Energy Source Optimization for Modular Building in India

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Abstract

In countries with severe energy quality concerns, such as India, where power outage occur on a weekly basis, backup renewable energy systems with solar panels and batteries, are proving themselves as an outstanding solution. With the falling prices in these kinds of technologies, standalone rooftop solar applications are a growing reality in India. Due to the complexity of these systems, the solutions available tend to take into consideration, the majority of the market rather than the specifications of each particular user. This thesis tries to fill this gap by developing an optimization algorithm that, based on the details of the client, provides the optimal system and its characteristics. This tool is a combination of not only physical models, which translate the natural phenomena such as, the sun position across the sky or the power outage occurrence probability. But also, a genetic optimization algorithm that, from the possible values for each parameter of the system, chooses the optimal ones. In order to evaluate the performance of the developed algorithm, three different approaches of the system will be studied regarding the same user. First, with solar panels only, then, with solar panels and batteries. Lastly, the system with both devices, however, the batteries are only used during power outage events. Since power outages are a random phenomenon, these three cases must be analysed from a probabilistic point of view.

Keywords: Power outage, Solar panels, Battery, Optimization algorithm.

1. Introduction

The energy quality is a problem that concerns almost every person that uses electricity in India, since power outages are phenomena that occur regularly. People and industries can experience power outages on a weekly basis, and, the country is home of some of biggest power outages in the history of mankind [1]. These outages have not only, a social impact, but also a negative economic repercussion. The final cost of electricity is overvalued [2] and the country’s GDP is lowered due to these persistent blackouts [3].

In vast countries, such as India, solar panels are an outstanding source of clean energy and a solution to the power outage concern [4]. Over the past years, the Indian government has already stated the importance of this energy source [5] and the country potential is undeniable [6]. These factors contribute to a great reduction in the solar arrays prices in India, with a global record price of 0.65$ per Watt, which means roughly 0.80€ per Watt [7]. With such low prices in the solar energy solutions, not only industrial but also domestic applications become viable.

When comparing solar array solutions, the first step is to understand how much radiation emitted by the sun is expected to be obtained in a given place. In order to model this phenomenon the Hay, Davies, Klucher and Reindl model was used [8]. Another important factor is type of technology of the solar cells, since it determines the solar panels efficiency [9], temperature coefficient [10] and price. Silicon-based cells are currently the most appropriate technology for these kind of applications, and, therefore have more that 70% of the worldwide market share [11].

Since the solar panels only produce energy during daylight hours, it is necessary that the system has some kind of energy storage device. This gap is filled by the usage of batteries, that store the remaining energy provided by the PVs. The usage of batteries, as a backup energy supply solution, in countries with unstable power grids is a present reality [12]. Alike the solar panels, there exist several technologies of batteries, and each of those technologies has different characteristics in what regards energy density [13], lifetime [14] and price. The lead acid technology is currently the world leader in domestic power storage [15], and therefore the most fitted technology for this type of application.

In complex models, such the one that will be developed, there exist dozens of variables that influ-
ence the overall system performance, however some are deterministic while others are probabilistic. In order to obtain the best possible results, the values of these chosen parameters must be optimal, and this is achieved by using an optimisation algorithm. The implementation of these kind of algorithms in renewable energy problems, has already been proven [16], [17]. The chosen algorithm was the NSGA-II, [18] due to its compatibility with the developed model. The results of the model will be evaluated from a probabilistic point of view, due to the random characteristic of some variables.

This article will be structured in four distinct sections: in the first, it will be presented the physical models that dictate how the different existent systems behave; the second, shows the framework in which the developed optimization model operates; the third, demonstrates the results of three different case studies that were submitted to the algorithm; and lastly, the in fourth section, it is outlined he conclusions from the optimization model and its results.

2. Physical models

The purpose of this chapter is characterization of the physical models that translate the behaviour of the system, in particular: the incidence model, the solar panel model and the battery pack model.

2.1. Incidence model

To estimate the yearly solar energy received by a PV it is necessary to model the radiation received by a tilted panel, located in the earth’s surface. According to the used model, the HDKR [8], the solar irradiance, that reaches the earth’s surface can be divided into five different components, as seen in Figure 1:

- **Beam** $[G_{b_{tilt}}]$, direct radiation that reaches a tilted surface;
- **Diffuse isotropic** $[G_{d_{iso}}]$, uniform radiation from all the sky;
- **Diffuse circumsolar** $[G_{d_{cs}}]$, radiation resulting from the forward scattering of the beam component;
- **Diffuse horizon** $[G_{d_{hz}}]$, resulting from the horizon brightening effect, it is concentrated near the horizon and is more pronounced in clear days;
- **Diffuse reflected** $[G_{d_{r}}]$, radiation reflected in the ground due to its albedo.

![Figure 1: Components of the solar irradiance by the HDKR model.](image)

The total irradiance that reaches a tilted surface can be obtained by the sum of all its components (1).

$$G_T = G_{b_{tilt}} + G_{d_{iso}} + G_{d_{cs}} + G_{d_{hz}} + G_{d_{r}}. \quad (1)$$

With the computation of each irradiance component, it is obtained the final equation used by the model (2), its result are in $kW/m^2$.

$$G_T = (G_b + G_d A_i) R_b + G_d (1 - A_i) \left( \frac{1 + \cos \beta}{2} \right) \times \left[ 1 + f \sin^2 \left( \frac{\beta}{2} \right) \right] + G \rho_g \left( \frac{1 - \cos \beta}{2} \right). \quad (2)$$

2.2. Solar panel model

In order to model the solar panel array one starts by defining the power output of a PV for a certain irradiance, present in the equation (3).

$$P_{PV} = G_T A \eta N_{PV}. \quad (3)$$

The PV efficiency is a function of its temperature, the NOCT model [19] provides a reliable approximation of this phenomenon. So that the solar panel efficiency is obtained, first it is necessary to compute the solar cell temperature (4).

$$T_{cell} = T_{air} + \left( \frac{NOCT - 20}{80} \right) G_T. \quad (4)$$

Then, the efficiency is a function of the solar panel temperature coefficient $c_t$, obtained by the expression (5).

$$\eta = \frac{P_{max_{NOCT}} c_t \times T_{cell} + 109}{G_{NOCT} \times A} + 100. \quad (5)$$

2.3. Battery pack model

Lastly, the model of the battery pack consists on a simple energy accumulator. There exist three parameters that state how the battery behaves: The
maximum capacity and the maximum charge and discharge ratings. In order to obtain the maximum capacity of the battery in [W h] the equation (6) is used.

\[
\text{Capacity}_{\text{MAX}} = N_{\text{bat}} \text{Ah} V.
\] (6)

To compute the maximum charge and discharge power for a given battery, respectively present in the equations (7) and (8) it is necessary to know its maximum charge, \( c_{\text{charge}} \), and discharge, \( c_{\text{discharge}} \), rating.

\[
C_{\text{MAX}} = N_{\text{bat}} c_{\text{charge}} \text{Ah} V.
\] (7)

\[
D_{\text{MAX}} = N_{\text{bat}} c_{\text{discharge}} \text{Ah} V.
\] (8)

3. India cases study

In order to get a broader understanding of the potentialities and limitations of the developed optimization model three cases were put to test:

- Only solar panels;
- Solar panels and batteries;
- Solar panels and batteries but using the batteries only in case of power outage.

However, first, it is necessary to define the framework on which the optimization model operates.

3.1. Power outages

In India, the outage phenomenon can not be neglected and, thus, needs to be considered when analysing solutions of renewable systems. To implement this phenomenon, in the developed model, some probabilistic distributions were used, due to the random character of these types of events. The two most important factors that influence the probability of occurring a power outage are: the hour during the day and the time of the year, which were both modelled using a normal distribution. A third distribution was used to take into account the duration of the power outage, although, in this case it was used a uniform distribution. To obtain a probabilistic model, for these types of events in India, it was used statistical data from [20], [2], [21] and [22].

From the database of [22], it was possible to obtain the standard deviations of the distributions. In the table 1 it is present all the parameters, regarding the three probabilistic distributions.

To better understand how the probabilistic distributions influence the power outages, it was generated 100000 outage profiles.

<table>
<thead>
<tr>
<th>Function</th>
<th>Int.</th>
<th>Dist.</th>
<th>Avg.</th>
<th>std.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day [h]</td>
<td>[1:24]</td>
<td>Norm.</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Year [day]</td>
<td>[1:365]</td>
<td>Norm.</td>
<td>230</td>
<td>115</td>
</tr>
<tr>
<td>Hours [h]</td>
<td>[1:3]</td>
<td>Uni.</td>
<td>2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 1: Probabilistic distributions parameters.

In Figure 2 one can clearly see, that the peak of outages occurs in the early morning and during the summer months.

3.2. Clearness index

The clearness index, \( k_t \), translates the effect of the weather, in the amount of radiation that reaches the earth’s surface. It is obtained by equation (9), which is a function of the extraterrestrial monthly average irradiation, \( \langle H_0 \rangle \), and the observed monthly average irradiation at earth surface level, \( \langle H \rangle \). Therefore, the first step is to compute the observed past irradiance data from [23].

\[
k_t = \frac{\langle H \rangle}{\langle H_0 \rangle}.
\] (9)

The extraterrestrial monthly average irradiation can be attained by averaging the daily irradiation during each month (10).

\[
\langle H_0 \rangle = \frac{\sum_{k=1}^{k+m} H_0}{3.6 \times k}.
\] (10)

In Figure 3 it is possible to see an example of the clearness index map computation.
3.3. Objective functions

The optimization algorithm computes the optimal results by minimizing a specific number of objective functions, it is crucial that these functions take into account the performance of the system. So that a good comparison is performed, all three cases were computed using the same set objective functions:

- **Investment** - The total cost of the system;
- **Missed energy** - The yearly energy that was not available either on the system, from the batteries nor the solar panels, nor on the grid, due to a power outage situation.

3.4. Decision variables

The decision variables are the parameters that the optimization algorithm controls in order to minimize the objective functions, these variables have a range in which the algorithm operates. All the three cases share the first three decision variables:

- **Tilt angle** \( \beta \), the angle between the surface receiving radiation and the horizontal plane, \( 0 \leq \beta \leq 180 \);
- **Surface azimuth angle** \( \gamma \), the angle between the projection on a horizontal plane of the sun with the surface from the longitude of the observer, with zero due south, east negative, and west positive, \( -180 \leq \gamma \leq 180 \);
- **Number of solar panels** \( N_{PV} \), the amount of solar panels used by the system, \([0; 60]\).

In the cases that, in addition to the solar panels, also have a battery pack a fourth decision variable is added:

- **Number of batteries** \( N_{Bat} \), the amount of batteries used by the system, \([0; 5]\).

3.5. Inputs

Lastly, the optimization model requires some physical parameters in order that real results are obtained. The algorithm uses several inputs, however the most influential are: the yearly temperature profile, the load profile of the user and the costs of the used equipment (solar panels and batteries). All of the inputs considered were chosen taking into account the Indian reality.

To obtain the yearly temperature profile it was used data from [24]. So that the results have a better approximation with the reality, the year was divided in five different temperature profiles, each of which represents an interval of 73 days, present in Figure 4.

![Daily temperature profiles](image)

Figure 4: Daily temperature profiles.

The yearly load profile, is another very important input to consider because it, determines the amount of energy that is requested by the consumer. Using the data from [25] it was possible to obtain the load profile of the average middle to upper class Indian family, this can be seen in Figure 5.

![Daily load profiles of the average middle to upper class Indian family](image)

Figure 5: Daily load profiles of the average middle to upper class Indian family.

The prices of the solar panels and the batteries translate the financial aspect of the system. From [26] it was possible to obtain the prices of these devices in India, the table 2 shows such values used by the optimization model.

<table>
<thead>
<tr>
<th>Solar panels</th>
<th>Batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>120.00</td>
<td>403.04</td>
</tr>
</tbody>
</table>

Table 2: Prices of the devices in Euro.
4. Results
4.1. Only solar panels case
In this case the system will use the power available in the PVs to match the demanding power of the load, therefore two situations may occur. The first is the power in the PVs being greater or equal to the demanding power: in this situation the system will provide enough energy to the load, hence the grid will not provide any power and the excess power will be discarded. Another factor of this situation is that consumer is not affected by power outages. The second situation is when the power available in the PV system is lesser than the demanding power, from here two outcomes can happen: on the first hand, if a power outage is not occurring, the grid will provide the remaining power to the load. On the other hand, when a power outage is taking place, there will be a lack of power. It is during this last case that the missed energy is calculated. In Figure 6 one can see the results of one execution of this first case, the elements present are the optimal results for a given power outage profile.

Figure 6: Optimization results for the first case.

To have a better understanding of the behaviour of the decision variables and objective functions, in Figure 7 it is possible to see parameters for all the elements of the results.

Figure 7: Objective functions and decision variables of the results in Figure 6.

The first thing to notice in Figure 7 is that, the linear behaviour of the amount of solar panels, translates in a exponential decreasing of missed energy. Because, for a high number of PVs, the missed energy tends do become constant.

To perceive how the probabilistic event of the power outages affects the results, one element of Figure 6 was submitted to several executions of the model, present in 8, marked in red. The majority of the elements are located on the left side of the selected one, therefore, they have a lesser missed energy. Which means that, the selected element has a higher probability of having a smaller missed energy, rather then a higher one (pessimistic result).

Figure 8: Histogram of the missed energy of 10000 executions using the same element.

Now that one knows how the effects of the probabilistic event of the power outages influence a single element, the same study can be made but for all elements of the results. In Figure 9 is presented the results of this simulation.

Figure 9: Objective functions of the results of 200 simulations.

The main effect to notice, in Figure 9, is the saturation of the missed energy. In all populations there exist a certain point where it becomes almost impossible to reduce the missed energy, even though the number of solar panels keeps increasing. The value of the missed energy of this saturation point is dependent on the outage profile.

With the data from 9 it possible to develop two distinct cumulative histograms: the probability of having more or less missed energy in a year for a given investment; and the expected missed energy
decrease with the increase of the investment. The Figure 10 contains the histogram of the missed energy for an investment of 4500€. It is possible to see that with this investment one has: an almost zero probability of having less that 30 kWh of missed energy; an 80% probability of having 50 kWh or less of missed energy; and lastly an almost certainty that the value of missed energy will never be higher than 70 kWh.

Lastly, to see how the investment influences the probability of a certain missed energy, in Figure 11 it is present the investment histogram for a missed energy of 60 kWh. It is possible to conclude that: an investment of 500€ has less than 10% of probability of guarantee the chosen missed energy (60 kWh); an investment of 4000€ has 80% of probability of guarantee the same missed energy.

4.2. Solar panels and batteries

In this particular case the battery pack will be added to the system as a means to store the excess energy, provided by the solar panels. In a normal operation situation, i.e. when a power outage is not taking place, the system, PVs and battery, will be the priority source of power to the load. Therefore, the grid will only provide power if the demand is greater than the supply and storage energy in the system. The situations in which it is necessary to rely on the power provided from the grid are: the load demand is greater than the PVs output and the battery is discharged or unable to provide more power, and during the times when the solar power is not available and the batteries are discharged. In a power outage episode the system will behave in the same way, however since the power from the grid is not available it might happen a situation where there is not enough power to supply the load demand.

As in the previous case, it is possible to see how the power outage event influences one optimal element from the optimization process, present in red in Figure 12. The marked element has most of the remaining elements on its right. Hence, it has a higher probability of having a greater value of missed energy rather than a lesser value (optimistic result).

The results obtained so far only take into account the data from a given year, that being said it is also important to see how the capacity loss of the battery, due to the performance of cycles, affects the optimal elements. In Figure 13 one can clearly see that, as the capacity from the battery pack decreases the missed energy increases.

In the same way as it was done in the previous case, the model will now be executed 200 times so
that it is possible to see how the power outage profile influences all the elements of the result, present in Figure 14.

![Figure 14: Objective functions of the results of 200 simulations.](image)

The Figures 15 and 16, present the cumulative histogram for an given investment and missed energy, respectively.

![Figure 15: Missed energy histogram for an investment of 4500€.](image)

![Figure 16: Investment histogram for a missed energy of 60 kWh.](image)

When observing Figures 11 and 16, Figure 16 shows higher probabilities for the same investment. So, for the same value of missed energy and probability it is necessary a lesser investment. Another important aspect to refer is that, since in 16 the maximum value is obtained with a smaller investment. Each increment in the investment has a greater increase in the probability when comparing to the one of Figure 11. Therefore, when considering if an investment should be increased, in the system with PVs and batteries the increment is more advantageous when oppose with the system with only PVs.

4.3. Solar panels and batteries but using the batteries only in case of power outage

In this third and last case, the system, will be characterized by the presence of both solar panels and battery pack, however the energy in the battery will only be used when a power outage is taking place. When no power outage is occurring, if the demand is higher than the PV energy production, the grid will compensate the required energy, regardless of the level of energy available in the battery. In a condition where a power outage is taking place, the system will behave like in the previous case, being the panels and the battery pack the main power sources. But, if the load demand is greater than the power in the system there will exist a lack of power. The results of the optimization were organized in an histogram present in Figure 17.
To get a better understanding on the results of the histogram, in Figure 17 it is present the cumulative histogram.

The histogram presented in 17 behaves differently from the previous two cases, since it is visible that the greater bin is located in the interval that contains the zero. This happens because with these input variables, the missed energy in the system is indeed zero. However, it is still possible to have a greater than zero value for the missed energy. In Figure 18 it is possible to see that the chances to obtain a value of zero missed energy with this elements are around 5%.

In the same was as it was done in the previous two cases, the optimization model will now be executed 200 times so that it is possible to see how the outage profile affects the last generations. In Figure 4.3 it is present all the 200 simulations.

With the information from 4.3 it is possible to compare the average investment for the second and third cases, this can be seen in Figure 21.
cases two and three, the third cases presents a lower value for the same amount of missed energy. So, it is possible to conclude that with this third case it is possible to reduce the amount of missed energy, with the same investment.

5. Conclusions

The optimization model was put to test using three different approaches with the same objective functions: the missed energy, which is the yearly energy that the user did not had available and the investment. However there are two important aspects to notice. First, the input parameters chosen were an example of a potential user. With different inputs, such as, the type of solar panels or the user load profile, the obtained results might have been distinct. The second important aspect is the randomness of the power outage phenomenon. The parameters of this event influence its occurrence probability and the average duration, therefore, it is crucial that these events are characterized in the best possible way. Due to the random nature of the outage event, the results of the optimization had to be analysed in a probabilistic point of view. Therefore, each of the three cases was submitted through the optimization algorithm a certain number of times, so that a pattern is achieved. The results of the optimization process were then organized into histograms for a easier interpretation.

The first two approaches of the system are characterized by, respectively, the presence of only solar panels and the conjunction of solar panels and batteries. Results show that from the 4500€ investment the approach with only PV has a 80% probability of obtaining 50 kWh or more of missed energy, while the PV plus battery case has $\approx 100\%$ chance of delivering the same amount of missed energy, which is a more positive result. When comparing both cases with the same amount of missed energy, it is visible that the approach with PV plus battery has a higher chance of obtaining the expected missed energy for the same investment. Both of these examples point towards the fact that the second case, PV plus battery, is a more reliable investment, since it delivers the expected missed energy with higher level of certainty.

The third and last case of the developed system, is, alike the second approach, characterized by solar panels and batteries, however, the batteries are only used during power outage events. The main difference of this case, when comparing it with the previous ones, is that it provided systems that had zero missed energy, which means that the user would be completely impervious to power outages. However, like the previous cases, there exist an associated probability for this third approach. Results show that the probability of obtaining 60 kWh missed energy with an investment of 2000€, is even greater than in the second case (PV + Battery). Meaning that, it is the more reliable system, in what regards the amount of missed energy for a given investment, of all the three approaches.

Lastly, it is important to notice that these certainty levels are probabilistic parameters, so, it can not be stated that the third system has for sure a better performance than the two previous ones. However, this approach obtained more satisfactory results when compared to the two previous cases, which leads to the conclusion that it is the more suitable solution for this type of application.

References


