of its aimed goals is to reach an electricity access of 30% by 2020. According to its background, the reason why Uganda was not able to grow at 7.2% per year is mainly related to the climate change and to the 2008 financial crisis, but despite this Uganda has been growing at a higher pace than the African average. Moreover, the total electricity supply increased by 7.1%, from 2737.8 GWh in 2012 to 2932.8 GWh in 2013. The *Second National Development Plan* detected the lack of a good mix of energy sources in power generation, the low level of access to modern energy, the inadequate infrastructures for generation, the high tariffs, the unreliable and insufficient supply and the inadequate institutional and regulatory capacity as the main challenges for Ugandan energy sector [40]. To address some of these constraints, the *Rural Electrification*

Strategy and Plan (RESP 2011) was issued for the period 2013-2022. Rural electrification is an integral component of the Government’s overall policy and programme to promote national economic and social development and integration. Furthermore, it is aligned to the Government’s vision of universal electricity access by 2040. The primary objective of RESP 2012 is “to achieve an accelerated pace of electricity access and service penetration to meet national development goals during the planning period and beyond”. A secondary objective is to ensure that progressively the programme facilitates access to all form of modern energy services to replace kerosene lighting and other forms of traditional cooking and heating by 2030. Rural electrification steps set up by the government are: 26% by 2022, 51% by 2030 and 100% by 2040 [41]. As opposed to the previous RESP, the strategy put in place focuses on centralizing rural electrification planning and program management, reducing complexity and eliminating overlapping roles. While the Government has to manage the programme implementation, the private sector has to fulfil its financial responsibilities. The main stakeholder group is the beneficiary population, by involving local priorities, managing demand aggregation and consumer outreach and managing and operating the schemes as cooperatives.

There is also a strong interest from the UNDP, which targeted some goals to reach by 2035 mainly focused on the promotion of sustainability, equality, democracy, legality, health and education. The UN strategy for addressing these challenges is to strengthen environmental mainstreaming capacity and support relevant sector ministries and partners in natural resources management, including development of innovative resilience and risk management strategies involving local communities. Support will also focus on establishing alternate livelihoods for communities, promoting conservation and use of alternate energy sources.

Due to the lack of data, it is very difficult to evaluate whether these goals have been even partially reached or not. Certainly, between 2013 and 2014 access to electricity at the global level (**Figure 14**) made great progress, proving the effectiveness of the policies and the private and public investments.

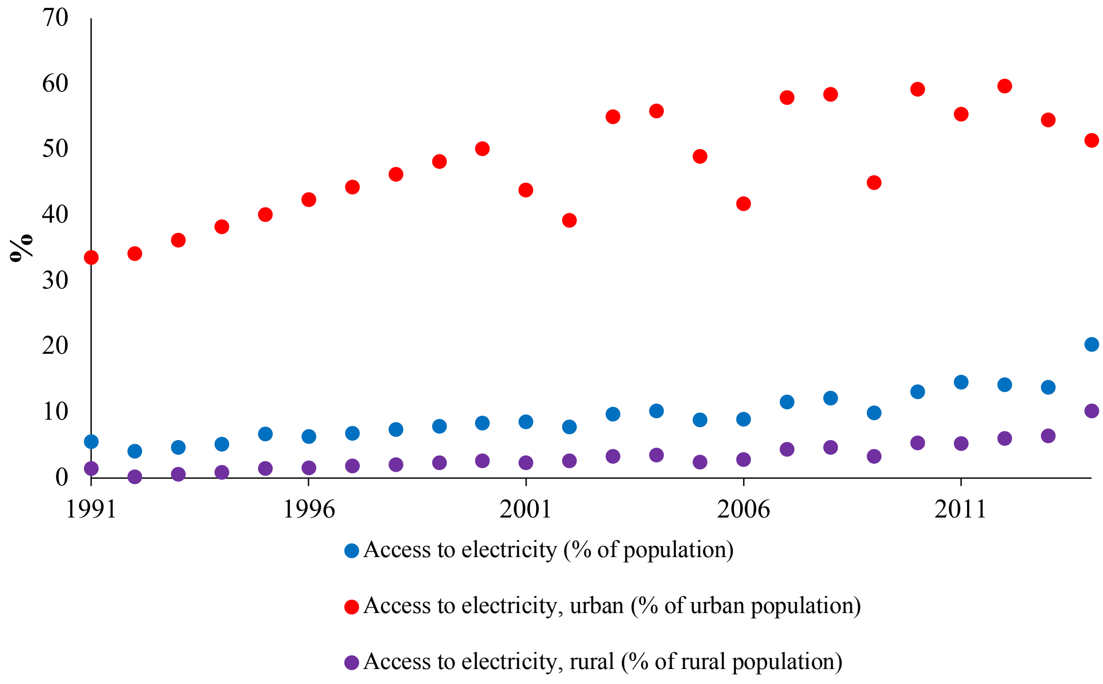


Figure 14 *Access to electricity %*

3.2 Description of St. Mary Hospital energy system

St. Mary's Hospital Lacor is the largest Referral private non-profit catholic based institution in Uganda. It is located in Lacor, a small village about six kilometres west of Gulu, the main town in the Northern part of the country. From a small 30-bed Hospital 55 years ago, Lacor Hospital is now a complex compound made of: outpatients department (OPD), two medicine wards, two Surgery wards, an Intensive Care Unit (ICU), six operating theatres (Theatre), a radiology ward, a maternity ward, a children ward, a laboratory, an isolation unit, a pharmacy, staff quarters, foundation residences (Corti's House, Bruno's House, Red Villa, White Villa, Comboni's House and Guest House) and finally a university.

For such a big structure, it was necessary to build a technical department inside it, also because of the distance from the town. People working in the technical department, called Workshop, deal with many functions:

- Utility management related to electrical system and water supply.
- Civil works and repairs of Hospital structures and furniture.
- Maintenance and management of mechanical plants (generators, compressors, air conditioning system, laundry equipment, etc.).

- Transport and mobility managements: mechanical works to repair ambulances, drivers.

The workshop includes staff's offices, the repair place, the distribution room and the generators' room.

Actually, the two most used diesel generators are located outdoor, while among the indoors one only the Fiat Aifo is still used, because the others are under maintenance.

The main electrical distribution is in star-system from the main distribution house with a network of 16000 m of underground cables [42].

As shown in **Figure 15**, in the distribution room, installed in 2003 by BBM and over time adapted to the new needs of the Hospital, there is a main switchboard (box 0) where the main busbar, the circuit breakers to choose either to use the national grid or the diesel generator and the main meters (one for UMEME and the other for the power coming from the diesel generators) are placed. In the other switchboards there are the meters related to the different wards. Besides, there is a circuit breaker dedicated to the emergency line, in which a voltage control system gives the input to the UPS to turn the battery bank on, with the task to feed only the emergency line in case of power outages. The UPS could be also by-passed, and the emergency line can be powered by the emergency generator in case of need of maintenance of the battery pack or other issues.

Beside the control room, there is the 1 MW three phase step down transformer, directly connected to 11kV national grid. The power coming from UMEME can be interrupted by a manual switch placed near the transformer.

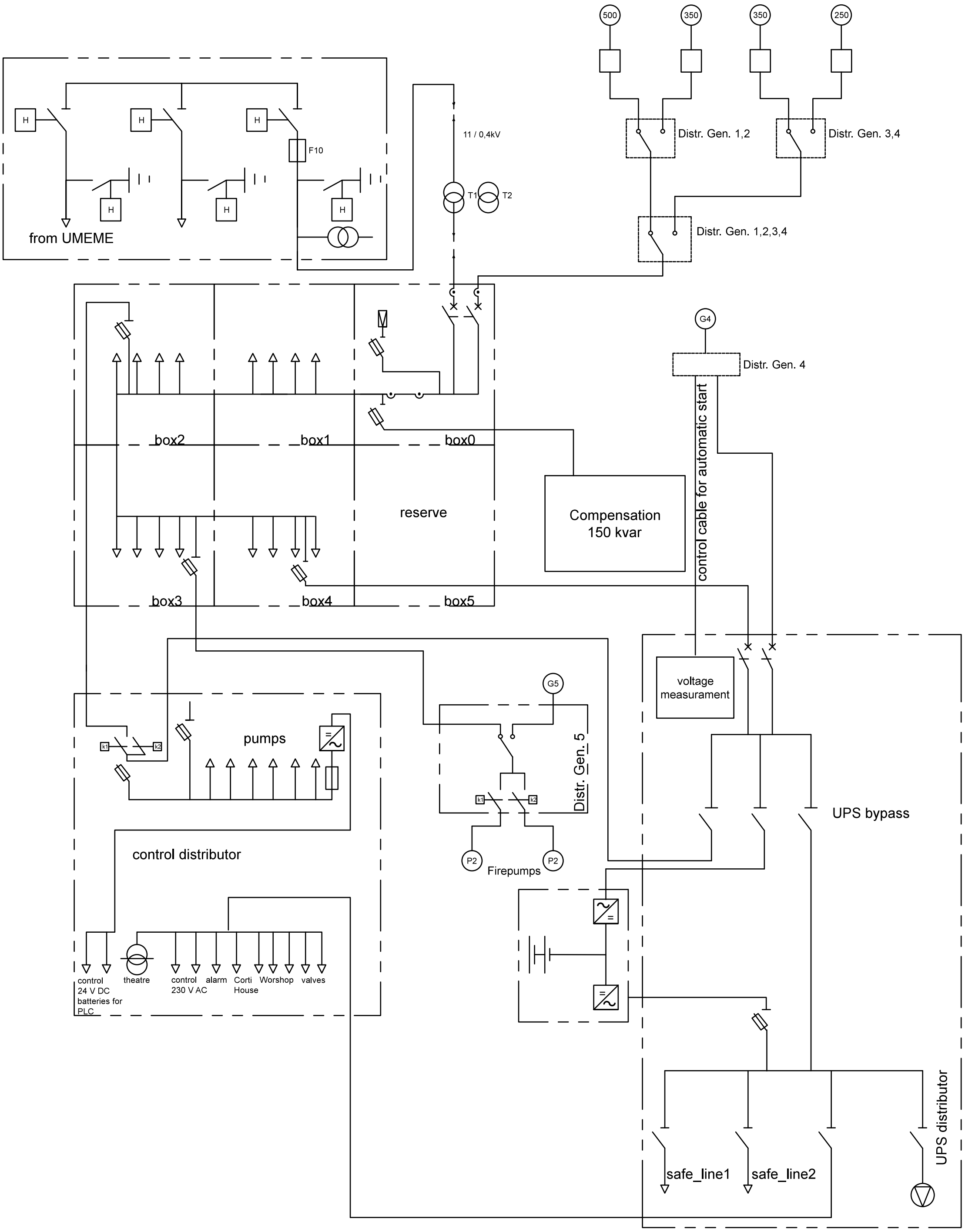


Figure 15 Distribution room, authors' elaboration

3.2.1 Distribution

Electricity is provided through two lines: the main line and the emergency line. The main line reaches every part of the Hospital, as far as the most remote areas. The emergency line is intended to feed only some dedicated utilities which necessitate continuity of the services, such as some medical machineries, the administration computers and the water pumps. Almost all the buildings, except for the staff quarters, are connected to the emergency line, but only partially, to have the possibility to use lights and small appliances; all the sockets and the switches marked with a red label are connected to the emergency line.

Main line

Due to the continuous updating of the lines and failure to track them step by step, it is difficult to have a complete understanding of current situation, in addition to not being fully aware of where the cables were laid.

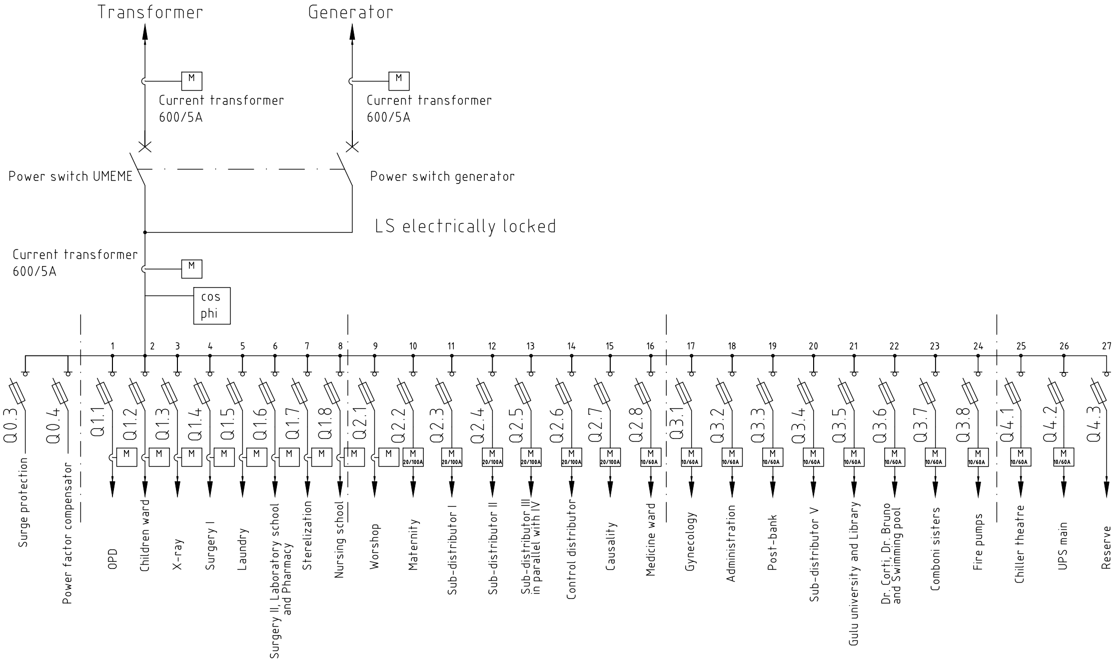


Figure 16 *Main Line, authors' elaboration*

A simplified drawing is proposed in **Figure 16**: the main circuit breaker –currently manual- allows to choose to power the main line from either UMEME to generator and vice versa. The main line is made of many branches among which five ones depart to reach five sub-distributors switchboards located near the residences: Red Villa, White Villa, Comboni's House, Guest House and the staff quarters. For what concerns the wards, each building is directly connected to the distribution room.

Emergency line

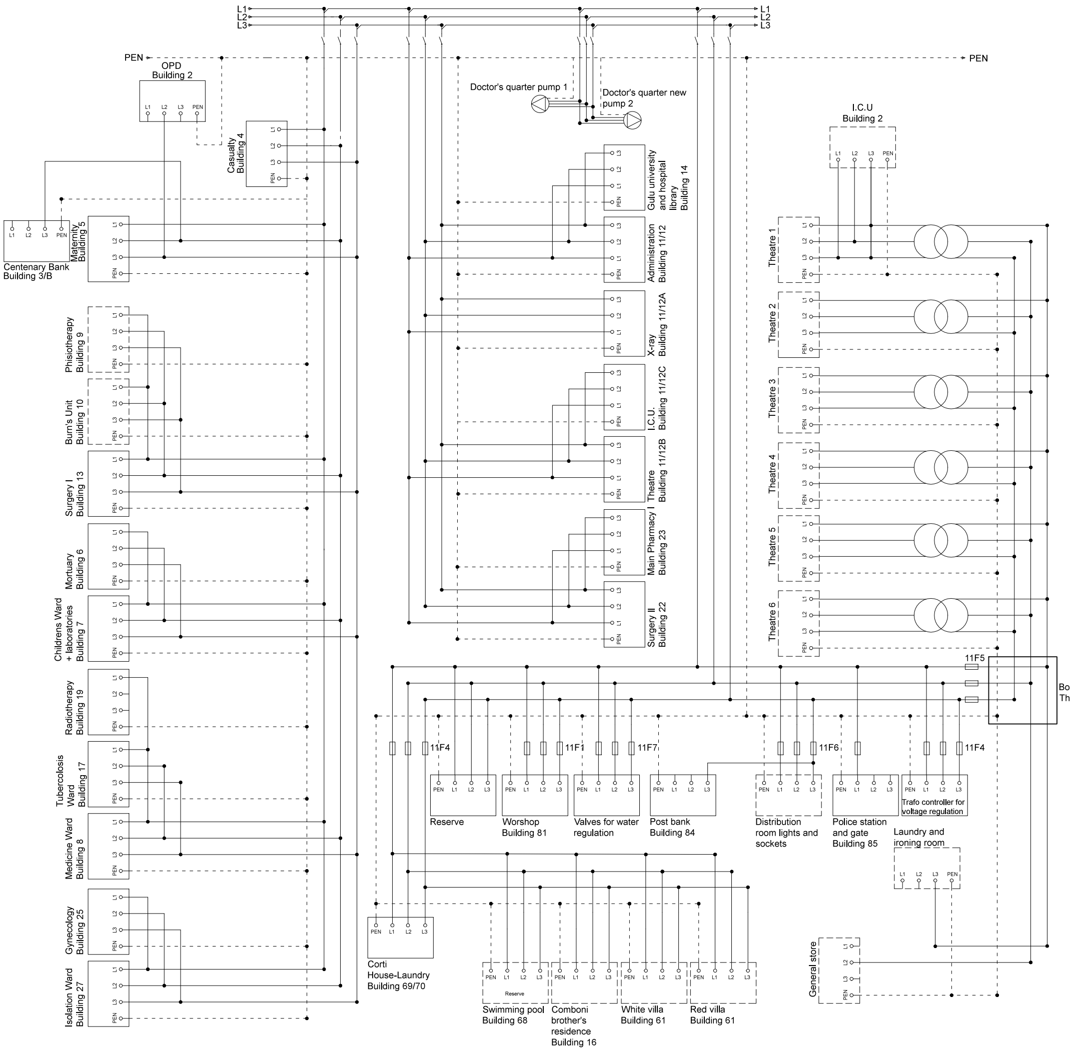


Figure 17 *Emergency Line, authors' elaboration*

The emergency line, as it is possible to see from **Figure 17**, consists mainly of two branches called "*safeline 1*" and "*safeline 2*", which respectively feed the right and the left part of the purely Hospital structure. At the beginning, the electrical line was a ring connecting all the wards, but accidentally some years ago the ring suffered a contingency during some construction works, consequently a more traditional radial structure is today adopted. Moreover, there are additional direct and dedicated connections to single buildings and/or devices (operational theatre, pumps, valves). For example, each operating theatre room has its own transformer connected to the control distributor.

3.2.2 Generation

Being the national grid not reliable, to optimally satisfy its needs, the Hospital is equipped with different sizes diesel generators, photovoltaic power systems, solar thermal systems for water heating and energy storage systems.

Diesel generators

The details of the present diesel generators, whether still in use or not, are in the **Table 4**. Currently only three among seven generators work, because of maintenance or inoperativeness of the others. Generators are turned on just in case of power outages of the national grid. According to the Hospital policy about energy management, either the 500 kVA or the 350 kVA (Perkins) are turned on during daytime power outages, apparently without a precise control logic. If a power outage occurs during the night the Fiat Aifo is used instead, in order to supply only the load connected to the emergency line. More precisely, in the past, during the night only the battery pack was used and the Fiat Aifo was turned on only in case of too low batteries state of charge. Now it is immediately turned on for safety, since the battery pack is not as reliable as in the past.

Engine	Alternator	Generator Group	Apparent Power [kVA]	Active Power [kW]
Pellizzari AB280M4	n/a	n/a	150	120
Fiat Aifo	n/a	n/a	175	140
Ansaldo M2B315MA4	n/a	n/a	350	280
Deutz DW230	Leroy Somer	n/a	250	200
Perkins 2006 TG2A	Leroy Somer	Ergen	250	200
Perkins 3008 TAG4	n/a	GTM P500-E4919-B2	500	400
Perkins 2306C- E14TAG2	n/a	VISA P355SSEVAU	350	280

Table 4 *Diesel Generators*

Batteries

The possibility that fuel was not available or insufficient, the weak reliability of national grid and the start-up time of the diesel generator led to the installation of an additional safety system: the uninterruptable power supply (UPS).

There are different energy storage systems in the Hospital, all consisting of gel technology, listed in **Table 5**. Since the last year only the biggest one has been used. In fact, the last two battery banks were initially directly connected to ICU and Laboratory, in order for these wards to have a further back up system in case of power outages. Currently, they are disconnected and no more available, because the photovoltaic system that used to feed them is planned to be connected to the main line and to contribute to supply the load. This decision has been taken because of the lack of use of these backup systems, due to the manual switch to turn them on and to the fact that the medical staff didn't even know their existence.

Quantity	Model
240	Hoppecke OPzV Reserve Power System 1250, 2 V, 1350 Ah
2x12	Victron OPzV solar battery, 2 V, 1500 Ah
2x12	Victron OPzV solar battery, 2 V, 1500 Ah 2 V

Table 5 *Energy storage systems*

After continuous disconnections of the UPS, an in-depth analysis of the battery status was carried out, leading to the removal of 15 of the batteries from the Hoppecke block. At present, the available UPS capacity is 562.5 kWh instead of original 600 kWh. Batteries are used only in case of power outage and can be recharged either by the main line or by the emergency diesel generator (Fiat Aifo).

Photovoltaic systems

During the last years, the Hospital has been provided of many photovoltaic systems by different donors. So far, the theoretical total installed photovoltaic power has reached 186 kW_p and it is supposed to keep on growing. Generally, the donors prefer giving the panels as a gift instead that paying the bills, to give a long-term contribution to the reduction of the energy expenditure of the Hospital.

There are seven photovoltaic systems, each of which is named as the building where it is mounted on. However, only the first fourth systems listed in **Table 6** are working: the fifth system is connected to the main grid, but shows voltage problems, so it has been put under maintenance; the last two systems were initially connected to the ancillary battery banks in the ICU and in the Laboratory, now they are going to be connected to the main grid to increase the total photovoltaic power. At present, therefore, the current available power is around 150 kW_p, considering that each inverter is able to provide at most 15 kW. It has to be specified that the 15 kW_p plant on the OPD has been completed the last days of the mission, so most of the analysis will be based on 140 kW_p.

Building	Inverter	Power [kWp]
Maternity	Three Grid inverters 3-phases Sma Sunny Tripower 15 kVA	48
OPD	Three Grid inverters 3-phases Sma Sunny Tripower 15 kVA	48
Theatre	Three Grid inverters 3-phases Sma Sunny Tripower 15 kVA	48
OPD	Grid inverter 3-phases Sma Sunny Tripower 15 kVA	15.6
ICU	Grid inverter 3-phases Riello Aros Sirio K15	15.6
ICU	Grid Victron Energy Blue Solar 2000/230 and a battery inverter Victron Quattro 24/5000/120-100/100 230V	5.2
Laboratory	Battery inverter Victron Quattro 24/5000/120-100/100 230V	5.6

Table 6 *Photovoltaic systems*

The inverters are connected to the building line they belong to; this implies that the power provided by them is firstly consumed by the single building and then, if the converted electricity by those inverters is in excess with respect to the consumption of the building, it goes where it is required. For this reason, the energy consumption supplied by the solar power is not accounted for by the main meter. Due to the current connections of the solar panels with respect to the internal distribution line, it is possible that the rotary meters turn in the opposite direction, leading to erroneous measurements over time. It would be better to connect the photovoltaic system to the main access point in the distribution room (where the main line departs from) to have a more precise knowledge of their production and better management possibilities. **Figure 18**, **Figure 19** and **Figure 20** better explain the connection of the inverters to the buildings they belong to and then to the main line.

The OPD’s and Maternity’s seven inverters have been placed in a specific room behind the Maternity ward, to make their access easy in case of data collection or maintenance. However, this room is small and not sufficiently ventilated, so the temperature inside it is harmful for the inverters. For what concerns the plant on the Theatre’s roof, the inverters are located in a technical room beside the laundry, where two air treatment units and the six transformers, one for each operational theatre, are placed.

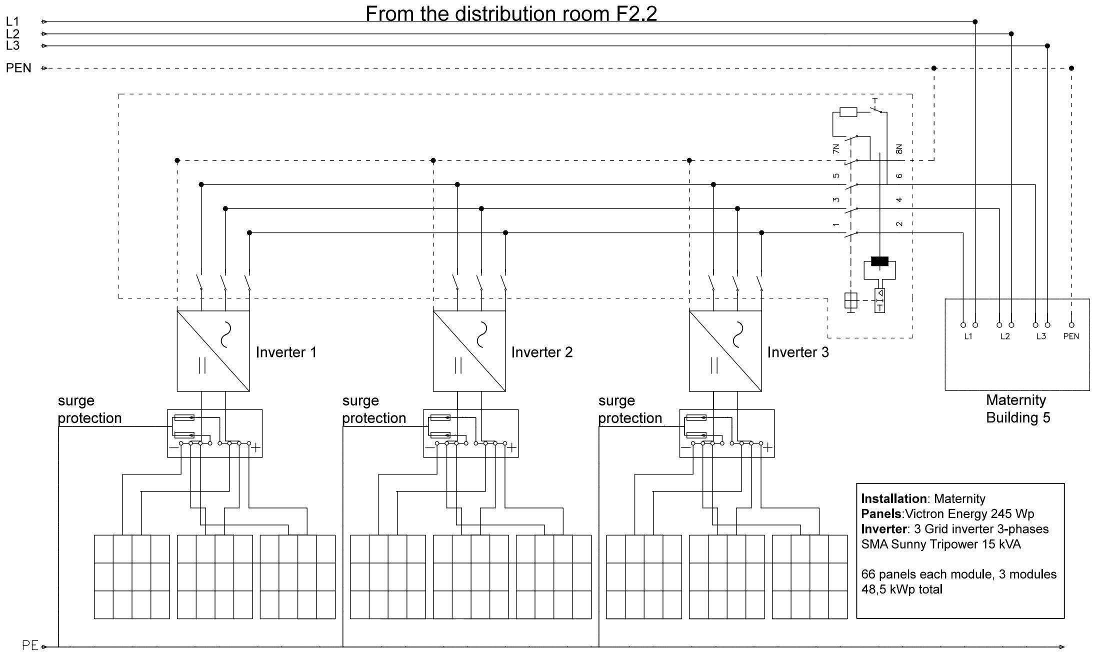


Figure 18 *Maternity inverters connection, authors' elaboration*

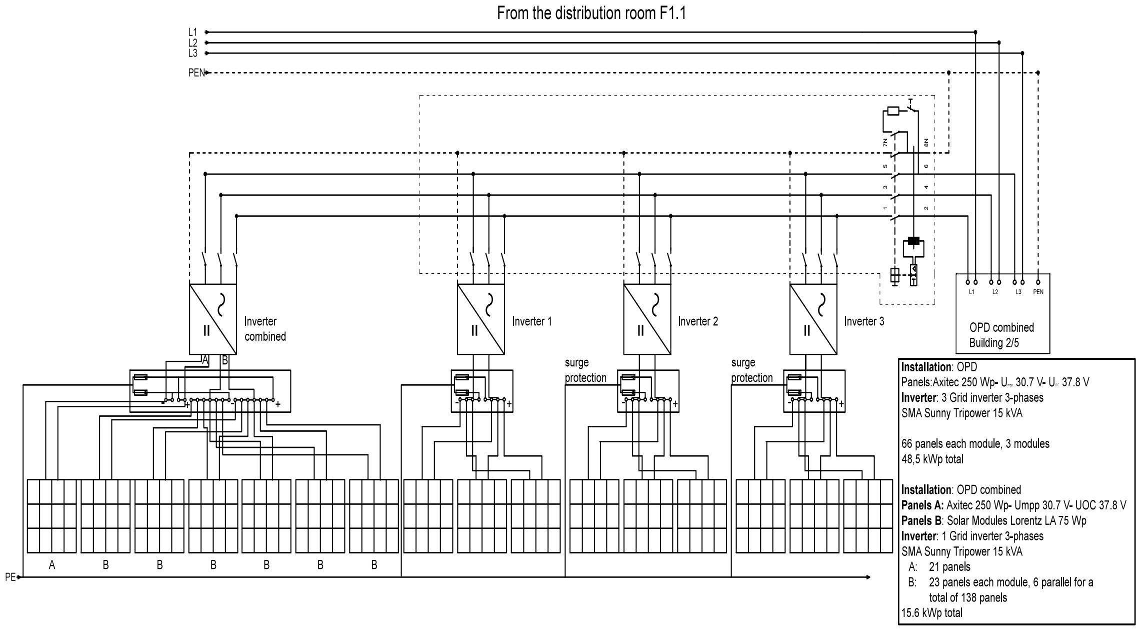


Figure 19 *OPD inverter connections, authors' elaboration*

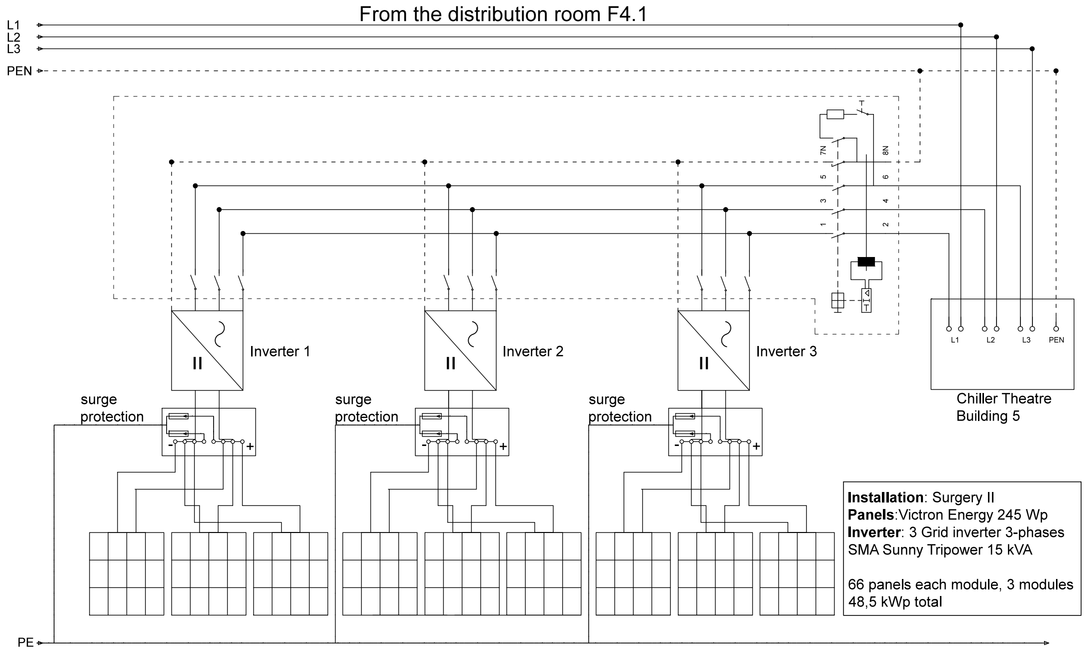


Figure 20 *Theatre inverters connection, authors’ elaboration*

3.2.3 Energy Management

There is no automatic device for the energy management, except for the UPS. The latter, is always on, managing and monitoring the state of charge of the batteries; when the power goes off for any reason, the UPS leads immediately the batteries to feed only the emergency line, so it is always powered and the important services cannot be undermined.

If the power outage occurs within 8:00 a.m. and 10:00 p.m., one among the two big size generators is turned one by the on-duty operator, since the automatic main switch got broken and it was almost impossible to be repaired. An operator, generally an electrician or the chief mechanic, must always be close to the distribution room to restore the power. For sake of simplicity, the 500 kVA will be called “white generator” and the 350 kVA “yellow generator”. Apparently, there is not a reason to choose whether one or the other: generally during the day, the white one is used because it is commonly believed that it is more able to face with load ramps and consumes less than the yellow one. This is partially true, since having a higher inertia means a better capability to follow the load. On the other hand, if there is a strong solar radiation, the diesel generator could be obliged to work below its optimal range, becoming inefficient and prone to internal damages.

The yellow generator is generally turned on during off-peak hours. When any of the two generator is turned on within the time interval defined above, the main line is restored, so the power reaches the entire compound and charges the batteries if necessary. Even in the totally hypothetical case in which the photovoltaic plants could be able to supply alone the whole load, a generator must be turn on anyway because the inverters are not grid forming, so they need another system to impose frequency and voltage.

If there is a power failure during the night (10:00 p.m. to 8:00 a.m.) and/or during the weekend, the Fiat Aifo is turned on as soon as possible. Formerly, only the battery pack was used during the night and it was able to last for the whole power outage; in case it wasn't, the Fiat Aifo was automatically turned on. Over the years the batteries got spoiled and now they are no more capable to stand the entire night. That's why it has been necessary to establish night shifts, in order for an operator to be always in loco and intervene as quickly as possible, since the automatic switch got broken as well. The decision not to supply the entire Hospital but only the emergency line, even if a generator must be turned on, is related to the noise and the reduction of fuel consumption. Fiat Aifo would be able to fulfil the overall load during night, but the cost of the fuel is much higher than the electricity from the national grid, so the aim is to save fuel at least at night.

The absence of automatic switches and, consequently, the continuous need of an operator in loco imply additional expenditures to guarantee a constant electricity; however, it is necessary to ensure a good quality health service.

The automatic switches haven't been replaced according to past experience: in developing countries would be better to avoid employing complicated devices, because spare parts are costly and difficult to come by, thus aiming for simple solutions

Chapter 4

Data acquisition in Uganda

This chapter describes the work in the field, i.e. data gathering and elaboration about energy systems in Lacor Hospital.

One of the main goals of the project was to develop a procedure capable to properly operate in “real life” scenario. For such a goal a “real life” study case has been evaluated. In particular, authors spent a two months internship in Lacor Hospital, Uganda, from April to June 2017. The former call of the mission was to find the inputs, to program, to install and test the BBM Power Control & Monitoring System (PCMS), to improve the energy management of the Hospital. PCMS was developed by BBM together with the research institution ASIC and it is able to [43]:

- Use solar PV power without batteries (using standard grid inverters).
- Prevent back-feeding power to the grid (if it is not allowed).
- Control solar PV power when grid power is off and a generator is running (to guarantee a minimum load for the generator).
- Monitor power consumption, power savings and performance of the whole power system.

Due to technical and organizational problems, goals had been partially achieved (in particular PCMS deployment is still un-completed). However, this has not prevented the carrying out of an energy analysis, necessary for subsequent work.

The first activity was to make an assessment of the Hospital energy facilities, which enabled the authors to make the aforementioned description. Actually, there was a previous assessment, but it was made in 2016 before many changes, so it had to be updated.

4.1 Load evaluation

After having examined the existing technologies and plant layouts, the study, as next step, focused on understanding the load needs. They were evaluated by means of two three-phases power quality analysers provided by the technical department:

- PQA 824.
- Fluke 434-II.

These devices are able to record much information about the grid they are connected to, such as voltage, current, power, harmonics distortion, frequency. Then, data collected can be transferred to a computer by means of USB cable and a specific software, respectively TopView2.2 and Power Log Classic 4.4. PQA 824 was used most of the times because it proved to be easier to handle than the Fluke.

With the assistance of Eng. Uma Santo Opoka, the electrical engineer working at Lacor Hospital, and his colleagues, the analyser was connected to the main busbar in the distribution room. To have a complete knowledge of the load, the inverters of the photovoltaic plants were disconnected in the last days of April, otherwise the measured load would have been only a partial one. This way, it was possible to record the load of both week and week-end days, except for the time in which power outages occurred during the night.

For this first data gathering, one-minute sampling was set. PQA 824 was connected to the busbar on April the 26th, at about 9 a.m., and the record was stopped on May the 2nd at 8:30 a.m. Record interruption is compulsory for data download.

Graphs in **Figure 21** and **Figure 22** show that the trend of the load during weekdays and weekend is quite similar. The existing variations can be linked to emergency surgery in operating theatres or in the ICU, or due to unfavourable weather conditions, leading to the lights turning on. The poor reliability of the grid can be noticed by looking at the points in which the power falls to zero. During the weekdays, the power is restored more or less immediately, except for the April the 26th, probably because the power outage occurred during lunch time. The weekend profile makes clearer the burden of the power shortages both for their occurrence and their lasting.

The load is quite constant during the night, around 90 kW, then it starts increasing at the first light, reaching peak loads of 180kW or more between 10 a.m. and lunch time. In the evening, there is another peak from about 5 p.m. (time at which the working day ends) to 9 p.m. The latter is more evident during the weekend, since the load is naturally lower than the weekdays. During working hours (from 8:30a.m. to 5:00p.m.) the load is around 120-180 kW, sometimes it even reaches 200 kW, but this rarely happens.

Data were recorded with a time step of 5 minutes, so the downward peaks are caused by the presence of a power outage.

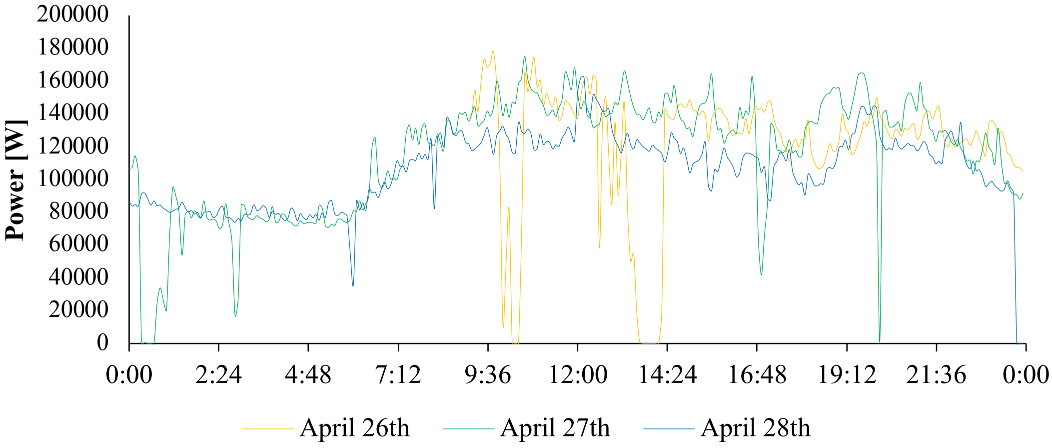


Figure 21 *Weekdays load on standard working conditions*

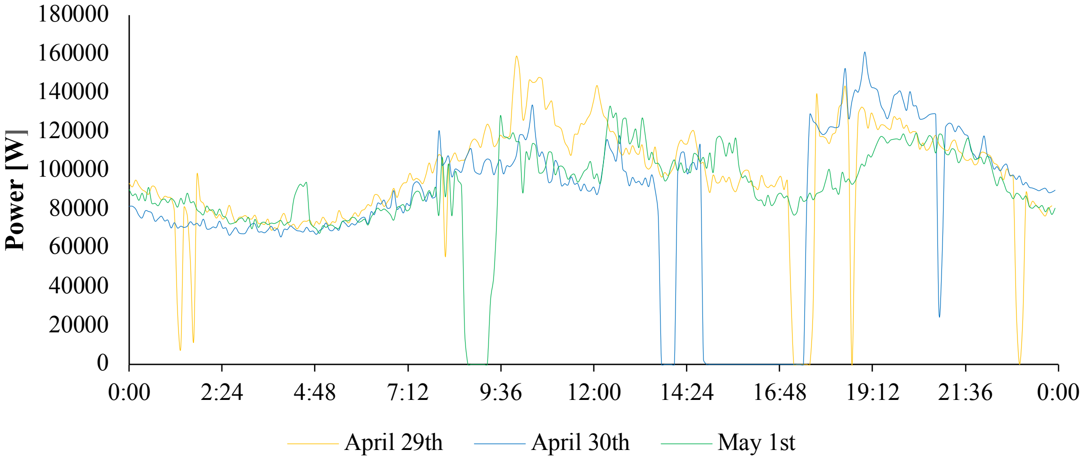


Figure 22 *Weekend days load on standard working conditions*

After this first data collection, the solar panels inverters were reconnected to the grid to understand to which extent they can feed the line. Data gathering from the solar inverters was possible by connecting a personal laptop by Bluetooth and downloading the information through the software Sunny Explorer. The inverters have also the possibility to save the record up to two months. When the authors arrived there, most of those devices had to be reset to the right time and date, that is, many practical problems had to be fixed in order to properly gather energy data.

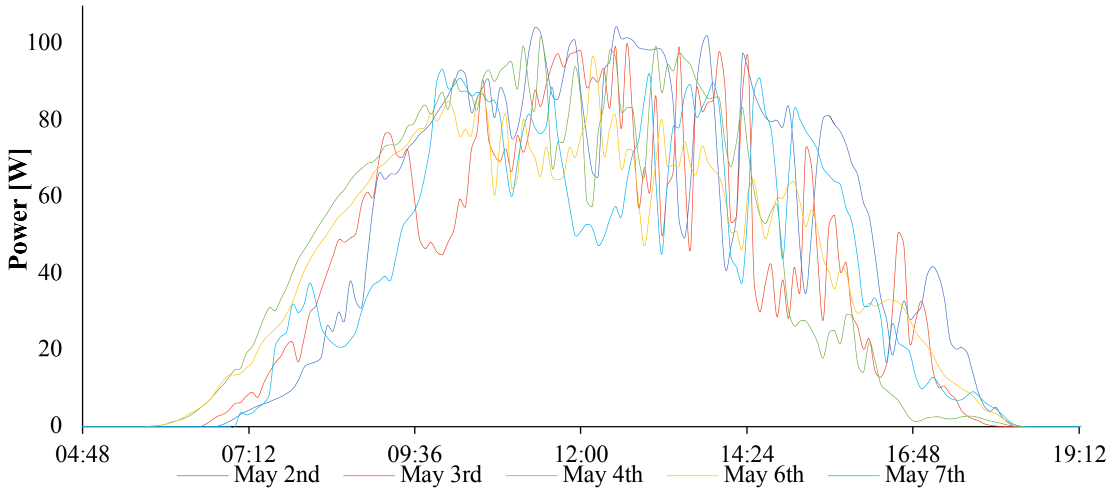


Figure 23 *Example of a typical photovoltaic plant power production*

Some samples of the downloaded data from the inverters are displayed in **Figure 23**. The total production of the photovoltaic plants exhibits the typical bell curve related to solar radiation. Data gathering occurred during rainy season, so it is normal to see sharp oscillations, especially at early afternoon, due to sudden storms or simply clouds. Over a total installed power of 140 kW, even at midday the maximum power reached is 105 kW, so at most the 75% of the potential is exploited. Among all the plants, the one installed on the OPD roof shows the best performances, being the newest.

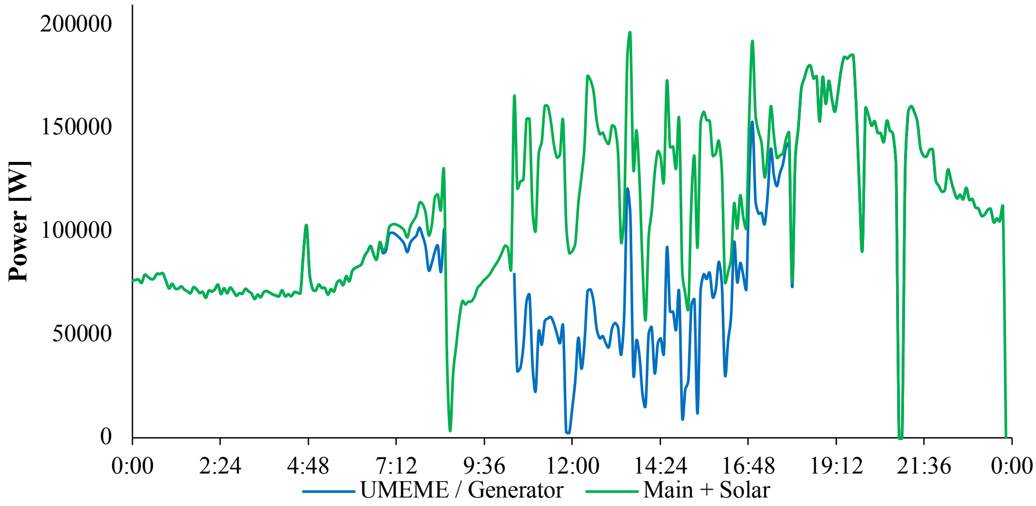


Figure 24 *Comparison between electricity production from the main sources and the sum of them and the photovoltaic plants, 2nd May*

To understand how much the photovoltaic panels and the main line (fed by either public grid or diesel generator) contribute to the total load, both of their production was measured. The obtained results are showed in the previous graph (**Figure 24**), referring to May the 2nd, where PV production is represented as the area between the two lines.

This record related to the main grid started on May 2nd at 10:37 a.m. and ended on May the 3rd at 9 a.m. It was performed with a sampling interval of one minute, so it was necessary to pass to 5 minutes to match it with the PV data.

It is noticeable a hole between 8:30 a.m. and 10:20 a.m. due to the record interruption of PQA 824 by the authors. Anyway, it is noticeable that the solar contribution is significant and sometimes is able to fulfil the supply almost by itself.

If the photovoltaic penetration is very high during a power outage, the generator could be obliged to work below its minimum with the negative consequences, as explained in Chapter 2.4.

In May 2017, the average energy from solar power plant was 645 kWh per day, over a total electricity consumption of about 2600 kWh per day, so about the 25% of the daily energy is produced by photovoltaic plants. Unfortunately, it was almost impossible to make an accurate calculation of the average energy produced because of too many power outages. Since the Hospital load exhibits a certain constancy it can be easily assumed that the average daily energy consumption is correct.

Subsequently, the emergency line was also analysed to understand the loads trends in time. For this purpose, the FLUKE 434 was connected to the input line of the UPS, while the PQA 824 was connected to the UPS output, to distinguish the power going only to the emergency line from the one that charges the batteries. Being two different instruments, the two analysers are not calibrated in the same way, so making the difference minute by minute between the data recorded by the two of them cannot be wise: they could not be perfectly synchronized while recording, hence the results can be shifted by few seconds. Moreover, it was not possible to set the sampling time of Fluke, since it records as much information as possible according to its memory. In this occasion, data sampling was of one minute for the Fluke, while PQA 824 was set on 30 seconds data sampling in advance.

For the previous reasons, the analysis is going to give qualitative results.

Both the graphs (**Figure 25** and **Figure 26**) refer to the entire recording period of a working day when national grid was available, that goes from 3:46 p.m. of May the 22nd to 8:50 of May the 23rd for PQA 824 and from 4 p.m. to 12 p.m. of the same days.

The PQA 824 measured that emergency line absorbs a power oscillating around 35 kW (**Figure 25**).

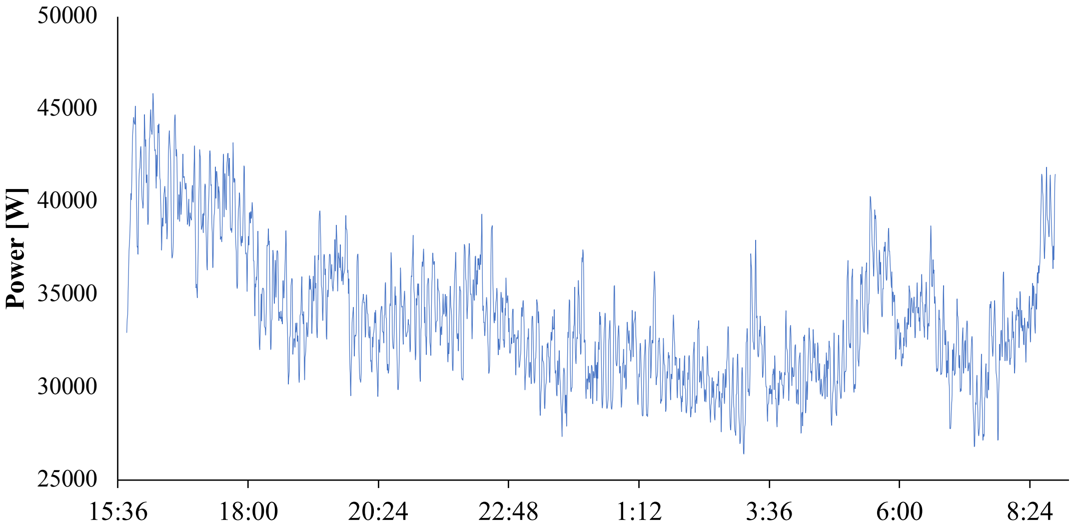


Figure 25 *Emergency Line load [W]*

During the same time interval, the UPS input was monitored as well, showing an almost horizontal pattern during working hours (43 kW) and then oscillating by night (**Figure 26**).

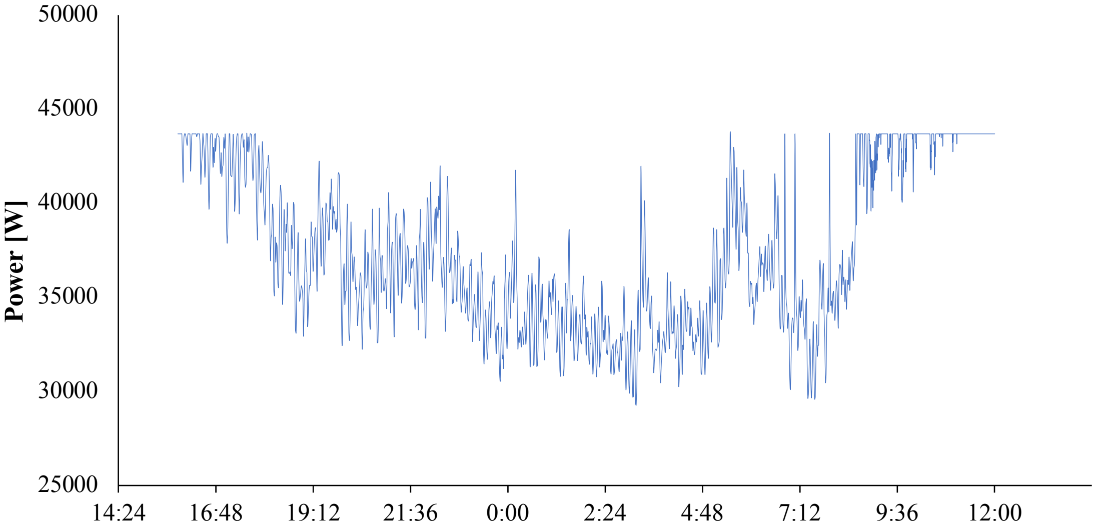


Figure 26 *UPS input*

As a function of all the analyses carried out, there is evidence on how the available devices on the field have affected the final evaluations. Due to their technical limitations as regards the maximum amount of information they can store and the different sampling times, the assessments had to be limited to short periods of time.

4.2 Battery pack analysis

Since the beginning of the mission, the UPS showed some issues: it suddenly turned down during a power outage, even if it displayed a higher state of charge (SOC) of the battery pack than the set acceptable minimum. Suspect of spoiled batteries came out, so a test was scheduled. There were many attempts to assess the batteries: at the beginning, it was tried to test them when discharging, but it took a lot of time and was too risky, so they were put in charge again and the remaining batteries were tested after having reached a good state of charge. This method didn't give good results; hence it was decided to completely bypass the UPS. For each battery, the voltage was recorded by a multi-tester, Fluke 115, to understand which of them presented a significantly lower value than the nominal one. After the first analysis, it was found out that too many batteries were spoiled, so it was decided to remove only the worst fifteen, according to the indications provided by Riello. Because of their removal, the UPS control parameters related to the total voltage were modified. Since the maximum default voltage for 240 batteries was 537 V, a new one of 504 V was set up. Accordingly, since the minimum default value was 444 V, so 1.85 V per battery, the new one was set to 416 V. The analysis allowed to find out that the best performing batteries are the ones put at the top or at the bottom of the shelving. This is a predictable result due to the higher convective heat exchange. With these adjustments, the battery pack is able to stand up to 45 minutes and the UPS displays the correct remaining time before the shutdown. This gives the operators the possibility to have half an hour to turn on the generator. Anyway, being such system so precarious, the Hospital is already thinking about a replacement.

4.3 Diesel generator assessment

To understand which diesel generator and when it has to be turned on, an analysis on diesel consumption has been carried out. Unfortunately, the only way to know the consumption of the fuel is to measure its level in the tank by means of a calibrated dipstick, taking the measurement at the beginning and at the end of generator running. Of course, the measurement is neither precise nor punctual. For what concerns the energy production in the meantime the PQA 824 was used, with a data sampling time step of 5 minutes, to be consistent with the inverters set up.

During the use of the white generator in the event of a power failure (9:31 a.m. – 14:31 p.m. on May the 11th), about 165 litres were consumed to produce of 328 kWh in five hours, hence with a specific average consumption of 0.50 l/kWh. Such a high consumption, with respect to the common 0.35-0.45 l/kWh, can be explained by the strong solar radiation which made the generator work at an average power of 65 kW. Running the generator at 16% of its rated power means that it worked for most of the time at significantly lower level than the recommended minimum one (**Figure 27**).

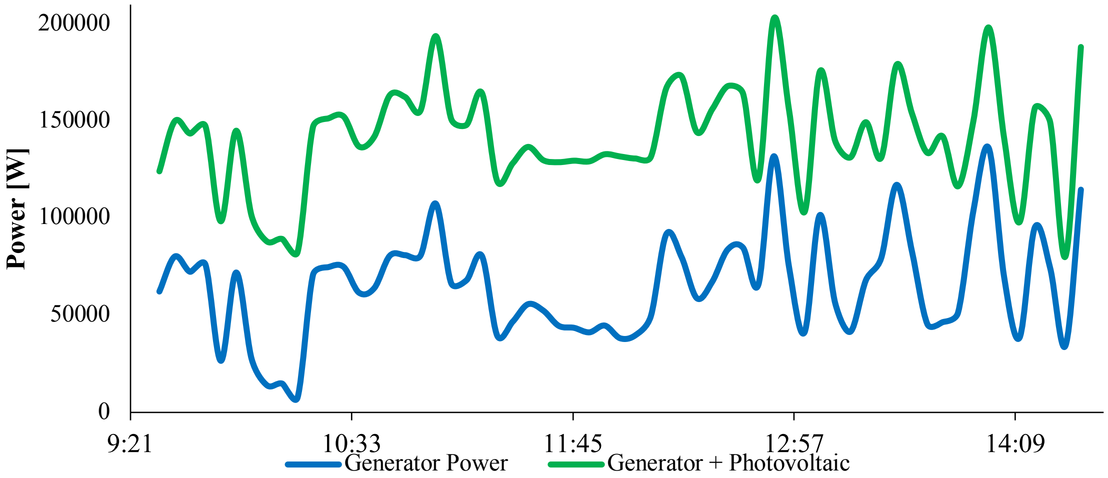


Figure 27 *Power produced by 500 kVA diesel generator vs the total power produced also by PV*

In the same way, the consumption of the yellow generator was evaluated (15:21 p.m.-17:47 p.m. on May the 11th). It displayed to work optimally: 45 litres were consumed to produce 190 kWh, so 0.273 l/kWh. Actually, such a low value suggests possible measuring errors due to the use of a dipstick instead than a flowmeter. Anyway, the yellow generator worked at an average power about the 26% of the rated one, respecting the minimum constraint (**Figure 28**).

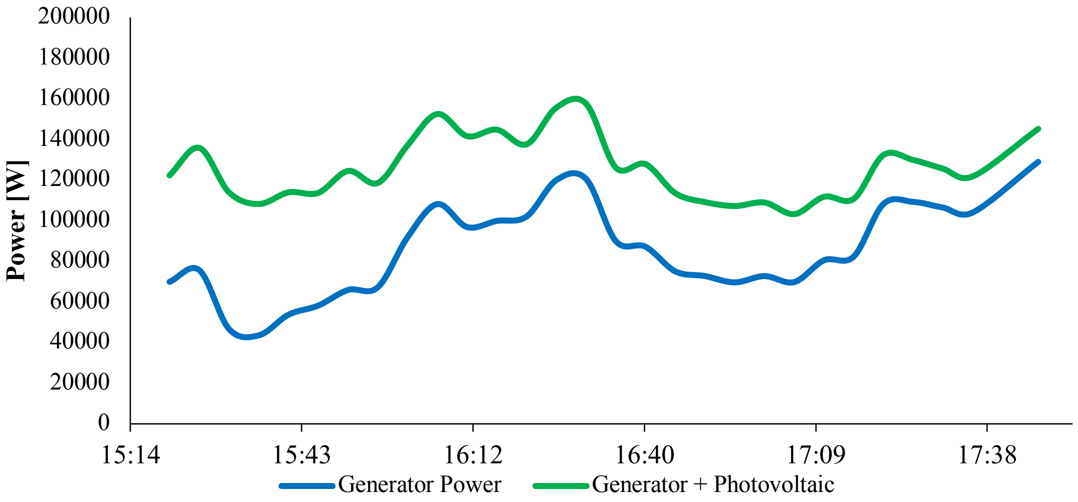


Figure 28 *Power produced by 350 kVA diesel generator vs the total power produced also by PV*

Solar Penetration and Harmonic distortion

From the various analysis of the load, notwithstanding the specific purpose, some problem arose. Solar penetration can be too high in some moments of the day and if it happens when the generator is on, it could be forced to work very far from its optimal range. This could cause abrupt variations in frequency, voltage and harmonics. The study on frequency and voltage quality showed no anomalies, highlighting slight oscillations of the latter in acceptable intervals, regardless of the generator used. On the other hand, the current harmonic distortion showed not admissible values during high solar penetration (**Figure 29**), especially for the third phase. On May 24th, during a power outage lasted from 8:30 a.m. to 14:13 p.m., the 500 kVA diesel generator was tested. In that occasion a 10 seconds data sampling was selected, to get a picture as accurate as possible.

According to Appendix B, the admitted values for the total distortion of the current are around 10%. Between 10 and 50% the distortion brings to overheating and so the cable must be oversized.

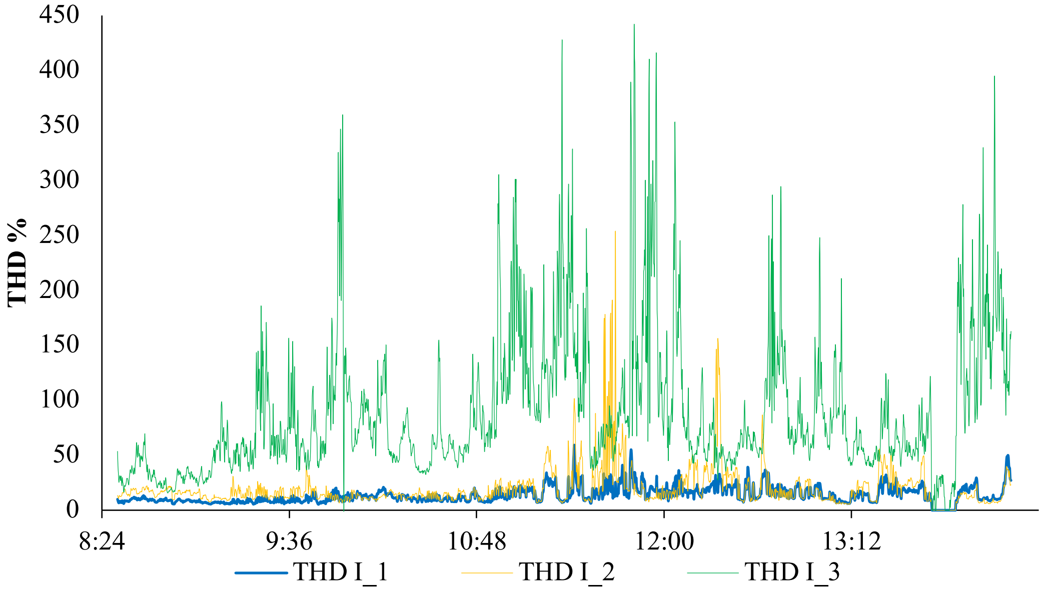


Figure 29 *Current harmonic distortion evaluated during generator operation, 24th May, 500 kVA generator*

In the investigated case, the total harmonic distortion of the third phase overcame 400%, a very harmful and dangerous value for the power quality of the grid. These results show up only when a high solar penetration occurs leading the generator to work at low power output, as in the case under analysis. In fact, the power fraction provided by photovoltaic systems is always higher than 30% and reaches even 90% (**Figure 30**), causing many instabilities in the diesel generator. In situations other than this one (generator working and low or null solar radiation), the power quality is quite stable.

To build **Figure 30**, solar data were reported from 5 minutes sampling to one, by repeating them, while THD data were integrated to one-minute sampling.

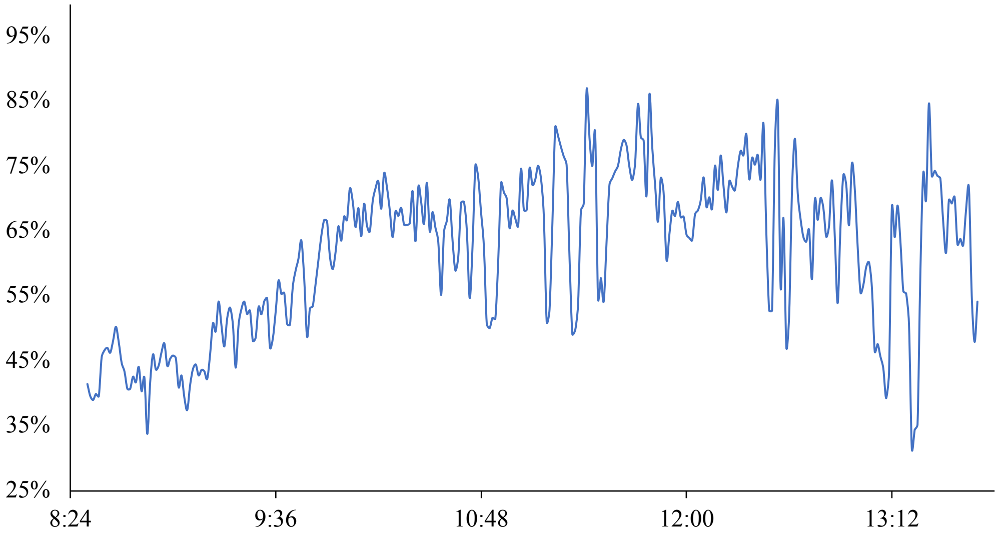


Figure 30 *Fraction of load supplied by photovoltaic plants [%], 24th May, 500 kVA generator*

To understand to which extent the generator could work at low capacity without overcoming the acceptable values for THD$_I$, the authors conducted another test on the generator on May 29th whose results are reported in **Figure 31**. Also in this case, 10 seconds data sampling was used, to record from 12:40 p.m. to 3p.m.

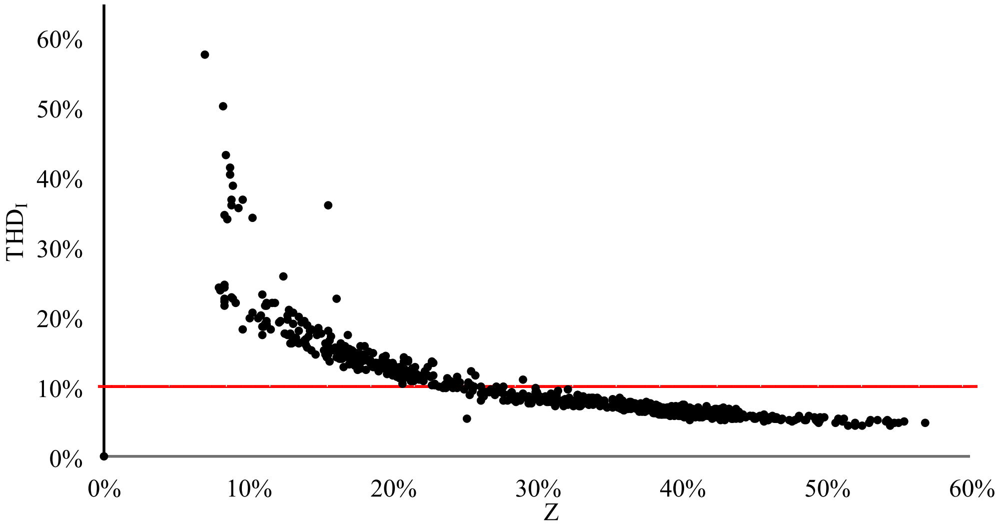


Figure 31 *Relationship between THD$_I$ and the generator power output*

In the abscissa, the ratio between the output power and the rated power of the gen-set is reported:

$$Z = \frac{\text{Output Power}}{\text{Rated Power}}\ [\%] \tag{4.1}$$

The trend of THD_I is strongly inversely proportional to Z; in particular, to not create an inadmissible THD_I, according to acceptable ranges defined in Appendix B, it should be higher than 25%. This parameter will be used to define the minimum admissible operating range of the generator in the logic discussed below.

4.4 Concluding remarks

During the two-month internship at Lacor Hospital, the authors had to face several practical problems that influenced the data collection campaign.

First of all, it was necessary to have a clear understanding of all the installed technologies within the structure, updating all the electrical schemes concerning the distribution room, the main line and the emergency line. Only after these arrangements, which took several weeks, it was possible to start the various tests regarding the measurement of the load demand during working days and weekends, the evaluation of the power quality of the distribution network, the assessment of the batteries' status and the estimated consumption of the two generators.

In addition, because of the instrumentation provided, only a limited and detailed set of data was collected. Poor equipment memory, depending on the selected sampling interval, influenced the amount of information that could be acquired in the two months of stay, allowing the record of just 26 days out of 60.

These issues, including the need to devote time to learning the reality under examination, are, however, typical of rural contexts and developing countries and lead to postponement of the primary activities of the mission.

The thesis work aimed at a procedure able to proceed to the sizing of the micro-grid with respect to a partial availability of data. In similar contexts it appears in many cases almost impossible to have complete load demand data but, nevertheless, this has not prevented the model from being implemented.

The data collected, often incomplete due to power failures, were statistically revised and used to generate a true and acceptable annual load profile of the Hospital, so that the micro-grid dimensioning procedure could subsequently take place.

Chapter 5

Micro-grid modelling

Starting from the concept of micro-grid, the following architecture scheme has been adopted to formulate the control logic of the model (**Figure 32**).

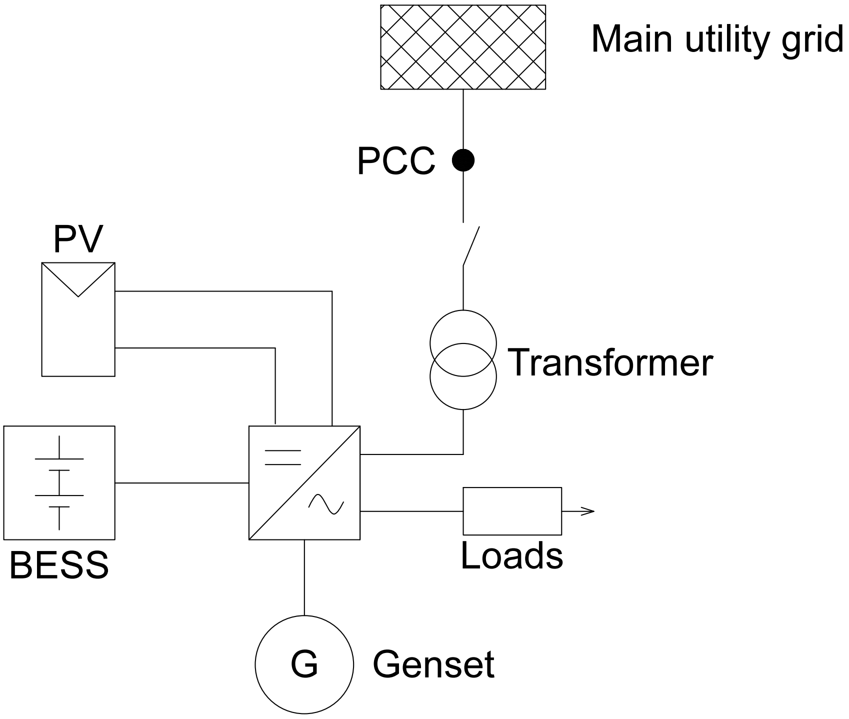


Figure 32 *Architecture of the micro-grid system implemented in Poli.NRG, authors' elaboration*

As alternative to PV and BESS, only diesel generator technology has been taken into account, in case of absence of national grid. This choice is related to the reliability that such a system has earned over the years in developing countries.

All the energy sources have been modelled as D.C. generators connected to a unique inverter, which is characterized by a conversion efficiency.

In this chapter, the specifics of the mentioned technologies will be examined and introduced in the proposed dispatching strategy for a micro-grid.

5.1 Technologies

For each selected technology, the main techno-economic parameters are discussed. All of them will be used to compute the energy balances and to evaluate the economic impact.

5.1.1 National grid

Considered as an infinite power busbar, it compensates the energy demand not satisfied by the photovoltaic panels. It also carries out the task of recharging the batteries after a power outage, in the event that the photovoltaic panels fail to provide the required energy. The hypothesis to sell back solar electricity excess to the national grid is neglected.

The yearly cost is calculated as follows:

$$YC_{NG}(y) = \frac{c_{ele} * E_{NG}(y)}{(1+r)^{y}} \tag{5.1}$$

- c_{ele}: specific cost of electricity from the main grid €/kWh.
- r: rate of interest.
- $E_{NG}(y)$: energy satisfied by the main grid during a year y.
- y: keeps track of the year and is limited by the plant lifetime.

5.1.2 Photovoltaic panels

The PV energy output for every k minute time step is formulated as follow:

$$E_{PV}(k) = \frac{PV_{size} * \eta_{BOS} * \left(1 - \eta_{derating}(y-1)\right) * H_{\beta}(k)}{h} \tag{5.2}$$

- PV_{size}: rated power of the panels at an irradiance h of 1 kW/m^2, an ambient temperature of 25°C and an air mass coefficient of 1.5.
- $H_{\beta}(k)$: per minute specific solar irradiation on the tilt panel surface.
- η_{BOS}: expresses in percentage the energy losses that occur in the system due to various factors, such as the coupling between the various PV modules, the connections with the converter, losses in switchboards, conductors, wirings etc.
- $\eta_{derating}$: decay rate of panel performances over the years.

From the economic point of view, photovoltaic panels are characterized by an initial investment cost IC_{PV} and by annual operative and maintenance fixed costs ($YC\_O\&M_{PV}$).

$$IC_{PV} = PV_{size} * PV_{cost} \tag{5.3}$$

$$YC\_O\&M_{PV}(y) = \frac{PV_{size} * O\&M_{PV}}{(1+r)^y} \tag{5.4}$$

- PV_{cost}: specific cost associated to the size of the photovoltaic panels $\left[\frac{€}{kW}\right]$.
- $O\&M_{PV}$: operative and maintenance fixed cost $\left[\frac{€}{kW\_peak}\right]$.

5.1.3 Battery Energy Storage System

The operating mechanism that regulates the functioning of the lead acid batteries, considered to be the best technology for the emerging countries scenarios, is modelled according to simplified hypothesis using some characteristic parameters:

- State of charge (*SOC*): used to describe battery remaining capacity.
- SOC_{min}: maximum battery state of discharge, below which the storage bank is never used. It is defined as a percentage of battery capacity and it is usually limited to 30%-50% in order to avoid damages due to excessive discharge.
- $SOC_{initial}$: SOC at time of purchase of the batteries;
- y_{BESS}: maximum years before replacement.
- k_{BESS}: power to energy ratio for which maximum power output is limited as regard the rated capacity:

$$k_{BESS} = \frac{P_{BESS}}{BESS_{size}} \tag{5.5}$$

- η_{charge} and $\eta_{discharge}$: charge and discharge efficiencies refer to how much energy is put into or drained from a cell compared to the amount of energy that is dissipated inside the cell itself due to impedance related dissipations. In this specific case they are considered constant, in spite of the fact that they are a function of the current.

The lifecycle of the batteries is calculated through a "*rainflow function*" capable of tracking the number of cycles Z_i occurred during the year and the corresponding Depth of Discharge (DoD). Knowing the DoD of the batteries, the number of Cycles to Failures (CF) is computed according to **Figure 33**. The knowledge of the CF allows to check hour per hour (h) if batteries are going to fail and need to be replaced. According to that logic, the initial investment cost IC_{BESS} and the yearly cost of the batteries (YC_{BESS}) are:

$$IC_{BESS} = BESS_{cost} * BESS_{size} \tag{5.6}$$

$$YC_{BESS}(y) = \sum_{m} \frac{BESS_{cost} * BESS_{size}}{(1+r)^{\frac{h}{y*8760}}} \tag{5.7}$$

- m: number of battery replacements occurred during a year.
- h: hour of the year at which replacement takes place.
- $BESS_{size}$: size of the batteries.
- $BESS_{cost}$: battery cost $[\frac{€}{\mathrm{kWh}}]$.

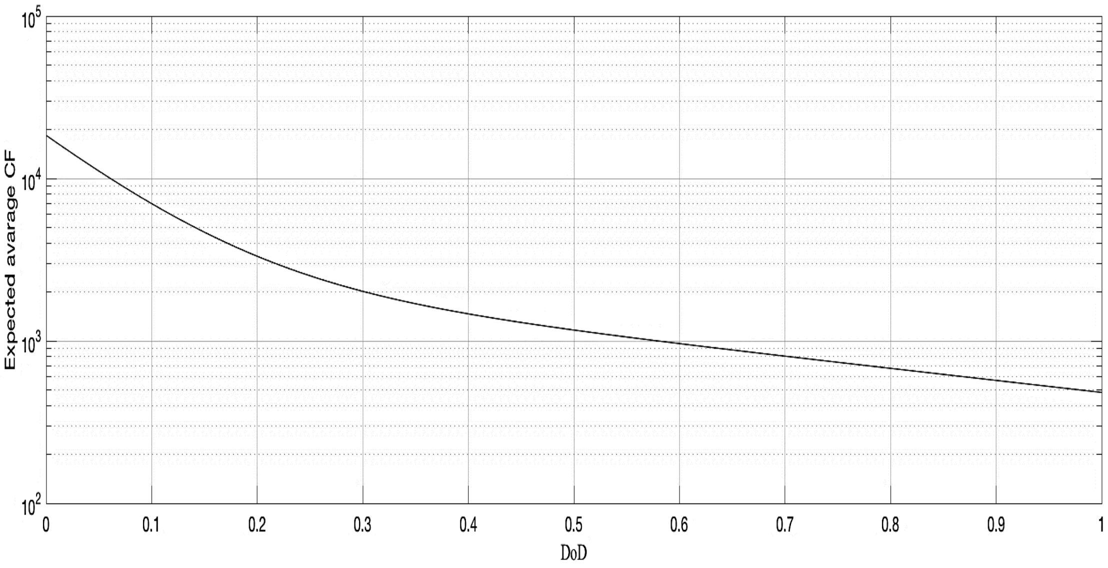


Figure 33 *DoD and CF plot for lead acid batteries*

The maximum energy input/output linked to the batteries is equal to the maximum deliverable power, function of their capacity, multiplied by the correction factor k_{BESS}:

$$Energy\ max = \frac{k_{BESS} * Power\_\mathrm{max}}{60} \tag{5.8}$$

5.1.4 Inverter

The inverter size is function of the maximum power peak of the load during the whole plant lifetime, and it is characterized by its own efficiency η_{INV}:

$$\eta_{INV} = \frac{P_{AC}}{P_{DC}} \tag{5.9}$$

where P_{AC} is the power output and P_{DC} is the power input.

For simplicity η_{INV} is considered constant, neglecting the correlation between η_{INV} and the power output. From the economical point of view the investment cost (IC_{inv}) is calculated as follow:

$$IC_{INV} = \frac{INV_{cost} * P_{max}}{\eta_{inv}} \tag{5.10}$$

5.1.5 Diesel generator

Also known as Gen-set, it consists of a combination of a diesel engine and an electric generator.

Diesel generator is scheduled to work only when a power outage occurs and energy production from batteries and solar panel is not enough to satisfy the load. It is supposed to have instantaneous engine start up.

The parameters introduced to describe the diesel generator are:

- c_{gen}: specific cost of electricity associated to the diesel generator €/kWh. In real applications this cost is linked to the fuel curve, expressed in l/h. For sake of simplicity and partial lack of information, it is taken as constant.
- P_{gen}: rated power [kW].
- LT_{gen}: lifetime of the generator.
- t_{min_gen}: minimum time of functioning for which damages to diesel generator linked to its continuous starts and stops are neglected.
- η_{up}: efficiency which considers that a small part of the rate power it is auto-consumed by the generator for internal regulator components functioning:

$$P_{gen\_max} = P_{gen} * \eta_{up} \tag{5.11}$$

- η_{down}: efficiency which evaluates minimum power output of the generator:

$$P_{gen\_min} = P_{gen} * \eta_{down} \tag{5.12}$$

Yearly cost associated to the diesel generator is formulated as follow:

$$YC_{gen}(y) = \frac{c_{gen} * E_{gen}(y)}{(1+r)^y} \tag{5.13}$$

For the evaluation of the specific investment and O&M costs, reference was made to report [44], where several generator sizes had been tested for the formulation of the investment and O&M cost equation curves:

$$IC_{gen} = 766.09 * P_{gen}^{0.876} \text{ [44]} \tag{5.14}$$

$$O\&M_{gen} = 0.0653 * P_{gen} + 0.399 \text{ [44]} \tag{5.15}$$

$$YC_{O\&M\ gen} = h_{y,gen} * O\&M_{gen} \tag{5.16}$$

- $h_{y,gen}$: operating yearly (y) hours of the Gen-set.

- $O\&M_{gen}$: specific cost per yearly hour of Gen-set operation $\left[\frac{€}{h}\right]$.

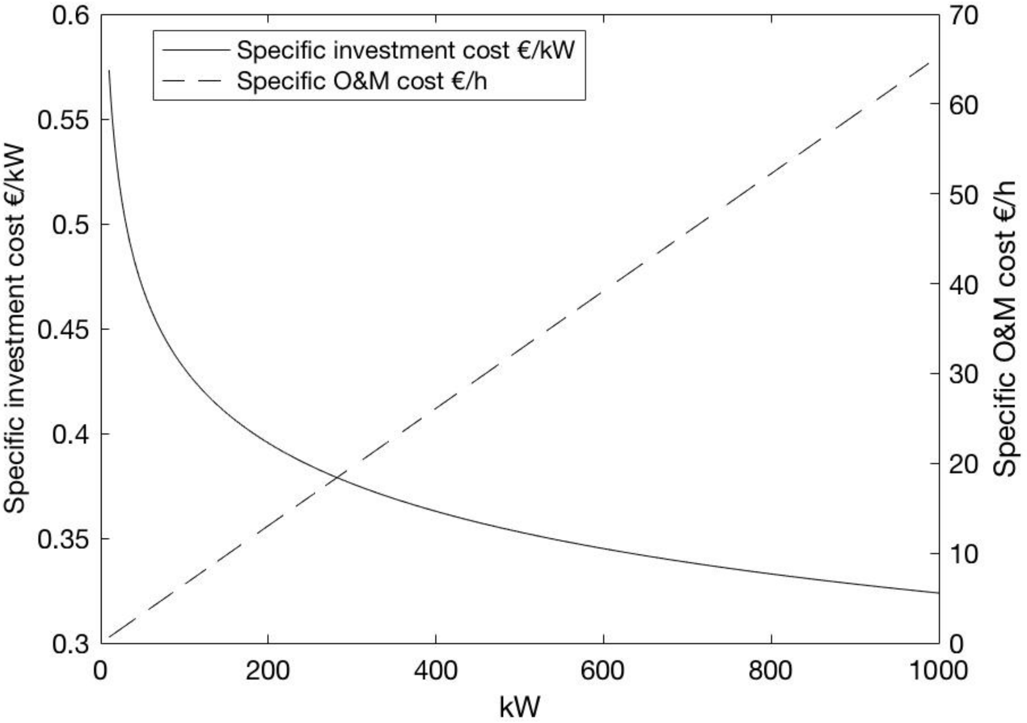


Figure 34 *Specific investment cost and O&M cost curves*

The curves in **Figure 34** were built according to equations 5.14 and 5.15. They show a linear behaviour of the specific operative and maintenance costs with respect to the generator size, while an inversely proportional relationship between specific investment costs and sizes.

5.2 Dispatching strategy

The implemented logic checks the status of the national grid minute by minute, so that the tool is routed into the right solution algorithm. In the event of a breakdown of the service provided by the main network, the system highlights the starting time of the event and simulates the power outage, assessing whether it is necessary to use the diesel generator or not. For the assessment of the implemented logic, the following **Table 7** will be used as benchmark for the energy balances.

Nomenclature

E_{bal}	Energy that is satisfied by the batteries	*Energy max*	Maximum input/output energy of the batteries
$E_{bal,teo}$	Energy that should be satisfied by the batteries	E_{NG}	Energy provided by the national grid
E_{gen}	Energy that is satisfied by diesel generator	E_{PV}	Energy supplied by the photovoltaic panels
$E_{gen,max}$	Maximum energy that generator can provide	E_{UNMET}	Energy that batteries are not able to provide due to their capacity
$E_{gen,min}$	Minimum energy that generator can provide	SOC_{max}	Maximum value at which batteries can be considered fully charged
E_{load}	Energy demand	SOC_{min}	Maximum state of dicharge
E_{loss}	Energy not satisfied	t_{gen}	Duration of generator functioning
		$t_{gen,\ min}$	Minimum duration of generator functioning

***Table** 7 List of variables introduced in the model*

For what concerns the logic, reference will be made to the flow chart inserted at the end of the paragraph (**Figure 35**). In addition, the energy flux related to BESS can be either positive or negative: positive if charging, negative if discharging. For the other technologies, since the energy is only an output, it is positive. The possible cases that may arise are now analysed, reporting the equations that the model elaborates with a time step of one minute (k).

5.2.1 CASE 1: National grid is available

When continuity of service provided by the main utility grid is ensured, the latter has the task of meeting the energy demand less than the energy produced by photovoltaic panels. In addition, if the batteries after a power outage have a *SOC(k)* below a certain predefined level SOC_{max}, in the event that the PV fails to meet simultaneously the total load required from the final user and the battery charging, the national electricity grid intervenes to compensate for the missing energy. After they have reached the upper limit, they are not used until the next power outage occurs.

Four different subcases have been developed:

1.a Batteries are not completely charged ($SOC(k)<SOC_{max}$) and photovoltaic production is able to both charge the batteries (at their maximum input) and to satisfy load demand:

$$E_{bal}(k) = Energy\ max \tag{5.17}$$

$$E_{NG}(k) = 0 \tag{5.18}$$

1.b Batteries are not completely charged ($SOC(k)<SOC_{max}$) and energy produced by photovoltaic panels is not enough to either charge the batteries or satisfy the load demand. In this case national grid will charge the batteries and, if necessary, satisfy the unmet load:

$$E_{NG}(k) = \frac{E_{load}(k)}{INV.eff} - E_{PV}(k) + Energy\,max \tag{5.19}$$

$$E_{bal}(k) = Energy\,max \tag{5.20}$$

1.c Batteries have reached an acceptable state of charge *($SOC(k) \geq SOC_{max}$)* and energy produced by photovoltaic panels is not enough to satisfy the load demand. Batteries will not be recharged and the load not fulfilled by PV panels is supplied by the national grid:

$$E_{NG}(k) = \frac{E_{load}(k)}{INV.eff} - E_{PV}(k) \tag{5.21}$$

1.d Batteries have reached an acceptable state of charge *($SOC(k) \geq SOC_{max}$)* and energy produced by photovoltaic panels is enough to satisfy the load demand. No energy is required from the national grid:

$$E_{NG}(k) = 0 \tag{5.22}$$

Excess solar energy is considered to be dissipated.

5.2.2 CASE 2: Power outage

In case of supply interruptions from the national grid a blackout occurs, so only an immediate action can safeguard the continuity of the services provided.

Such a situation implies the introduction of a new technology, which in the model proposed is the diesel generator: it is necessary to provide the unmet demand whenever the batteries and/or solar panels are not sufficient.

For this purpose, a logic has been implemented to ensure that the load demand is always satisfied and to assess whether certain plant configurations lead to losses that cannot be avoided in any way (technical limits or unsuitable technology mix).

The first step is to evaluate the energy that should be satisfied by the BESS in case solar production is not able to meet the demand ($E_{bal,teo}(k)$). If photovoltaic generation is even higher than the request it charges the batteries, complying with their capacity constraint.

$$E_{bal}(k) = E_{PV}(k) - \frac{E_{load}(k)}{INV_{eff}} \tag{5.23}$$

$$E_{bal}(k)(E_{bal}(k) > Energy_{max}) = Energy_{max} \tag{5.24}$$

$$E_{bal,teo}(k) = E_{bal}(k) \tag{5.25}$$

Then the real energy that BESS is capable to provide is assessed:

$$E_{bal}(k)(E_{bal}(k) < -Energy_{max}) = -Energy_{max} \tag{5.26}$$

Comparing $E_{bal,teo}(k)$ to $E_{bal}(k)$, the eventual unmet load is calculated ($E_{UNMET}(k)$):

$$E_{UNMET}(k) = E_{bal,teo}(k) - E_{bal}(k) \tag{5.27}$$

Afterwards, two main situations can arise:

- ***2.a*** Batteries are not charging and can be used in case of necessity;
- ***2.b*** Batteries are charging and cannot be used until they have reached their SOC_{max}.

In the following, a deep explanation of both is reported:

2.a

When batteries are not charging, namely they are available, and $E_{UNMET}(k)$ is positive, the generator has to provide this energy. In case of null $E_{UNMET}(k)$ and gen-set previously turned on, it continues to be operative only if its minimum working time ($t_{gen,min}$) has not been reached yet. At this point three checks are examined to guarantee the correct functioning of the generator, by meeting the constrains on maximum and minimum power capacity ($E_{gen,min}$, $E_{gen,max}$):

$$Check1_1(k) = E_{gen}(k) - E_{gen,min} \tag{5.28}$$

$$Check1_2(k) = E_{bal}(k) - Check1_1 \tag{5.29}$$

$$Check1_3(k) = E_{gen}(k) - E_{gen,max} \tag{5.30}$$

Every time the generator is required to work within its admissible functioning range ($E_{gen,min} \leq E_{gen}(k) \leq E_{gen,max}$), no further control logics are introduced. On the contrary, two possible situations can occur:

2.a.1 *The energy supplied by the generator should be lower than its acceptable minimum* ($E_{gen}(k) < E_{gen,min}$)*, so:*

$$Check1_1(k) < 0 \tag{5.31}$$

The $SOC(k)$ has to be compared to its maximum (SOC_{max}). If $SOC(k)<SOC_{max}$, the energy provided by the batteries is reduced, in certain circumstances even making them recharge, to enable the generator to reach at least its minimum.

$$Check1_2(k) \leq Energy\,max \tag{5.32}$$

$$E_{bal}(k) = Check1_2(k) \tag{5.33}$$

$$E_{gen}(k) = E_{gen,min} \tag{5.34}$$

It can happen that, by forcing the gen-set to work at its minimum, the batteries would receive a higher energy input than the acceptable one (*Energy max*). In this instance, the generator is not turned on or is forced to stop to protect both itself and the batteries, inducing a loss of load only related to the unmet demand by the gen-set:

$$E_{gen}(k) = 0 \tag{5.35}$$

$$E_{loss}(k) = E_{UNMET}(k) \tag{5.36}$$

An analogous procedure is used in the event that $SOC(k) \geq SOC_{max}$. The only difference consists of preventing them to recharge, because they have already reached their maximum state of charge:

$$Check1_2(k) \leq 0 \tag{5.37}$$

$$E_{bal}(k) = Check1_2(k) \tag{5.38}$$

$$E_{gen}(k) = E_{gen,min}(k) \tag{5.39}$$

As stated above, if this constrain is not satisfied, the diesel generator is forced to stop, inducing a loss of load only related to the unmet demand by the gen-set.

$$E_{gen}(k) = 0 \tag{5.40}$$

$$E_{loss}(k) = E_{UNMET}(k) \tag{5.41}$$

***2.a.2** The energy supplied by the generator should be higher than its acceptable maximum*

$$Check1_3(k) > 0 \tag{5.42}$$

Whenever this situation shows up, the generator is limited to its maximum rated power ($E_{gen,max}$) and consequently part of the load is not satisfied:

$$E_{gen}(k) = E_{gen,max} \tag{5.43}$$

$$E_{loss}(k) = Check1_3 \tag{5.44}$$

2.b

Every time BESS falls below the lowest admissible state of charge (SOC_{min}) after a discharge cycle, it must be recharged until SOC_{max} is achieved again. This procedure has been employed to make them available again in the event of a prolonged power outage, to ensure their availability for the next power outage and to avoid unstable behaviour in the surroundings of SOC_{min}. The instability could be caused by using immediately the BESS when exceeds SOC_{min} instead of waiting their fully recharge.

Under this condition, the positive or negative unbalance between photovoltaic production and load is evaluated:

$$Check2_1(k) = \frac{E_{load}(k)}{INV_{eff}} - E_{PV}(k) \tag{5.45}$$

If the energy produced by PV is equal or higher than the demand, the eventual surplus is used to charge the BESS and the generator is not turned on, unless previously it was on: if the latter condition is true ($0 < t_{gen} < t_{gen,min}$) it is forced to run at its minimum rated power with the consequent shutdown of some photovoltaic panels

$$Check2_1(k) < 0 \tag{5.46}$$

$$E_{bal}(k) = -Check2_1(k) \tag{5.47}$$

In the event of positive unbalance, the generator has to compensate it:

$$E_{gen}(k) = Check2_1(k) \tag{5.48}$$

Since battery charging has not yet been considered, three checks on the hypothetical operating outputs of the generator are carried out, to understand whether it would be able to charge them or only supply the load.

$$Check2_2(k) = E_{gen}(k) + Energy_{max} \tag{5.49}$$

$$Check2_3(k) = E_{gen}(k) - E_{gen\ ,max} \tag{5.50}$$

2.b.1 *The generator is capable to satisfy the demand and charge the BESS at their Energy$_{max}$.*

$$E_{gen,min} \leq Check2_2(k) \leq E_{gen,max} \tag{5.51}$$

$$E_{gen}(k) = Check2_2(k) \tag{5.52}$$

$$E_{bal}(k) = Energy_{max} \tag{5.53}$$

2.b.2 *Even though the gen-set is forced to charge the BESS at Energy$_{max}$, it is not capable to go beyond E$_{gen,min}$.*

$$Check2_2(k) \leq E_{gen,min} \tag{5.54}$$

In this case the generator requires to be turned off, inducing a loss of load:

$$E_{gen}(k) = 0 \tag{5.55}$$

$$E_{bal}(k) = 0 \tag{5.56}$$

$$E_{loss}(k) = Check2_1(k) \tag{5.57}$$

2.b.3 *The generator is supposed to overcome its maximum, either if it recharges the BESS at Energy$_{max}$ as well, or not.*

If the gen-set is supposed to work over $E_{gen\ max}$ without taking into account the recharge of the batteries, the exceeding energy will be lost:

$$Check2_3(k) > 0 \tag{5.58}$$

$$E_{gen}(k) = E_{gen,max} \tag{5.59}$$

$$E_{bal}(k) = 0 \tag{5.60}$$

$$E_{loss}(k) = Check2_3(k) \tag{5.61}$$

It could happen that the generator can provide some energy to charge the BESS, but not at Energy$_{max}$ in order to comply with the constrain on the maximum rated power:

$$E_{gen}(k) < E_{gen,max} \cup Check2_2(k) > E_{gen,max} \tag{5.62}$$

$$E_{gen}(k) = E_{gen,max} \tag{5.63}$$

$$E_{bal}(k) = Check2_3(k) \tag{5.64}$$

This procedure, as said before, is carried out every minute for the entire lifetime and provides the energy dispatching from every technological combination. In this way, it is possible to know the per minute contribution of every technology to the energy supply and to have a good understanding of battery charge/discharge cycles, resulting in more accurate evaluation of the cycles to failure.

The implemented dispatching strategy is not aimed to find the optimum of an objective function, but it turns out to be an advanced decision tree, compatible to currently available Programmable Logic Controls for micro-grids. Its approach is mainly based on conditions and thresholds that have to be respected minute by minute.

The final purpose of the proposed control logic is to provide a methodology for the monitoring and management of the different technologies of the micro-grid, regardless the search of the optimum. Hence, it becomes a means of implementing the dispatching strategy in widespread applications.

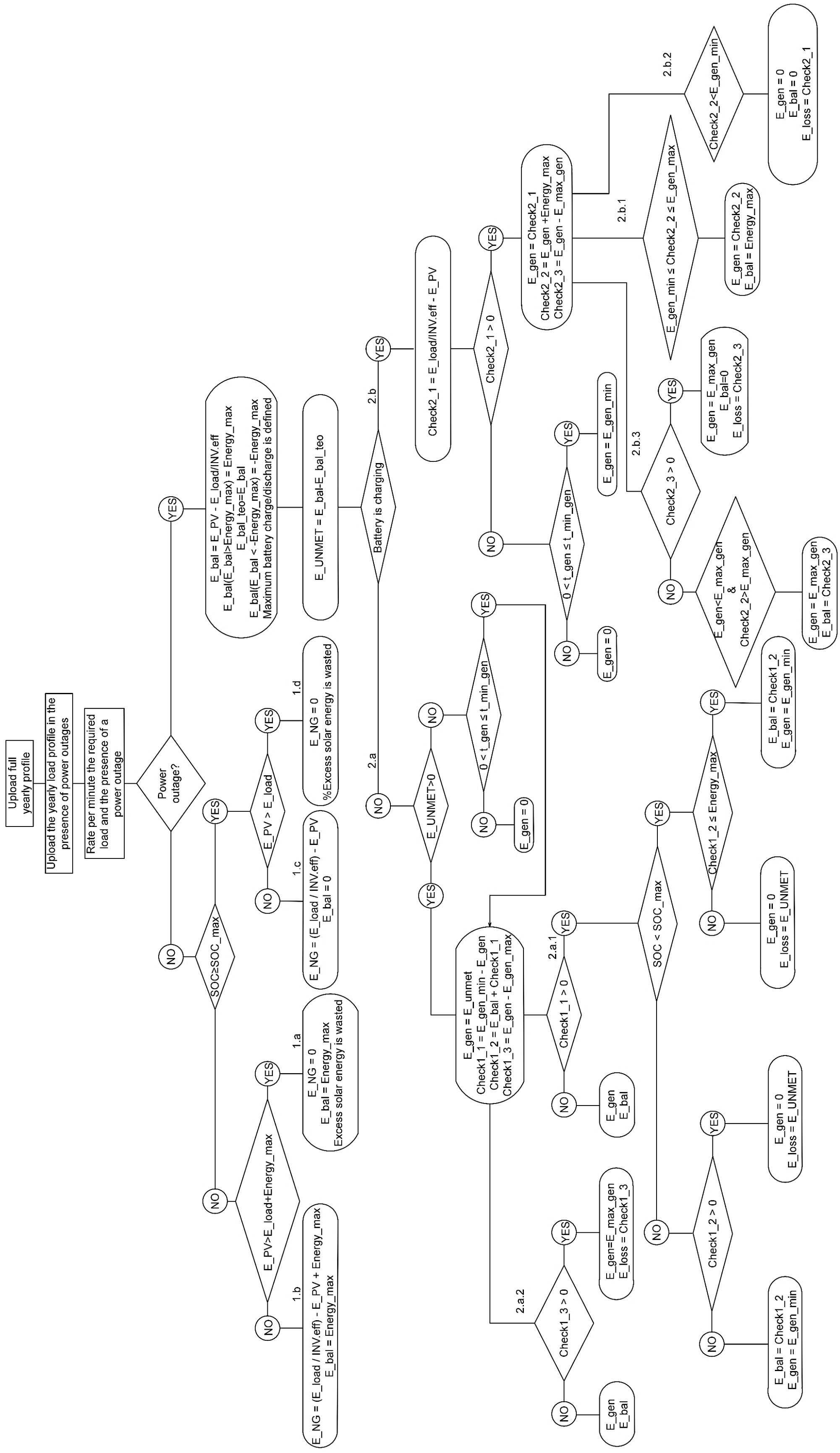


Figure 35 *Flow chart of the control logic implemented in Poli.NRG*

5.3 Techno-economic optimization

During the lifetime simulation of the plant, several combinations of BESS and PV are tested, showing how the ignition of the diesel generator occurs only for specific plant configurations.

For each combination, every time $E_{gen}(k)$ is positive, the tool records this event and evaluates the cumulative operating time ($Operatinghours$) at the end of the year and for the entire lifetime.

According to the per minute energy contribution from each technology, following the dispatching strategy explained above, it is possible to evaluate the eventual loss of load (LL) for the entire lifetime (LT):

$$LL_{LT} = \sum_{k=1}^{LT} E_{loss}(k) \tag{5.65}$$

Reminding that the batteries have both charging and discharging efficiencies, the effective input/output energy is calculated:

$$E_{batt}(k) = E_{bal}(k) * \eta_{charge} \tag{5.66}$$

$$E_{batt}\,(k) = \frac{E_{bal}(k)}{\eta_{discharge}} \tag{5.67}$$

After this step, *SOC(k)* can be updated:

$$SOC\,(k) = SOC(k-1) + \frac{E_{batt}(k)}{BESS_{size}} \tag{5.68}$$

Every hour batteries cycles are evaluated, to estimate their remaining lifetime and the eventual necessity of BESS substitution. In this preliminary phase, the yearly costs related to the possible BESS replacement, lifetime expenditures linked to the main grid and Gen-set usage are computed. This information is then integrated with the assessment of all operating and maintenance costs for the final calculation of the Net Present Cost (*NPC*) for the whole lifetime of the plant LT. The NPC is defined as the sum of the present value of all the costs over the period of interest:

$$NPC = IC_{LT} + YC_{LT} \tag{5.69}$$

$$IC_{LT} = IC_{PV} + IC_{gen} + IC_{BESS} + IC_{INV} \tag{5.70}$$

$$YC_{LT} = \sum_{y=1}^{LT} YC_{NG}(y) + YC_{gen}(y) + YC_{BESS}(y) + YC_{PV,O\&M}(y) \tag{5.71}$$

A further indicator to evaluate the final specific expenditure that consumer would face for load supply is introduced under the name of Levelized Cost of Energy ($LCoE$). It is calculated through a "discounting" method, for which satisfied energy during the LT is discounted back to a present value:

$$LCoE = \frac{NPC}{\sum_{y=1}^{LT} \frac{E(y) - LL(y)}{(1+r)^y}} \tag{5.72}$$

This indicator takes into account only the energy really satisfied, removing the possible energy losses. At this point, Loss of Load Probability (LLP), defined as amount of energy demand not satisfied during the LT over the total energy demand during power outages ($E_{power\ outages}$), is assessed as following:

$$LLP = \sum_{y=1}^{LT} \frac{LossOfLoad(y)}{E_{power\ outage}(y)} \tag{5.73}$$

The definition of LLP is crucial for the operation of the model, as the user will be asked to define an acceptable value according to his needs. Under this rule certain solutions will be excluded.

Chapter 6

Set up of the model

Load data collected during the internship proved to be incomplete, due to many issues with their recording. This kind of obstacles are quite common when working in the developing countries, due to the lack of proper measurement instruments and to the necessity of preparatory work, which required several weeks.

Despite of these, an intensive statistic elaboration of gathered data allowed to obtain complete and realistic load profiles. Such a procedure is typical when dealing with rural electrification projects, whose development is delayed by the continues troubles that show up on the field.

In this chapter, a preliminary load data revision, solar radiation data acquisition and power outages estimation were required. Finally, the model has been implemented within the Poli.NRG package, a tool developed by Politecnico di Milano to simulate off-grid systems.

6.1 Load profiles

As previously explained, a load assessment was done during the authors stay in Lacor Hospital.

Some difficulties were encountered during data collection:

- The power recorded by the solar inverter software is sampled every five minutes, while the one recorded by the PQA 824 is per one minute, ten second or thirty second according to the needs.
- Sometimes the PQA 824 was disconnected by the operators because of line maintenance.
- Frequent and unexpected power outages.

An incomplete and spotty load profile is thus obtained.

The different measuring ranges required an elaboration of the collected data, capable of simulating the Hospital loading profile at its best. Knowing that load is not predictable and that it is very oscillating and variable, for data sampled every five minute or ten/thirty second it is not possible to estimate any kind of progression. For this reason, two different methods have been applied:

- Five-minute samples: No information to determine if the load is increasing or decreasing. The best option is to repeat the value for 5 times to reproduce each minute.
- Ten/thirty second samples: computation of average value for every interval of one minute.

Measured power χ in a defined minute is a continuous aleatory variable (stochastic variable), whose possible values are numerical outcomes of a random phenomenon.

Starting from this statement, a reasonable statistic method for data elaboration must be found to fill in the missing data due to power outages. Data normality is applied by the authors ex-ante, as an initial hypothesis that has to be checked and confirmed.

6.1.1 Verification of the normality of a sample: Shapiro Wilk test

A lot of applications in engineering problems require verifying statements or assumptions. In statistic language, the statement is called hypothesis, while the related decision making is the hypothesis testing. This kind of test is based on the usage of all the information contained in a casual sample of a population. The absolute truthfulness or falsehood of a particular hypothesis can never be known with certainty, unless it is possible to study the whole population.

It is defined null hypothesis H_0 an assumption related to probability distribution of one or more casual variables. H_0 is the one to be tested, and its refusal always leads to accepting the alternative hypothesis H_1.

Two kinds of errors can be done while testing the correctness of null hypothesis:

- Type I error: occurs when H_0 is true but is rejected (false hit). Input data sample is not a good representative of the population.
- Type II error: occurs when H_0 is false, but erroneously fails to be rejected.

The significance level defined for a study, α, is the probability of the study rejecting the null hypothesis, starting from the assumption that it was true, while the probability to make a II type error it is defined with letter β.

It exists a link between α and β: a diminishment of α entails an increase of β and vice versa (if the size of the sample n is not changed). Increasing n will result in a decrease of α and β, if the extremes of the study region remain unchanged.

An easy way to report the results of a hypothesis check, is to establish that H_0 has not been rejected under a predefined level of significance α. This kind of test does not give any information about the accuracy of the hypothesis, so how far or not we are from the critical region of the test. To avoid that, the p-Value approach is used: it represents the smallest value of significance that would lead to the rejection of the null hypothesis. In other words, the p-Value can be seen as the smallest value of α for which data are significant.

- If p-Value > α, empirical evidence is not sufficiently contrary to the null hypothesis, that cannot therefore be rejected.
- If p-Value < α, empirical evidence is strongly contrary to the null hypothesis which should therefore be rejected.

Shapiro Wilk test is used to prove statistical properties (especially for small samples), and it is considered one of the strongest methods to verify normality of a sample. It tests the null hypothesis that a sample $\{x_1, x_2, x_3 \dots x_n\}$ came from a normal distributed population. The verification of normality is done comparing two alternative estimators to variance: a non-parametric estimator, based on optimal linear comparison of the statistic order of an aleatory normal variable and the sampling variance [45]:

$$W = \frac{\left(\sum_{i=1}^{n} a_i x_{(i)}\right)^2}{\sum_{i=1}^{n} (x_i - \bar{x})^2} \tag{6.1}$$

Where:

- $x_{(i)}$ is the i^{th} order statistic.
- $\bar{x}$ is the sample mean.
- a_i is a constant.

The null hypothesis of the test proposed is that the sample considered is normally distributed. So according to previous information, if the p-Value is lower than the selected significance level, then the H_0 is rejected and there is evidence that the hypothesis is not correct. However, considering that the result is strictly correlated to sample size, the test could be statistically more significant with larger samples and normality could be verified.

W can vary between 0 and 1: if W is smaller than an acceptable value W_a (function of α), the test rejects the normality distribution.

A significant aspect of this kind of test is that failure to reject H_0 is not proof that sample is normally distributed: data does not give enough evidence to discard the initial assumption. Moreover, rejection of H_0 does not give any information about how much the distribution differs from normal. The graphical representation of the quantiles of the distribution has to be used in addition to the test.

Quantiles divide the probability distribution of a dataset into contiguous intervals with equal probability, or in other words they divide the data sample into subsets of equal size. Quantile-quantile plot, also called Q-Q plot, is a graphical method used to check the validity of a distributional assumption for a dataset. It is just a visual check so it interpretation is somewhat subjective. It allows to see if the initial assumption is reasonable and, if not, what data points contribute to the violation. A Q-Q plot is a scatterplot with quantile values of the standard normal distribution on x-axis and the corresponding quantile values of the dataset are plotted on the y-axis. Points on the Normal Q-Q plot provides a signal of unchanged normality of the dataset. If the data is normally distributed, the points will fall on the 45° reference line, otherwise points will deviate from it. It can also be deduced from the slope of the Q-Q graph which of the two distributions is more dispersed: in fact, if this line is closer to the horizontal axis, it means that on the abscissa are represented more dispersed data than those of the ordinate, and vice versa.

Although a Q–Q plot is based on quantiles, in a standard Q–Q plot it is not possible to identify which point in the Q–Q plot determines a given quantile.

6.1.2 Data processing

Now that the statistic method is defined and all data collected are sampled each minute, it is possible to start processing using the software MATLAB.

Power usage during workdays and weekends is different so, as a first step, data are split into two "pools". During the permanence in St. Mary's Lacor Hospital were collected data for a total of 26 days, of which 8 holidays and 18 working days.

Two different matrixes have been created ('Working', 'Weekends'), with a number of rows equal to 1440 (minutes in a day), and 18/8 columns, number of recorded working/ weekend days (**Table 8**).

The methodology used to close the loopholes is the same for both matrixes, for simplicity just the case of working days will be analysed into details.

	Apr 26th	Apr 27th	Apr 28th	May 2nd	May 3rd	May 10th	May 11th	May 12th	May 15th	May 16th	May 19th	May 23rd	May 24th	May 25th	May 26th	May 31st	June 1st	June 2nd
15:36	139900	177200	110900	168010		130790	108158	134314	97100	170464	133378	128438			158500	159478		102698
15:37	146100	163400	109200	168190		130790	108158	134314	97100	170464	143328	120503			168509	161228		99873
15:38	141100	157900	110500	168130		130790	108158	134314	97100	190264	133278	128873			159859	144268		101793
15:39	140500	142800	101600	163720		130790	108158	134314	98620	190264	147128	129268			157724	132248		108203
15:40	146800	153200	103400	153062		122942	113892	132370	106468	172312	147112	133661			150778	126735		96020
15:41	139400	147400	103300	161652		143882	113892	132370	106468	172312	147662	125308			149485	126240		97135

Table 8 *Load example for different sampled days in a defined time interval, white spaces represent power outages*

For every single row the standard deviation and the mean have been computed and later used to define the normal distribution of the data.

Shapiro Wilk test is then applied to establish if there is evidence to say that initial hypothesis (normality) can be confirmed or rejected. First and foremost, it should be remembered that its response cannot be considered absolutely true. The test just checks if the initial null hypothesis of normality is verified or not, without giving any information about other possible distribution alternatives.

$$[H, p\_Value, W] = swtest(x, \alpha) \tag{6.2}$$

A significance level α of 0.05 is used, while x is a vector from an unknown distribution that has to be studied (in this case the power demand in a defined minute in the different recorded working days). The sample dimension must exceed 3 and be lower than 3000, for correctness of the analysis.

The outputs of the function are p-Value, W and H, where H is a Boolean vector:

- H=0 means to not reject H_0 at significance level α.
- H=1 means to reject H_0 at significance level α.

The H histogram (**Figure 36**) gives relevant result to the initial statistic hypothesis. According to the Boolean vector H, 1290 elements confirm the null hypothesis (samples are normally distributed), and consequently 150 are not. This kind of result is still not sufficiently clear for the study and it has to be compared to the p-Value plot (**Figure 37**).

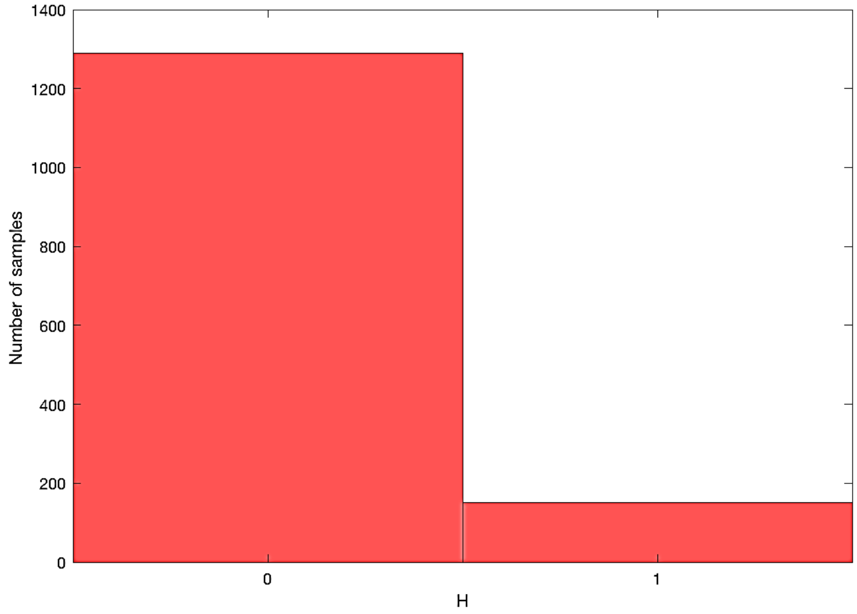


Figure 36 *Number of samples that confirms normality hypothesis*

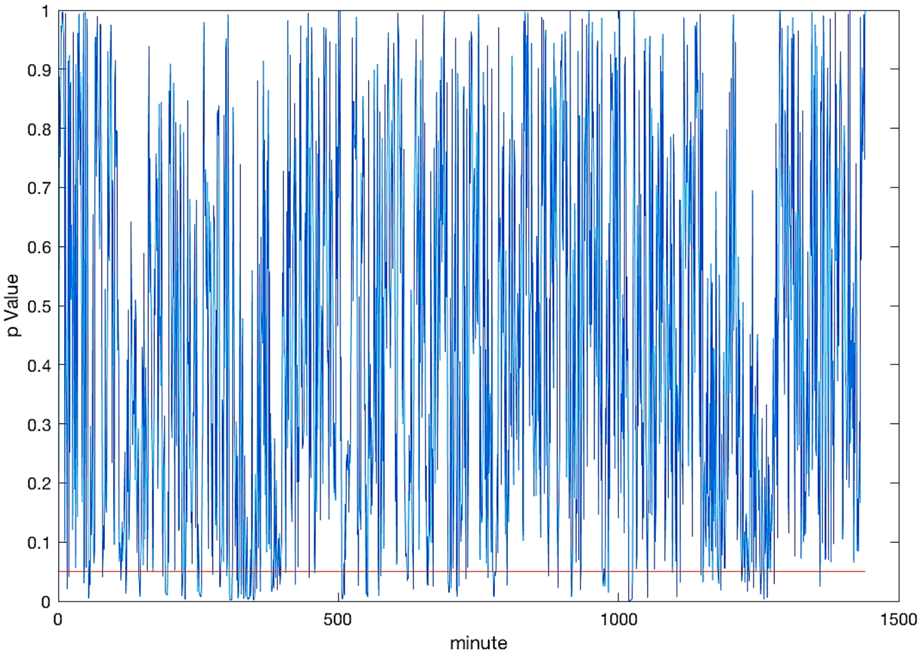


Figure 37 *Samples p_Value variation*

An analysis of the samples that rejected the normality test shows that they are almost completely concentrated where there is the greatest lack of data.

It can be concluded that 10.4% of the data reject null hypothesis and are concentrated where data are missing more.

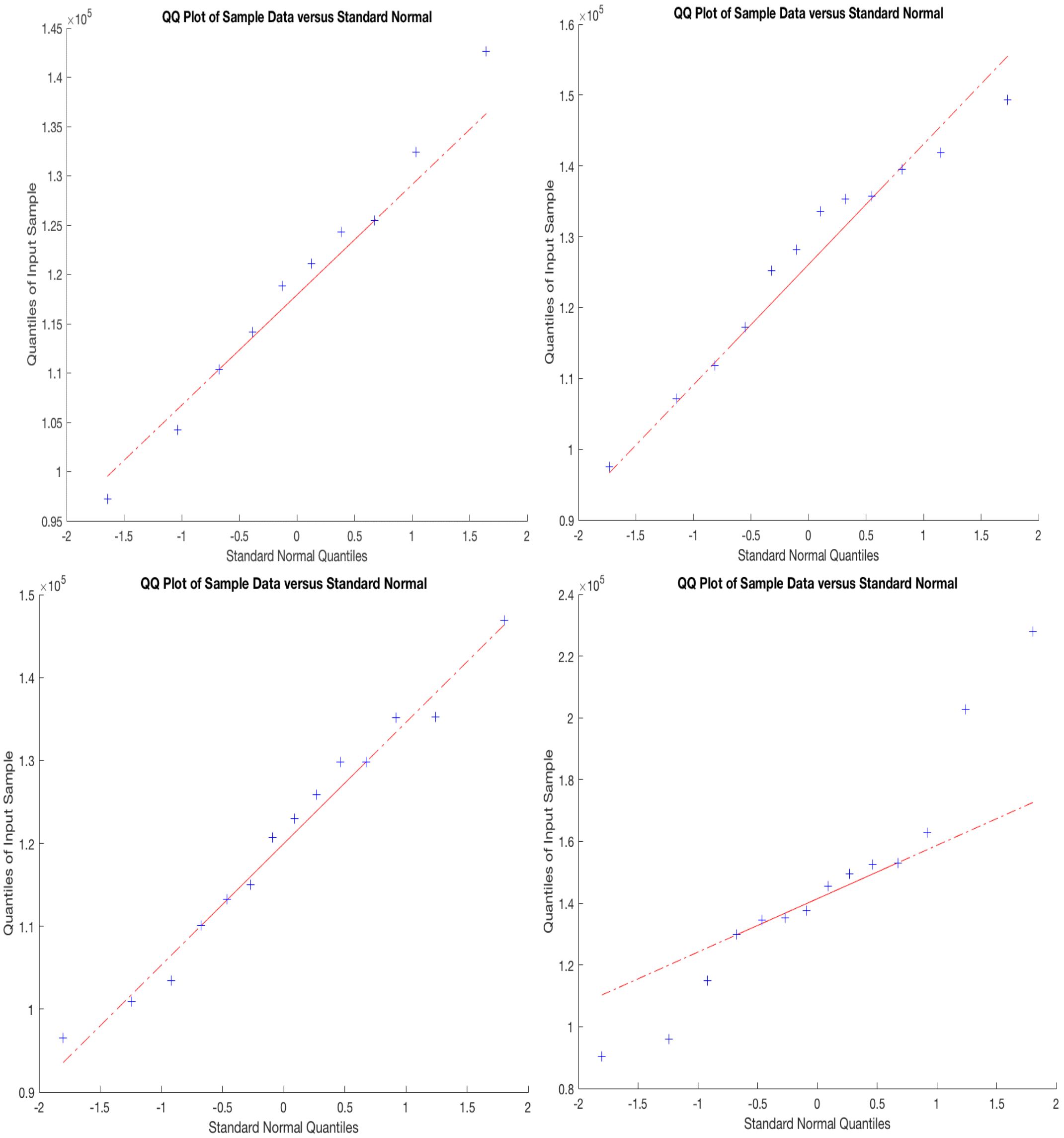


Figure 38 *Q-Q plots of 4 different moments of the day: top left 503 minute of the day, top right 686 minute of the day, bottom left 1048 minute of the day, bottom right 772 minute of the day*

In order to simplify the study a hypothesis has to be done, so even if the test confirms the rejection of $\mathcal{N}$ for this samples, they will be considered anyway coming from a normal distribution $\chi \sim \mathcal{N}\ (\mu, \sigma^2)$.

It is now necessary to apply an additional method capable to strongly validate the obtained normality results, like Q-Q plot representation. As a title of example four different minutes of a day have been considered and analysed for this additional study.

The Q-Q plots (**Figure 38**) confirm the obtained results with Shapiro Wilk test, showing that data can be approximately considered really close to the 45° red line. The bottom right plot shows a strong distortion of the data and consequently for this case normality is rejected, as

Shapiro Wilk test confirms.

As next step, a new matrix '*Delta*' is computed, defined as the power variation at time *t* with respect to the previous minute *(t-1)* for "Working matrix" and "Weekend matrix"; such variability can be positive or negative.

Moreover, the day is subdivided in 3-time intervals, regardless of whether it is a working day or weekend:

- 00:00 to 7:30 sleeping hours.
- 7:31 to 17:00 working hours.
- 17:01 to 23:59 post work hours.

Each time interval is characterized by different power variation boundaries. As a matter of fact, **Figure 39** shows how oscillations are more concentrated during the working hours, especially close to noon, while during night and the early morning they are small.

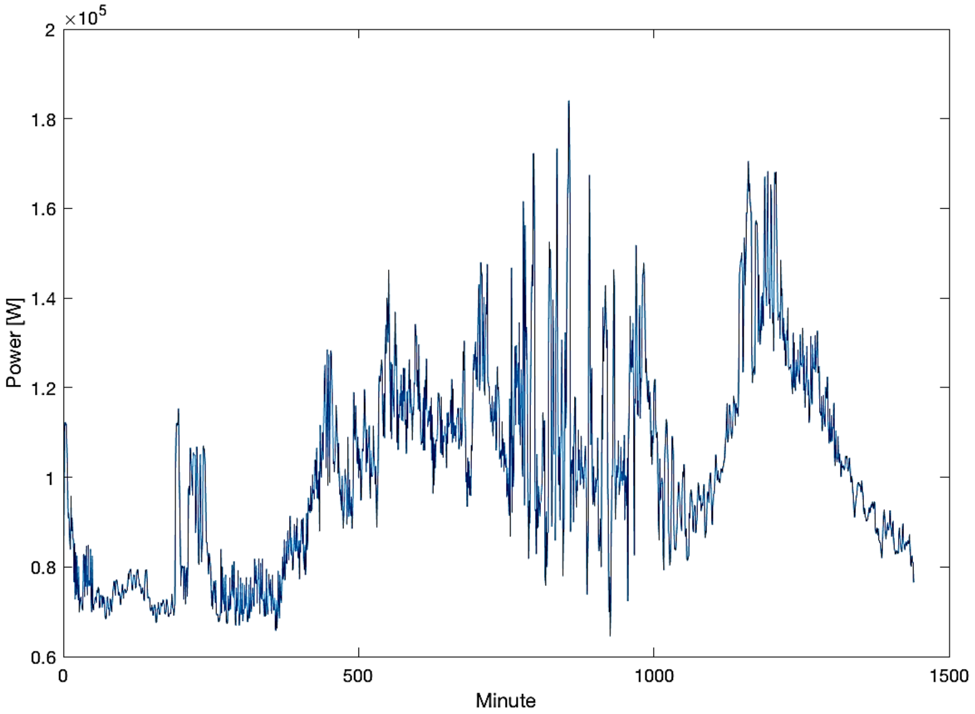


Figure 39 *Example of completed Hospital load profile in a day*

Starting from this remark, according to time frames chosen above, Delta matrix has been split in three smaller ones: Delta1, Delta2, Delta3.

Interest is now focused on searching for the extremes of the range in which power can oscillate for the three-time intervals: values obtained in every Delta matrix can be used to identify a plausible variation range in the following way:

- Apply absolute value to the three delta matrixes in order to obtain positive power variations.

- Ensure equal negative power variations.

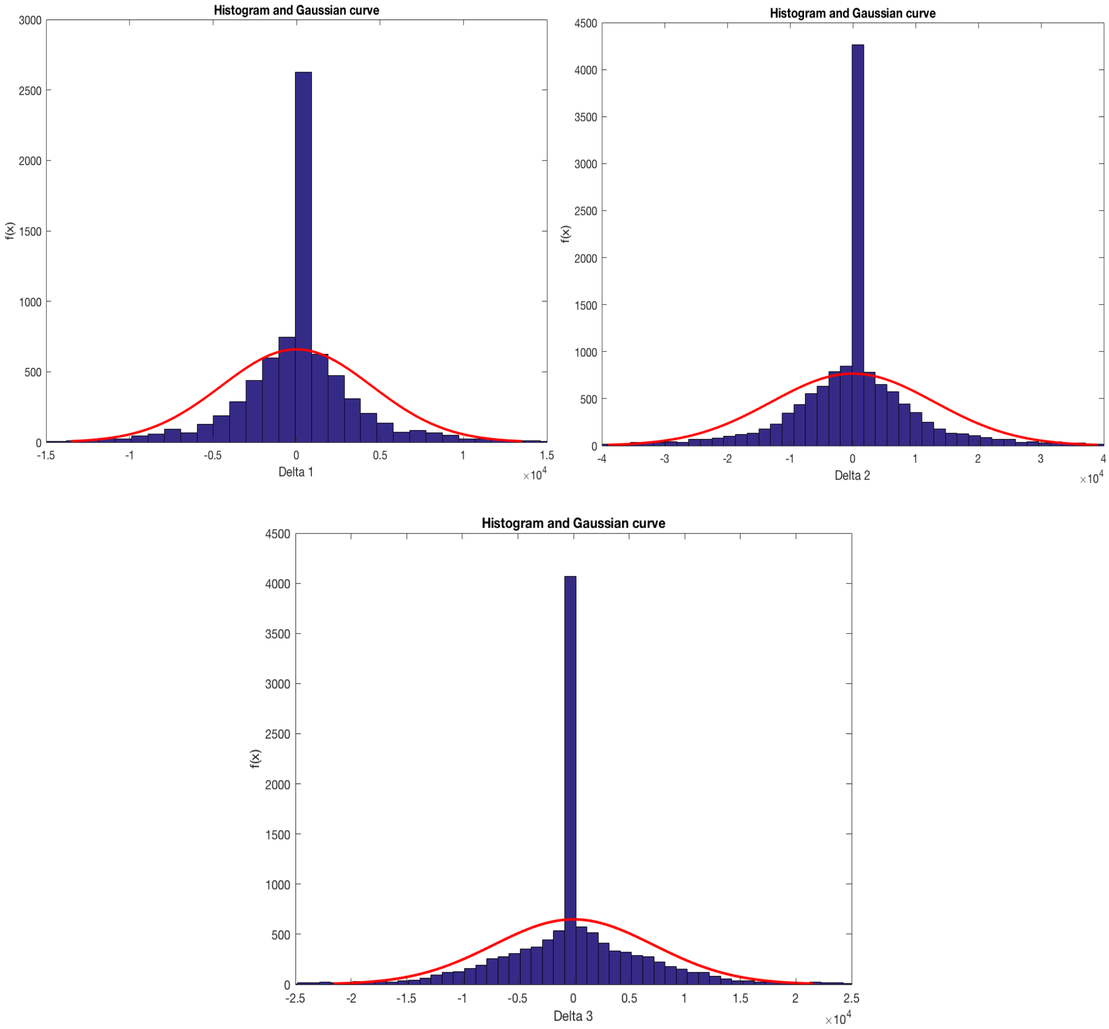


Figure 40 *Histograms and Gaussian curves of power variations Delta1, Delta2 and Delta3*

All three distributions are characterized by a normal distribution (**Figure 40**), and for each of them the interval boundaries can be computed (**Table 9**), assuming:

$$P(\mu - 3\sigma < X < \mu + 3\sigma) = 0.9973 \tag{6.3}$$

	Delta 1	**Delta 2**	**Delta 3**
μ	0	0	0
σ	4501.3	13003,4	7194.01
Delta Interval (x10^3)	-13.50<Δ<13.50	-39.00<Δ<39.00	-21.58<Δ<21.58

Table 9 *Interval variation for each Delta*

Now that all the necessary hypotheses are demonstrated, procedure for completing the initial matrix ‘Working’ can begin.

MATLAB analyses the initial matrix searching for the holes, positions were outages are present, and tries to feel the gaps with the procedure reported below:

- Find a gap.
- Identify the minute of the day and at which of the recorded days it corresponds.
- Estimate a value of power using a random weighted function on normal distribution of the picked minute of the day. This will allow to select a plausible value according to the probability density function *f(x)*.
- Calculate the differential between new power estimated and power valuated at minute t-1 of the corresponding day.
- Compare this variation with the equivalent delta interval: if the estimated power is inside this range it can be accepted, otherwise restart with the procedure from point three.

The load profiles measured by the PQA 824 are now complete and usable for estimating an annual load profile.

The next step requires the use of the previous completed matrixes ‘Working’ and ‘Weekends’: starting from the first day of the year, remembering the division between working days and holidays, a random load profile is chosen from among those just corrected day by day. This action must be carried out for all days of the year, until its completion.

The choice to use only the data collected during the campaign, in the absence of further data available, means that the possible variations in the Hospital's load during the year are considered non-existent. Two hundred possible load profiles have been evaluated in accordance with the principle of ensuring the greatest possible variability for next calculations.

6.1.3 Power outages estimation

Regarding specific values for the occurrence of power outages and their duration in Uganda, few and mostly incongruous information has been found. The occurrence rate of power supply interruption depends on the location and is therefore not perceived in the same way throughout the country. There is currently no reliable information and the only way to understand its impact on continuity of services is to record zone by zone the frequency of breakdowns and their duration.

For this reason, reference was made to the data collected by Hospital technicians who, measuring the energy satisfied by the main grid, the energy produced by solar panels and generators, estimated an annual frequency of about 10% (**Table 1**).

Since the generator is designed to satisfy the total load during the day, while at night only that of the emergency line, it can be seen that the result obtained is not really accurate, since it cannot actually take into account the total overnight load in the event of a power failure. Despite this, 10% annual frequency will be held as a baseline, being the most plausible and scientifically proven value.

On the other hand, there is no information about the duration of power outages and their frequency in particular months of the year, such as rainfall, which is very critical due to violent storms. It was therefore decided to simulate different blackout profiles by varying their duration in hours, to understand if prolonged interruptions can result in subsequent different plant solutions (1h-2h, 3h, 4h, 6h, 8h, 10h). The duration of interruptions is not expected to vary for the individual simulated profile, and no variability between the years it is considered.

Defined the input parameters for the correct simulation of shutdowns, MATLAB was used to create an annual matrix. Depending on the annual frequency and average hourly duration, the number of power outages that occur during the year can be defined, finding *n* intervals in which at least one blackout must take place. In a completely random way, it introduces power outages, trying to avoid their overlapping. If there are too many outages (or the durations are too long), some of them do overlap. A matrix consisting of 1 and 0 will be returned at the end of the process, where 1 indicates the presence of the main network, while 0 indicates the opening of the PCC, so the beginning of a power shutdown of the main grid. Below is an example of the construction of this matrix, where black lines represent system shutdowns (**Figure 41**).

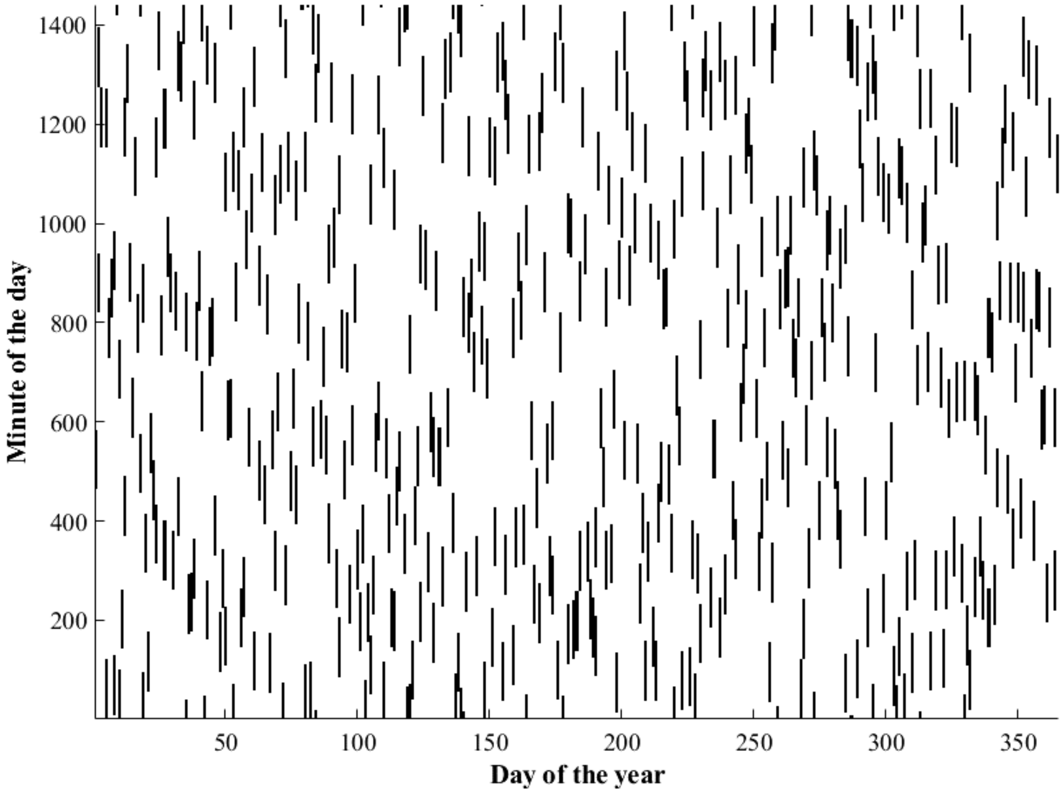


Figure 41 *Power outages during a year, mean hour duration equal to 2h*

6.1.4 Solar data acquisition

Due to the lack of tools and the impossibility of measuring solar intensity radiation throughout the year at the study site, online meteorological databases have been analysed. Many of these are unreliable, not affordable or incomplete, which is why it was decided to use the consolidated and validated model of Stefan Pfenninger and Iain Staffell [46].

The model algorithm is available free of charge at the website "www.renewables.ninja", where it has been possible to evaluate the hourly solar radiation for the whole year and the hourly power output (kW/kW$_p$). The following information was requested from the user for the computation:

- Longitude and latitude of the Hospital (2.8764 – 32.4191).
- Presence of a solar tracker with two axes (No).
- Tilt angle (13°).
- Optimal angle of Azimuth (180°).
- Year of interest (2014, last dataset available).
- System losses (0%, as losses are implemented in the model yet).

Since the solar panel is strongly influenced by the external environment temperature, the tool is also able to evaluate its overall effect on the panel efficiency according to the logic proposed by Huld et al. [47].

Since solar radiation is an hourly average, it is not able to keep track of any instantaneous variation such as the passage of a cloud, leading to define these curves as ideal.

The thesis model includes a minute by minute evaluation of the power output of solar panels, in the same way as the load: solar irradiance data are so processed with a MATLAB script, looking for a polynomial that best represents the solar radiation trend in the required time interval, as represented in **Figure 42**. The script returns a vector with the annual PV production profile (525600x1), which will then be managed and extended according to the lifetime of the system under examination.

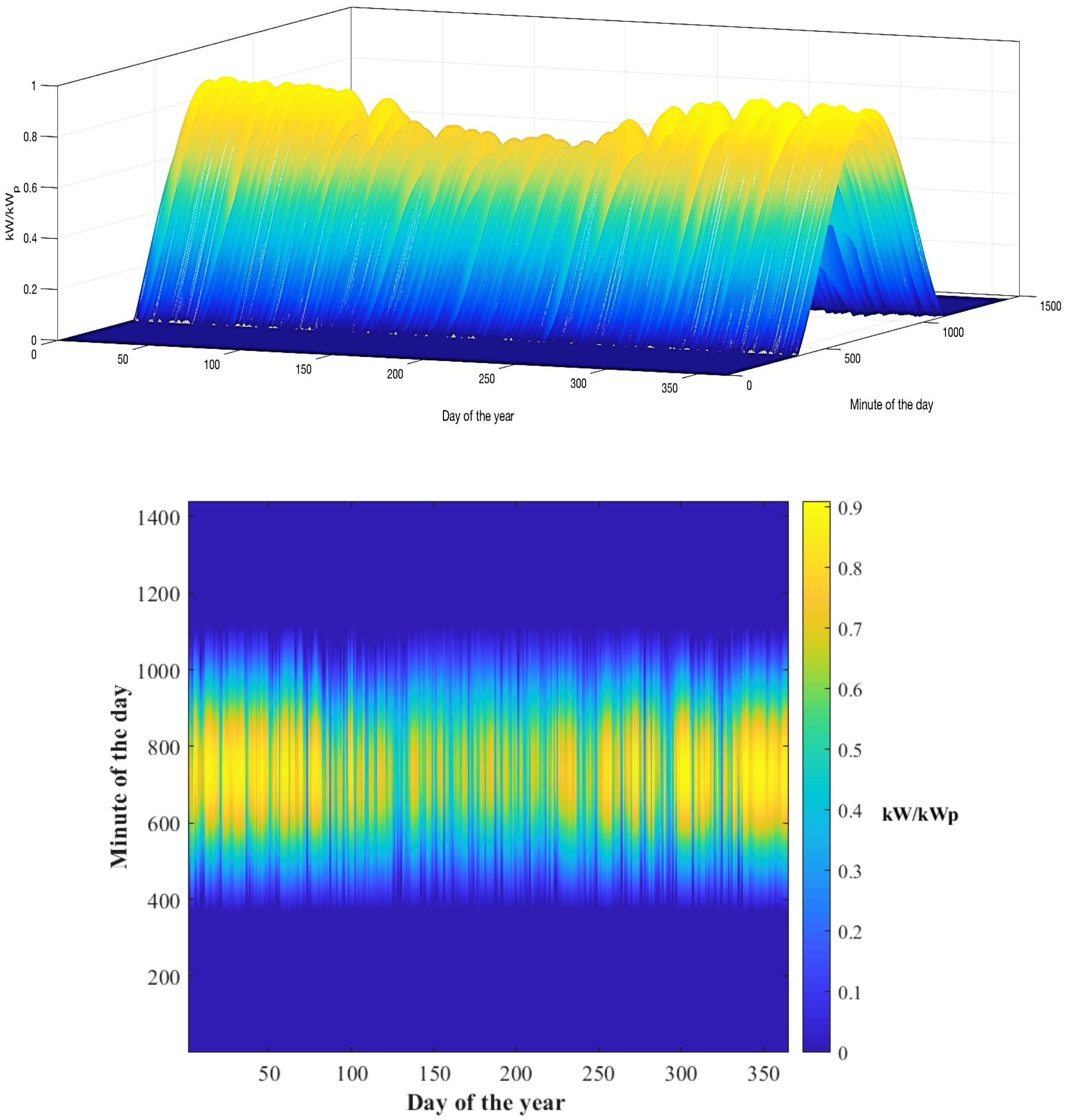


Figure 42 *Solar radiation output for the whole year for Gulu, Uganda*

6.2 The optimization tool

The Politecnico di Milano developed a new robust procedure called *Poli.NRG* (POLItecnico di Milano - eNergy Robust desiGn), capable of simulating at best off-grid systems according to a bottom-up logic.

The aim of the tool is to test, for a given load profile, different combinations of PV and battery energy storage systems in the searching space, calculating for each of them the Net Present Cost (*NPC*), the Loss of Load Probability (*LLP*) and Levelized Cost of Energy (*LCoE*); then, through a techno-economic optimization method, the tool defines which technology combination (PV_{opt} and $BESS_{opt}$) can minimize final cost while respecting the constraints of LLP imposed by the user.

The main innovation brought by Poli.NRG compared to other famous software tools is the ability to recreate in detail the annual load profile knowing the user's needs through a tool called LoadProGen, taking always into account the uncertainty of the loads. Moreover, it is free itself from the strong hypothesis of static user demand over the years, thus better formulating design phase and optimal solutions.

A logic capable of simulating the increase in energy demand over the years is therefore integrated.

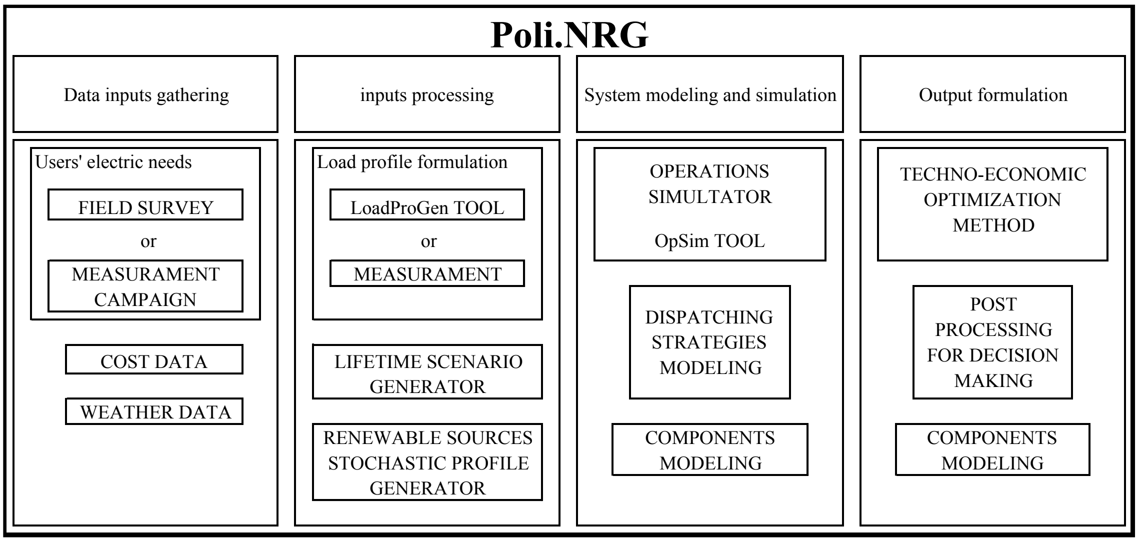


Figure 43 *Poli.NRG structure* [48]

Poli.NRG is structured on four sub-procedures required for optimal off-grid system design (**Figure 43**):

1. Data input gathering: allows the acquisition of all fixed and variable costs, user's electric needs and data concerning weather.

2. Inputs processing: input data is reworked and used to generate a load and sources yearly profile formulation (this procedure has been developed with a software tool LoadProGen). The annual load profile can also be obtained through field data acquisition, avoiding its usage.
3. System modelling and simulation: key process block, performs all the viable simulations of the off-grid system, following the imposed logics, managing energy dispatching strategies through an algorithm called OpSim (Operation Simulator), formulated under steady state hypothesis. The lifetime simulation of the system occurs performing minute per minute energy balances between energy demand, energy produced and energy stored.
4. Output formulation: through an optimization process identifies the most robust and appropriate solution.

The identification of the search space and the optimal solution criteria are two basic stages for Poli.NRG functioning. Depending on the chosen load profile, the maximum acceptable loss of load imposed by the user, a proportionality factor w_j and the solar production profile, the tool finds the boundaries of PV search area. The PV_{min} must ensure full load satisfaction, including possible system losses, while PV_{max} is function of w_j. As far as batteries are concerned, there is no limitation below their size, so the minimum capacity is considered to be zero; on the contrary, the maximum size is a function of the average daily energy.

A heuristic optimization model is used for a robust design structure of the tool. In particular, during the lifetime operative simulation (OpSim), the possible technologic combinations are simulated for the defined searching space and for a given load profile (function of selected evolution scenarios s and lifetime load profiles n). For each PV-BESS couple OpSim evaluates the NPC, LLP and LCOE as reference indicators.

Once the distribution in the search space of this reference indicators has been defined, the heuristic model is applied: the process looks at the best technology arrangement for which NPC is minimum, respecting constrains on LLP (**Figure 44**). Then, focusing on the surroundings of the solution, it checks whether it exists or not a better PV_{opt} and $BESS_{opt}$ as long as the convergence criterion is not fulfilled. The process is then repeated for a new load profile, using the same search space, selected scenarios and life time previously imposed. Since the loading profile is different from the previous one, the optimal solution

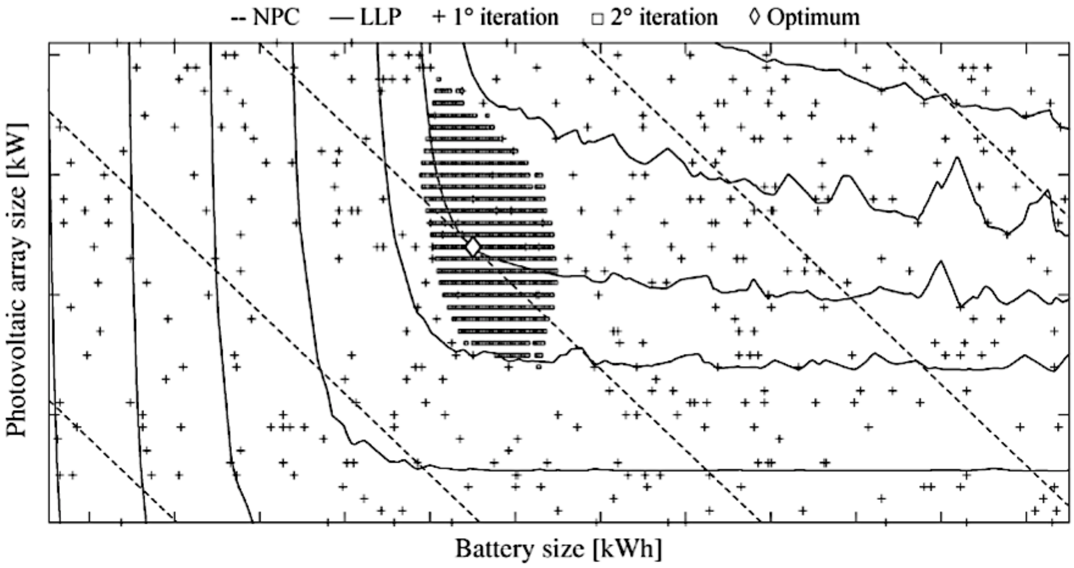


Figure 44 *Searching space of the Poli.NRG optimization procedure* [48]

will not be coincident and it will deviate from the latter more or less significantly. Optimum points (PV and BESS optimum combination of each load profile) are then saved in an *area of solutions* instead of a single deterministic solution. The final step is to calculate the weighted average of the points of optimum found in the solution area, knowing the frequency with which a certain combination PV_{opt} and $BESS_{opt}$ is common to the different simulated load profiles. The process ends when an additional load profile (*N)* test cannot increase the robustness of the solution. It is therefore necessary to apply a converge criteria, formulated according to the standard deviation and average of the robust solutions (*rbt*) obtained, so as to identify the number *N*.

$$abs\left|\frac{std[PV_{rbt}(N-1,s)] - std[PV_{rbt}(N,s)]}{std[PV_{rbt}(N-1,s)]}\right| \leq std_{requirement}\ \forall\ scenario \tag{6.4}$$

$$abs\left|\frac{std[BESS_{rbt}(N-1,s)] - std[BESS_{rbt}(N,s)]}{std[BESS_{rbt}(N-1,s)]}\right| \leq std_{requirement}\ \forall\ scenario \tag{6.5}$$

$$abs\left|\frac{mean[PV_{rbt}(N-1,s)] - mean[PV_{rbt}(N,s)]}{mean[PV_{rbt}(N-1,s)]}\right| \leq mean_{requirement}\ \forall\ scenario \tag{6.6}$$

$$abs\left|\frac{mean[BESS_{rbt}(N-1,s)] - mean[BESS_{rbt}(N,s)]}{mean[BESS_{rbt}(N-1,s)]}\right| \leq mean_{requirement}\ \forall\ scenario \tag{6.7}$$

Having the possibility of studying different loading scenarios, different areas of solution can be identified with the same proposed methodology, allowing the creation of an overall map, highlighting how different load profile scenarios are able to modify robustness of the best solutions.

Consequently, the model proposed by Poli.NRG has been used as starting point of the implementation of the micro-grid model.

6.2.1 Adjustments by the authors

Since the tool was originally designed only for off-grid solutions, the authors adapted Poli.NRG to micro-grid applications. For this purpose, the national grid and the diesel generator were added as new technologies. Moreover, the dispatching strategy explained in Chapter 5.2 was implemented modifying the former one but maintaining the original structure.

Turning to the details of the adjustments, all the new energy balances were introduced in "*LifeTimeSimulation*" function, while the economic evaluation was added to "*EconomicAnalysis*" function. A tangible change is related to the definition of the loss of load probability: previously it was defined as the ratio between the unmet load and total energy demand in the LT; now the denominator is given by the total energy that should be supplied during a power outage over the LT.

Another substantial difference has to do with the choice of the optimal gen-set size: in contrast to PV and BESS, only one size per simulation can be investigated to make the computation as fast as possible.

Chapter 7

Simulations and results

Data collected and processed (Chapters 4.1 and 6.1.2) are used to launch several simulations of ex novo energy system for power supply in St. Mary's Lacor Hospital as a general assumption. No distinction is made between emergency line and main line: during the power outages the entire Hospital demand must be ensured. The lack of information about the reliability of the national Ugandan grid (common to many other developing countries), led to a first sensitivity analysis on the average duration of each power interruption. Moreover, to find out the best matching among PV, BESS and diesel generator, two sizes of gen-set are tested. The latter have been chosen to guarantee operation of the system in the hypothesis of partial absence of other technologies, according to the sizing recommendations explained in Chapter 2.

To consider all the possible load variations over the time, a "flat scenario", namely with constant demand for the whole lifetime, and a 1% linear growing per year scenario are compared.

7.1 Assumptions

Table 10 displays the inputs chosen by the authors for the simulations. Their selection has been done after a deep research about electrification in rural areas and data collection on the field.

Starting from the generator, the specific cost of energy c_{gen} refers to some previous analysis carried out by the technicians, with respect to the different sizes installed in the Hospital [42]. On the other hand, the cost of electricity from the national grid has been computed making an average on the monthly consumption according to UMEME bills [49].

Input Data

η_{inv}	90	%	*LLP target*	0.4	%
η_{BOS}	85	%	*Pvcost*	1200	€/kWp
$\eta_{derating}$	2	%	$Inverter_{cost}$	300	€/kW
η_{charge}	85	%	$BESS_{cost}$	200	€/kWh
$\eta_{discharge}$	90	%	$O\&M_{PV}$	20	€/kWp
SOC_{min}	42	%	$mean_{requirement}$	0.5	%
SOC_{max}	95	%	$std_{requirement}$	1	%
y_{BESS}	5	years	LT	20	years
k_{BESS}	0.5	kW/kWh	r	6	%
c_{ele}	0.13	€/kWh	c_{gen}	0.34	€/kWh
P_{gen}	150/200/250	kW	t_{mingen}	30	min
η_{up}	95	%	η_{down}	25	%

Table 10 *List of input data used for all the simulations*

The evaluation of quotations by private companies led to the choice of investment costs for BESS, PV and inverters. The operative and maintenance costs relative to PV panels are associated to the current estimated workforce expenditure at Lacor.

For what concerns the technical minimum of the generator, the authors chose a value for which the analysed total harmonic distortion was within the admissible range for the security of the system, as explained in Chapter 2.4. Another constraint on the diesel generator is the minimum operating time. To safeguard its correct functioning and to avoid continuous on/off, the gen-set must be turned on at least for 30 minutes.

The acceptable state of charge interval aims to preserve the correct functioning of the battery package, maximizing their lifetime. Such a high upper boundary (SOC_{max}) allows to guarantee good charge/discharge cycles, preventing continuous oscillations, and to make them efficiently available for the next utilization.

The solution search space lies within the range 0-3000 kW_p for PV with 1 kW step and 0-3000 kWh for BESS with 1 kWh step. To ensure a strongly reliable electricity service, a maximum allowed loss of load of 0.4% is imposed.

The 200 load profiles are extended over the entire lifetime of the system, following the 0% selected evolution scenario, and used to verify the robustness of the design solution.

No increase in energy demand over the 20 years is considered, due to the Hospital internal policy aimed at keeping it almost constant for the next years.

7.2 Results

To understand the way in which the tool researches the robust ones, it is useful to plot the preliminary islands of solutions. After simulating one of the 200 profiles lifetime for many combinations in the search space and after evaluating their economic impact, it is possible to identify the different LLP and NPC associated to the technological combinations. This way, the contours allow to visualize the distribution of these variables in the search space. By way of example, **Figure 45** and **Figure 46** show the NPC and LLP contours under the hypothesis of average power outage duration of 2h and the use of a 250 kW gen-set.

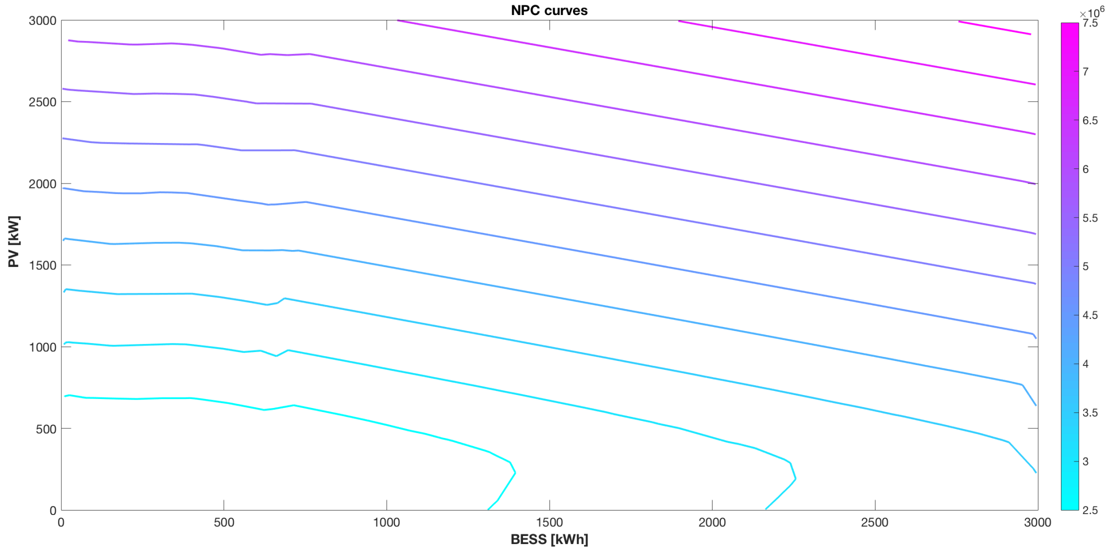


Figure 45 *NPC curves for 2h power outage lasting, 250 kW gen-set*

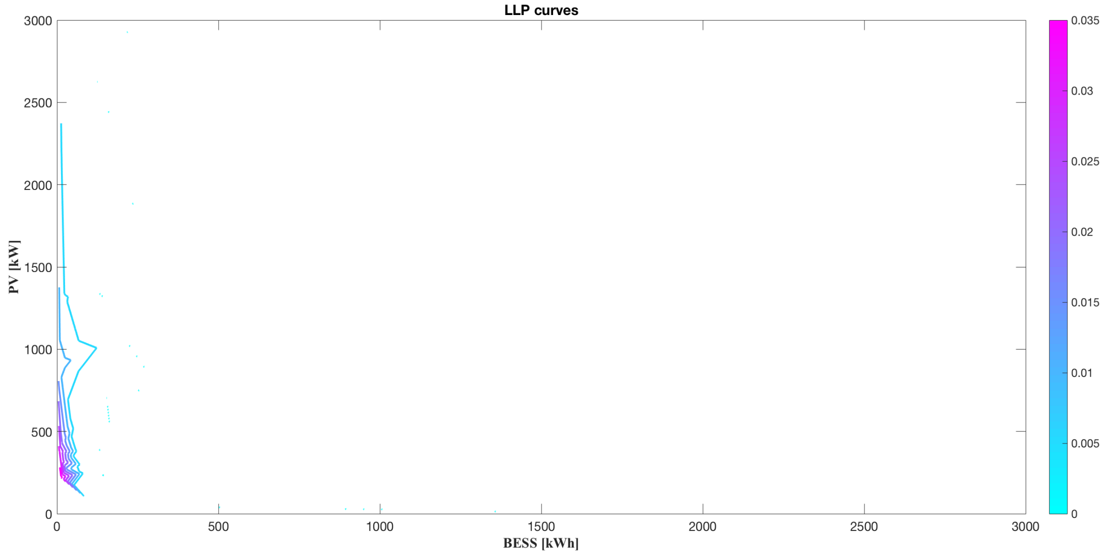


Figure 46 *LLP curves for 2h power outage lasting, 250 kW gen-set*

Comparison of the two figures, recalling the constraints of LLP imposed by the user, allows to predict the possible area of solution. In this specific case, losses are more concentrated for small batteries sizes, as they bring the generator to work in conditions close to the permissible operating limits.

7.2.1 Case 0: Off-grid

To establish a benchmark between an ideal off-grid solution and a micro-grid one, a first simulation has been developed assuming to feed the whole Hospital with a PV and storage micro-grid. It is recalled that, the off- grid loss of load represents the unmet demand by the PV – BESS couple in the whole lifetime. In addition, the search space is broader (0-10000 kWh BESS, 0-10000 kW_p PV), due to the necessity to satisfy the load in the absence of alternative sources, and the acceptable LLP is set at 5%.

The following **Table 11** encompasses the reference case solutions for the "flat scenario" and the 1% evolution scenario.

Yearly increase in the loads [%]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]
0	1170	2865	4726977	0.0498	0.4581
1	1355	3065	5213660	0.0500	0.4679

Table 11 *Results off- grid case for two scenarios*

A yearly load increase by 1% brings the PV size to increase 15%, while the BESS one by only 7%. This can be justified by the fact that during the day the load is higher than by night, so the PV system will be exploited more than BESS. It is clear that being able to predict load trend over the years ensures a more performing technological solution for the future. However, sizing the system with respect to the growth of future loads could overestimate the technological mix for the first years.

The obtained values, especially the high NPC for developing countries, encourage to look for alternative electrification systems as for instance the proposed micro-grid. Nevertheless, it is worthwhile to stress that a 0.46 €/kWh is a quite "normal" cost for PV and storage off-grid system. In the case under study it has been taken just as a term of reference.

The comparison of LCoE in off-grid case with the specific price of the electricity (0.13 €/kWh) confirms the reasonableness of the chosen strategy to not use BESS when the national grid is present. The batteries have only the duty to preserve the continuity of the service in the event of a power interruption.

7.2.2 Micro-grid

The 200 processed yearly load profiles, related to the Hospital demand and the blackout matrixes, are initialized for the computation of the results. Each combination of a possible load profile and power outage profile gives a technological matching for a fixed generator size and a blackout average duration.

The merging of the robust results (*rbt*) allows to identify an "*area of robust solutions*". For sake of simplicity and to ease the comparison, these areas were aggregated in two plots per each generator size.

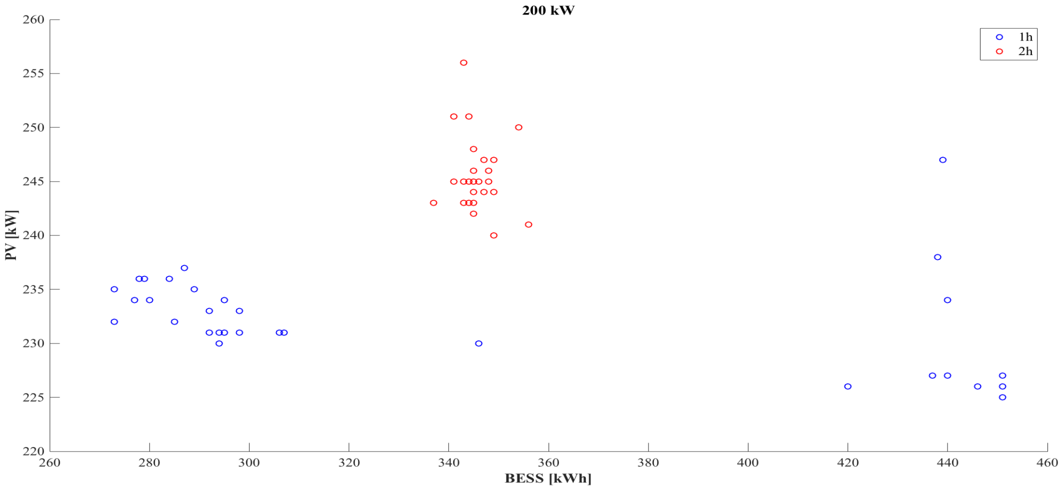


Figure 47 *Areas of robust solutions for short average power outage durations, 200 kW diesel generator*

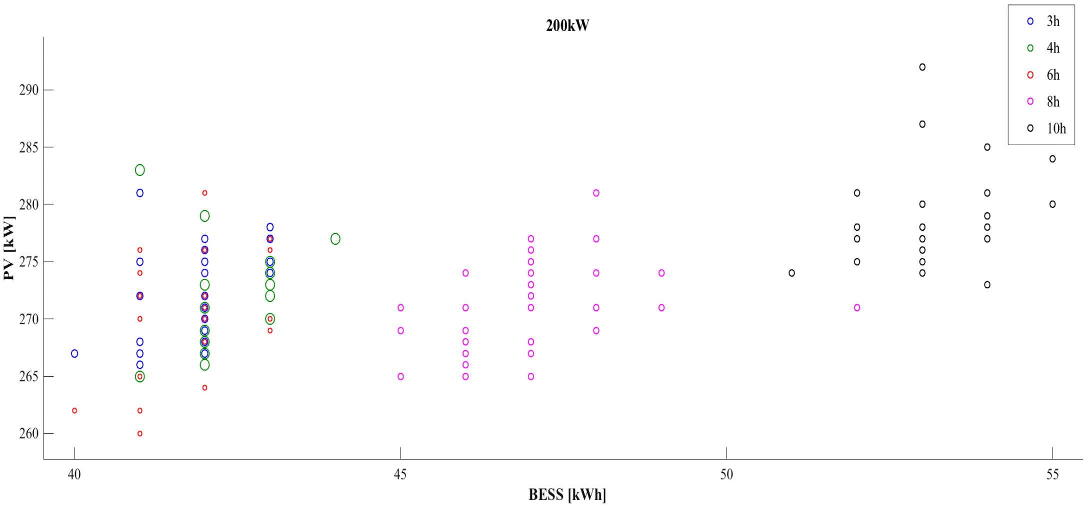


Figure 48 *Areas of robust solutions for long average power outage durations, 200 kW diesel generator*

Short power outage durations (**Figure 47** and **Figure 49**) prefer to use bigger BESS than long lasting power failures: in such conditions the usage of the generator (both for 200 and 250 kW) is limited or null. The generator becomes auxiliary and only intervenes when the batteries and PV fail to meet the energy demand.

In the event of 1 hour mean power failure and use of a 200 kW gen-set, $BESS_{rbt}$ solutions have in some cases sizes larger than the average, as a result of more frequent power cuts during the night.

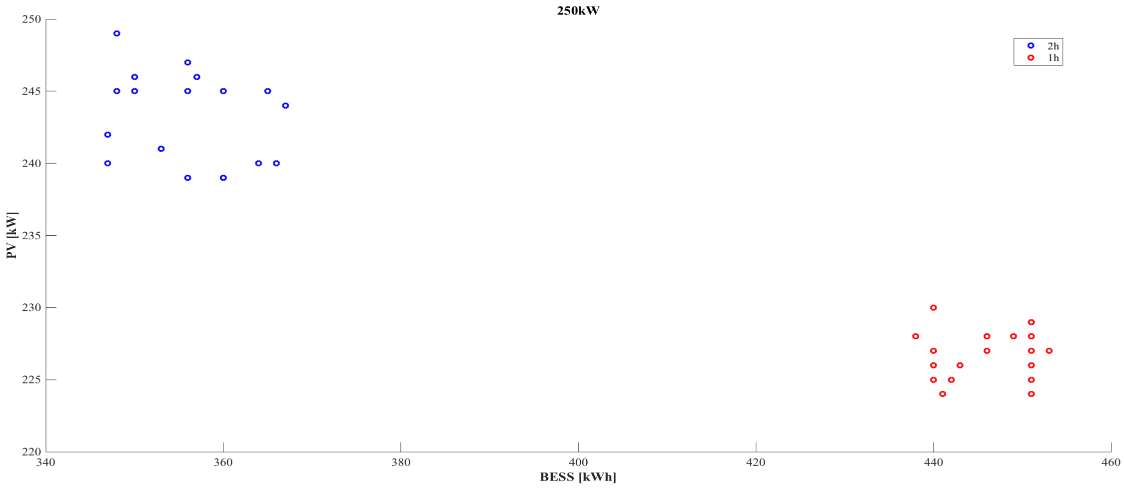


Figure 49 *Areas of robust solutions for short average power outage durations, 250 kW diesel generator*

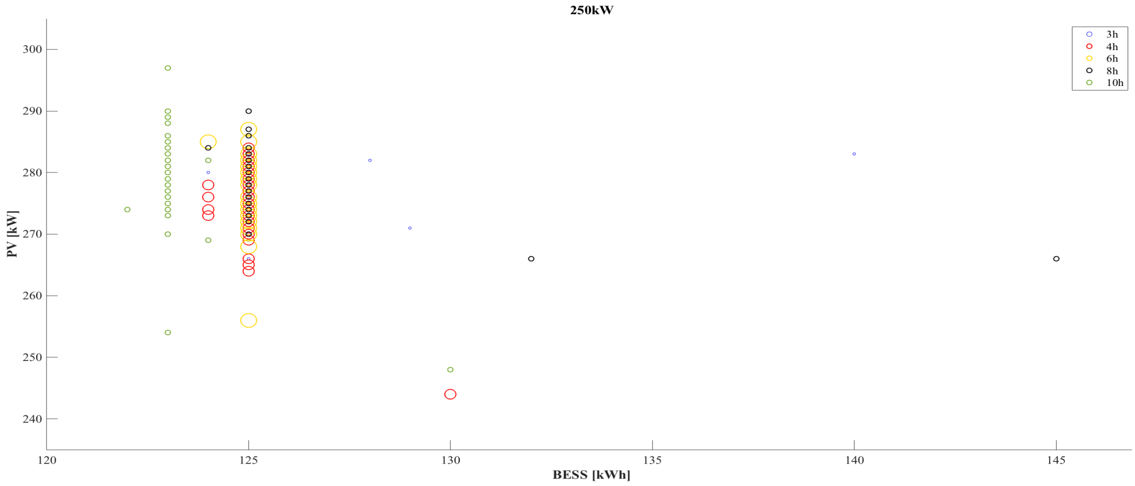


Figure 50 *Areas of robust solutions for long average power outage durations, 250 kW diesel generator*

For long lasting power outages (**Figure 48** and **Figure 50**), diesel generator becomes more affordable than BESS: their size guarantees a good operation of the generator, respecting its constraints. Moreover, PV_{rbt} oscillates more than $BESS_{rbt}$, being strictly dependent on whether the blackout occurs more frequently by night or during the day.

All these rbt solution areas are summarized considering the mean of PV and BESS, to compare how different generator sizes influence the results. **Figure 51** shows the trend of the technological solution as a function power outages average duration for each selected generator size.

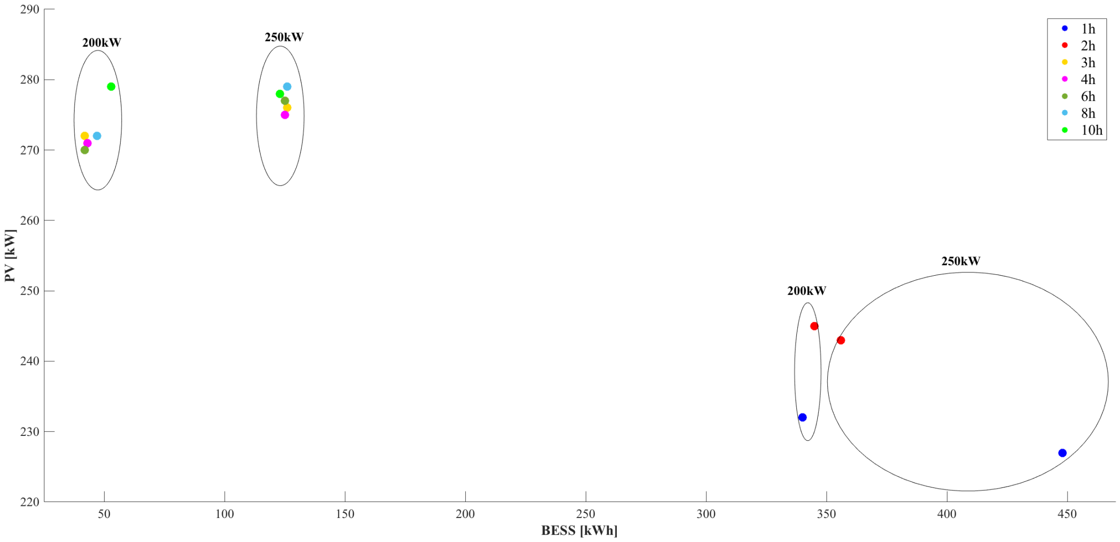


Figure 51 *Technological solutions for each generator size varying the number of power outages average duration*

Increasing the gen-set size (beyond two hours of power failure) brings the BESS to approximately triplicates the suggested capacity, while no significant variation is obtained with regard to photovoltaic panels.

Furthermore, the duration of blackouts, fixing generator size, does not relevantly affect the technological combination, except for short lasting power outages.

In the latter case, it is more favourable to use almost exclusively BESS to satisfy the load, requiring the generator to intervene only in the most critical moments: they are therefore recharged mainly through the national electricity grid, being very economically advantageous compared to the specific cost of energy associated with gen-sets (0.13€/kWh vs 0.34 €/kWh respectively).

Table 12 and **Table 13** summarize the details of the mean robust solutions for each generator size, reporting also the NPC, LLP, LCoE, annual operating hours of the generator and number of battery replacement over the lifetime (LT), corresponding to different blackout durations.

NPC grows (for both gen-sets) as the duration of power outages increases, as it is even more probable to occur at times of day with high energy demand, reducing dependence on the national electricity grid.

On the contrary, Loss of Load decreases to zero when switching from a 200 kW to a 250 kW generator: power required by the Hospital sometimes exceeds 200 kW, and consequently the generator may have to supply power beyond its upper limit ($P_{gen,max}$), resulting in a loss of load. The 250 kW diesel generator, on the other hand, has problems of minimum ($P_{gen,min}$), given its larger size.

Recalling the observations made for **Figure 47**, **Figure 48**, **Figure 49** and **Figure 50**, the consideration of the mean value of the robust solutions could be inappropriate: for larger areas of solution, taking the mean value could lead to either underestimate or overestimate the technological mix. In fact, the mean value is farther to each optimal solution, for the individual simulated load profile, compared the cases of small areas of solutions.

Average power outage duration [h]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]	Annual generator operating hours [h]	N° of replacements per lifetime
1	232	340	1946597	0	0.1809	71	4
2	245	345	2005176	4.565E-05	0.1863	92	4
3	272	42	2037659	1.863E-03	0.1894	807	4
4	271	43	2042873	1.878E-03	0.1900	808	4
6	270	42	2047497	2.379E-03	0.1903	816	4
8	272	47	2048523	1.179E-03	0.1904	808	4
10	279	53	2097214	3.876E-03	0.1950	798	4

Table 12 *Robust solutions for 200 kW generator, 0% scenario*

Average power outage duration [h]	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]	Annual generator operating hours [h]	N° of replacements per lifetime
1	227	449	1939249	0	0.1802	0	4
2	243	356	2032266	0	0.1889	82	4
3	276	126	2105371	0	0.1956	696	4
4	275	125	2116784	0	0.1967	710	4
6	277	125	2126237	0	0.1976	722	4
8	279	126	2127355	0	0.1977	717	4
10	278	123	2129273	0	0.1979	722	4

Table 13 *Robust solutions for 250 kW generator, 0% scenario*

From the table it is evident that the operating hours of generator per year are high for power outages exceeding 2 hours. Having imposed as initial hypothesis that 10% of the year is affected by a detachment of the micro-grid from the national electricity grid, power outages correspond to 876 hours per year. On average, the 200 kW generator is working for 807 hours, while the 250 kW generator for 713 hours, covering 92% and 81% of the 876 hours respectively. The fundamental role of the generator is therefore clear, capable of supporting batteries and photovoltaic panels throughout the whole year.

As previously introduced, 1h and 2h blackouts prefer to rely just on PV and BESS, with consequent reduction of the operating hours of diesel generator.

For an immediate comparison among the off-grid (Case 0) and the different micro-grid studied configurations, the percentage variations %Δ of the main parameters are gathered in the following **Table 14**.

%ΔPV	%ΔBESS
%ΔLCoE	%ΔLLP

		Case 0	
200kW	1h	-82.88%	-88.91%
		-61.34%	-100.00%
	2h	-81.92%	-88.45%
		-60.18%	-99.91%
	3h	-79.93%	-98.63%
		-59.52%	-96.27%
	4h	-80.00%	-98.60%
		-59.39%	-96.24%
	6h	-80.07%	-98.63%
		-59.33%	-95.24%
	8h	-79.93%	-98.47%
		-59.31%	-97.64%
	10h	-79.41%	-98.27%
		-58.32%	-92.25%

		Case 0	
250kW	1h	-80.60%	-84.36%
		-60.66%	-100.00%
	2h	-79.23%	-87.57%
		-58.76%	-100.00%
	3h	-76.41%	-95.60%
		-57.30%	-100.00%
	4h	-76.50%	-95.64%
		-57.06%	-100.00%
	6h	-76.32%	-95.64%
		-56.87%	-100.00%
	8h	-76.15%	-95.60%
		-56.84%	-100.00%
	10h	-76.24%	-95.71%
		-56.80%	-100.00%

***Table 14** Comparison of the mean robust results with the off-grid ones (Case 0)*

For each power outage duration there is a box divided into 4 cells: on the top left is the percentage variation of PV average robust solution with respect to the off-grid ones, $\%\Delta PV$, as reported in Equation 7.1. Similarly, the variations of BESS, LCoE and LLP are evaluated.

$$\%\Delta PV = \frac{\overline{PV_{n,rbt}} - \overline{PV_{off-grid,rbt}}}{\overline{PV_{off-grid,rbt}}} * 100 \tag{7.1}$$

Transition from an off-grid system to a micro-grid one not only influences technological solutions, but is able to reduce losses and at the same time reduces the specific cost of energy, with consequent considerable savings during the LT.

A substantial reduction in battery usage is highlighted, showing $\%\Delta BESS$ close to 99% for the 200 kW gen-set and 96% for the 250 kW, for power outage lasting higher than 2 hours. The same consideration can be made with regard to photovoltaic panels, with $\%\Delta PV$ around 80% for the 200 kW gen-set and 77% for the 250 kW.

7.3 Support for the decision makers

To make the comprehension of the above results easier, useful and effective to define the best option, a further analysis is required:

1. LCoE ranking.
2. Robustness evaluation.
3. Loss of load in terms of energy.
4. Trade off finding among LCoE, robustness of the solutions and LLP.

LCoE ranking

With reference to **Table 12** and **Table 13**, the specific energy costs for the 200 kW generator are lower than those obtained with a 250 kW, except in the case of a 2 hour average power failure. Moreover, once the generator is fixed, as the average duration of the interruption increases, the energy satisfied by the national grid decreases, leading to higher energy expenditure.

A purely economic decision would encourage the purchase of the small generator regardless the power outage average duration.

Robustness evaluation

For every single case under investigation, the distribution of the obtained robust results (PV_{rbt} and $BESS_{rbt}$) allows to identify their variability and, for this purpose, **Table 15** reports the corresponding standard deviations.

Standard deviation

Gen-set	200 kW		250 kW	
Average Blackout duration [h]	PV	BESS	PV	BESS
1	4.17	71.82	1.39	4.44
2	3.14	3.59	3.08	6.94
3	3.76	0.73	3.84	2.22
4	5.04	0.83	6.26	0.75
6	5.33	0.85	5.37	0.14
8	3.93	1.31	5.39	2.98
10	4.33	1.04	7.80	1.01

Table 15 *Standard deviation of robust solutions*

Analysing the obtained values, no critical gaps are identified, i.e. there is no significant difference between the reported standard deviations, except for the case 1 hour 250 kW. Nevertheless, the more reliable solutions are labelled in red, bringing again the choice in favour of the small generator for most of the cases.

LLP in terms of energy

Starting from the 200 load power outage profiles, the average yearly energy required during these time lapses allows to understand the eventual amount of unmet load (**Table 16**).

Average power outage duration [h]	Yearly Blackout Energy [kWh]
1	93825
2	93683
3	94033
4	93967
6	93583
8	94117
10	94383

Table 16 *Average energy demand during power outages, 0% scenario*

No relevant variation among different power outage durations are highlighted, due to the casualty of their occurrence. In terms of energy losses, reference is made to **Table 17**.

Average power outage duration [h]	**Yearly Blackout Energy [kWh]**	
Gen-set	**200 kW**	**250 kW**
1	0	0
2	4	0
3	176	0
4	177	0
6	223	0
8	111	0
10	366	0

Table 17 *LLP in terms of energy per year [kWh]*

Considering that the average daily energy demand is around 2570 kWh, the employment of 200 kW generator corresponds in the worst case to 4 hours of unmet load per year, while the 250 kW provide zero losses.

Finding the trade-off among LCoE, robustness of the solution and LLP

Given these findings, the three of them must be compared simultaneously. For what concerns the LCoE the 200 kW generator prove to be the best performing, even though it differs from the 250 kW only by 0.01€. Focusing on the robustness of the solutions, it belongs to the 200 kW generator. Nevertheless, the Loss of Load related to the 200 kW generator cannot be admissible for a Hospital and, in case of total absence of PV and BESS (maintenance works or sudden breakage of a component), the 250 kW generator can supply the total demand by itself. The last considerations lead to prefer a higher expenditure to ensure a better continuity of the service, so the 250 kW is chosen as the best one.

7.4 Detailed description of the selected option: 250kW

For the chosen solution, assuming that the load will not increase over the years, a focus on the BESS cycles behaviour and on dispatching strategy is undergone.

According to the obtained results, the analysis is split into two groups:

- Short power outages (1h- 2h)
- Long power outages (3h- 4h- 6h- 8h- 10h)

This division is consistent with the different usage of the generator and of the BESS size.

1h – 2h Blackout lasting

Figure 52 shows the behaviour of cycles of charge and discharge of the BESS throughout the day, for all days of the year. The beginning of a coloured band identifies the occurrence of an interruption, even if the figure does not allow to understand when such event ends, since the batteries are also recharged by the national electric network.

The use of the batteries, depending on the SOC reached, is more marked during the evening hours, since during the day part of the load is satisfied by photovoltaic panels. The latter are able to meet a large part of the load, requiring less battery effort.

For 1h case, it is noticeable how the size of the batteries prevents the SOC to reach critical values. On the other hand, for 2h case, BESS are exploited to their full potential, especially in the evening hours, as visible from the dark red in the top part of the figure, leading sometimes the turning on of the generator.

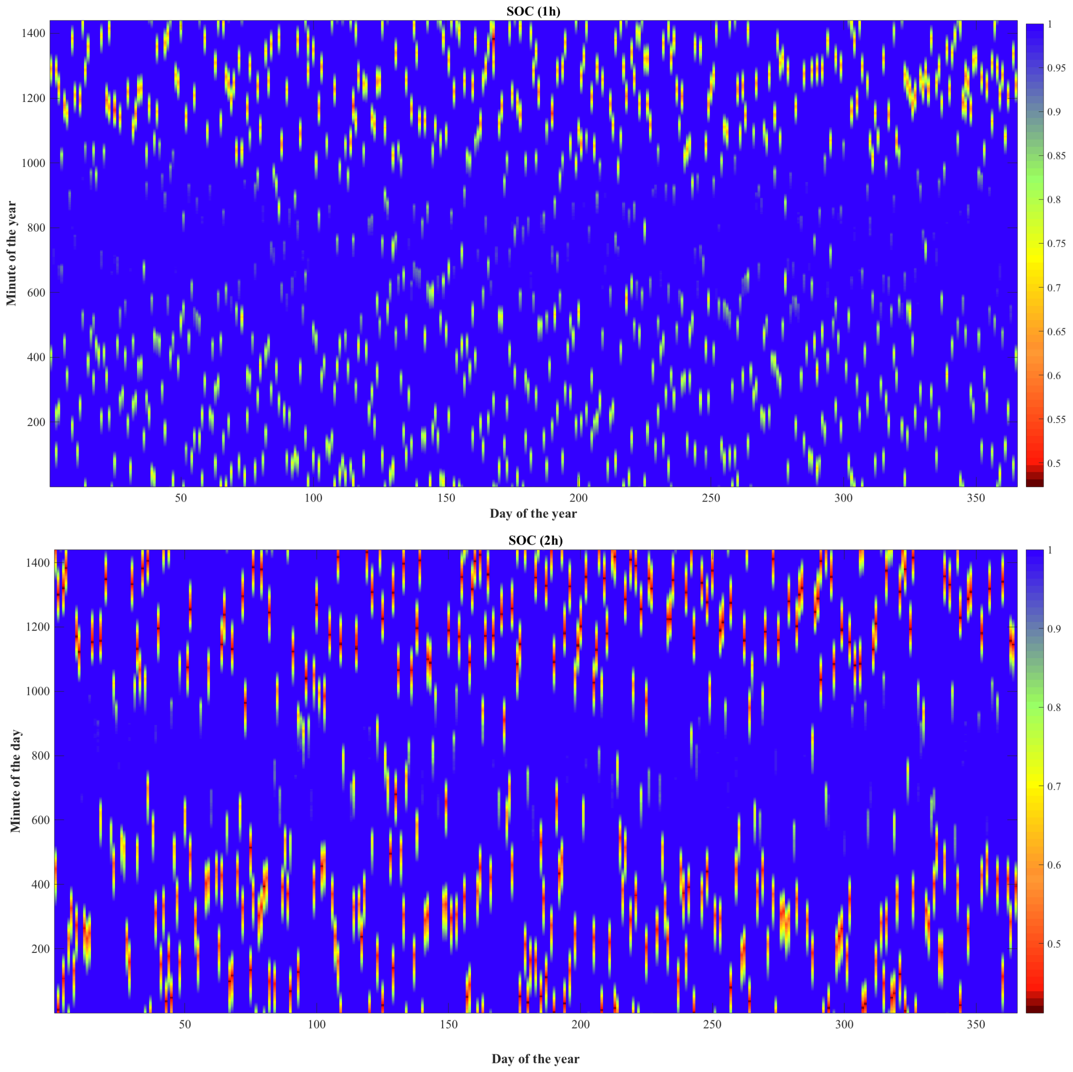


Figure 52 *SOC trends for short average duration of power failure, 250 kW*

To better understand the details of how the dispatching strategy acts, the kWh trends of PV, BESS, SOC, generator, national grid and loss are displayed in **Figure 53**. The dotted green line represents the charge status of the battery pack and is reported as an identifier of the occurrence of a possible power failure, since the batteries are used only in this circumstance. For both the cases, BESS plays a leading role, especially when 1h blackouts occur, being the generator never used. When the average power failure lasting is of 2 hours, the gen-set is just ancillary and intervenes in the last few minutes every time is required. This means that batteries are almost always able to withstand until the end of the power failure without reaching the SOC_{min}, except for some cases during the evening.

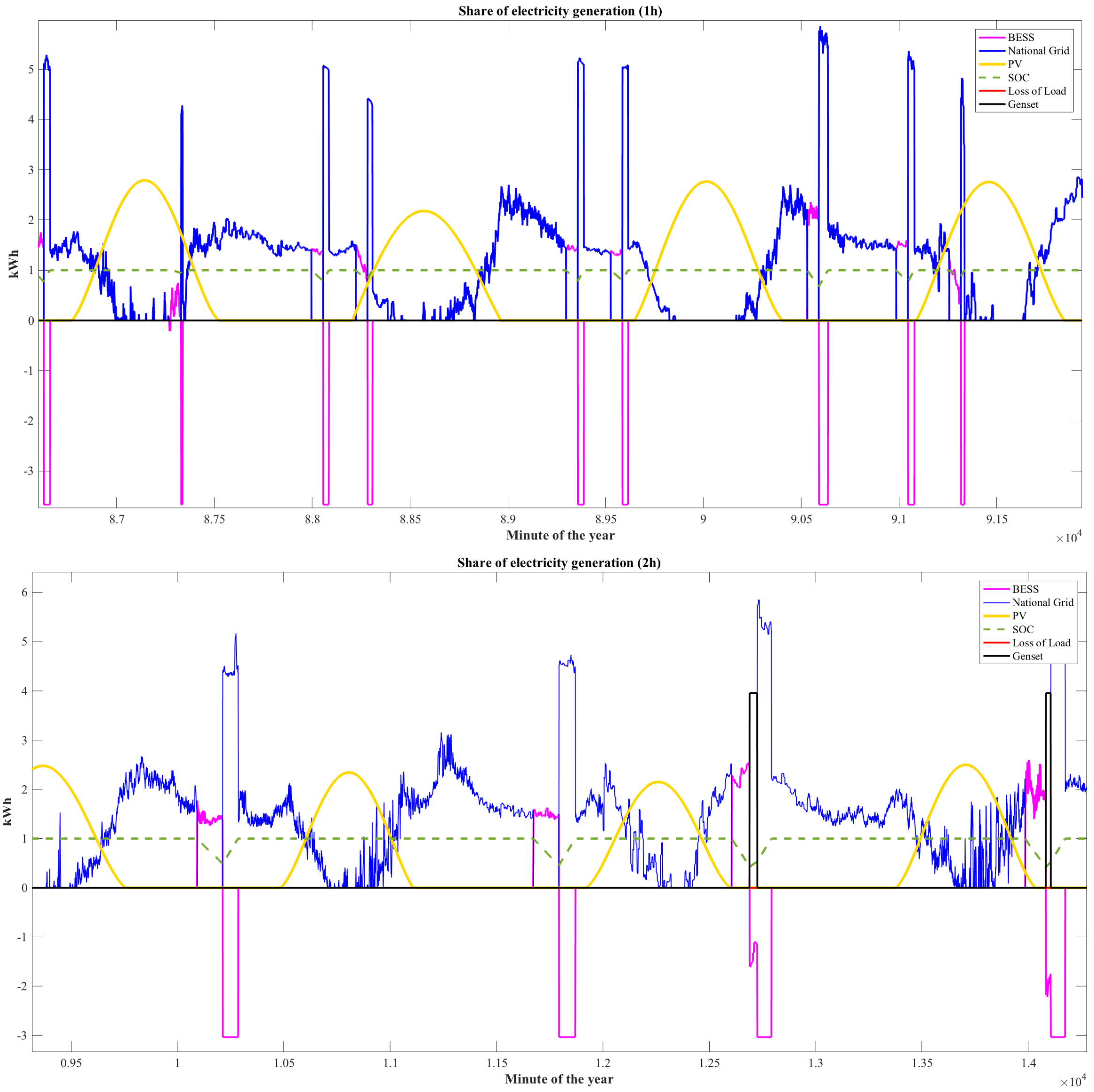


Figure 53 *Example of share of electricity generation for 1h and 2h power outages, 250 kW generator*

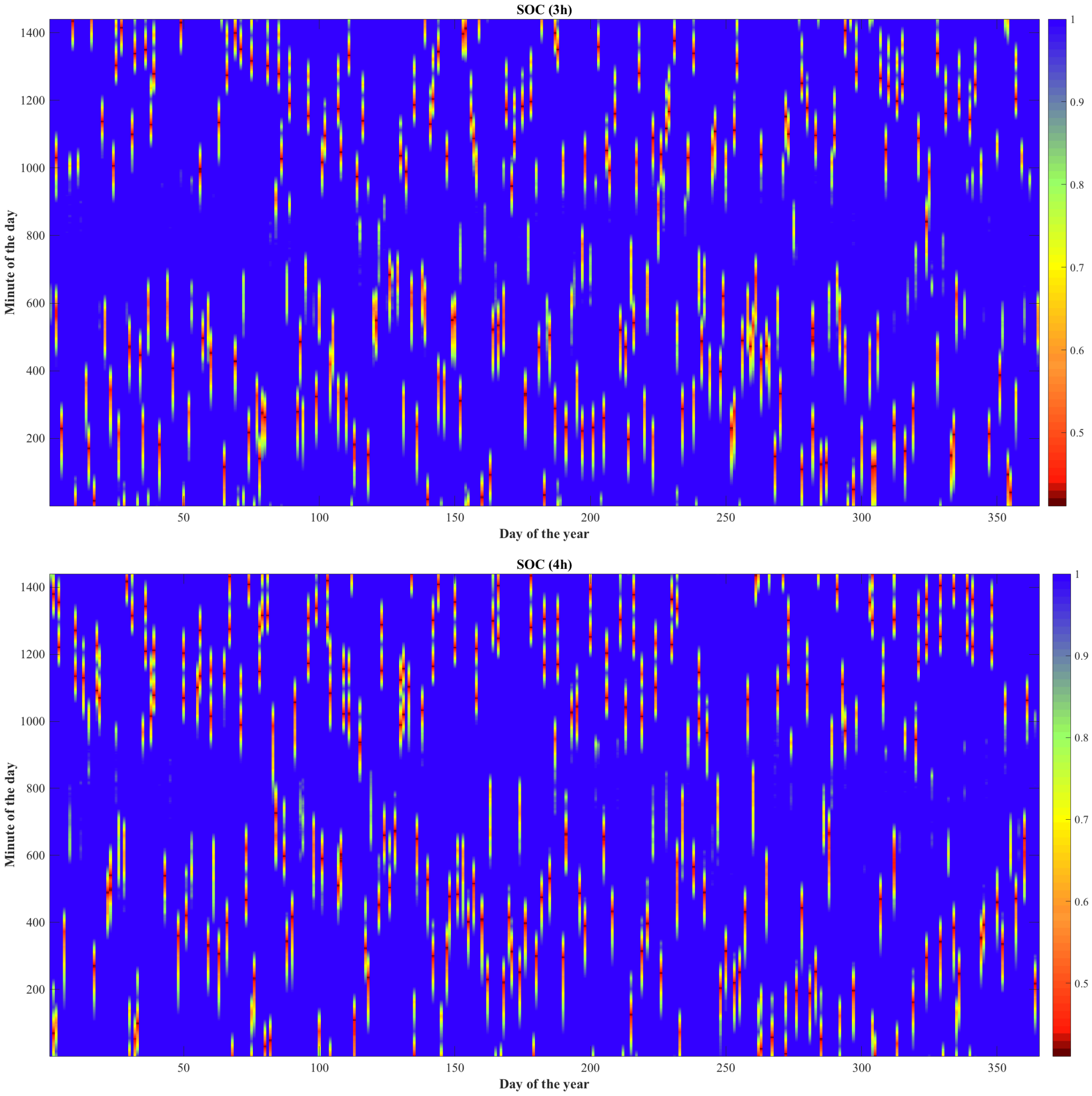
In addition, the BESS charge is predominantly provided by the national grid and PV.

The abundance of PV power production allows to minimize the requirement of energy withdrawal from the national grid during the daily hours.

3h- 4h- 6h- 8h- 10h Blackout lasting

The same kind of analysis can be carried out for longer power failures, highlighting the strong difference with respect to the short ones.

The trends of BESS cycles in **Figure 54** bring out the importance of this technology throughout the day, regardless the presence of solar power. As their size is smaller than the previous ones, their discharge is slower because they are always coupled with the generator, reducing the energy output.



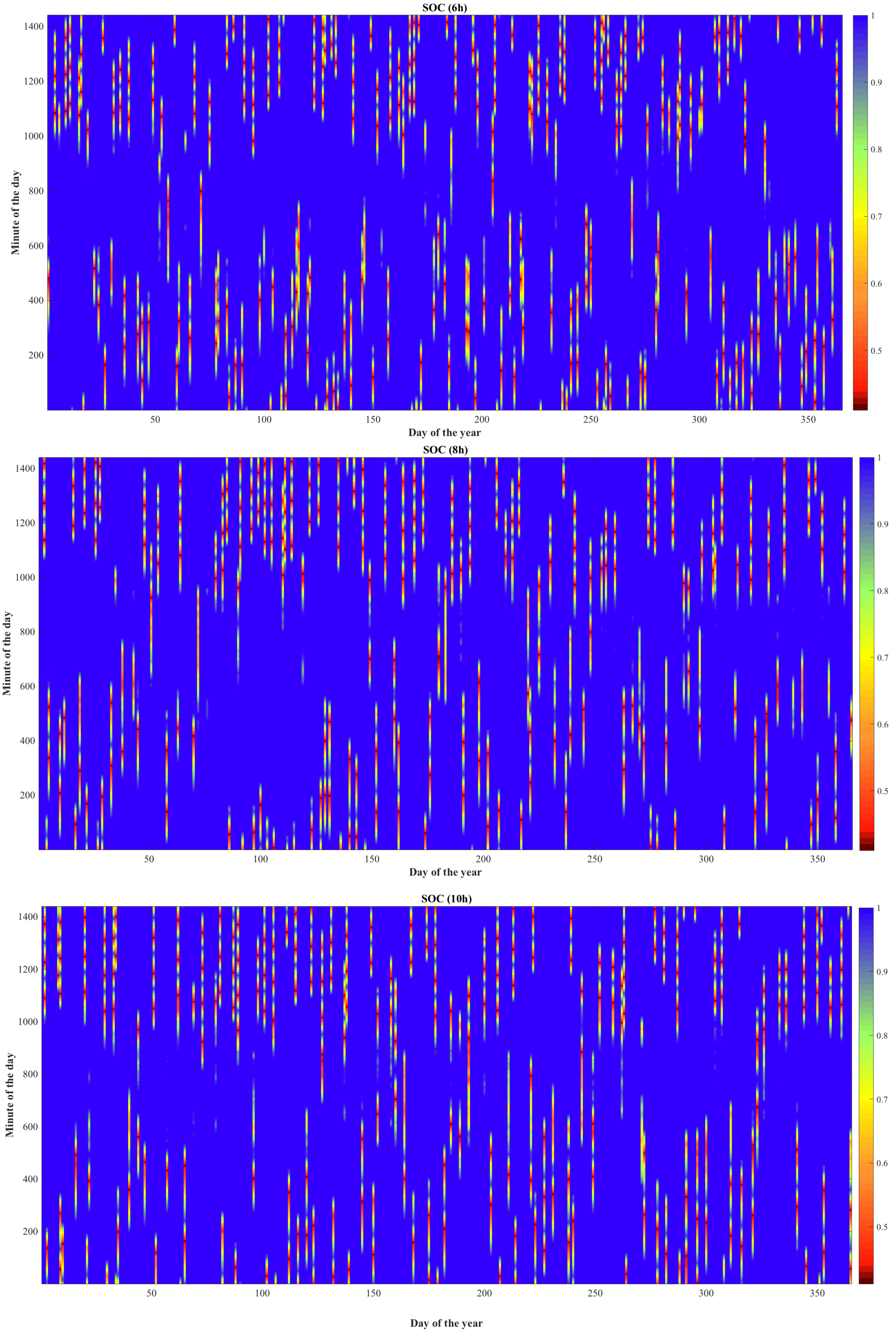
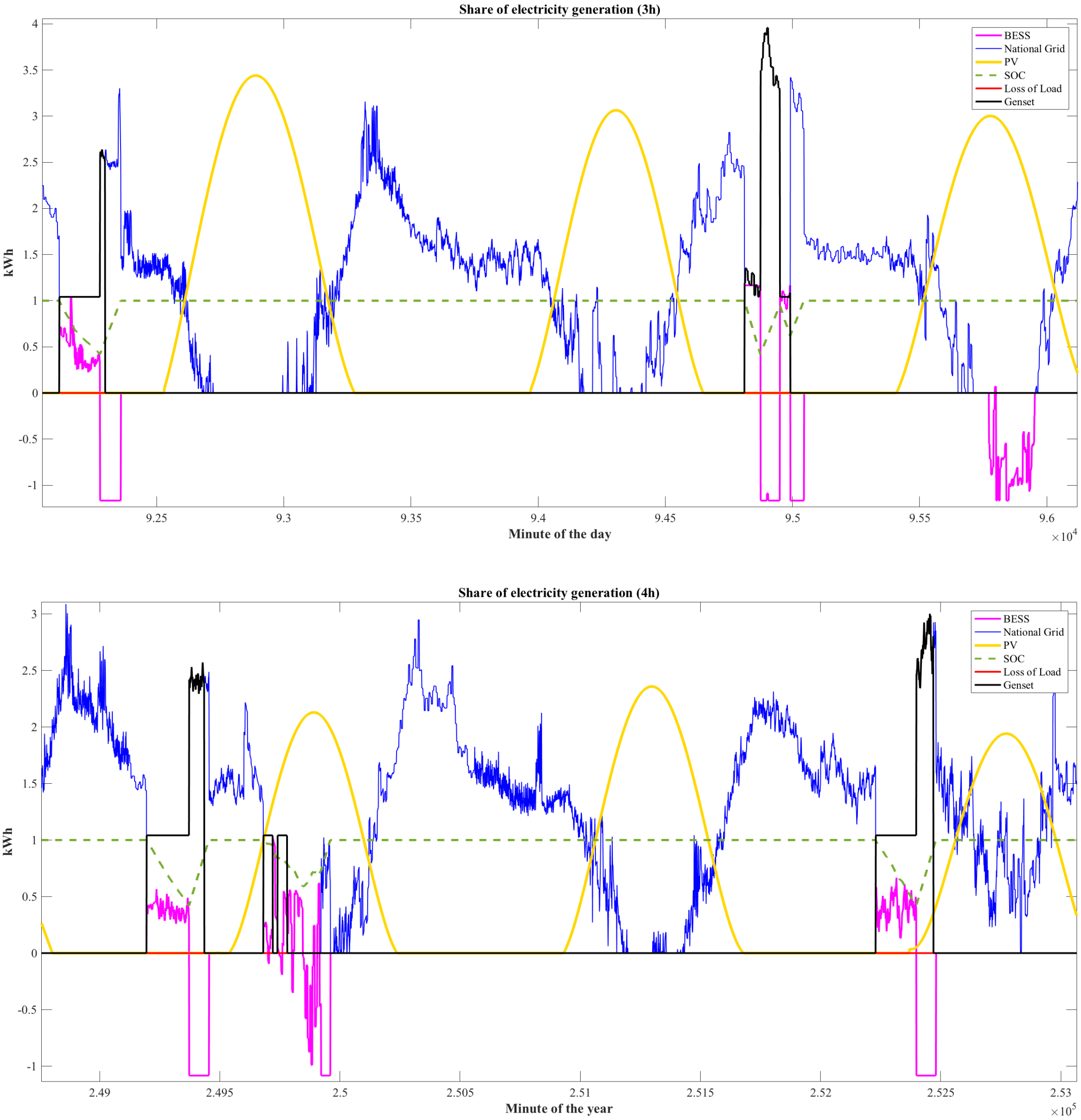


Figure 54 *SOC trends for long average duration of power failure*

As the blackout lasting increases, the number of BESS cycles per power outage increases as well, especially during the last hours of the day. This is due to the high load demand in the evening time frame and to the absence of solar radiation. In particular, recalling that $BESS_{rbt}$ is almost independent from power outage lasting (**Table 13**), from 3 to 10 hours the number of cycles per power outage goes from one to four (number of dark red spots per single blackout).

As before, it is useful to represent the energy output supplied by the different sources over time (**Figure 55**).



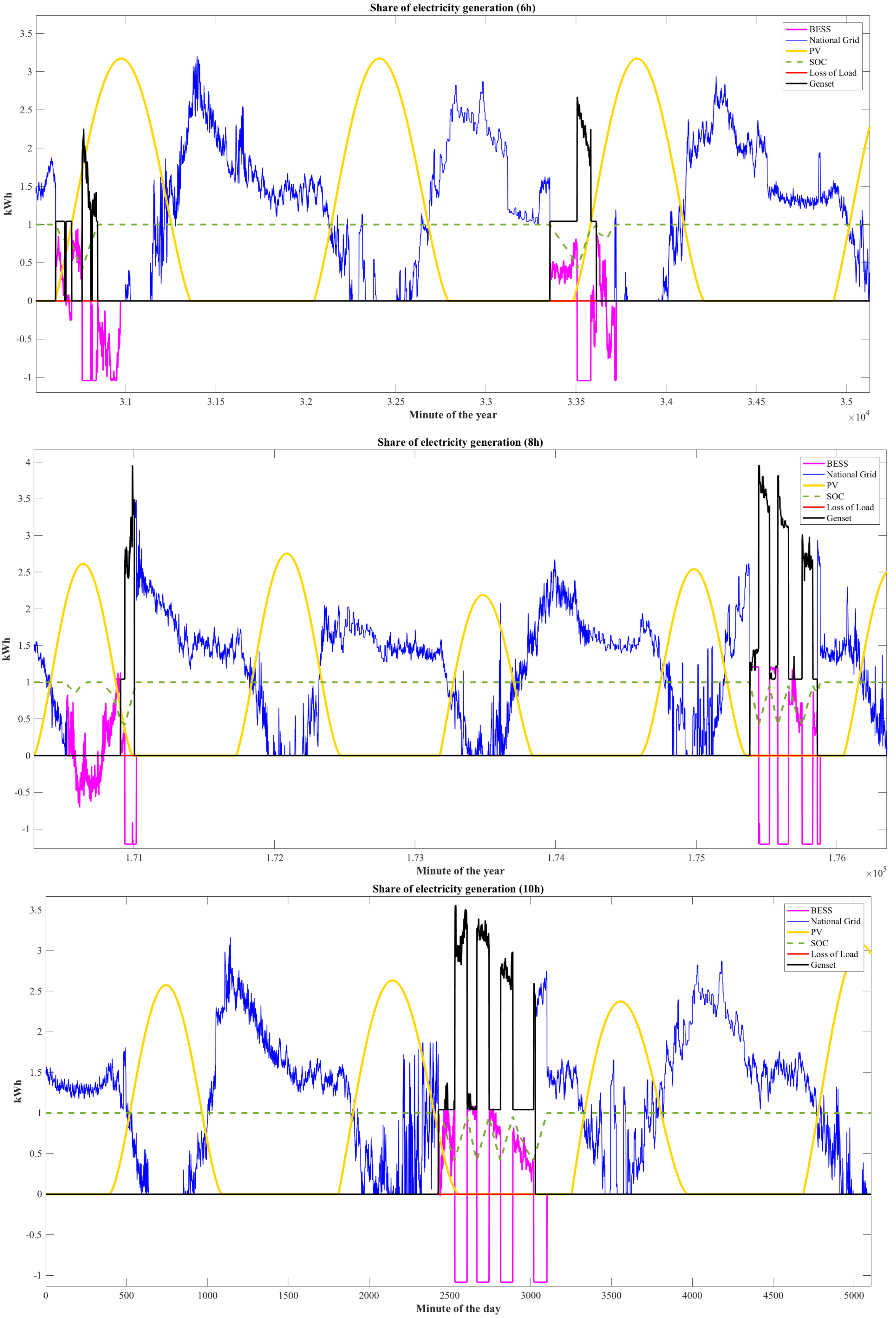


Figure 55 *Example of share of electricity generation for 3h, 4h, 6h, 8h and 10h power outages, 250 kW generator*

In the presence of the national grid, most of the load is satisfied by the photovoltaic panels, bringing the energy demand from the national grid to zero when solar radiation is high. Each time the system is disconnected from the network, if solar radiation is abundant, BESS could satisfy the residual demand or gen-set is required at most to run at its minimum rated power. The predominant usage of the generator occurs after twilight, when batteries by themselves could never cope with the entire demand.

After the national grid is restored, the batteries, if necessary, are charged as fast as possible to be prepared for the next power outage, respecting the maximum charge limit.

As the system is optimised to manage as effectively as possible energy during power outages, it can occur sometimes that solar production is in surplus, leading to excess energy dissipation.

It may also happen that solar penetration is so high that batteries can be recharged during the blackout whenever their SOC is lower than SOC_{max}, as can be seen for the case “8 hours average power failure” reported above.

Figure 55 also proves what stated before about the number of charge / discharge cycles during the same blackout. This behaviour, linked to generator capability to recharge the batteries, allows them to reach the end of the power failure with a good SOC and be faster ready for the next one.

Since power failure, by definition, is not predictable, there is no possibility to estimate in which part of the day it will occur.

7.4.1 Selected technological combination

Comparing the Hospital requirements, authors personal experience on the field and obtained results, some considerations can be made:

- Past experience led the administration to prefer a system solution characterized by an increasingly low presence of batteries, due to their high investment cost and short lifetime.
- During the authors staying the duration of power outages was most of the times longer than three hours.
- Technological robust solutions for power failures lasting more than two hours do not show substantial differences, making this mix flexible to several conditions. Regardless the duration of blackout, the micro-grid will be able to satisfy the demand

without any problem.

In the light of the above, the selected solution corresponds to the 4 hours (**Table 18**), which represents a good compromise between the obtained results.

Hours	PV [kWp]	BESS [kWh]	NPC [€]	LLP [-]	LCoE [€/kWh]	h gen per year	N° of replacements per LT
4	275	125	2116784	0	0.1967	710	4

Table 18 *Final selected technological combination*

7.5 Techno-economic evaluation for the selected solution

Referring to the robust solutions related to 250 kW diesel generator for a hypothetical blackout lasting of 4 hours, the main results are reported in **Table 18**.

So far, it is interesting to evaluate the effectiveness of the investment with respect to the current expenditure in Lacor Hospital: the financial statement for the year 2016 points out that 180,000 € is the energy related expenditure [42].

Table 19 shows the details of the discounted to year zero cash flows over the expected lifetime of the micro-grid (6% interest rate), under the hypothesis of installing a completely new micro-grid.

Year	Capital cost	Replacement cost	National Grid Bills	Fuel Cost	O&M Cost	Overall annual cost	Current Expenditure	Cash Flow	Cumulative Cash Flow
0	-633838	0	0	0	0	0	180000	-453838	-453838
1	0	0	-74665	-19807	-16391	-110863	169811	58948	-394890
2	0	0	-70899	-18818	-15463	-105180	160199	55019	-339871
3	0	0	-67344	-17878	-14588	-99810	151131	51321	-288550
4	0	0	-63978	-16980	-13762	-94720	142577	47856	-240693
5	0	-22418	-60798	-16104	-12983	-112303	134506	22203	-218490
6	0	0	-57793	-15282	-12248	-85323	126893	41569	-176920
7	0	0	-54933	-14567	-11555	-81055	119710	38655	-138265
8	0	0	-52243	-13834	-10901	-76978	112934	35956	-102309
9	0	0	-49688	-13152	-10284	-73124	106542	33418	-68891
10	0	-16752	-36263	-12537	-9702	-75254	100511	25257	-43634
11	0	0	-55973	-11939	-9153	-77065	94822	17757	-25877
12	0	0	-42804	-11361	-8635	-62800	89454	26655	778
13	0	0	-40745	-10825	-8146	-59716	84391	24675	25453
14	0	0	-38804	-10282	-7685	-56771	79614	22843	48296
15	0	-12518	-36953	-9793	-7250	-66514	75108	8594	56890
16	0	0	-35199	-9317	-6839	-51355	70856	19501	76391
17	0	0	-33512	-8917	-6452	-48881	66846	17964	94355
18	0	0	-31912	-8528	-6087	-46527	63062	16535	110890
19	0	0	-30395	-8155	-5743	-44293	59492	15200	126090
20	0	-9354	-28967	-18753	-5418	-62492	56125	-6367	119723

Table 19 *Payback period evaluation for 4h power outage solution, 250 kW*

The heading "Current Expenditure" is calculated under the hypothesis of constant annual electricity expenditures. Moreover, PV system is supposed to exceed 20 years, so no replacement of the present panels will be considered.

Below, the cash flow related to the purchase of only 125 kWp PV plant (instead of 275 kW_p), 125 kWh BESS and 250 kW gen-set is proposed (**Table 20**).

Year	Capital cost	Replacement cost	National Grid Bills	Fuel Cost	O&M Cost	Overall annual cost	Current Expenditure	Cash Flow	Cumulative Cash Flow
0	-357838	0	0	0	0	0	180000	-177838	-177838
1	0	0	-74665	-19807	-16391	-110863	169811	58948	-118890
2	0	0	-70899	-18818	-15463	-105180	160199	55019	-63871
3	0	0	-67344	-17878	-14588	-99810	151131	51321	-12550
4	0	0	-63978	-16980	-13762	-94720	142577	47856	35307
5	0	-22418	-60798	-16104	-12983	-112303	134506	22203	57510
6	0	0	-57793	-15282	-12248	-85323	126893	41569	99080
7	0	0	-54933	-14567	-11555	-81055	119710	38655	137735
8	0	0	-52243	-13834	-10901	-76978	112934	35956	173691
9	0	0	-49688	-13152	-10284	-73124	106542	33418	207109
10	0	-16752	-36263	-12537	-9702	-75254	100511	25257	232366
11	0	0	-55973	-11939	-9153	-77065	94822	17757	250123
12	0	0	-42804	-11361	-8635	-62800	89454	26655	276778
13	0	0	-40745	-10825	-8146	-59716	84391	24675	301453
14	0	0	-38804	-10282	-7685	-56771	79614	22843	324296
15	0	-12518	-36953	-9793	-7250	-66514	75108	8594	332890
16	0	0	-35199	-9317	-6839	-51355	70856	19501	352391
17	0	0	-33512	-8917	-6452	-48881	66846	17964	370355
18	0	0	-31912	-8528	-6087	-46527	63062	16535	386890
19	0	0	-30395	-8155	-5743	-44293	59492	15200	402090
20	0	-9354	-28967	-18753	-5418	-62492	56125	-6367	395723

Table 20 *Payback period evaluation for 4h power outage solution, 250 kW, specific to Lacor Hospital*

Switching from the current Hospital situation to the proposed one allows to recoup the investment in 3.3 years (payback time). In addition, the quality of the electrical service will increase, since during a power failure by night the whole Hospital will be powered, not only the emergency line as it works so far. The optimized management of the energy technologies guarantees saving of 395,723 € at the end of 20 years.

Such a short payback time can be addressed to the current not optimized energy mix of the Hospital: being the present generators oversized with respect to the Hospital load trend, they run far from their optimal range, increasing their specific consumptions (€/kWh). Furthermore, according to Chapter 4.3, the measured specific generator consumptions (0.40

€/kWh) are higher than the assumed one (0.34 €/kWh) for the simulations.

Finally, the current Hospital configuration turns out to have low efficiencies of the equipment, because of their deterioration over the years and the incorrect combination among the technologies.

7.6 Discussion on the possible issues with the selected option

One of the main hypothesis of the dispatching strategy provides for the immediate ignition of the diesel generator. However, it requires about 30 seconds to effectively supply energy to the micro-grid. Being BESS chosen size of 125 kWh and having a power to energy factor of 0.5 kW/kWh, for the first 30 seconds they could not be sufficient to provide the unmet demand by the PV panels. It could be advisable to oversize BESS up to 450 kWh, which is the average robust solution for one-hour blackout. Similarly, to give an indicative size of BESS that would be able to power the Hospital for half a minute limiting loss of load, it is interesting to carry out a statistical investigation about the times in which the Hospital load, except for that provided by 275 kWp PV, is higher than different thresholds.

As displayed in **Table 21**, the minimum load that BESS should satisfy to minimize the losses is 160 kW, which is overcame only for 0.5% of the year, assuming a maximum k_{BESS} equal to 0.5. The corresponding BESS capacity would be of 320kWh, but such a choice would imply an additional investment cost of about 45,000 €, which must be repeated every five years. This hypothetical solution would bring to use the generator for less hours, consuming less fuel. Nevertheless, its optimal range of function could be no longer guaranteed.

Load Max [kW]	Annual Probability [%]
120	11.3
130	6.1
150	1.3
160	0.5

Table 21 *Annual average probability of load demand overcoming different imposed thresholds*

If, for economic reasons, there is no intention of increase the size of the batteries, a control system could isolate no priority electric lines for 30 seconds, until the generator turns on. In the specific case of St. Mary Hospital, powering only the wards and the administrations, excluding all the residences for few seconds, would reduce significantly the load demand: such a solution would not require any BESS oversizing.

7.7 Computational effort

The evaluation of the energy balances with a one-minute time step, the complex energy dispatching strategy and the lifetime of the plant have resulted in a considerable computational effort by Poli.NRG. The advantages involved in using such a small time-step derives from:

- BESS performances, which are strictly time dependent. The better comprehension of SOC variation in time allows to identify more precisely the number of charge/discharge cycles, thus the Cycles to Failure and the correlated necessity to substitute the batteries if required.
- Ability to simulate energy demand more truthfully, reducing the approximations and showing any further load peaks during the day.
- Better management of functioning operating parameters of diesel generator, such as its minimum operating time.
- Improved identification of possible technological incompatibilities and consequent related loss of load.

The choice of the maximum acceptable LLP by the user and the convergence criteria are also critical and can amplify the required time: stringent LLP values lead to increased calculation times, as a result of difficulties in finding the best robust solutions.

Three different personal computers with the following technical components (**Table 22**) have been used for the calculations:

	RAM	**Processor**
Personal computer 1	8 GB 1600 MHz DDR3	2.6 GHz Intel Core i5
Personal computer 2	8 GB 2.400 MHz DDR4	2.7 GHz Intel Core i5
Personal computer 3	6 GB 664 MHz DDR3	3.40 GHz Intel Core i7

Table 22 *Technical Specifics of used devices*

Starting from the “off-grid” case, the time required for the simulation of the lifetime and the evaluation of all the robust solution is showed in **Table 23**. It is recalled that in the simulations, to check the robust solutions many lifetime scenarios are evaluated.

Single Lifetime simulation [min]	Total Computational time	N° of Lifetime scenarios
12	5.40h	28
9	4.20h	28
10	4.40h	28

Table 23 *Off-grid computational time*

It is evident how different calculator processors and RAM influence the required computational time.

Considering the micro-grid system, the calculation time per lifetime is increased, thereby increasing the total time needed to achieve convergence as well. As different power failure durations and gen-sets have been investigated, the number of robust solutions needed to verify the convergence criterion is different. By way of example, the 250kW generator, 4 hours average power lasting required the processing of 50 different lifetime scenarios with a consequent computational effort reported in **Table 24**.

	Single Lifetime simulation [min]	Total Computational time
Personal computer 1	26	22:40h
Personal computer 2	19	16:50h
Personal computer 3	20	17:50h

Table 24 *Micro-grid computational time, 250 kW, 4h power outage*

The overall time required to satisfy the convergence criteria for all the examined cases amounts to 192 hours, which approximately correspond to 8 continuous days of computation.

Conclusions

The aim of the thesis is to provide a methodology capable of replicating national grid connected micro-grid systems, mainly made of photovoltaic panels, battery energy storage systems and diesel generators. Recognising the importance of electrification as promoter of development, especially in low income countries, a literature review about the current status is carried out. One of the most critical aspect that comes out from it is the substantial absence of data in developing countries, implying relevant difficulties in electrification projects. For example, there are no information about Ugandan grid reliability neither in terms of yearly frequency or average duration.

Since micro-grid application is widely acknowledged by the international community as the best solution for rural electrification, the focus shifted to the investigation about its state of the art and possible related issues in its design (minimum generator power output, total harmonic distortion).

A model able to combine the technological and economic aspects of micro-grid has been developed. The proposed methodology can simulate either the presence or the absence of the national grid and the relative dispatching strategy of the technological combination.

When the national grid is available, it contributes to the residual energy demand which is not satisfied by PV panels and eventually recharge the batteries if they were discharged during a previous blackout. Every time a power outage occurs, the only energy sources are PV, BESS and diesel generator. PV plays a pivotal role and, whenever it is not sufficient, BESS is activated. Generator task is to supply the eventual unmet load and to charge the batteries, if necessary.

The dimensioning and optimizing tool chosen to implement the described model has been solved adopting Poli.NRG package, developed by Politecnico of Milan for off-grid systems made of PV and BESS. It has been adapted and integrated for the new micro-grid dispatching strategy, adding the national grid, its reliability and diesel generator.

To test the effectiveness of the proposed model, the case of St. Mary's Lacor Hospital, Gulu, Uganda has been chosen. A data collection campaign on the field has been undergone by the authors from April to June 2017. During that internship, present technologies, load demand, power quality and electric schemes have been assessed, to find the inputs for model implementation.

The unreliability of the Ugandan national grid and other collection issues required further efforts to obtain complete and correct load curves and blackout estimation matrix. Once the load profiles have been adjusted through a statistical methodology, together with solar radiation daily profiles and economic data have been inserted as input to run Poli.NRG. According to the average Hospital demand and load peak two generator sizes have been chosen, 200 and 250kW. In addition, being unable to predict the average duration of the power failures, for each generator size different outage periods have been simulated.

Results showed that short interruptions (1-2 hours) favour large BESS size and low usage of diesel generator, as BESS are able to almost always meet the total load demand for the entire blackout and to be recharged by PV and national grid.

On the other hand, long interruptions (3-4-6-8-10 hours) can be better managed adopting technical solutions strongly relying on gen-set instead than batteries. As compared to the previous situation, BESS and diesel generator work always in parallel finding a trade-off between batteries discharge and fuel consumption.

The advantage of a smaller generator is the lower NPC given by lower battery size, although this implies the presence of significant energy losses for healthcare facilities. The evaluation of the robustness of the solutions and LCoE would lead to choose a 200kW generator. However, the willingness to make the system as reliable as possible prompted authors to opt for the 250kW solution, also because the variation of LCoE between the two gen-set for the same blackout lasting is almost negligible.

Finally, the solutions related to short power outages have been skimmed according to personal experience on the field. Since the remaining solutions do not differ significantly among each other, an average size of PV and BESS have been chosen.

The cash flow analysis for the selected option shows a payback time of 12 years, comparing the current Hospital status (under the hypothesis to pay 180,000 €/y for energy expenditure) with the proposed new configuration.

Considering that the Hospital already owns a 150 kW PV plant, the investment cost is substantially reduced, bringing the payback time to only 3.3 years. The evident economic benefit and system reliability of the proposed micro-grid make such an investment very attractive.

The simulations allowed to validate the implemented model which proved to be solid and effective in supporting decision making about the best techno-economic solution. The latter is strongly influenced by the operative range constraints of diesel generator, tending to exclude the most harmful combinations for its proper functioning.

It would be interesting to couple the dispatching strategy with a per minute analysis of the power quality in terms of frequency and voltage. Clearly, this would imply a longer computational time, which at present is around 20 hours. Moreover, to make the model suitable for all the developing countries, other renewable sources should be integrated.

APPENDIX A

Link between energy and development

The increasing awareness of the role of energy as a promoter of development has led to the comparison of aspects about energy accessibility (primary or electricity) with socio-economic ones. Below are some remarkable examples of how to understand this possible correlation It should be remembered, however, that it is not appropriate to give hasty conclusions regarding the results highlighted by observing the graphs, as only a multidimensional analysis of the phenomenon allows a more truthful view of the possible correlations.

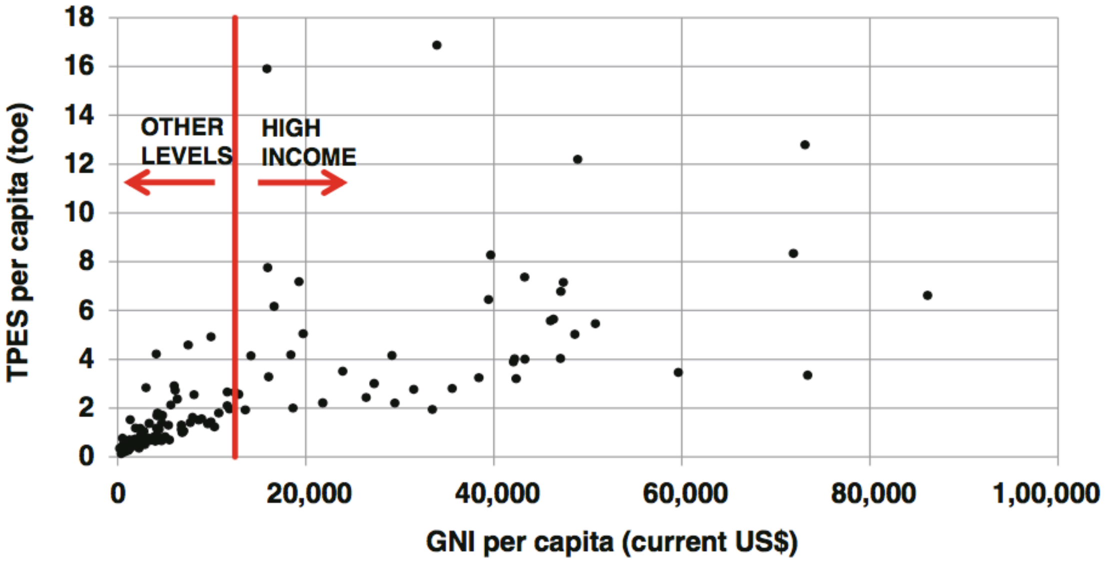


Figure 56 *Link between GNI(PPP) and Total Primary Energy Supply, 2012*

Figure 56 shows how economy and energy are interrelated. According to World Bank classification of the countries by their income, in all high-income ones the total primary energy supply is around 2 toe / per capita, while middle-low income countries are below this threshold (bottom left of the graph where points are less scattered). Developing countries are indeed subject to an underdeveloped productive sector, also because of the unreliability of the national electricity network, and considerable energy inefficiencies. Regarding the last thing mentioned, a clear example is the reliance on traditional cook-stoves, recognised as inefficient systems and, in addition, harmful to the health of users.

In **Figure 57** the advantages of electrification are clear: as the electric power consumption increases, the number of under five deaths decreases, because family members are able to provide better services for their survival, as well as better hygiene conditions.

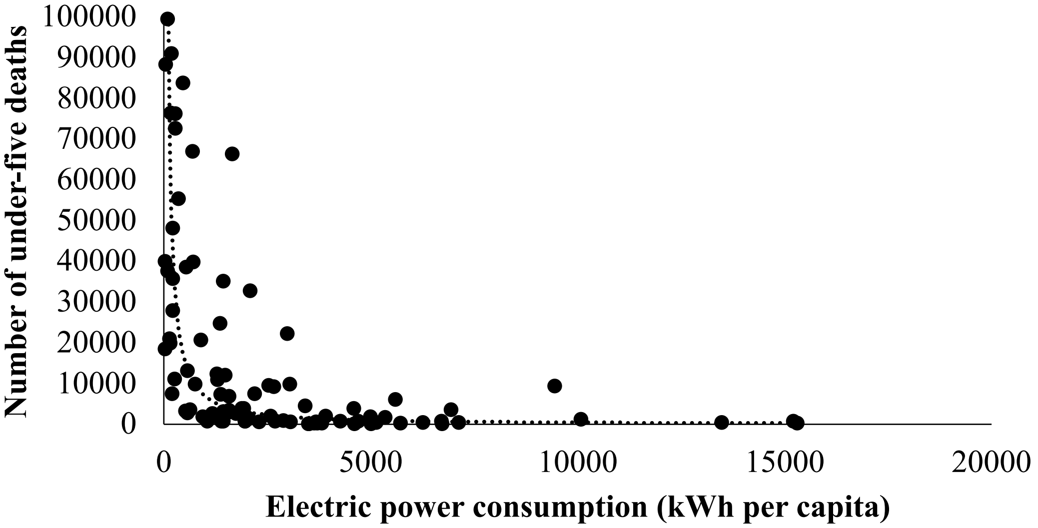


Figure 57 *Correlation between electric power consumption kWh per capita and number of under five deaths, 2014*

Figure 58 shows again how the increase in the electric power consumption is a promoter for the safeguard of children' life. However, there are points that differ particularly from the average trend in both the graphs, proving how, for example, the study of the electric power consumption is not sufficient to have an overall compression of the problem under study.

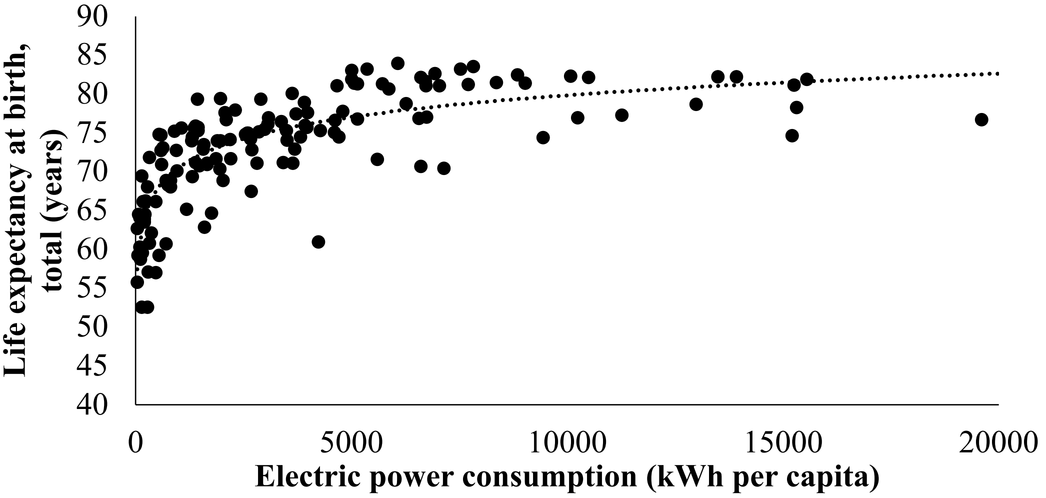


Figure 58 *Correlation between electric power consumption and life expectancy at birth, 2014*

Finally, the Human Development Index and the GNI per capita (PPP) are compared (**Figure**

59). The high correlation between GNI and the overall HDI is quite evident: it is not surprising, in fact, that economic growth constitutes the material basis for progress in other dimensions of development. Being a structured index, which includes several factors and different domains, HDI gives a truer picture of every country' reality.

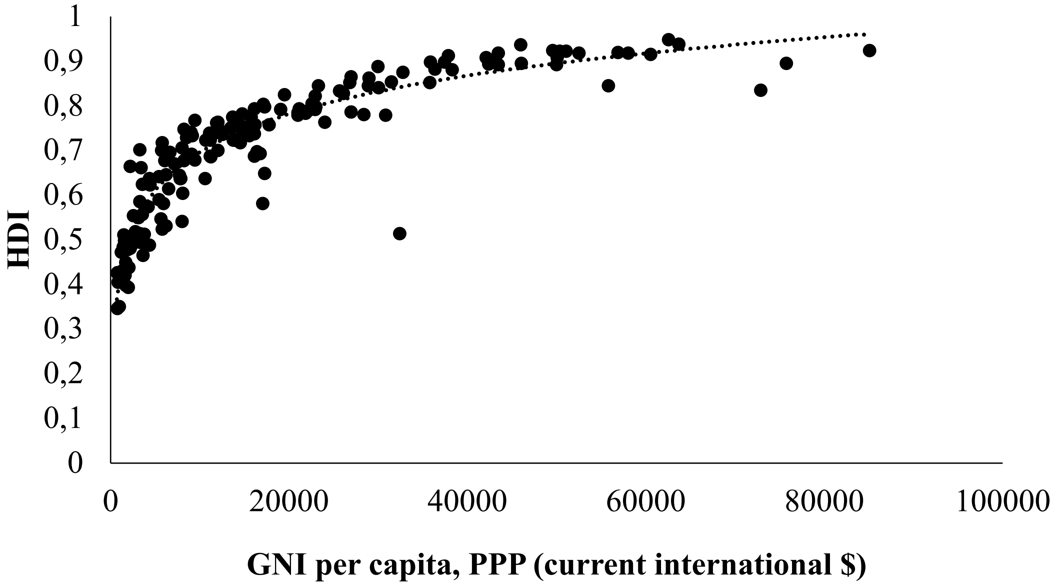


Figure 59 *Correlation between GNI(PPP) per capita and HDI*

APPENDIX B

Short introduction to harmonic distortion

The presence of harmonics in the micro-grid network is an indicator of current or voltage deformation; this means that the distribution of electrical energy occurs in a sub-optimal quality. In this case, the most sensitive equipment may be subject to malfunctions and the entire system may be exposed to additional stresses. Compared to what happened in a recent past, it is not only the industrial sector that is affected; now electrical installations in the tertiary and civil sector are frequently exposed to such "contamination" due to the type of loads, defined as non-linear, in which the relationship between voltage and current is no longer represented by a straight line, so its impedance changes with the applied voltage: these are devices like personal computers, printers, photocopiers, decoders, video equipment, which contain electronic components such as diodes, transistors, silicon controlled rectifiers, triodes for alternating current, AC/DC AC/AC DC/DC DC/AC converters, uninterruptable power suppliers (UPS) etc.

Harmonics are sinusoidal currents or voltages (IH, VH) with a frequency equal to a whole multiple of the distribution system frequency, called fundamental (50 or 60 Hz).

If added to the sinusoidal fundamental current or sinusoidal fundamental voltage respectively, harmonics distort its original waveform (**Figure 60**).

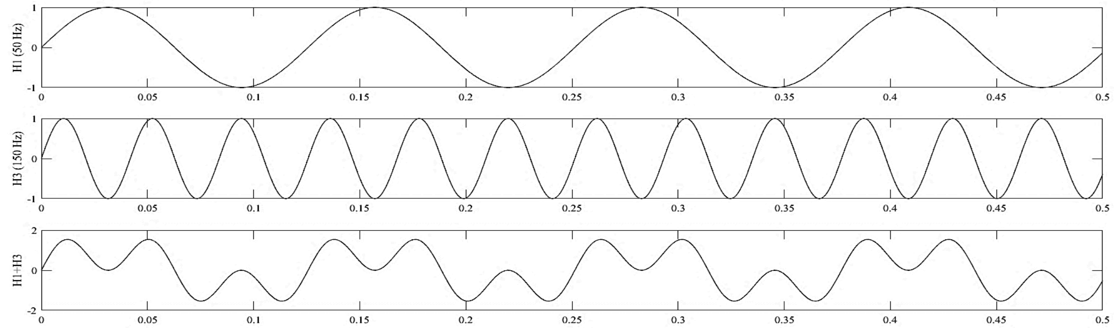


Figure 60 *Example of harmonic distortion*

They are usually indicated with H_k, where k represents the order, ratio between harmonic frequency and the fundamental frequency:

$$k = \frac{H_k}{H_1} \tag{B.1}$$

Harmonics are steady-state distortions to current and voltage waves and repeat every cycle, and their characteristic equation is structured according to the Fourier transform:

$$y(t) = Y_0 + \sum_{k=1}^{\infty} Y_k \sqrt{2} \sin{(kwt - \varphi_k)} \tag{B.2}$$

made up of the contribution of sinusoidal functions of different frequencies, where:

- $\mathrm{Y_0}$ is the value of Direct Current (DC) component;
- $\mathrm{Y_h}$ is the root mean square value of the harmonic of order h;
- ω is the angular frequency of the fundamental frequency;
- $\mathrm{\varphi_k}$ is the displacement of the harmonic component at t = 0.

Non-linear loads generate three types of harmonic currents, all odd in order (since the sinusoid is an "odd" function): positive sequence $7 + (\mathrm{k} - 1)\ 6$, negative sequence $5 + (\mathrm{k} - 1)6$ and homopolar sequence H3 and $3(2\mathrm{k} + 1)$. Even-order harmonics, if exceptionally present, are the sentinel of faults in power supply circuits, such as rectifier or variable speed driver malfunctions. Positive sequences are responsible for overheating system components, while negative sequences generate problems with the motor torque.

With regard to homopolar harmonic currents (H3, H9, H15, etc.), in three-phase systems are added together in the neutral conductor. This because their order is multiple of the number of phases 3, therefore they coincide with the displacement (one third of the period) of phase currents. In systems with distributed neutral (commercial and infrastructural applications), when harmonics are present, the neutral current is equal to:

$$I_1 + I_2 + I_3 = 3I_{H3} \tag{B.3}$$

resulting in overheating and voltage drops. The amplitude of the neutral current, due to homopolar harmonics, could exceed in amplitude the phase current at the mains frequency. In this case, the neutral current should be taken into account for the purpose of sizing the circuit cables.

The problem of neutral harmonics thus only appears under certain conditions, i.e. unbalanced loads or non-linear loads. If the system is symmetrical and balanced, the neutral conductor is not run through by any current and, according to Kirchhoff law:

$$I_1 + I_2 + I_3 = 0 \tag{B.4}$$

The harmonics of the third order are therefore very damaging to the system if present and require prompt intervention in order to avoid malfunctions or interruptions of the electrical service. However, current harmonics do not affect loads in the system which are linear. Variations in the current waveform result in a distortion of the voltage, more or less marked depending on the source impedance involved: if the latter is small, IH will generate negligible VH.

Harmonics, if not properly damped, could compromise the system, resulting in a number of problems, including:

- Reduction of the final power factor of the system;
- Overheating and dissipations;
- Equipment malfunctions and lifetime reduction;
- Generator failures linked to eddy currents and hysteresis in the iron core.

Homopolar harmonics generates also counter electromotive forces, acting in the opposite direction of motor rotation.

Indicators for the study of harmonics

Total harmonic distortion (THD) is an important index widely used to describe power quality issues in transmission and distribution systems [50]. THD can be formulated for both current and voltage and is defined as the ratio of total harmonic distortion to the reference frequency:

$$THD_I = \frac{\sqrt{\sum_{k=2}^{\infty} {I_k}^2}}{I_1} \tag{B.5}$$

$$THD_V = \frac{\sqrt{\sum_{k=2}^{\infty} {V_k}^2}}{V_1} \tag{B.6}$$

If THD_V has a value of less than 5%, which is to be regarded as normal, it is not necessary to take any action. If its value is between 5% and 8%, it means that a high degree of harmonics characterizes the system, and it is very likely that it will malfunction. If the value exceeds 8%, action must be taken to compensate, by means of appropriate systems, for the excessive presence of harmonics

A study carried out by the Canadian Electrical Association showed that a THD_V of 10% causes a decrease of 32.5% of the lifetime of monophasic appliances, 18% for three phase ones and 5% for transformers.

As regard to THD_I, acceptable values are in the range of 10%, while for values between 10% and 50% harmonics are overheating the system with consequent degradation of the electric equipment's in time. Values above 50% are unacceptable and destructive if they occur for long periods of time, requiring immediate action to damp these harmonics.

With regard to other useful indicators, the power factor is the ratio of active power P (kW) and apparent power S (kVA) at the ends of a given non-linear load:

$$\lambda = \frac{P}{S} \tag{B.7}$$

This is not the phase shift between voltage and current, because they are not more sinusoidal. The phase displacement between the basic current and voltage, both sinusoidal, can be defined as follows:

$$\cos\varphi_1 = \frac{P_1}{S_1} \tag{B.8}$$

where P_1 and S_1 are respectively the active power and apparent power of the fundamental. The identification of these new indicators is useful for the definition of a distortion factor, according to IEC 60146:

$$\nu = \sqrt{1 - \frac{1}{1 + THD^2}} = \frac{\lambda}{\cos\varphi_1} \tag{B.9}$$

When there are no harmonics, ν equals 1 and λ is simply equal to $\cos\varphi_1$.

The frequency spectrum, also called spectrum analysis is one of the classical representations of the harmonic content of a periodic parameter. It is a very practical graphic representation that allows to understand at a glance the presence of harmonics and whit what incidence.

The frequency spectrum is a histogram in which each harmonic present is represented in percentage value of the fundamental (**Figure 61**).

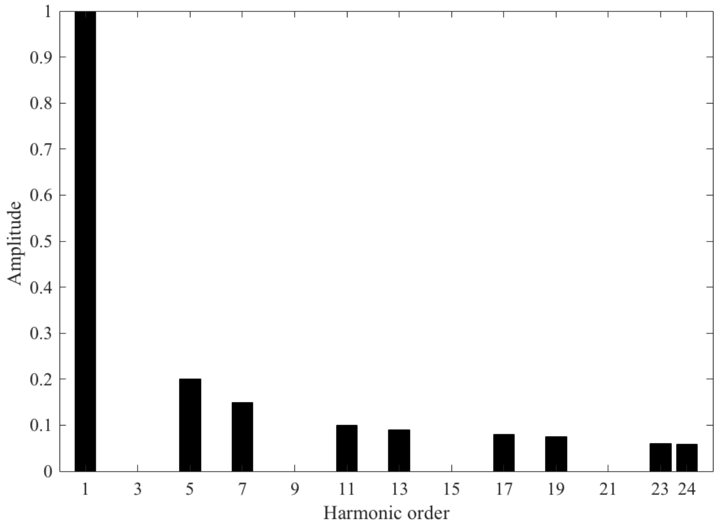


***Figure 61** Example of harmonic histogram*

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