Sizing optimization study of a Stand-alone Photovoltaic System in Huambo, Angola

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Abstract

Electrification on the African continent remains a major problem today. In Angola, for example, about 60% of the people have no connection to the electricity grid, and most of these people live in isolated/rural areas, where there are no plans to build an electricity grid. In order to change this situation, photovoltaic systems, supported by batteries or other generation systems, are already used to bring electricity to many of these more remote locations. The problem, especially with these stand-alone photovoltaic systems, is that they always end up not providing all the energy needed for the basic activities of the consumers, which in the end always leads to a loss of load supply, and subsequently, to an extra cost from the other forms of energy production (generators, biomass, kerosene lamps). These extra costs in the end can make the photovoltaic system itself take longer to pay back, or can lead to large fluctuations in the price consumers pay per kWh at the end of each month. Therefore, a methodology to size off-grid photovoltaic systems for remote locations, where the price of energy losses for the consumers is added to the total investment, has been developed and used together with an optimization algorithm to obtain what would be the best dimension for a photovoltaic system to be built in the Huambo area. This was achieved thru the computation of the daily consumption based on surveys done in the area, the irradiance, and also, temperature of the area. The off-grid photovoltaic system will consist of photovoltaic panels, $LiFePO_4$ batteries, an inverter, a battery management system and a diesel generator in combination with kerosene lamps, as examples of more traditional energy sources used in these more underdeveloped countries. In addition, the final value of the energy losses (VOLL) will already be included in the final investment of the photovoltaic system, so that over the life of the system, consumers will always have almost uninterrupted power supply, even if the photovoltaic system cannot supply all the energy needed to feed the loads. Therefore, our studies proved that it would be possible to scale a sustainable photovoltaic system for the area in question, with a positive return at the end of 20 years, but with the downside that the price per kWh is too high for Angolan wages, as will be analyzed at the end of this thesis.

Keywords: Off-grid PV systems, lithium batteries, system simulation, VOLL, MATLAB

1. Introduction

In the last couple of years, photovoltaic (PV) systems have greatly increased their presence in the world's energy production. It's a simple form of energy, modular, noiseless, with efficient methods of energy conversion and relatively easy to install on both big solar plants and on the roof of residential and commercial buildings. According to [1], the photovoltaic market grew by 75 GW in the 2016, making a total of 303 GW around the globe, largely due to the fall of the price/W_p ratio between 2009 and 2015.

Renewable systems, like photovoltaic systems, can be deployed not only in areas with electrification but also in rural areas where there is no electricity available, like the most part of Angola, where this work will focus. In rural cases, electrification has pivotal role in promoting local development, bringing improvement of households welfare, provision of local services and development of new productive activities. The biggest problem with rural electrification utilizing isolated PV systems is in the frame of sustainable development and appropriate technologies [2], which are immensely reviewed in literature [3, 4, 5, 6, 7]. For this situation, there is a need of a multi-criteria system sizing method, which embraces the technical, economic and environmental parameters of the context and population.

2. Background

2.1. Angola's case study presentation

This study will focus on Angola, a country in Central Africa at the west coast of Southern Africa, staying mostly between latitudes 4° and 18°S, and longitudes 12° and 24°E. The Angola's energy sector is characterized by a low consumption per capita (250 kWh/per capita) [8] and the electricity is mostly consumed in Luanda, which accounts for 65% of the total demand of the country.

Due to its location on the African continent and its proximity to the Atlantic Ocean, its climate is tempered by a cool sea current along the coast and by the altitude on the plateau in the interior, thus making for a sub-tropical climate almost everywhere in the country. Huambo's irradiance levels stay between 2000 and 2300 kWh/m^2/year, which, with a few simple calculations, can be estimated to produce between 4,9 kWh/m^2/day to 6,2 kWh/m^2/day, with the panel tilted with the optimum angle (β_{opt}).

João Baptista Borges, the Angolan Minister of Energy and Water, announced that the Angolan government was considering increasing the rate of access to electricity, which has set targets of 9,9 gigawatts (GW) of installed generation capacity (current installed capacity is estimated at 5,01 GW) and a 60% electrification rate by 2025, with great focus in rural areas [9], including an increase in low-carbon energy.

2.2. Photovoltaic systems

There are two types of solar technology that are used, namely solar thermal and solar cell [10]. A solar cell or PV cell, how it's most commonly known, is a semiconductor device which directly convert the solar radiation into electrical energy, by photovoltaic effect. There are different types of solar PV cells available in market i.e. monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, micromorph, CIGS, and hetero-junction modules [11].

Nowadays there are three types of PV systems connectivity: stand-alone systems with and without battery packs, grid-tied systems and, the more recent one, hybrid systems that utilize a renewable energy (PV, wind, biomass) with other more conventional form of energy (fossil fuels, coal).

2.3. Energy sustainability in sizing solar systems

Energy supply to the rural or isolated people in developing countries, like many villages in Angola, is a complex activity that transcends the simple selection of a best technology. The majority of the isolated population lives a socio-economic imbalance between them and the urban areas, which leads to more energy deficient communities in developing countries. Therefore, there is a need to apply the concept of energy sustainability in these communities so that they can enjoy greater development and provide better quality services.

For the context of rural electrification and renewable technologies, stand-alone solar systems are those expected to contribute the most in the development of new forms of energy in isolated places in the near future. However, scaling an off-grid PV system is not so trivial as it seems, due to the fact that it means matching an unpredictable energy source with an uncertain load demand, while providing the most advantageous conditions in terms of system reliability and cost. The power reliability is directly proportional to the cost of the system, which means the higher power reliability, higher will be the cost, so a balance must be reached. An optimum sizing needs pondering cost with high power reliability [12].

2.3.1 Power reliability

Power reliability is defined as the percentage of mean energy demand satisfied by a PV system without interruptions. For quantification purposes, the reliability of a system can be expressed, mainly, through the Loss of Power Supply Probability (LPSP) [13, 2, 14, 15]. The LPSP can be interpreted as the probability that an insufficient power supply will result when the system is unable to satisfy the load demand. It is calculated using the following formula:

$$LPSP = \frac{\sum_{t=1}^{T} LPS(t)}{\sum_{t=1}^{T} E_D(t)} \tag{1}$$

where $LPS(t)$ is the Loss Power Supply on timestep t and can be expressed as:

$$\begin{aligned} LPS(t) = E_D(t) - (E_{PV}(t) + \\ E_{Bat}(t-1) - E_{Bat\_Min}) \cdot n_{inv} \end{aligned} \tag{2}$$

with $E_{PV}(t)$ being the output produced by the PV panels at time (t), $E_{Bat}(t-1)$ being the energy balance in the battery pack in the previous time step and E_{Bat_Min} the minimum power level that the battery can reach, as provided by the manufacturer. A LPSP from 0 to 1 means the power cannot fully supply to the load when the solar power is not enough while the battery has been in the allowable maximum DOD or the allowable SOC.

2.3.2 System cost

The cost is one of the most inhibiting factors in the growth and development of the system and the most governing factor in its sizing. Many researchers have already used various procedures and techniques to reach the optimal point such as minimizing the Net Present Cost, lifetime and Levelized Cost of Energy of the projects [16, 17]. The Net Present Cost (NPC) used in the optimization of the cost is estimated by:

$$NPC = \sum_{y=1}^{LT} \frac{Inv(y) + O\&M(y)}{(1+r)^{y}} \tag{3}$$

where, for each year (y): $Inv(y)$ considers the investment and replacement costs of the system components, $O\&M(y)$ are the operation and maintenance costs and $(1+r)^{y}$ is the discount factor. Finally, it represents the total investment costs plus the discounted present values of all future costs during the lifetime of the system. The other way of finding the optimal systems, other than through the lifetime, is by minimizing the Levelized Cost of Energy:

$$LCoE = \frac{r \cdot (1+r)^{LT}}{(1+r)^{LT} - 1} \cdot \frac{NPC}{E(y)} \tag{4}$$

where $E(y)$ is the electricity served each year to the consumers by the system; LT is lifetime of the project; and is defined as the total cost of the entire system divided by the energy supplied by the system (in one year period) [2].

3. Simulation - Inputs, weather and load informations

3.1. Weather data

3.1.1 Solar resources

For the first step of the simulation, it will be necessary to calculate the hourly irradiance values. For this calculation one will need daily average irradiance data in kWh/m^2/day to be processed by the mathematical model. It was decided to use a method widely used in solar system simulations, the worst year method, which uses the irradiance data from the worst year in history so that the system is oversized in order to operate on very low radiance days and still be able to provide energy to consumers, as seen in Table 1.

Month	**Mean daily irradiation [kWh/m^2/day]**		
	NASA website	Model prediction	Difference between predicted model and NASA data in percentage (%)
Jan	4,89	4,89	-0,01%
Feb	4,92	4,92	-0,04%
Mar	5,43	5,43	-0,16%
Apr	5,65	5,64	-0,18%
May	5,97	5,97	-0,05%
Jun	5,53	5,54	0,14%
Jul	5,51	5,52	0,18%
Aug	5,55	5,55	0,01%
Sept	5,40	5,39	-0,13%
Oct	5,84	5,84	-0,02%
Nov	5,31	5,31	-0,02%
Dec	4,74	4,74	0,12%

Table 1: Comparison between mean irradiation data from NASA website and Gueymardt model for Huambo in 2015

3.1.2 Temperature

After entering the insolation data, it is also necessary to enter the temperature data into the simulation. The ambient temperature values are highly important, since the output of the PV system is directly linked to both insolation and temperature, due to their effect on the PV cells. The method of creating temperature data is very similar to the insolation data, since for these isolated sites it will be impossible to have hourly data of the average ambient temperature. Therefore, it will be necessary to use a mathematical model in order to synthetically create the temperature data, as seen in Table 2.

Month	**Average daily temperature [ºC]**		
	NASA website	Model prediction	Difference between predicted model and NASA data in percentage (%)
Jan	19,50	20,55	5,42%
Feb	20,08	21,20	5,58%
Mar	20,50	21,73	6,05%
Apr	20,47	21,71	6,07%
May	19,22	21,10	9,79%
Jun	17,89	20,21	12,97%
Jul	18,73	20,81	11,13%
Aug	19,82	22,04	11,22%
Sept	23,36	24,94	6,76%
Oct	24,65	25,90	5,06%
Nov	22,54	23,96	6,27%
Dec	20,94	22,17	5,84%

Table 2: Difference between predicted model and NASA data values

3.2. Load profile

For a successful optimization process, one of the most important sources of information about the location and its community will be the demanded load data. For the creation of the load curve, it was used the energy consumption information presented in [18], all from Huambo area. For the construction of the daily load, a 5 step methodology will be used [2]:

1. The first step will be to separate people/companies into classes ($ClassType$), each class will have its number of elements identified (N_{users}) and each group of users will be separated in households, if they are part of any of the residential classes (N_{houses});

2. Next, all electrical applications will be identified ($AppName$) and described according to their nominal power (P_{app}) and equipment number per user or house (N_{app});

3. After collecting information about users and their equipment, it will be necessary to assume an operating schedule, in hours (h_{funct}), for each application and its respective number of operating intervals ($NumWin$) and operating interval in hours ($W_{f,n}$), as described in the

following equations:

$$Tot_W = \sum_{n=1}^{NumWin} W_{f,n}$$
$$h_{funct} \leq Tot_W \tag{5}$$

4. In order to calculate the power of each application over the operating hours, the following expression is used (kWh):

$$P_{eq,App} \cdot Tot_W = P_{app} \cdot h_{funct} \cdot N_{app} \tag{6}$$

5. Finally, the complete daily curve is built based on each application, its contribution and user within each class.

From the survey done in [18], it is possible to determine that, in the rural district, the most important service that needs energy would be the lighting, followed by television and finally the conservation of food and its confection. This only describes what would be the most important electrical equipment in so-called "normal" houses in Angola. For people with a few more incomes or for companies, the equipment will be different.

Functioning assumptions and associated buildings will be arranged, together with their user class (*Class Type*), how many devices will be used (N_{App}), their nominal power (P_{App}) and, finally, their equivalent power ($P_{Eq,App}$), according to Equations Eq.(5) and Eq.(6). Furthermore, with all this information it is also possible to calculate the energy needed for each residence/company or for each user per day or per year, as can be observed in Table 3 and 6.

Class Type	**Nº houses**	**Nº users**	E_{user_day}	E_{class_day}	E_{class_year}
			kWh/day	kWh/day	kWh/year
Residential I	10	4	1,48	14,80	5402,00
Residential II	7		3,1	21,7	7920,5
Residential III	5		4,31	21,55	7865,75
Residential IV	4		5,76	23,04	8409,6
Street lights	-	1	23,2	23,2	8468
Primary School		1	2,388	2,388	871,62
Health Care Unit		1	7,692	7,692	2807,58
Market		1	17,5	17,5	6387,5
Local Council		1	4,71	4,71	1719,15
Total Load	-	-	70,14	136,58	49851,70

Table 3: Energy consumptions for Huambo's microgrid

3.3. Techno-economic assumptions and specifications of the system

Finally, and as a last step before starting the system simulation and the consequent search for the optimal system, it is necessary to introduce some characteristics of the solar panels, batteries, inverter. In addition, it is necessary to have a notion of the state of the photovoltaic market on the African continent, since one of the main tools in the optimization process is the economic evaluation of the installation.

The main values necessary to later deduce the investment/cost of the system are the values relative to the market price, in €/kW, of the panels, batteries and inverters. Regarding the soft costs and the price of other hardware, these will have a weight of 25% in relation to the sum of the investments in the three main components of the system.

Finally, presented in the Table 3.3, are the techno-economic characteristics of the photovoltaic system which will be later introduced to start the simulation.

Component	**Variable**	**Value for simulation purposes**	**Unit**
PV Panels	ρ_T	-0,46	%/°C
	T_{ref}	25	°C
	λ	1250	€/kW
Batteries	SOC_{ini}	50	%
	SOC_{min}	10	
	SOC_{max}	90	
	η_{CH}	95	
	η_{DISCH}	96	
	$N_{cycles\_100\%}$	2000	cycles
	ψ	400	€/kWh
Inverter	Inv_{size}	20	kW
	$LT_{inverter}$	10	years
	ζ	500	€/kW
Cables	η_{cables}	95	%
Project lifetime	LT	20	years
Maintenance fee	-	50	€/kW
Discount rate	r	6	%

Table 4: All techno-economic assumptions used for the system simulation

4. Simulation - Physical components simulation and system sizing optimization process

4.1. System constitution and physical model

Stand-alone PV Systems (SAPVS) are the focus of this work and that is why it is necessary to dissect the way this system will be simulated in order to reach the desired optimization. A system simulation consists in solving the energy balance of the system and the change in the battery state of charge (SOC) for each time-step considered, usually an hour [2]. In addition, it will be assumed from the beginning that this community in question already had some forms of energy such as kerosene and diesel generators, so the focus can be only on the constitution of the PV system without mixing with other forms of energy production.

4.1.1 PV panels

The interest of this thesis is in solving the energy balance problem of the system, a mathematical model that considers not only the flow of energy generated by the PVs in kWh, but also includes the losses in cables and in all the equipment that is not responsible for energy conversion will be used in this work. Assuming that the system will already have an MPPT included, one already knows that the panels will always work at the maximum operating point, so that they will always maintain their maximum production regardless of the variation in solar radiation. The following equation will output the results for each (t):

$$E_{PV}(t) = PV_{size} \cdot (1 - \rho_T \cdot (T_{cell} - T_{ref})) \cdot H_{\beta}(t) \cdot \eta_{BOS} \tag{7}$$

where:

- $H_{\beta}(t)$ is the specific solar irradiation on tilted surface for the chosen instant;
- PV_{size} is the rated power of the panels under simulation at the irradiance of 1 kWh/m^2, an ambient temperature of 25 ºC and an air mass value of 1,5;
- ρ_T is the temperature coefficient of power respect to solar cell temperature provided by the manufacturer (usually 0,35÷0,45%/ºC);
- η_{BOS} is the balance of system efficiency which are all the losses not directly related to the sun energy conversion process;
- T_{ref} is the reference temperature at which the panels are usually tested, usually 25 ºC.
- and T_{cell} is the solar cell temperature in each time-step, which can be estimated by means of the following equation, presented in [19]:

  $$T_{cell}(t) = T_{amb}(t) \cdot (1 + 1,25 \cdot H_{\beta}(t)) \tag{8}$$

  where $T_{amb}(t)$ represents the average ambient temperature on the instant (t).

4.1.2 Batteries

The second step consists in estimating the amount of energy that flows through the battery and the change in the battery State of Charge. For this simulation, the batteries will work in such a way that when the difference between the panels' production and the energy demanded by the consumers (ΔE) is positive, the system will charge the batteries, but when this difference is negative it should always supply the consumers first, as will be the case during the night hours. The following equation will be used to find this difference:

$$\Delta E(t) = E_{PV}(t) - \frac{E_D(t)}{\eta_{inv}} \tag{9}$$

where $E_{PV}(t)$ and η_{inv} is the PV output production on instant (t) and inverter efficiency, respectively. Knowing these data it is now possible to calculate the energy that will pass through the batteries E_{Bat}, updating it with the value they have at the previous instant, as the following formula indicates:

$$E_{Bat}(t) = \begin{cases} E_{Bat}(t-1) + \Delta E(t) \cdot \eta_{CH} & \Delta E > 0 \\ E_{Bat}(t-1) + \frac{\Delta E(t)}{\eta_{DISCH}} & \Delta E < 0 \end{cases} \tag{10}$$

where $E_{Bat}(t-1)$ is the value of energy balance of the battery at the previous time instant, η_{CH} is the charge efficiency of the battery pack and η_{DISCH} is the discharge efficiency of the battery pack.

After the power value in the batteries is updated, another important aspect to estimate will be the SOC of the battery. The state of charge (SOC) is the level of charge of an electric battery relative to its capacity. The SOC will be updated based on the following model:

$$SOC(t) = \begin{cases} SOC(t-1) + \frac{\Delta E_{Bat}(t)}{B_{size}} & \Delta E > 0 \\ SOC(t-1) - \frac{\Delta E_{Bat}(t)}{B_{size}} & \Delta E < 0 \end{cases} \tag{11}$$

The last point for calculating the battery specifications will be its lifetime. Using analytical methods, it is possible to model the life of the battery using a mathematical equation that can then be solved. These models take into account degradation, corrosion, effect of the temperature, and more and can be calculated as the energy that can be cycled during its life (capacity · number of equivalent full cycles) divided by the annual energy discharged from the battery [20]:

$$Life_{Bat} = \frac{\text{Energy cycled during battery life}}{\text{Annual energy disch. from battery}} = \frac{C_{Bat} \cdot N_{cycles}}{\frac{E_{Bat\_year}}{\eta_{DISCH} \cdot \eta_{inv}}} \tag{12}$$

with N_{cycles} being the number of equivalent full cycles until battery failure.

4.1.3 Management system

For good control and prevention of damage to the battery pack, it will be necessary to add a Battery Management System (BMS) to the design and simulation. This device will be responsible for protecting the battery pack, maximizing efficiency, controlling the temperature of the cells and cell operation since during the cell operation period there are situations where the battery can over-charge or even over-discharge, which exponentially affects the useful life of the batteries. The most important for this simulation will be the SOC, since this simulation is only working with raw energy values and not system voltages and currents.

4.1.4 Inverter

Usually in the world, the loads at alternative current are used for homes and in order to convert DC to AC, an inverter becomes necessary. The inverter energetic performance is not constant and an important point to note here is that the energy performance of the inverter is never constant, since it is highly dependent on its output power [10]. In this case, the performance model used is an polynomial function carried out from a quadratic interpolation of an experimental curve generated at the INES - Institute of Energy Systems Technology [21]:

$$\eta_{inv}(t) = 1 - \frac{1}{\varphi_{inv}(t)} \cdot (0,0094 + 0,043 \cdot \varphi_{inv}(t) + 0.04 \cdot \varphi_{inv}(t)^2) \quad (13)$$

where

$$\varphi_{inv}(t) = \frac{P_{in}(t)}{P_{rated\_conv}} \quad (14)$$

with $P_{in}(t)$ being the input power in instant (t) and P_{rated_conv} the inverter output rated power. The output rated is chosen according to the peak load values that will need to be supplied at certain times.

4.2. Value of Lost Load

4.2.1 Definition and assumptions

In the literature there are various meanings for what the VOLL is, from [22] mentioning that it may be the value of unserved energy to [23] where they argue that it is an average of what consumers are willing to pay to avoid without running out of their primary source of electricity. At the end of the day, it ends up being a monetary expression for the costs associated with interrupting power supply [2].

In order to estimate the total value of VOLL in relation to the off-grid and sustainable energy context, five steps were proposed in [2] and followed with the results presented in 6.

4.2.2 Estimation of values

To calculate the VOLL values, as already mentioned, it will be considered that there were already people with diesel generators and, in spite of this, there are still people using more traditional means like coal and kerosene, in order to reduce the consumption costs. Therefore, to calculate the total VOLL it will be necessary to estimate the percentage of users that still use these more traditional fuels, the value that these fuels will add to the final VOLL value and also to add the part of the cost of consumers with diesel generators.

With the equations presented in [2] and the information contained in the table 6 regarding the various values of the user loads, one may already be able to conclude the results regarding $VOLL_{diesel}$, $VOLL_{ker\_lamp}$ and $VOLL_{mobile}$, as presented in the Table 4.2.2.

Resulting VOLL values		
$VOLL_{diesel}$	0,065	€$/kWh_{LL}$
$VOLL_{ker\_lamp}$	0,148	
$VOLL_{mobile}$	6,722	

Table 5: Estimated values of VOLL for the different classes

To calculate the VOLL of the various household classes, first it is necessary to have an idea of which ones use a mix of electricity and which ones use only diesel generators, before the installation of the photovoltaic system. If one calculates the weight that these various energy applications have in the total load of *Family_1* class of users, one can get a value of 97% for lighting and 3% for the mobile phones. For *Family_2* the results are 70% for lighting, 1% for charging mobile phones, 24% for the refrigerator and 5% for the television. With these weights the VOLL referring to *Family_1* and *Family_2* are, respectively:

$$\begin{aligned} &VOLL_{family\_1} = \\ &0,97 \cdot VOLL_{ker\_lamp} + 0,03 \cdot VOLL_{mobile} \\ &= 0,326€/kWh \end{aligned} \quad (15)$$

$$\begin{aligned} &VOLL_{family\_2} = \\ &0,70 \cdot VOLL_{ker\_lamp} + \\ &0,01 \cdot VOLL_{mobile} + (0,24 + 0,05) \cdot VOLL_{diesel} \\ &= 0,209€/kWh \end{aligned} \quad (16)$$

Knowing now the results of the families where there is still more than one energy source, one can calculate the weights of these two families and the remaining families and businesses to the total load, since they only use generators,one can calculate their total weight. It can calculated that the *Family_1* and *Family_2* have a weight, respectively, of 15,4% and 15,1% of the total daily load, and that the remaining classes have a weight of 69,5%. These values will cause the result of $VOLL_{Total}$ to be as given by the following equation:

$$\begin{aligned} &VOLL_{Total} = 0,108 \cdot VOLL_{Family\_1} + \\ &0,159 \cdot VOLL_{Family\_2} + 0,733 \cdot VOLL_{diesel} \\ &= 0,116€/kWh_{LL} \end{aligned} \quad (17)$$

4.3. Sizing optimization methodology and context

As mentioned at the beginning of this thesis, the main objective of this simulation is to arrive at a size of panels and batteries that is completely thought out and designed according not only to the needs of the population where this system will be installed, but also to the climatic conditions of this same location. For this to be possible, a thorough analysis of the power reliability and cost of the system must be done, using their respective indices for this purpose.

More criteria were created as a way to change the way of predicting the best values for isolated sites, like the methodology that is used in this work, making use of two modifications [2] to the already known indicators of system cost, namely (3) and (4). These modifications were made, mainly, due to the following three conditions:

- Both the process and the results should be directly linked to the local context, making the conditions and assumptions for the design cannot be defined externally;
- Being an off-grid system, priority will be given to more reliable systems over less reliable ones, thus putting much emphasis on LPSP;
- and finally, the cost of electricity should be as low as possible, much due to the impoverished population of these locations.

To achieve the first two points, it was proposed to change the traditional NPC formula so that it now includes an economic value referring to the energy that was not supplied. Therefore, the new equation referring to the Net Present Cost (NPC) of the system will be:

$$NPC^* = \sum_{y=1}^{LT} \frac{Inv(y)+O\&M(y)+\sum_{t=1}^{T} LPS(t)\cdot VOLL}{(1+r)^y} \tag{18}$$

where $LPS(t)$ is the Lost of Power Supply in instant (t) and VOLL the total value of Lost Load. With this amendment, this definition contributes to favor the most reliable systems because it internalizes into the NPC a cost associated with the Loss of Load which contributes with higher values for less reliable and cheaper systems, and with smaller values for more reliable and more expensive systems. With this change and knowing that the LCoE comes from the NPC, it is possible to rewrite equation Eq.(4), now taking the name of *Levelized Cost of Supply and Lost Energy* (LCoSLE) as follows:

$$LCoSLE = f(PV_{size}, B_{size}) = \frac{r\cdot(1+r)^{LT}}{(1+r)^{LT}-1}\cdot\frac{NPC^*}{E(y)} \tag{19}$$

As the new LCoSLE already incorporates all the system information, including load demand, climate values, physical model characteristics and VOLL, it can be used to arrive at the identification of the perfect size of solar panels (in KW) and batteries (in kWh). This identification is reached by minimising the LCoSLE value of all simulated systems. By minimizing these values it is possible, not only to conclude an optimal panel and battery size, as described above, but also this value will lead to an optimal NPC* and an optimal LPSP, thus making its input problem non-existent and making this variable just another output of the system optimization process.

4.3.1 MATLAB algorithm exemplification

In order to arrive at the optimal system, a MATLAB algorithm was built based on the equations used by [2] and [15]. This algorithm is started in three main input blocks: the first block receives the geographic location and respective climatic data of the site; the second block is composed by receiving the hourly value of the local consumers' loads and respective pre-assessment of the Value of Lost Load (VOLL); and finally, the third block is composed by inputting the physical system and all the techno-economic data of the solar panels and batteries, which could possibly be used in the installation of the system, for the calculation of the solar energy production and storage used in the optimization process.

Following the input data entry it will be necessary to limit a window size for both the solar panels and the battery bank. The values chosen for this simulation for the PVs were from 20 KW to 50 kW with a step of 0,3 kW and for the batteries from 125 kWh to 250 kWh with a step of 0,5 kWh.

5. Simulation - Results, observations and discussion

5.1. Technical evaluation of the system

The first result to analyse is Figure 1, which presents the total daily energy produced by the solar panels during one of the 20 years of the project's life time. The first and third quarters comprise the days of the rainy season, while the second quarters comprises the Angolan dry season or Angolan winter.

It is in this quarter that the production per day shows the highest average, this value being 170 kW per day. In the other two quarters, comprising the rainy season, the inconsistency in production is greater, averaging 138,4 kW and 140 kW per day for the first and third quarters of the year, respectively. Although the production can be higher than during the dry season, the inconsistencies in production can lead to little energy being stored in the batteries, leading to loss of power and supply problems later on.

The profile of the difference between the energy generated and consumed can be observed in Figure 2, where it can be seen in fact that there are days when consumption far exceeds production. That is, even though the average production of electricity through solar panels in the three quarters is above the average load consumption of the location, due

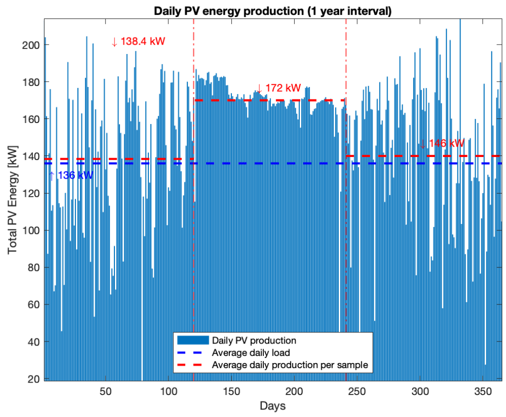

Figure 1: Simulation result for the total daily PV production (1 year time interval)

to the large inconsistencies in production, in the first and third quarters of the year there will be a large deficit between production and demand.

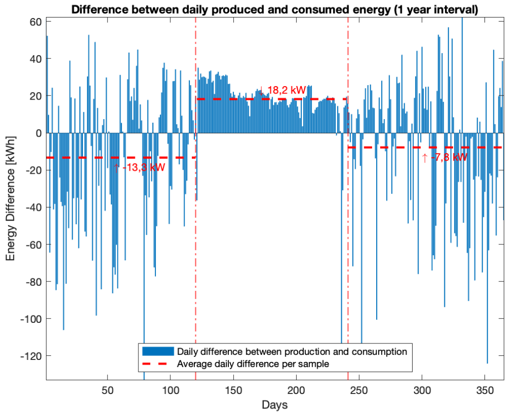

Figure 2: Simulation result for the difference between produced energy and consumed in 1 year time period

Since this work is using a fixed daily load, the main reason for the inconsistencies in production is only due to the irradiance levels presented on those days. Seeing this difference, one can immediately conclude that this will have a tremendous impact on the charge of the batteries, something that can be confirmed by Figure 3, which shows the charge level (*SOC* level) of the batteries at midnight each day in one year interval. Using the same sample days used to analyze Figure 1, it can be noted that in the first 120 days of the year, in the first part of inconsistency in production, the batteries finish these days with 17% of their capacity or less, making only 7% of their capacity available to be able to supply consumers in times of lack of production of solar energy. Now doing some calculations, the energy expenses from midnight to 6h are about 22,2 kWh and 7% of the capacity of the batteries equals 11,5 kWh, which means that most days during this season there will not be enough solar energy stored to satisfy the basic needs of consumers at night. At this time of the year, in order for there to be no power outages and for there to be no return to other more traditional forms of energy, the batteries would have to reach midnight with an average value of 23,7% (38,5 kWh) on most days so that the power shortage at night would not be so great. With this value, the 16,25 kWh of minimum battery energy level and the 22,2 kWh of energy supplied to the load would be completely safe. Nevertheless, in this first quarter, only on 18% of these days do the batteries reach midnight with more than 23,7% of charge.

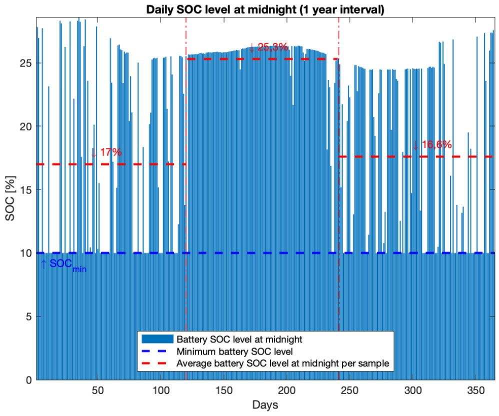

Figure 3: Simulation result for the battery levels at midnight in 1 year time period

Additionally, one can observe that despite the rainy days presenting less irradiance, the system throughout the year manages to maintain a level of batteries well above the minimum limit, ending up having a value close only on the days that the daily irradiance reaches levels below 2000 W/m^2. It was very much because of this that LiFePO$_4$ batteries were chosen for this project, as it was seen in the very first simulations that this project would bring very high cyclic wear to the batteries. With these lithium batteries it is possible to increase the useful life of the batteries to 7 years, as can be seen in Figure 4, thus making it necessary to replace the batteries only twice in the 20 years of the project's useful life.

5.2. Economic assessment

Here a comparison between the prices of the so-called "Traditional" methodology and the modified methodology will be made in order to understand the benefits and disadvantages. Analysing Figure 5, it can be observed that for the simulated optimal

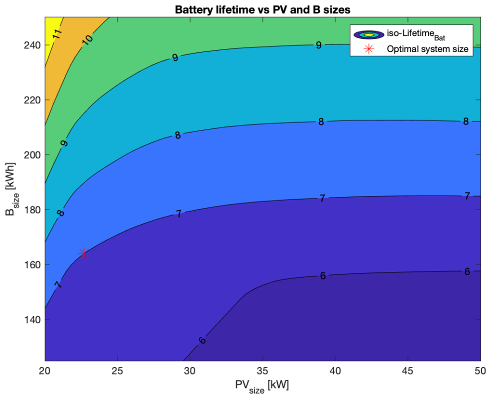

Figure 4: Simulation result for various batteries lifetimes

system of 20 kW for PV size and 144 kWh for battery capacity, for this context and conditions, this system through the traditional methodology would have an NPC and LCoE of 184.724,29 € and 0,39 €/kWh, respectively. These figures only refer to the total value of the system over 20 years, not including the lack of electricity supply to consumers throughout these years. Furthermore, this system has a LPSP of 21%, something that cannot occur, due to the imposed limit of 20% minimum LPSP, meaning that almost one fifth of the required energy is not supplied.

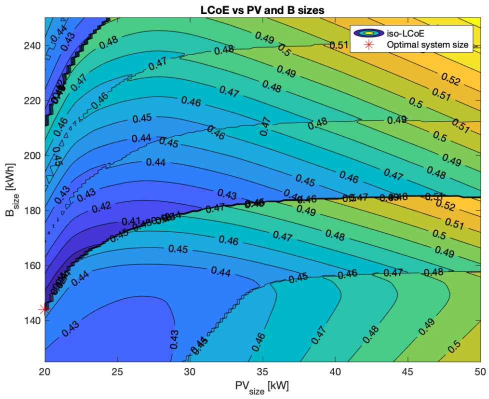

Figure 5: Traditional LCoE

On the other hand, the sizing of the system using the modified methodology concluded that the optimum system size would be 22,7 kW for the total power of the solar panels and 164 kWh for the capacity of the batteries, concluding with a final value for the project of NPC* of 215.290,48 € over 20 years. In this sense, the final value of the electricity price for consumers, according to the final LCoSLE value, would be 0,41 €/kWh, as can be analysed in Figures 6 and 7. As can be observed, there is an increase in the total value of the system, over the 20 years, of about 14% and of 5% in the price that the kWh of electricity needs to be sold so that at the end of the 20 years the investment has some return.

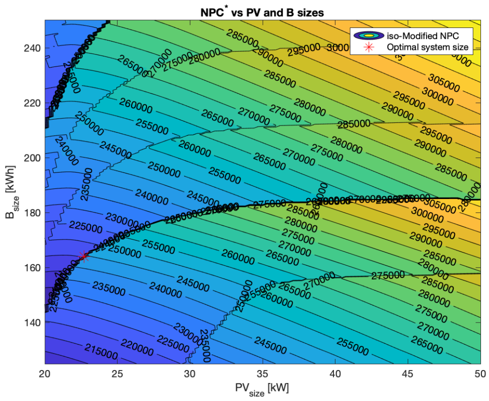

Figure 6: Simulation result for the Modified NPC for the optimal system

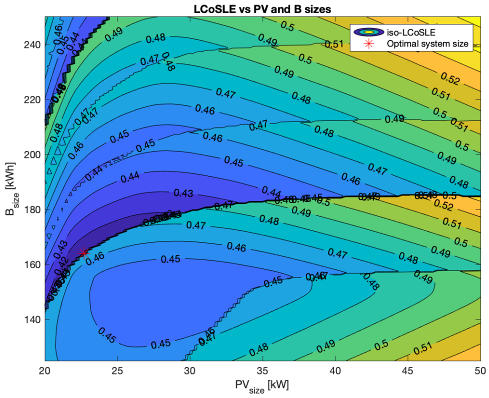

Figure 7: Simulation result for the LCoSLE for the optimal system

In addition, as can be seen in Figure 8, the LPSP value given by the simulation is 9,96%, which means that over its useful lifetime the plant will not provide 4,9 MW of the 49,85 MW per year of the energy needed to satisfy people's basic needs and will be lost. That said, one can conclude that this 14% increase, or 30.566,20 €, in the total price of the PV system covers the 9,96% energy shortfall for consumers, despite the use of more basic and polluting forms of energy supply.

More can be added by mentioning that if ones looks closely at the Figure 7, one can still see that there seems to be a little convergence to the set of systems that need a change at the end of 8 or 9 years. Since this change in terms of number of replacements makes no difference over the 20 year

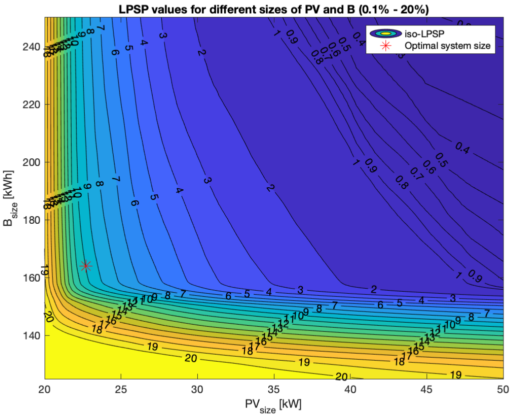

Figure 8: Lost of Power and Supply Probability between 0,1% and 20%

period that exists for the project, one can conclude that these "flaws" in the graph have more to do with the numerical way the LCoSLE and the NPC* were calculated. As a way of proving this, the isoreability graph below (see Figure 9), shows all the simulated systems and their Investment values. Having said this, observing the Figure 9, one can confirm that the different convergence zones due to the replacement of systems every 7 years and 10 years, exist due to the large discrepancy of costs in the replacement of the batteries. It can also be noted that this image does not show the distinction for the systems that need to be changed every 6 years due to the fact that the capacity of the batteries used in these systems is not as high to make such a difference, as in the other systems analyzed.

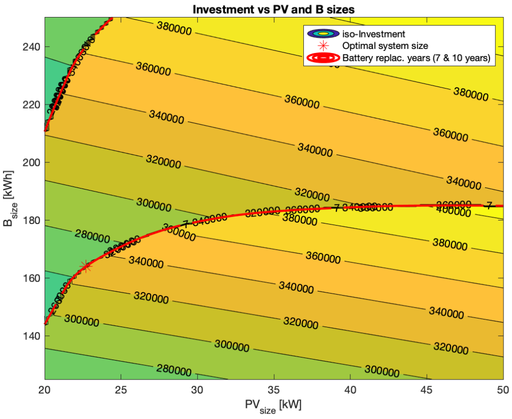

Figure 9: Investment and PV/Bat sizes

5.3. Social evaluation

If this simulated system were now built under the economic conditions that the Angolan electricity system faces, there would be a difference of 0,35 €/kWh which would need to be subsidized by the state or by some other identity. As can be seen in Section 4, the minimum wage in Angola is currently 21.454,10 Kz per month, which, at the time of writing this dissertation, is equivalent to 27,29 €. Now analyzing this value, and looking at a monthly load based on a user of the $Family_2$ class of this work (93 kWh/month), with price per kWh at 0,06 €, one can calculate that of his salary, this type of user uses 20,44% of this value for his energy needs, which seen this way presents an extremely high value, since it is practically one fifth of the salary.

Knowing all this, one can conclude that with the value of electricity given by the simulated LCoSLE it would be impossible to set up such a system in Huambo, unless its consumers are highly subsidized by the state or other entity. Using $Family_2$'s energy consumption as an example again, with the price of electricity at 0,41 €/kWh, this would mean a monthly electricity bill of 38,13 €, which these days is impossible for an Angolan to pay due to the minimum wages in the country. If salaries stay the same, the only way to set up a system like this is to subsidize about 75% of the price per kWh of electricity, which would make the price be around 0,10 €/kWh. With this value, the price paid for electricity would already be similar to today's price, with an increase of 67%. For an Angolan to spend the same portion of their salary on electricity as a Portuguese at the end of the month (2,51%), their bill at the end of the month could only be 0,68€ using $Family_2$'s load. Knowing that over a month, with this solar system, the bill of $Family_2$ would be 37,20 €, it is known that the Angolan government would have to subsidize about 98% of the electricity bills of all consumers of this photovoltaic system.

Despite these high costs, one cannot forget the advantages that this project would have for communities that do not even have access to electricity or are completely isolated. For these areas it would be a way to bring a clean form of energy, with fewer emissions into the environment, less noise and possibly fewer outages than they are used to.

One way to analyze the difference that this modified methodology makes in contrast to the traditional methodology is to observe Figure 10, which shows the various optimal systems, for the Huambo zone, for various values of VOLL.

Firstly, if one analyzes the line of *LPSP 1* present in the figure, one can conclude that a system for the same LPSP, in this case of 9,96%, for this zone would have two completely different cost values (points L1 and L2 of Figure 10). The difference in this cost is the costs associated with the use of more traditional sources of electricity (e.g. kerosene lamps, diesel generators), which would not be included in the traditional methodology (point L1).

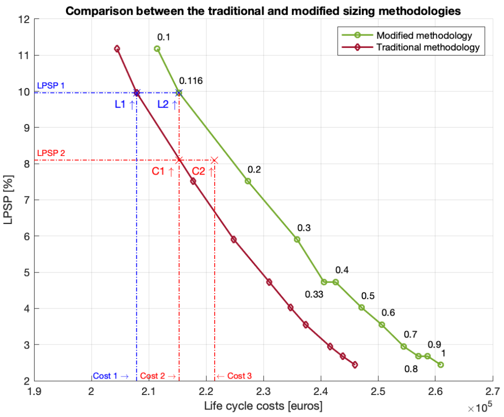

Figure 10: Comparison between the traditional and modified sizing methodologies

In other words, if one wanted a system with the same amount of losses, it would have an increase of about 7.000 euros (point L2) but would have all expenses for the next 20 years of energy coming from other sources completely guaranteed. On the other hand, if one wanted a system with this cost (point L2) but with lower losses, or lower LPSP, one could take advantage and invest in a larger system, as shown with the system in point C1. The problem in this situation was what this thesis always wanted to avoid, that people using a system sized by the traditional methodology would end up having several energy losses during the nights. That's because it has already been seen in the technical analysis that this system will always end up, at least during the night, not being able to provide solar energy to the consumers and they will have to turn to other ways in order to have their basic needs satisfied. This, when it happens, will end up creating an even greater cost (point C3) than the other two points mentioned above, concluding that for this type of off-grid systems, this methodology ends up having good results, because it will always end up finding the most reliable system, with the cheapest price, thus always guaranteeing an almost uninterrupted supply throughout the year, with about 90% of this energy being completely clean.

6. Conclusions

A case study was then set up for the locality of Huambo, in a rural area, which has an average daily irradiance of 5,4 kW/m^2, with consumers presenting an average daily consumption of 136 kWh of electricity. Since the intention of this thesis was to come up with the cheapest and most reliable system possible, an algorithm was assembled in MATLAB with the help of the [2] methodology, so that this system, besides the referred conditions, has incorporated in its costs the values referring to the expenses spent when there is a lack of solar electric energy supply (VOLL - Value of Lost Load). With the incorporation of this value, the final LCoSLE will already have all the extra costs associated with the extra expenses throughout the useful life of the project.

That said, the optimal simulated solar system for the Humbo area, with the load, irradiance and economic conditions mentioned, would have to have a solar panel power of 22,7 kW, with a battery pack capacity of about 164 kWh. This system over the 20 years would present a LPSP of 9,96%, an NPC* of 215.299,48 € and a LCoSLE of 0,41 €/kWh. In addition, this system would be equipped with LiFePO$_4$ batteries capable of lasting twice as long as normal lead-acid batteries. With this system, over the 20 years, about 90% of the energy supplied would be totally renewable, with good production all winter long and an uninterrupted supply during sunny hours, with all the costs associated with the loss of load during some nights already built into the equation. Although the price difference for a traditionally sized system would be almost 20%, the amount payable per kWh of energy would only differ by 0,02 €/kWh, a small price to pay for uninterrupted and mostly clean energy supply throughout the years.

Unfortunately, with these values and the incomes received by the people of Angola, it would be impossible for these consumers to pay an electricity bill of this value, so about 75% of the value of this system would have to be subsidized by the local government or other entities, so that the amount to be paid for electricity would be a reasonable value. On the other hand, as was seen in the previous chapter, for an Angolan to spend the same part of his salary on his electricity bill as a Portuguese pays, the Angolan government would have to subsidize about 98% of the users' final electricity bill.

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A. Appendix

Consumer Type	Nº users	Nº households	Class User	Applications	P_{app}	N_{app}	h_{funct}	$W_{(f,1)}$		$W_{(f,2)}$		Tot_W	$P_{eq,app}$
					[W]		[h]	h_{start}	h_{stop}	h_{start}	h_{stop}		
Residencial	4	10	I	Lights	60	4	6	18	24			6	240,00
				Mobile charger	5	1	8	0	8	18	24	14	2,86
		7	II	Lights	60	6	6	18	24			6	360,00
				Mobile charger	5	1	8	0	8	18	24	14	2,86
				TV	42	1	4	18	24			6	28,00
				Fridge	61	1	12	0	24			24	30,50
		5	III	Lights	60	8	6	18	24			6	480,00
				Mobile charger	5	2	8	0	8	18	24	14	5,71
				TV	42	1	4	18	24			6	28,00
				Fridge	61	1	12	0	24			24	30,50
				Standing fan	45	1	10	8	24			16	28,13
		4	IV	Lights	60	10	6	18	24			6	600,00
				Mobile charger	5	4	8	0	8	18	24	14	11,43
				TV	42	1	4	18	24			6	28,00
				Fridge	61	1	12	0	24			24	30,50
				Radio	50	1	4	6	9	18	24	9	22,22
				Standing fan	45	2	10	8	24			16	56,25
Street lights	-	1	-	Lights	50	50	8	0	6	18	24	12	1666,67
				LED	8	50	8	0	6	18	24	12	266,67
Primary school		1	-	Lights (tubes)	36	15	4	8	16			8	270,00
				Mobile charger	5	2	6	8	16			8	7,50
				TV	42	1	4	8	16			8	21,00
Health care Unit	-	1	-	Lights (tubes)	36	10	14	0	24			24	210,00
				Vitals Monitor	50	2	16	0	24			24	66,67
				Fridge	61	1	12	0	24			24	30,50
				Mobile charger	5	2	12	0	24			24	5,00
				Sterilising machine	100	1	2	0	24			24	8,33
Market	-	1	-	Lights (tubes)	36	15	4	6	8	17	21	6	360,00
				Conservation of food	610	2	12	0	24			24	610,00
				Mobile charger	5	5	10	8	20			12	20,83
				Standing fan	45	1	10	8	13	15	20	10	45,00
Local Concil	-	1	-	Internet router	10	1	12	0	24			24	5,00
				Lights (tubes)	36	15	6	6	8	18	24	8	405,00
				PC	100	1	2	8	12	14	18	8	25,00
				Mobile charger	5	5	10	0	7	17	24	14	17,86
				Standing fan	45	2	10	8	13	15	20	10	90,00

Table 6: Load assumptions for Huambo’s micro-grid