Energy Source Optimization for Modular Building in India

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Thesis to obtain the Master of Science Degree in

Electrical and Computer Engineering

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June 2018
Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Acknowledgements

First, I would like to thank my supervisors: Professor João Fernandes, for helping me transform the simple idea that originated this thesis. And Professor Paulo Branco that, through his experience, provided crucial contributions.

To the Técnico Solar Boar team, a project that I had the privilege of leading during two years. It was not only, the most challenging experience of my life, but also the most gratifying. Due to the people that I had the pleasure to work with, and for the opportunity to put in practice the concepts learned through the course.

Lastly, to my parents: to my mother, for being present in the hardest moments, and my father for being the example of the engineer I aspire becoming.
Resumo

Em países como a Índia, onde a qualidade energética é uma preocupação constante e onde as interrupções na rede de distribuição de energia são uma constante, sistemas energéticos de apoio com painéis solares e baterias são cada vez mais uma solução primária. Com a queda nacional de preços neste tipo de tecnologias, sistemas fotovoltaicos domésticos são uma realidade crescente na Índia. Contudo, devido à complexidade destes sistemas, as soluções disponíveis tendem a ter em consideração o mercado e não as especificações de cada usuário. Esta tese tem como objetivo o preenchimento desta lacuna, através do desenvolvimento de um modelo de otimização que, segundo as características de cada cliente, gera o sistema ótimo. Através da interação entre modelos físicos, que traduzem os fenômenos reais e um algoritmo de otimização, a ferramenta desenvolvida produzirá os resultados ideais para cada caso específico. De forma a perceber as potencialidades do algoritmo, três abordagens distintas foram testadas. Uma primeira, em que o sistema é apenas composto por painéis solares, depois, com painéis solares e baterias e, por último, um sistema fisicamente igual ao anterior, no qual as baterias são apenas utilizadas em caso de falha energética. Visto que as interrupções no serviço de energia são um fenômeno probabilístico, estas três abordagens do sistema serão interpretadas de um ponto de vista probabilístico.

Palavras-chave: Interrupções energéticas, Painéis solares, Bateria, Algoritmo de otimização.
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.
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Nomenclature

Irradiance model

\(\alpha_z\)  Altitude angle.
\(\delta\)  Declination angle.
\(\omega\)  Hour angle.
\(\theta\)  Angle of incidence.
\(\phi\)  Latitude.
\(\gamma\)  Surface azimuth angle.
\(\beta\)  Tilt angle.
\(\theta_z\)  Zenith angle.
\(t_c\)  Clock time.
\(f\)  Cloudiness modulation factor.
\(t_{\text{Solar}}\)  Solar time.
\(B\)  Day to degree conversion.
\(n\)  Day of the year.
\(E\)  Equation of time.
\(\rho_g\)  Ground albedo.
\(G_b\)  Beam irradiance.
\(G_{b,\text{tilt}}\)  Tilted beam irradiance.
\(G_{sc}\)  Solar constant irradiance.
\(G_d\)  Diffuse irradiance.
\(G_o\)  Direct extraterrestrial irradiance.
\(G_{d,cs}\)  Circumsolar diffuse irradiance.
$G_{hz}$ Horizon diffuse irradiance.
$G_{iso}$ Isotropic diffuse irradiance.
$G_{dr}$ Reflected diffuse irradiance.
$G_{dtotal}$ Total diffuse irradiance.
$G_{ext}$ Extraterrestrial irradiance.
$G$ Global irradiance.
$G_T$ Total irradiance.
$\langle H \rangle$ Observed monthly average daily irradiation.
$\langle H_0 \rangle$ Extraterrestrial monthly average daily irradiation.

$k_t$ Clearness index.
$T_{loc}$ Localization factor.
$R_b$ Tilt ratio.
$A_i$ Anisotropy index.

**Solar panel model**

$A$ Area.
$\eta$ efficiency.
$P_{maxNOCT}$ Irradiance at NOCT.
$N_{PV}$ Number of solar panels.
$P_{maxNOCT}$ Maximum power at NOCT.
$P_{PV}$ Power output of solar panels.
$T_{air}$ Temperature of the air.
$T_{cell}$ Temperature of the solar cells.

$NOCT$ Normal operation cell temperature.
$c_t$ Temperature coefficient.

**Battery model**

$Ah$ Cell capacity.
$Capacity_{MAX}$ Maximum cell capacity.
$V$ Cell voltage.
$C_{\text{max}}$ Maximum charge.

$c_{\text{charge}}$ Charge rating.

$D_{\text{max}}$ Maximum discharge.

$c_{\text{discharge}}$ Discharge rating.

$N_{\text{bat}}$ Number of batteries.

$P_{\text{bat}}$ Battery power.

$P_{\text{grid}}$ Grid power.

$P_{\text{load}}$ Load power.

**India case study**

$Cap_{\%}$ Cell capacity.

$k$ Days in a month.

$H_0$ Extraterrestrial irradiation.

$f$ First day of the month.

$E_{\text{missed}}$ Missed energy.

$Norm_{\text{factor}}$ Normalization factor of outage probability per day.

$p_{\text{bat}}$ Price of battery.

$p_{\text{PV}}$ Price of solar panel.

$P_{\text{system}}$ PV and battery power.
Glossary

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td><strong>DOD</strong></td>
<td>Depth of discharge is the lowest percentage of energy remaining in a battery.</td>
</tr>
<tr>
<td><strong>GDP</strong></td>
<td>Gross Domestic Product is a way to measure a country’s wealth, it represents the balance between consumption and profit.</td>
</tr>
<tr>
<td><strong>HDKR</strong></td>
<td>Hay, Davies, Klucher and Reindl is a solar irradiance model that takes into account not only direct but also reflected radiation components.</td>
</tr>
<tr>
<td><strong>NSGA-II</strong></td>
<td>Non-dominated Sorting Genetic Algorithm II is an optimization algorithm that uses genetic combination and selection.</td>
</tr>
<tr>
<td><strong>PV</strong></td>
<td>Photovoltaic panels are devices that convert the radiation provided from the sun into electric energy.</td>
</tr>
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</table>
Chapter 1

Introduction

1.1 Introduction

In a world where the demand for electric energy is ever growing, it is already well established that the solution is to have sustainable energy systems that reduce the impact, of its usage, in the whole ecosystem. The crescent need for these kinds of energy sources, provided a great opportunity for companies and governments to invest and develop better technologies. With these investments, and the improvements in the manufacturing processes, the prices of these kinds of technology are becoming more competitive. This factor led to the emergence of domestic renewable energy systems. In countries where the energy demand is not a concern, this type of domestic system is used as micro production plants, where the power is injected in the grid. However, in certain countries, such as India, where power outages are daily episodes, these kinds of systems provide an alternative to the current backup power sources, as the internal combustion generators already in use. Domestic renewable energy systems, specially solar generated and with battery storage, are part of the solution to the energy quality problem in India therefore, some Indian companies, well aware of this market opportunity, are investing in the development of thesis kind of systems.

With new renewable energy backup solutions appearing on the market each year, it is important to perform an evaluation in order to understand which are the most viable solutions. These kinds of systems are complex, with several variables, parameters and even some probabilistic events, such as the weather or the probability of occurring a power outage. Therefore, during the design process, manufacturers tend to develop their systems so that they are optimized for the majority of their costumers. Thus, some of the consumers will acquire suboptimal systems. The purpose of this thesis is to fill this gap, and develop an optimization algorithm that manages to optimize the system to the individual characteristics of each consumer. This algorithm will take into account several parameters from the user and the devices, in order to optimize a renewable energy system made up of solar panels and a battery pack.
1.2 Objective and work plan

This thesis’ focus is to develop an optimization tool for a renewable energy system with solar panels and batteries. This system is meant to be optimized for each user specifications, although the main part of the study is focused the Indian reality. The purpose of this system is to provide energy to the user in the eventuality of a power outage occurrence. The first step to achieve this, is the usage of proper models, that take into account the physical phenomena. These models are managed by numerous variables and parameters. However, some are determined by the user (inputs) while others have a wide range of values. Then, from these ranges of values, the optimization algorithm will determine a set of optimal results. From these results, it is then possible to obtain conclusions on how the system performs for each particular user. In what regards the structure of the report it is divided in:

- **Chapter 2 - Theoretical review:** Since there exist several types of technologies, in what regards solar panels and batteries, it is necessary to state the advantages and disadvantages of each type. These kinds of devices have numerous parameters. Therefore, one must understand which are the crucial ones, so that, for each specific application, the most appropriate technology is chosen. The main goal of this chapter in understanding these parameters, and, performing a comparison between types of technologies.

- **Chapter 3 - Physical models:** During this study there will be taken into account some physical phenomena. So, in order to understand how these events work, it is fundamental to acquire mathematical models that translate it. In this chapter, the models of incidence, solar panels and battery pack will be defined. It will be described how these interact with each other and with the consumer.

- **Chapter 4 - Optimization algorithm and Portugal-India comparison:** Since the physical models have numerous variables and parameters, it is necessary to use an optimization algorithm so that the system performs in the best way possible. Across this chapter, the processes and mechanics of the algorithm will be explained. Later in the chapter, a comparison between the Indian and Portuguese realities is perform, in order to understand how the differences between both countries affect the developed system.

- **Chapter 5 - India case study:** The developed model has a certain number of parameters that need to be defined. In the first part of this chapter it is defined: the inputs, that translate the specifications of the consumer; the decision variables, which are the parameters optimized by the algorithm; and the objective functions, whose results ought to be minimized in order to obtain the best results. Then, three different approaches of the system will be studied: Only solar panels; solar panels and battery pack; solar panels and battery back in case of power outage. The optimization model will compute the optimal values for each of the three previously stated cases. Lastly, these values will be compared in order to conclude which one the best performance.

- **Chapter 6 - Conclusions and future work:** In this chapter the conclusions taken from the optimization tool are outlined, as well as some future perspectives.
Chapter 2

Theoretical review

2.1 Power outages in India

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 in India can experience power outages on a weakly basis, and, the country is home of some of the biggest outages events in the history of mankind. With around 620 million people affected by an outage in 2012, [1], as seen in Figure 2.1. These outages have not only, a social impact, but also a negative economic repercussion. In India, the final cost of electricity is overvalued [2] and the country’s GDP is lowered due to these persistent blackouts [3].

![Figure 2.1: Largest blackouts in the world, [1].](image)

From the Figure [1] one can see that, blackouts tend to happen in heavy populated zones, as well as in developing countries. To overcome theses concerns, in the energy distribution, domestic and large
scale renewable energy systems are nowadays seen as a solution [4]. In Figure 2.2 one can see the expected growth, by the Indian government in New Delhi, in rooftop solar backup solutions. It is clearly visible that the residential share is the solution with the largest market size, with 1242 MW.

![Figure 2.2: Prevision in solar rooftop solutions in New Delhi, [5].](image)

2.2 Solar panels

In vast countries, such as India, solar panels are an outstanding source of clean energy. Over the past years, the Indian government has already stated the importance of this energy source [6] and the country’s potential is undeniable [7]. 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 [8]. In Figure 2.3 it is possible to see that India leads the world, as one of the countries with least expensive solar panels.

With such low prices in solar energy solutions, not only industrial but also domestic applications become viable. However, when performing an investment to obtain a domestic solar panel system, there exist numerous parameters to take into account: weather, geographical localization, grid energy price, load profile of the consumer, PV efficiencies and costs. Therefore, the optimization tool, that will be developed, must take into consideration these parameters in order to be accurate.
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 geographical place. The solar irradiance is, by definition, the power per area that reaches the earth’s surface [9]. However, there exists a considerable part of the solar radiation that does not reach the earth’s surface in a direct way. Thus, it is necessary to model this phenomenon, to do so, one of the following mathematical models must be used [10]:

- Liu and Jordan model;
- Koronakis model;
- Badescu model;
- Hay and Davies model;
- Reindl et al model;
- Hay, Davies, Klucher and Reindl model.

The model that was used by the optimization tool was the Hay, Davies, Klucher and Reindl model (HDKR). In comparison to the other models this one is more complete, because it takes into consideration more components of the non direct solar irradiance. This model, in order to translate the received solar irradiance, not only contemplates the earth’s movement (rotation and translation) but also the effects of the weather, defined by the clearness index, $k_t$, [11]. Without the consideration of this index, the results of the available irradiances at earth’s surface, would be unrealistically high, because some of this irradiance is naturally absorbed by the meteorological phenomena. In Figure 2.4 one can see how the clearness index, $k_t$, relates with the visible weather.

Another important factor to state when analysing different solar options is the efficiency of the solar cells. This efficiency is defined by the quotient between, the power output and the solar irradiance.
received by the PV. The main characteristic that influences the solar panels efficiency, is its technology type. Some examples of photovoltaic technologies are presented in Figure 2.5. Here it is possible to see that using concentrators it is possible to obtain up to 25%, typical crystalline silicon panels raised up to 15% while thin film cells have around 13% of efficiency.

However, it exists another aspect that conditions the solar panels efficiency, which is the cell temperature. This phenomenon translates to the solar model as a parameter called the temperature coefficient. It is defined by the dependence of the efficiency with the variation of the temperature, and is also dependent on the type of technology of the cell [14]. Its value is always negative, because the cell's efficiency decreases with the temperature. In Table 2.1 it is possible to see the temperature coefficients for some solar cell technologies. On the first hand, Amorphous silicon is the technology least affected by temperature although it has low efficiencies, while on the other hand, CIGS (Thin film) is the most affected by temperature changes.
### Table 2.1: Coefficients for different PV technologies, [15].

<table>
<thead>
<tr>
<th>Technology</th>
<th>Temperature coefficient [%/°C]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crystalline silicon (c-SI)</td>
<td>-0.45</td>
<td>15</td>
</tr>
<tr>
<td>Amorphous silicon (a-SI)</td>
<td>-0.24</td>
<td>8.1</td>
</tr>
<tr>
<td>CdTe (Thin film)</td>
<td>-0.29</td>
<td>11</td>
</tr>
<tr>
<td>CIGS (Thin film)</td>
<td>-0.47</td>
<td>12</td>
</tr>
</tbody>
</table>

Despite the existence of different solar cells technologies, the one that will be used by the developed optimization model will be crystalline silicon. Although this technology is not either, the most efficient nor the one with the lesser temperature coefficient, it is the most widely spread, and therefore the most economically competitive. In Figure 2.6 it is presented the market share for the different solar panel technologies. It can be seen that the silicon cells have more that 70% of the worldwide market share, distributed by 44.8% on silicon-based cells and 25.61% of advanced crystalline silicon cells.

**Figure 2.6: Market share for different solar cell technologies, [16].**

### 2.3 Batteries

Since 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 in the usage of batteries, that store the remaining energy provided by the PVs. The utilization of batteries, as a backup energy supply solution in countries with unstable power grids, is a present reality [17]. Alike solar panels, there exist several technologies of batteries. Each of these technologies has different characteristics in what regards energy density, lifetime
and price. When choosing a battery for a specific solution it is fundamental to take these parameters into consideration, battery technologies can be divided into three groups [18]:

- Lead acid;
- Lithium base;
- Nickel–cadmium base.

The energy density of a battery is by definition, the energy stored per unity of weight or volume. In Figure 2.7 it is presented a graph, where it is possible to see the energy densities of different battery technologies. One can see that lithium based batteries have the best performance in what regards energy density, both in weight and in volume. However, in this particular application, the batteries are going to be installed in residential homes, so, weight and volume are usually of no concern.

![Energy density for different battery technologies](image)

**Figure 2.7: Energy density for different battery technologies, [19].**

When comparing the lifetime of different battery technologies there exist two important factors to take into account: the number of cycles (charge and discharge) that a battery can perform and how does the total capacity diminish throughout its lifetime. In Table 2.2 one can see the different number of cycles of each battery technology. Thus, it is possible to conclude that lithium base batteries can perform a higher number of cycles, however, the difference for the other two technologies it is not that significant.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Life [years]</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead acid</td>
<td>15</td>
<td>2000</td>
</tr>
<tr>
<td>Nickel-cadmium base</td>
<td>20</td>
<td>2000</td>
</tr>
<tr>
<td>lithium base</td>
<td>15</td>
<td>2500</td>
</tr>
</tbody>
</table>

**Table 2.2: Expected lifetime and maximum number of cycles for different battery technologies, [18].**

Now, to understand how the total capacity of a battery diminishes throughout its lifetime, it is presented in Figure 2.8 the total capacity versus the number of cycles for each technology. It is possible
to see that, in lead acid batteries, the depth of discharge (DOD), which is the lower limit of discharge, influences the loss of total capacity. With a low percentage of depth of discharge, lead acid batteries have a similar behaviour to lithium base batteries.

When choosing a certain type of battery technology for a specific application, it is crucial to not only take into consideration the physical parameters, but also the economical factors. In Figure 2.9 one can see the price of each technology versus its total installed capacity. It is clearly visible that lead acid batteries (yellow), have the lowest prices and therefore the highest installed capacity. So, in the developed model, it will be used the lead acid battery type technology. Because, although it underperforms when compared to lithium base batteries, it is the most used technology in this kind of application [18].
2.4 Optimization algorithm

In complex models, such as one that will be developed, there exist dozens of variables that influence the overall system performance. Some variables are deterministic, like the position of the sun at any given time, others are probabilistic, as the phenomenon of the occurrence of a power outage. And some are chosen by the user or the manufacturer, such as the amount of solar panels or batteries. In order to obtain the best possible results, the values of these chosen parameters must be optimal, and this is achieved by using an optimization algorithm. The implementation of this kind of algorithms in renewable energy problems, has already been proven [22], [23].

In this specific implementation, there will exist several parameters to be taken into account when performing the optimization process. Therefore, it was mandatory to use an algorithm had multi-objectives [24]. Due to this fact, the chosen algorithm was the NSGA-II, [25]. It is important to understand that this kind of algorithm does not output one single optimal value. Instead, the optimal result is given by a curve of potentially optimal elements, pareto curve, where no element is strictly better than its neighbour, as seen in Figure 2.10.

![Figure 2.10: Pareto curve, [25].](image-url)
Chapter 3

Physical models

3.1 Incidence Model

To estimate the yearly solar energy received by a solar panel it is necessary to model the yearly movement of the sun across the sky. The first definition that one needs to take into account is that the clock time, does not correspond to the actual sun position, for instance the solar noon, the time which the sun reaches its highest point, might not happen exactly at midday. This being said and according to [26], a different time is used in the calculation of the sun-angle relationships, called solar time, $t_{solar}$, which is given by the equation (3.1).

$$t_{solar} = t_c + T_{loc} + E.$$  \hspace{1cm} (3.1)

Besides the $t_c$, which is the actual clock time, there are two factors that influence the solar time. One due to the localization of the observer, and another due to the effects of the tilt in the earth’s axis, respectively $T_{loc}$ and $E$. The localization factor depends on the longitude of the observer, in degrees, and respective time zone (3.2), east time zones are considered positive. The factor $E$ is also called the equation of time and it is presented in the equation 3.3, it is dependent of the $B$ factor which is function of the present day $n$.

$$T_{loc} = \left( \frac{\text{longitude}}{15\degree} - Z_c \right) \times 60.$$  \hspace{1cm} (3.2)

$$E = 229.2 \left( 7.5\times 10^{-5} + 1.868 \times 10^{-3}\cos(B) - 3.2077 \times 10^{-2}\sin(B) - 1.4615 \times 10^{-2}\cos(2B) \\ - 4.089 \times 10^{-2}\sin(2B) \right).$$  \hspace{1cm} (3.3)

$$B = 360\degree \frac{n - 1}{365}.$$  \hspace{1cm} (3.4)

The equation of time takes into account not only the effects of obliquity, i.e. the tilt of the earth’s axis of rotation relative to the plane of the ecliptic, but also to the eccentricity of the earth’s orbit. Figure 3.1 shows how this factor influences the solar time throughout the year.
The sun irradiates the same amount of energy all year long, however, the earth distance to it changes, due to the earth’s orbit eccentricity. Thus, the irradiance that reaches the earth’s surface, extraterrestrial irradiance, $G_{on}$, is different each day of the year. This phenomenon is translated by model with the equation (3.5).

$$G_{on} = G_{sc} \left(1 + 0.033 \cos \left( \frac{360^\circ \times n}{365} \right) \right). \quad (3.5)$$

Where $G_{sc}$ represents the solar constant irradiance. Which is the power, received on a area unit in a surface perpendicular to the direction of propagation of the radiation outside the atmosphere. Unless stated, the value of $G_{sc}$ is the global average of 1000 W m$^{-2}$. In Figure 3.2 one can see the variation of the irradiance that reaches the earth’s surface each day of the year, due to the distance variation between the earth and the sun.
In order to understand how the position and localization of a solar panel influences the radiation received, it is necessary to define the angles that translate its relative position with the sun:

- **Latitude** $[\phi]$, the angle of the location from the equator regarding the north or the south, north being a positive angle; $-90^\circ \leq \phi \leq +90^\circ$.

- **Declination** $[\delta]$, the angular position of the sun at its highest point of the day with respect to the plane of the equator, as seen in Figure 3.3. By default, north is considered the positive angle; $-23.45^\circ \leq \delta \leq +23.45^\circ$. With the equation (3.6) one can obtain the declination in degrees.

  \[ \delta = 23.45 \sin \left( 360 \frac{284 + n}{365} \right). \] \hspace{1cm} (3.6)

- **Tilt** $[\beta]$, the angle between the surface receiving radiation and the horizontal plane; $0^\circ \leq \beta \leq 180^\circ$, visible in Figure 3.4.

  \[ \beta \]

- **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; $-180^\circ \leq \gamma \leq 180^\circ$, presented in Figure 3.5.
Figure 3.5: Surface azimuth angle.

- **Hour angle** $[\omega]$, the angular movement of the sun east or west of the longitude of the observer due to the rotation of the earth with a speed of $15^\circ \text{ h}^{-1}$, morning negative, afternoon positive and zero at the solar noon; $-180^\circ \leq \omega \leq 180^\circ$. The hour angle in degrees can be obtained with the equation (3.7).

$$\omega = \left( \frac{t_{\text{solar}}}{60} - 12 \right) 12^\circ/\text{hour}. \quad (3.7)$$

- **Angle of incidence** $[\theta]$, the angle between the direct radiation from the sun and the normal of the surface in which it is radiating; $0^\circ \leq \theta \leq 180^\circ$, as one can see in Figure 3.6. With angles over $90^\circ$ the radiation is striking behind the panel, the angle of incidence can be obtained from the other angles of the model through the equation (3.8).

$$\cos \theta = \sin \delta \sin \phi \cos \beta - \sin \delta \cos \phi \sin \beta \cos \gamma + \cos \delta \cos \phi \cos \beta \cos \omega + \cos \delta \sin \phi \sin \beta \cos \gamma \cos \omega + \cos \delta \sin \beta \sin \gamma \sin \omega. \quad (3.8)$$

- **Zenith angle** $[\theta_z]$, the angular distance between the vertical (zenith) and the line to the sun, which means, the angle of incidence on a horizontal surface; $0^\circ \leq \theta_z \leq 180^\circ$. 
To obtain the zenith angle one must simply use the expression in (3.8) with $\beta = 0^\circ$, which represents a flat surface,

$$\cos \theta_z = \cos \delta \cos \phi \cos \omega + \sin \delta \sin \phi.$$  \hspace{1cm} (3.9)

Now that all the angles are defined it is possible to state how they influence the irradiance that a panel is exposed to, however, neglecting any shading or reflective effects that may decrease it. The first step is to compute the amount of extraterrestrial irradiance that strikes a surface, named direct extraterrestrial irradiance, $G_o$, and presented in (3.10) and which is a function of the total extraterrestrial irradiance (3.5) and the zenith angle for a flat surface (3.9).

$$G_o = G_{on} \cos \theta_z.$$  \hspace{1cm} (3.10)

The atmosphere and the whether affect how much irradiance actually reaches the earth’s surface. The clearness index, $k_t$, translates how the model replicates this events. Since these are probabilistic phenomena, the only way to proper obtain the clearness index is through statistical analysis. Thus, it is possible to compute it with the ratio of the actual observed monthly average daily irradiation and the extraterrestrial monthly average daily irradiation in the same month,

$$k_t = \frac{\langle H \rangle}{\langle H_o \rangle}. \hspace{1cm} (3.11)$$

With the clearness index one can obtain the global irradiance that reaches the earth’s surface, $G$, defined in the equation (3.12).

$$G = k_t G_o.$$  \hspace{1cm} (3.12)

The global irradiance is divided into two components: the first being the radiation that strikes the surface in a direct way, called beam irradiance; and the radiation that is reflected, by the floor or the atmosphere, before reaching the surface, named diffuse irradiance. The global irradiance is given by the sum of these two components, presented in the equation (3.13).

$$G = G_d + G_b.$$  \hspace{1cm} (3.13)

To obtain the amount of the global irradiance that is due to the diffuse irradiance it is possible to use the correlation with the clearness index of [27], seen in the equation (3.14). In Figure 3.7 it is presented the $G_d/G$ coefficient.

$$\frac{G_d}{G} = \begin{cases} 
1 - 0.09 k_t, & k_t \leq 0.22 \\
0.9511 - 0.1604 k_t + 4.388 k_t^2 - 16.638 k_t^3 + 12.336 k_t^4, & 0.35 \leq k_t \leq 0.8 \\
0.165 & k_t > 0.8.
\end{cases} \hspace{1cm} (3.14)$$

Now that is known the total diffuse irradiance it is necessary to model its components, there exist
several models that represent the diffuse irradiance however, the more complete is the anisotropic sky model. This model is called HDKR (the Hay, Davies, Klucher, Reindl model [26]) and it subdivides the diffuse irradiance into four components:

- **Isotropic** $[G_{d_{iso}}]$, uniform radiation from all the sky;
- **Circumsolar** $[G_{d_{cs}}]$, radiation resulting from the forward scattering of the beam component;
- **Horizon** $[G_{d_{hz}}]$, resulting from the horizon brightening effect, it is concentrated near the horizon and is more pronounced in clear days;
- **Reflected** $[G_{d_{r}}]$, radiation reflected in the ground due to its albedo.

It is possible to see the solar irradiances stated above in Figure 3.8.

![Figure 3.7: Erbs et al correlation [27].](image)

From the HDKR model it is also possible to obtain the total irradiance, from the individual components, of the diffuse and the tilted component of the beam irradiances, presented in the equation (3.15).

![Figure 3.8: Components of the solar irradiance by the HDKR model.](image)
To know the total irradiance one must first compute the beam irradiance that a tilted surface receives, \(G_{b,\text{tilt}}\). This is achieved with a ratio named \(R_b\) presented in the equation (3.16), and the expression of the beam irradiance (3.17).

\[
R_b = \frac{\cos \theta}{\cos \theta_z}.
\] (3.16)

\[
G_{b,\text{tilt}} = R_b \cdot G_b.
\] (3.17)

The HDKR model unifies the isotropic, circumsolar and horizon diffuse irradiiances in a single computation, therefore, the equation (3.15) becomes the expression presented in (3.18). That being said, the total diffuse irradiance is given by the equation (3.19).

\[
G_T = G_{b,\text{tilt}} + G_{d,\text{iso}} + G_{d,\text{cs}} + G_{d,\text{hz}} + G_d.
\] (3.15)

\[
G_T = G_{b,\text{tilt}} + G_{d,\text{tot}} + G_d.
\] (3.18)

\[
G_{d,\text{tot}} = G_d \left(1 - A_i\right) \left(1 + f \sin^3 \frac{\beta}{2}\right) + A_i R_b.
\] (3.19)

The ratios \(A_i\) and \(f\) are respectively the anisotropy index, which is a function of the transmittance of the atmosphere for the beam irradiance, and the modulation factor that takes into account the cloudiness, both presented respectively in the equations (3.20) and (3.21).

\[
A_i = \frac{G_b}{G_o}.
\] (3.20)

\[
f = \sqrt{\frac{G_b}{G}}.
\] (3.21)

By adding the reflected diffuse irradiance term, \(G_{d,r}\), presented in the equation (3.22), where \(\rho_g\) is the albedo, that is the ground reflectance, it is possible to obtain the complete equation of the irradiance received by a tilted surface seen in the equation (3.23).

\[
G_{d,r} = G \rho_g \left(1 - \cos \beta\right)\left(1 + \frac{\cos \beta}{2}\right) + G \rho_g \left(1 - \cos \beta\right)\left(1 + f \sin \frac{\beta}{2}\right) + G \rho_g \left(1 - \cos \beta\right).
\] (3.22)

\[
G_T = \left(G_b + G_{d} A_i\right) R_b + G_d \left(1 - A_i\right) \left(1 + f \sin^3 \frac{\beta}{2}\right) + G \rho_g \left(1 - \cos \beta\right).
\] (3.23)

As an example, in Figure 3.9, it is presented the annual irradiance for a surface with one square meter and with the solar angles from Table 3.1.
Table 3.1: Solar angles used in Figure 3.9.

<table>
<thead>
<tr>
<th>Tilt angle [°]</th>
<th>Azimuth angle [°]</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>20</td>
</tr>
</tbody>
</table>

In Figure 3.10 one can see two days of Figure 3.9, it is clearly visible the difference of sunset and sunrise as well the difference of max irradiance.

3.2 Solar panel model

In order to model power produced by the solar panel array, one starts by defining its output for a certain irradiance, as presented in the equation (3.24).
\[ P_{PV} = G_T \ A \ \eta \ N_{PV}. \] (3.24)

Where \( G_T \) is the available irradiance, defined by the previous model and \( A, \eta \) and \( N_{PV} \) are respectively the area, the efficiency and the amount of solar panels. The performance of a PV is a function of its temperature. Thus, to model this phenomenon, it was used the NOCT model [28], presented in the equation (3.25), this expression is used to obtain the cell temperature, \( T_{cell} \). This simplified model is of particular interest because, the parameters which it needs to operate, are always present in the panel datasheet.

\[ T_{cell} = T_{air} + \left( \frac{NOCT - 20}{80} \right) G_T. \] (3.25)

In the expression (3.25) the \( T_{air} \) is the air temperature in \( ^\circ \text{C} \), \( G_T \) is the irradiance in \( \text{mW cm}^{-2} \) and NOCT is the nominal operating cell temperature which is a parameter obtained from the datasheet. Now, it is necessary to find out how the temperature affects the overall efficiency of the cell, as seen in the equation (3.26). To do so it was used the temperature coefficient of the maximum power, \( c_t \), given in \([\% \ ^\circ \text{C}^{-1}]\) also present in the datasheet.

\[ \eta = \frac{P_{max_{NOCT}}}{G_{NOCT} \times A} \times \frac{c_t \times T_{cell} + 109}{100}. \] (3.26)

Where \( P_{max_{NOCT}} \) is the maximum power at NOCT and \( G_{NOCT} \) is the irradiance at NOCT as well. From the expression (3.26) one can clearly see that the PV efficiency has a decreasing and linear behaviour since \( c_t \) is always a negative parameter. Using the data from [29] it is possible to obtain the temperature profile in a typical day of summer and winter in India. In Figure 3.11(a) and 3.11(b) it is presented the ambient, cell temperatures and the efficiency throughout a day, respectively, during the summer and the winter.

![Figure 3.11: Ambient, cell temperatures and efficiency throughout a day.](a) Summer. (b) Winter.

Since during the summer months the temperature is greater, the efficiency of the solar array is lower. Another important aspect to refer is that the temperature of the cell is different from the ambient temperature when there exists radiation provided by the sun, this phenomenon is visible in Figure 3.11 during the sunlight hours.
3.3 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, the maximum charge and discharge ratings. These last two are of particular importance because they translate the maximum power that, the battery can provide or receive from the rest of the system. In order to obtain the maximum capacity of the battery in \([\text{Wh}]\) the equation (3.27) was used.

\[
\text{Capacity}_{\text{MAX}} = N_{\text{bat}} \, \text{Ah} \, V. \tag{3.27}
\]

Where \(N_{\text{bat}}\) is the amount of batteries and \(\text{Ah}\) and \(V\) are respectively the capacity in \([\text{Ah}]\) and the voltage in \([\text{V}]\) of each battery. The maximum charge and discharge ratings of a battery are given by the manufacturer in C-ratings, which means that a battery with 2C maximum discharge rating and a capacity of \(2\,\text{Ah}\) is able to provide a \(4\,\text{A}\) maximum discharge current. With this information it is possible to compute the maximum charge, \(C_{\text{MAX}}\), and discharge power, \(D_{\text{MAX}}\), for a given battery, respectively presented in the equations (3.28) and (3.29).

\[
C_{\text{MAX}} = N_{\text{bat}} \, c_{\text{charge}} \, \text{Ah} \, V. \tag{3.28}
\]

\[
D_{\text{MAX}} = N_{\text{bat}} \, c_{\text{discharge}} \, \text{Ah} \, V. \tag{3.29}
\]

where \(c_{\text{charge}}\) and \(c_{\text{discharge}}\) are the maximum charge and discharge ratings given in C-rate by the datasheet.

The battery pack main functions are: storing the excess power from the solar panels and, when there exists a lack of solar power, provide energy to the load. However, the battery can only receive power as long as it is lesser or equal than the maximum recharge rating, and it is not full. And, can only provide power with the maximum discharge rating and while it has energy stored on it. To understand how the charging and discharging take place in the developed model, in Figure 3.12 it is presented one day in the charge and discharge cycle of a battery with the parameters from Table 3.2.

<table>
<thead>
<tr>
<th>Maximum capacity ([\text{Wh}])</th>
<th>Discharge Rating ([\text{kW}])</th>
<th>Charge Rating ([\text{kW}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>6000</td>
<td>6</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 3.2: Parameters of the battery used in 3.12.

In Figure 3.12 the \(P_{\text{bat}}\) represents the power that is provided by the battery, that being said it is positive when the battery receives power and negative when the battery is recharging. It is possible to see that, around the twelfth hour, \(P_{\text{bat}}\) becomes constant around the 1.2 kW, this happens because the battery is being charged at its maximum charging rate, as seen in Table 3.2. When the battery is fully charged, around the sixteenth hour, the power that the battery receives becomes zero, this is also true when the battery is fully discharged around the fourth hour. In Figure 3.13 it is presented the same figure as in 3.12 but with a maximum charge rating of 3 kW.
Figure 3.12: Example of a charge and discharge cycle of the battery pack.

Figure 3.13: Example of a charge and discharge cycle of the battery pack with a maximum charge rating of 3 kW.

In Figure 3.13 it does not happen the saturation in $P_{\text{bat}}$ around the twelfth hours, this example showed the difference that the charge and discharge ratings have in the system.

### 3.4 Interaction between models

Now that all three physical models are defined it possible to understand how they interact with each other. The complete system is composed by:

- **Solar panels**, the main power source.
- **Battery pack**, where the excess power from the solar panels is stored and the secondary power source in a case where the power from the PVs is not available.
- **Power grid**, which is the emergency power source, only to be used when the battery is discharged or at its maximum discharge rate and the power provided by the solar panels is not sufficient.

- **The load**, it represents the power that is demanded by system at any given time.

In Figure 3.14 it is presented the physical general diagram of the system.

![Physical representation of the system](image)

**Figure 3.14**: Physical representation of the system.

From Figure 3.14 it is possible to see that the battery pack is only powered by the solar panels, while the load is powered by the solar panels, the battery and, in last case scenario, the power grid. At any given time the equation that translates the power flow in the system is presented in (3.30). In Figure 3.15 it is presented the flow chart that states the system performance.

\[
P_{PV} + P_{bat} + P_{grid} = P_{load}. \tag{3.30}
\]

From Figure 3.15 it is possible to understand that the system uses the solar panels as the main power source. However, when the PVs can not provide enough power to the load, the battery, if charged, provides the remaining power, as long as it is lesser than its maximum discharge rating. In all situations where the solar panels and the battery are not able to provide the necessary power to the load, the power grid provides the remaining power. In Figure 3.16 it is presented an example of a summer and a winter day, respectively, of all the power flows between the system.

All the quantities in Figure 3.16 are relative to the output of power, which means that negative values refer to the input of power, while positive refer to the output of power. In 3.16 it is clearly visible that the power from the solar panels is used as the main source of power, powering the load and charging the battery with the remaining energy. When the power from the solar panels is not enough, the battery compensates the difference as long as it has the necessary energy. Now, in Figure 3.17 it is presented the same as in Figure 3.16 but now with less solar panels.

In Figure 3.17 since the power from the solar panels is much lesser, the grid needs to provide most of the load demand. Also, since the battery is only charged by the solar panels, when there exists a over
supply to the load, the presence of the battery is almost unnoticeable. As a second example, in Figure 3.18 it is presented again, the same as in Figure 3.16, however, with an increase in the amount of solar panels.

The main phenomenon to notice, in Figure 3.18, is that, around the eighteenth hour, the power of the battery becomes zero although the solar panels are still having an excess power, this happens because the battery is fully charged. Another aspect to note is that, around the twelfth hour, the power of the battery becomes constant, this occurs because the battery is at its maximum charge rating. To better understand this two situations, in Figure 3.19 one can see the remaining power from the panels, which means the power that is available to charge the battery, the power from the battery and its state of charge.

In Figure 3.19, one can clearly see that the remaining power from the solar panels is the same as the
power charging the battery, as long as the battery is not at its maximum charge rating or fully charged. As a last example, in Figure 3.20 it is presented a situation where the power provided by the solar panels and the battery are sufficient to supply the load. Therefore, the grid does not provide any power to the system.

To comprehend how the solar panels and battery provide all the power to the load, as seen in Figure 3.20, in the 3.21 it is presented the state of charge of the battery. It is visible that the battery SOC is always above zero, which means that the battery never gets fully discharged.
Figure 3.18: Example with more solar panels.

Figure 3.19: Remaining power from the PVs, battery power and state of charge.
Figure 3.20: Example where the solar panels and the battery are sufficient to supply the load demand.

Figure 3.21: Remaining power from the PVs, battery power and state of charge for the example 3.20.
Chapter 4

Optimization algorithm and
Portugal-India comparison

4.1 Optimization algorithm

As seen in the previous chapter, the physical models that were defined have numerous variables that need to be taken into account. The purpose of the optimization algorithm is to find out, in which range of values, the system has the best performance. The algorithm that was chosen to perform the optimization was the NSGA-II [25]. As a optimization algorithm, the NSGA-II starts by creating a population of elements, individually characterized by a genetic code. This code represents the values of the decision variables. The algorithm then decides, which elements are more fitted to be preserved by comparing the results of their objective functions. These elements are subsequently combined, process named crossover, (merging the variables) and mutated (slightly changing the variables of a given element) in order to create new elements. Lastly, the best performing elements of the previous generation are combined with elements of the current generation, so that the elite ones are always preserved. In Figure 4.1 it is presented the flow chart of how the NSGA-II and the physical models execute the optimization process.

In the developed model, the genetic code of each element has three or four decision variables. The optimization process will now be explained in detail, according to the order presented in the flowchart 4.1. In the examples that follow, each element will be characterized by three decision variables: tilt angle, azimuth angle and the number of solar panels, as seen in Figure 4.2.

The algorithm starts by creating the genetic code, of each element of the first generation, using the range of values defined for each decision variable. Since these variables are chosen at random, there is no initial relation between the elements. Then, the physical model performs the computations, for each element set of variables, and delivers, as an output, the values of each objective function. For an exemplification purpose, the following optimization will have two objective functions. In Figure 4.3 is possible to see the first generation objective function values of a optimization process, where it is clearly visible that the elements are located randomly.
These elements will now be subjected to the process of evaluation, during which they will be sorted into ranks according to their value. The ranks range from the first (rank 1), where are present the most optimal, to the last (rank N), which contains the least optimal elements. The evaluation criteria is the minimization of both objective functions, so an element that has both objective functions greater than
another element is automatically a worse result. Therefore this element shall be placed in an upper rank. However, there might happen a situation where, when comparing two elements, an element has a greater value on the first objective function but a lesser value in the second function. In this situation both elements are considered potentially optimal, thus, they shall be placed in the same rank. In Figure 4.4 it is presented a schematic on how the evaluation process takes place.
crossover procedure. The amount and which variables are exchanged by the elements is chosen at random. This process's goal is, not only the conservation of the best genes of one generation to the subsequent one, but also to obtain more optimal elements. In Figure 4.5 one can see a representation of the crossover process.

![Figure 4.5: Example of the crossover process.](image)

The next step in the optimization is the mutation. In this process, some potentially optimal elements are chosen, so that their variables are slightly modified. Without this procedure, the elements could start converging to a local minimum, instead of the absolute minimum result. With the mutation, the elements undergo through modifications that would never be achieved with the crossover process. In Figure 4.6 one can see an example of the mutation procedure.

![Figure 4.6: Example of the mutation process.](image)

After the mutation process, the algorithm begins the last step of the optimization mechanism. Which is the combination of the potentially optimal elements, of the current generation, with the previous one. With this procedure the best variables of both generations, have a better chance to be carried over to the next generation.

When using the NSGA-II there exist two external parameters that need to be defined: the number of elements in the populations and the amount of generations desired. As the number of elements in a single population becomes greater, its genetic diversity also increases. This leads to a greater pool of
potentially optimal elements, therefore more optimized results in the end. The amount of generations
determines how much generations the algorithm will compute before it ends. The greater the amount
of generations, the more optimized the results will get. However, with a large amount of generations,
the improvement from one generation to another becomes less noticeable. Both of these parameters
increase the complexity of the algorithm, thus, when defining them, one needs to take into account the
quality of the results and the computational time. In Figure 4.7 it is possible to see the evolution of the
populations in the optimizations process.

![Figure 4.7: Evolution of the optimization algorithm populations.](image)

### 4.2 Portugal and India

In this section the Indian perspective will be compared with the one that exists in Portugal. Many aspects
differentiate both countries, specially in what regards:

- **Physical differences**, geographical localization, yearly temperature and weather (which deter-
mines the clearness index);

- **Economic differences**, cost of electricity and the quality of the energy supply;

- **Mentality differences**, what a person takes into account and expects when investing in a renew-
  able energy system.

When comparing the geographical localization of two countries, the only coordinate that need to
be taken into account is the latitude. This occurs because the longitude only influences the time zone
difference, while the latitude has a direct impact on the solar angles. Despite the fact that both countries
are located in the northern hemisphere, Portugal has a greater latitude than India (positioned further
Therefore, throughout the year the sun will be located lower in the horizon for an observer in Portugal. This fact has a direct connection with the solar panel tilt angle. The solar altitude angle $\alpha_z$ is the complement of the zenith angle (3.9), therefore it can be obtained with the equation (4.1).

$$\alpha_z = 90 - \theta_z.$$  \hspace{1cm} \text{(4.1)}$

In Figure 4.8 one can see the effect of the latitude in the solar altitude angle, during two days of the year. It is possible to understand that, the tilt angle in Portugal will have lower values compared to India, due to the sun position in the sky.

![Figure 4.8: Solar altitude angle in Portugal and India.](image)

The economic differences have a particular impact in the distinction of both countries. In Table 4.1 it is possible to see the average cost of the electricity in both countries, according to [30].

<table>
<thead>
<tr>
<th>Country</th>
<th>India</th>
<th>Portugal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Price of electricity [€/kWh]</td>
<td>0.06</td>
<td>0.20</td>
</tr>
</tbody>
</table>

Table 4.1: Average electric energy prices.

From Table 4.1 it is visible that the energy in India in roughly one third when compared to Portugal. The other main economic difference is the quality of the supply of electric energy. In Portugal, as in most European countries, the power grid is robust and redundant, which means that power outages are a rare phenomenon. However, in India, with a disorganized and always growing power grid, power outages are a daily anomaly that affects the majority of the population. These two factors combined, influence the mind set of a person, when acquiring a domestic renewable energy system.

In India, since the power outages are a recurring phenomenon, the main purpose of a domestic renewable energy system is to act as a backup energy supply. The power grid still works has the main energy supply, since the energy price is modest. So, when acquiring such system, a consumer expects to be less affected by power outages while performing the lesser investment possible. On the other
hand, in Portugal, the main purpose of an investment in a renewable energy system is the payback time. This is due to the benefits given by the energy providers to such systems. So that the payback time is reduced, it is important that the system produces the maximum yearly energy possible.

These differences between the two countries, translate into the optimization model by modifying the objective functions. In Table 4.2 it is possible to see the chosen objective functions for both countries.

<table>
<thead>
<tr>
<th>Objective function 1</th>
<th>India</th>
<th>Portugal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Objective function 2</td>
<td>Missed energy</td>
<td>Negative of the total energy</td>
</tr>
</tbody>
</table>

Table 4.2: Objective functions for India and Portugal

As stated before, the algorithm performs a minimization of the objective functions. In what regards India, both functions are minimized, since the investment is expected to be as lower as possible. And the missed energy, which is the energy throughout the year that the consumer loss due to power outages, is also expected to be minimal. In the same way as India, in the Portuguese case, the payback time is expected to be low. However, the total energy, which is the total yearly energy produced by the system, is meant have the highest possible value, so, its necessary to use its negative in the optimization process.
Chapter 5

India case study

5.1 Power outages

In India, the outage phenomenon cannot be neglected and, thus, needs to be considered when analysing solutions of renewable energy 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, the data provided by [31],[2], [32] and [33] was used.

Using the data from [31] it was possible to obtain the time interval of the duration of the power outages, which is from 1 to 3 daily hours. This event was modelled by a uniform distribution, as seen in Figure 5.1.

Figure 5.1: Probabilistic distribution of the duration of a power outage.
The parameters of the normal distribution that takes into account the time of the day in which the outage can occur, were obtained using the data from [2] and [31]. The highest probability of an outage event, happens during the morning, due to the start of the industrial processes. In Figure 5.2 it is represented the normal distribution of the probability of occurring an outage for each hour of the day.

![Normal distribution of outage probability](image)

**Figure 5.2: Probabilistic distribution of the most likely hour to occur a power outage.**

Lastly, the data from [32] and from [2] was used to obtain the parameters, of the normal distribution, that models the influence of the time of the year in the outage phenomenon. The month that is more likely to have power outages is August, due to the excess use of cooling devices. This distribution had to be normalized with the average probability of happening a power outage in a day, according to [32]. The value of this normalization comes from the average amount of 13.8 outages that happen per month and it is presented in the equation (5.1).

\[
Norm_{\text{factor}} = \frac{13.8 \times 12}{365} = 0.454.
\]

(5.1)

With the normalization factor of 45.4% obtained in (5.1) it is possible to model the probabilistic distribution of yearly power outages, presented in Figure 5.3.

From the database of [33], it was possible to obtain the standard deviations of the distributions. In Table 5.1 it is presented all the parameters regarding the three probabilistic distributions.

<table>
<thead>
<tr>
<th>Distribution</th>
<th>Interval</th>
<th>Average</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time of the day [h]</td>
<td>Normal [1:24]</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Time of the year [day]</td>
<td>Normal [1:365]</td>
<td>230</td>
<td>115</td>
</tr>
<tr>
<td>Amount of hours [h]</td>
<td>Uniform [1:3]</td>
<td>2</td>
<td>N/A</td>
</tr>
</tbody>
</table>

**Table 5.1: Probabilistic distributions parameters of the power outages.**

In Figure 5.4 one can see a typical outage profile generated by the optimization model, with a total of 76 outages. The outage event considers two states: 1, when there is an outage and the electric grid is not available and 0, when the electric grid is working normally.
To better understand how the probabilistic distributions influence the power outages, it was generated 10000 outage profiles. In Figure 5.5 it is presented the output of this simulation.

In Figure 5.5 one can clearly see that the peak of outages occurs in the early morning and during the summer months. Another important aspect to notice, is the mean value of the total yearly outage hours. From the simulation it was obtained a value of 331.3 h, and if this number is divided by the mean outage duration of 2 h and the number of days in a year, \( \frac{331.3}{2 \times 365} = 0.454 \), it is obtained the probability of happening a outage in a day. This result helps to understand the normalization performed in the normal distribution regarding, the time of the day phenomenon.
5.2 Clearness index in India

As stated before, the clearness index translates the effect of the weather in the amount of radiation that reaches the earth’s surface. Due to the fact that India has a vast country area, with multiple climate types, it would be imprecise to not take into account the different clearness indexes throughout the territory. To obtain the clearness index, it was necessary to collect the monthly irradiation in the past five years from [34], with the goal of creating a pattern from which it would be possible to forecast future irradiations.

Before using the equation (3.11), which determines the clearness index, it is necessary to compute the extraterrestrial monthly average irradiation and acquire, the observed monthly average irradiation at earth surface level. Therefore, the first step is to obtain the data from [34], using a software image recognition and reading functions this is easily achieved. In Figure 5.6 it is possible to see an example of the data collected.

The second process is the calculation of the extraterrestrial monthly average irradiation, from (3.10) and (3.9) it is obtained the extraterrestrial irradiance, $G_0$. Since the extraterrestrial irradiance is a power quantity, it is possible to integrate it, over the duration of one day, to obtain the extraterrestrial irradiation, $H_0$. In the equation (3.10) the only angle that changes throughout the day is the hour angle $\omega$, and since the objective is to obtain the daily irradiation, the limits of the integral will be the sunrise and sunset hour angles, that are symmetrical. That being said, the extraterrestrial irradiation, $H_0$, can be obtained from (5.2) where $\omega_s$ is the sunset hour angle.

$$H_0 = \frac{12}{\pi} \int_{-\omega_s}^{\omega_s} G_0 \, d\omega.$$  \hspace{1cm} (5.2)

At the sunset, the angle $\theta_z$ is $90^\circ$, since it is the angle between the zenith axis and the sun direction. The equation (3.9) can then be simplified into (5.3). 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure5.5.png}
\caption{Results of 100000 simulations of the outage profile.}
\end{figure}
\[ \cos \omega_s = -\frac{\sin \phi \sin \delta}{\cos \phi \cos \delta} = -\tan \phi \tan \delta. \] (5.3)

With the equation (3.7) and knowing that the term \( \frac{12}{\pi} \) corresponds to the conversion factor from time to radians, the equation (5.2) results into (5.4).

\[ H_0 = \frac{24 G_{on}}{\pi} \left( 1 + 0.033 \cos \frac{360/n}{365} \right) \left( \cos \phi \cos \delta \sin \omega_s + \omega_s \sin \phi \sin \delta \right). \] (5.4)

Since \( G_{on} \) is presented in kW m\(^{-2}\) the result of (5.4) is given in kJ m\(^{-2}\). Now, to obtain the monthly average, one needs to obtain the total irradiance in a month, presented in the equation 5.5, and divide it by the number of days. Since the latitude angle \( \phi \) only depends on the geographical localization, it remains constant. However, the declination angle \( \delta \) is dependent of \( n \), as presented in (3.6). Thus, the total irradiance in a month only depends on the day of the year \( n \). Shown in the equation (5.5), where \( k \) is the total days in a month (it may be 28, 29, 30 or 31 days), the factor \( m \) is the beginning day of the given month and the factor 3.6 corresponds to the conversion of the result into kWh.

\[ \langle H_0 \rangle = \frac{\sum_{n=m}^{k+m} H_0}{3.6 \times k}. \] (5.5)

With the results from (5.5) and the database exemplified in 5.6 the clearness index can be computed. In Figure 5.7 it is possible to see an example of the clearness index map.
5.3 Simulation results

5.3.1 Inputs and objective functions

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** - To comprehend how the PVs and their angular position influence the system.

- **Solar panels and batteries** - To see the effect of the batteries in the solar power system.

- **Solar panels and batteries but using the batteries only in case of power outage** - To understand the difference between, using the energy available in the batteries only when a power outage is taking place, and using that energy at any given time.

In all three cases, the system will use energy from the grid, when the demand is greater than the maximum supply.

So that a good comparison is performed, all three cases where computed using the same set of inputs and objective functions. Since the power outages are a major concern in India, one of the objective functions will be the yearly missed energy. This function translates the yearly energy that the user was not able to use, since it was not available in the power grid nor on the PVs and batteries system. The second objective function will take into account the total price of the system, since the financial aspect is always crucial to take into account.

The inputs of all three cases were:

- **Localization**.
The geographical place that was used is situated in the urban area of Bengaluru. This location has a longitude of $77.5^\circ$, a longitude of $12.944.47^\circ$ and a time zone of $+5.5$ h, as seen in Figure 5.8.

![Geographical localization](image)

**Figure 5.8: Geographical localization.**

- **Yearly temperature.**

  To obtain the yearly temperature profile, of the chosen localization, it was used data from [29]. 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 days. It would have been possible to use a greater amount of profiles, but in order to simplify and to reduce the computational time, five were assumed as enough. In Figure 5.9 one can see the temperature profile used in the optimization model.

  Since India is located in a low latitude zone, near to the equator, the temperatures do not vary much during the year. The warmest months are April and March, due to the fact that from June to September happens the monsoon season. In Figure 5.10 is possible to see the temperature profiles throughout the year.

- **Yearly load profile.**

  The yearly load profile is another very important input to consider, because it determines the amount of energy that is requested by the consumer, at any given moment. Using the data from [35], it was possible to obtain the load profile of the average middle to upper class Indian family, this can be seen in Figure 5.11.

  With the load profiles from both the summer and the winter it is possible to divide, the year, into two different profiles. From Figure 5.11 one can clearly see the differences in the average of the summer and the winter months, this happens mainly due to the influence of the cooling machines during the summer.
Figure 5.9: Yearly temperature profile.

Figure 5.10: Daily temperature profiles.
Figure 5.11: Daily load profiles of the average middle to upper class Indian family.
• Solar panel characteristics.

By being the main subsystem, the solar panels have a considerably influence on the overall system performance. The parameters of the solar panels have a wide range of values, but in this case it was used the characteristics of a real and available panel, [36]. In Table 5.2 one can see the main parameters of the solar panels used in this study.

<table>
<thead>
<tr>
<th>Area [m²]</th>
<th>Irradiance at NOCT [W m⁻²]</th>
<th>Temperature coefficient</th>
<th>Power at NOCT [W]</th>
<th>NOCT [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.3</td>
<td>800</td>
<td>-0.45</td>
<td>139</td>
<td>45</td>
</tr>
</tbody>
</table>

Table 5.2: Parameters of the solar panels.

• Battery pack characteristics.

The second subsystem is the battery pack, and like the solar panels, is defined by multiple parameters obtained from a real battery [37], which are listed in Table 5.3.

<table>
<thead>
<tr>
<th>Capacity [A h]</th>
<th>Voltage [V]</th>
<th>Discharge rating</th>
<th>Charge rating</th>
<th>Maximum cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>12</td>
<td>1</td>
<td>0.3</td>
<td>5000</td>
</tr>
</tbody>
</table>

Table 5.3: Parameters of the battery pack.

• Monetary price of the physical devices.

The prices of the solar panels and the batteries are another important inputs to consider, because the financial aspect of the system is as crucial as the system itself. From [38], it was possible to obtain the prices of such devices in India, the Table 5.4 shows the 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 5.4: Prices of the devices in Euro.

Now that the inputs are defined the next step is to characterize the objective functions. As stated before, all the cases that will be studied will be executed using the same set of objective functions. The first objective function will be the total yearly energy that was not available on the system, from the batteries or the solar panels, neither on the grid, due to a power outage situation. From now on this quantity will be denominated by "Missed energy", and can be obtained from the equation (5.6).

\[
E_{\text{missed}} = \int_{1}^{365} \int_{0}^{24} P_{\text{load}} - P_{\text{system}} \, dt \, dn. \quad (5.6)
\]

In the normal operating situation, the difference between the load power and the power available in the system (PVs and batteries) would be provided by the grid. However, as stated before, the missed energy is only computed during a power outage. The second objective function will take into account the necessary investment when acquiring the system, as seen in the equation (5.7)

\[
\text{Investment} = p_{\text{PV}} N_{\text{PV}} + p_{\text{bat}} N_{\text{bat}}. \quad (5.7)
\]

Next are presented the results for each study-case.
5.3.2 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 aspect from 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 things may 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.

Before the results are shown one must first state what decision variables were used in this case. The boundaries that they were subjected to, and the number of populations and generations, that the genetic algorithm used. In what regards the populations and the generations, the amount used by the optimization algorithm was 150 populations and 50 generations. These quantities were chosen taking into account the quality of the results and the computation time. In what respects the variables, in Table 5.5 it is possible to see the details.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV tilt angle [°]</td>
<td>[0 ; 180]</td>
</tr>
<tr>
<td>Solar azimuth angle [°]</td>
<td>[−180 ; 180]</td>
</tr>
<tr>
<td>Number of solar panels</td>
<td>[1 ; 60]</td>
</tr>
</tbody>
</table>

Table 5.5: Variables and their boundaries on the first case.

Now that the decision variables are defined it is possible to run the optimization algorithm and obtain the results. In Figure 5.12 one can see the population of the last generation in a performed execution.

![Figure 5.12: Last generation of the first case.](image)

To have a better understanding on the characteristics of the variables, in Figure 5.13 it is possible to
see all parameters variation for all 150 elements of the population of the last generation.

![Objective functions and variables of the 150 populations of the last generation.](image)

The first thing to notice in Figure 5.13 is that the linear behaviour in the amount of solar panels translates into an exponential decreasing of the missed energy, because for a high number of PVs, the missed energy tends to become constant.

When analysing the solar angles, it is possible to see that when the value of missed energy is high the tilt and azimuth angles are respectively around $20^\circ$ and $-60^\circ$. Since, in this cases the amount of solar panels is low, the solar angles have a significant influence in the power output of the system. Therefore, the optimization algorithm chooses these angles so that the PVs produce more power in the morning, since most of the power outages happen during this period, as seen in Figure 5.5. When the amount of solar panels becomes greater, and the missed energy becomes lesser, the solar angles have less significance, thus, the algorithm decides for a tilt angle close to zero (flat surface). With these angles the PVs produce power more throughout the day, rather than in a specific hour. In Figures 5.14 and 5.15 this phenomenon is depicted.
To get a better understanding of how the probabilistic event of the power outages affects the results, one element of Figure 5.12 was submitted to several executions of the model. Since the main point of this exercise is to keep the variables and inputs the same, the investment will be constant through all executions, because the number of PVs remains unchanged. However, the different outage profiles lead to a different missed energy results. In Table 5.6 one can see the selected element of the 5.12.

<table>
<thead>
<tr>
<th>Tilt angle [°]</th>
<th>Azimuth angle [°]</th>
<th>Number of PVs</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.7075</td>
<td>-64.5945</td>
<td>16</td>
</tr>
</tbody>
</table>

Table 5.6: Variables of the selected element.

In Figure 5.16 it is presented the histogram of the missed energy of 10000 executions of the de-
veloped model, using the variables of the element presented in 5.6. It is possible to see the selected element by the bar 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 than a higher one (pessimistic result). This fact becomes more visible in Figure 5.17, where it is possible to see that the selected element is located in the 70% of the cumulative probability. Hence, it has a 70% probability of having a better performance (less missed energy), and a 30% probability of having a worse performance (more missed energy).

Figure 5.16: Histogram of the missed energy of 10000 executions using the same element.

Figure 5.17: Cumulative 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 performed but now for all the elements of the last generation.
In the same way as the data from Figure 5.12 was obtained, the program was executed 200 times. This number of executions was chosen taking into account the computational time. In Figure 5.18 it is presented the results of this simulation.

![Figure 5.18: Objective functions of the last generation of 200 simulations.](image)

From Figure 5.18 one can see the significance of the outage event in the optimization process. The main effect to notice 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 information from 5.18 it is possible to obtain a bivariate histogram of both objective functions. This can be seen in Figure 5.19.

![Figure 5.19: Bivariate histogram of the 200 execution last generations.](image)
With the data from Figure 5.19 it is possible to perform two comparisons: the first is the probability of having more or less missed energy in a year for a given investment; and the second is the expected missed energy decrease with the increase of the investment. To perform these analysis in Figures 5.20 and 5.21 are presented the cumulative probability functions of, respectively, the missed energy and the investment.

![Cumulative probability functions of the missed energy.](image1)

![Cumulative probability functions of the investment.](image2)

As an example, from Figure 5.20 it was chosen the row of the 4500€ investment, presented in Figure 5.22. It is now possible to see that with this investment one has: an almost zero probability of having less than 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 greater than 70 kWh.
Lastly, to have a better understanding on how the level of the investment influences the probability of a certain missed energy. It was chosen the column of 60 kWh from Figure 5.21, which is presented in Figure 5.23. 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.
5.3.3 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 outages is not taking place, the system, PVs and battery, will be the priority power source. Therefore, the grid will only provide power, if the demand is greater than the supply and stored 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, due to the maximum discharge rating; and during the times when the solar power is not available and the batteries are discharged. In a power outage situation 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.

Regarding the variables of this second case, they are all the same as the previous case with the addition of the number of batteries. The amount of populations and generations are as well respectively 150 and 50.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Boundaries</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV tilt angle [$^\circ$]</td>
<td>[0 ; 180]</td>
</tr>
<tr>
<td>Solar azimuth angle [$^\circ$]</td>
<td>[−180 ; 180]</td>
</tr>
<tr>
<td>Number of solar panels</td>
<td>[1 ; 60]</td>
</tr>
<tr>
<td>Number of batteries</td>
<td>[1 : 5]</td>
</tr>
</tbody>
</table>

Table 5.7: Variables and their boundaries for the second case.

In Figure 5.24 one can see the objective functions of the last generation of this case.

Figure 5.24: Last generation of the second case.

In order to analyse the behaviour of the variables, in Figure 5.25 it is possible to see all the parameters of the 150 populations of the last generations.

There exist three points worth mentioning in Figures 5.24 and 5.25, which are marked by the coloured
lines. What makes these points interesting is the fact that, they correspond to the increase on the number of battery packs, by result of the optimization process. This increment has effects in the number of solar panels and in both objective functions. In Table 5.8 one can see the exact values of the selected points and the point that precedes it.

<table>
<thead>
<tr>
<th></th>
<th>Red</th>
<th>Previous</th>
<th>Green</th>
<th>Previous</th>
<th>Yellow</th>
<th>Previous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Missed energy [kWh]</td>
<td>44.21</td>
<td>46.19</td>
<td>36.02</td>
<td>36.97</td>
<td>12.5</td>
<td>12.82</td>
</tr>
<tr>
<td>Investment [€]</td>
<td>1733</td>
<td>1693</td>
<td>2620</td>
<td>2580</td>
<td>5562</td>
<td>5522</td>
</tr>
<tr>
<td>Tilt angle [°]</td>
<td>16.08</td>
<td>9.882</td>
<td>27.45</td>
<td>12.04</td>
<td>13.39</td>
<td>15.19</td>
</tr>
<tr>
<td>Azimuth angle [°]</td>
<td>-41.41</td>
<td>-104.7</td>
<td>-56.51</td>
<td>-125.9</td>
<td>-159.7</td>
<td>-158.1</td>
</tr>
<tr>
<td>Number of PVs</td>
<td>11</td>
<td>14</td>
<td>15</td>
<td>18</td>
<td>36</td>
<td>39</td>
</tr>
<tr>
<td>Number of batteries</td>
<td>1</td>
<td>0</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.8: Selected points data from the second case.

In all three points from Table 5.8 it happens a decrease in the number of PVs when the number of batteries increase, this leads to a slight increase in the investment but also a significant decrease in the missed energy. Although, as the missed energy becomes lesser the variation from the previous case also becomes smaller. Another aspect to notice is the behaviour of the areas between the selected points. In this zones, the optimization, gives a result similar to the case with only the solar panels. This happens because in these areas only the amount of PVs is changing.

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 its usage, affects the optimal elements. In order to do so, the elements from Figure 5.24 will be reintroduced to the developed model with a different battery capacity. From [20] it is possible to obtain the capacity loss in a cell versus the charge and discharge cycles,

\[ \text{Cap}_{\text{loss}} = -0.04 \times \text{Cycles} + 100. \]  

(5.8)
Since the average amount of cycles per year in the elements of Figure 5.24 is 215, it will be assumed a loss of 8% of the total capacity per year. In Figure 5.26 it is presented the result of simulation. One can clearly see that, as the capacity from the battery pack decreases, the missed energy increases as well.

![Figure 5.26: Different maximum capacity simulation results.](image)

As done in the previous case, it will now be study the situation where one element from Figure 5.24 last generation is submitted to several outage profiles. In order to see how the probabilistic event of the power outage profile affects the missed energy quantity. In Figure 5.27 it is presented the histogram of 10000 simulations using the element (marked in red) from the green line in Table 5.8.

![Figure 5.27: Histogram of the missed energy of 10000 executions using the same element.](image)

In Figure 5.27 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). In Figure 5.28 this fact becomes more noticeable, it is possible to see that the selected element
has a 20% probability of performing better while a 80% probability of performing worse than expected.

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 last generation. In Figure 5.29 it is presented all the computed last generations and in Figure 5.30 the respective histogram.

From the bivariate histogram it is possible to compute the cumulative probabilities of the missed energy and the investment, respectively presented in Figures 5.31 and 5.32.
The reason why both cumulative histograms, 5.31 and 5.32, are so similar, is the linear distribution of elements in 5.29. In the same way as the previous case, from Figure 5.31 it was obtained the row from the 4500€ investment and from 5.32, the column of 60 kWh missed energy, presented respectively in 5.33 and 5.34.

When comparing Figure 5.33 with the same of the previous case 5.22, it is visible that 5.33 has higher probabilities for the same missed energy value. For instance, in Figure 5.22 for a missed energy of 50 kWh one had a probability of 80%, while on Figure 5.33 the same missed energy has a probability of nearly 100%. With this information it is safe to assume, that, the system with PVs and batteries is more reliable than the one with only PVs. Since, for the same investment lesser missed energies, have a higher probability.
When observing Figures 5.23 and 5.34, Figure 5.34 shows higher probabilities for the same investment. Which means that, for the same value of missed energy and probability it is necessary a lesser investment. Another important aspect to refer is that, since in Figure 5.34 the maximum value is obtained with a smaller investment. Each increment in the investment has a greater increase in the probability comparing to the one of Figure 5.23. 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.

Using the information from 5.19 and 5.30 it is possible compute the the average investment for a certain amount of missed energy, in Figure 5.35 this is presented.
5.3.4 Solar panels and batteries but using the batteries only in case of power outage

In this third and last case, the system will be as well 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 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. It is during this episodes that the missed energy is calculated.

The variables and objective functions are the same as the previous case. In Figure 5.36, one can see the objective functions in the last generation of this third case. And, in Figure 5.37, the variables and objective function of all the populations of the last generation.

![Figure 5.36: Last generation of the third case.](image)

![Figure 5.37: Objective functions and variables of the 150 populations of the last generation for the third case.](image)
In this case study there exist two points worth mentioning, which are represented in Figures 5.36 and 5.37 by the red and green line. The first point, marked in red, represents the transition from zero to one in the amount of battery packs. In the zone, from the element of population 0 to the red line, the curve in 5.36 behaves like in the first case, since no batteries are present. The green line shows the point where the missed energy becomes zero, which means that the system became fully unaffected by the power outages generated by this particular outages profile. As it was done in case two, the green point is now subjected to several executions of the program, so that, it is possible to understand how the outages profile influences the missed energy. The variables of the green marked point can be seen in Table 5.9 and the respective histogram in Figure 5.38.

<table>
<thead>
<tr>
<th>Tilt angle [°]</th>
<th>Azimuth angle [°]</th>
<th>Number of PVs</th>
<th>Number of batteries</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.1555</td>
<td>-30.3733</td>
<td>21</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5.9: Variables of the green marked point.

Figure 5.38: Histogram of the missed energy of 10000 executions using the green point as the selected element.

The histogram presented in 5.38 behaves differently from the previous two cases, it is visible that the greater bin is located in the interval that contains the zero. This happens because, with these input variables and some outage profiles, 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 5.39 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 two previous 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 5.40 it is presented all the 200 simulations.

Now, one may build a bivariate histogram from the data of 5.40. However, since some of the elements of 5.40 have zero missed energy, the information would be difficult to understand. That being said, in Figure 5.41 one can see the bivariate histogram of 5.40 but excluding the cases with zero missed energy.
Figure 5.39: Cumulative histogram of the missed energy of 10000 executions using the same element.

Figure 5.40: Last generation objective functions of the last generation of 200 simulations for the third case.

The Figures 5.42 and 5.43 show the cumulative histograms of Figure 5.41. In Figure 5.42 it is visible that for investments over 3500€ the missed energy has a almost certain probability of being zero. This is a information of particular interest because only in this case, (PV and Battery for emergencies) it is possible to assume, that the user becomes immune to power outages.

In Figure 5.44 it is presented the column of 60 kWh of Figure 5.43. When comparing this to the same figure of the previous case 5.34, it is possible to see that the probability reaches its maximum first in this case. Which means that it requires a lesser investment in order to obtain the expected missed energy.

With the information from 5.40 it is now possible to compare the average investment for the second and third cases, this can be seen in Figure 5.45.
When comparing the average investment from 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, one is able to reduce the amount of missed energy with the same investment.
Figure 5.43: Cumulative probability functions of the investment.

Figure 5.44: 60 kWh missed energy column from Figure 5.43.
Figure 5.45: Average investment for a given missed energy for cases two and three.
Chapter 6

Conclusions and future work

6.1 Conclusions

The analytical models translate the physical phenomena into mathematical equations, so that the optimization algorithm is able to, by modifying the parameters of these models, obtain the values that allow the system to have the most optimal performance. The precision of these models influences the outcome of the optimization process, therefore, it is important to take this fact into consideration when opting for the most fit model for a specific application. In chapter 3, the three physical models that rule the behaviour of the system were presented. The used incidence model (HDKR) is characterized by taking into account all the diffuse irradiance components, fact that make this model very complete. However, due to relying in probabilistic factors, such as the clearness index, its performance is limited by the precision of such aspects.

Power outages are a weakly occurrence in India, which combined with the low energy price, translates into a different mentality, in a user, when purchasing these kind of system. In Portugal, clients rely in these kind of renewable energy system to reduce the electrical energy consumption, by selling the excess energy to the provider. However, in India, the main goal is to act as a backup energy supply during an power outage episode. These two different mentalities affect how the optimization process handles both countries. On the first hand, in the Indian case, it is minimized the amount of time the situation of outage is felt and also the total cost of the system. Since the user wishes to be impervious to power outages with the minimum investment possible. On the other hand, in the Portuguese case, the user expects that the system produces the maximum amount of energy, so that the return from the energy provided is maximized, while keeping the payback time low. These factors show that different countries have distinct meanings of what is considered optimal.

During the chapter 5, 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. There were 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 factor is the
randomness of the power outage phenomenon. The parameters of this event influence its occurrence probability and 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 showed that with a 4500€ investment, the approach with only PV’s had a 80% probability of obtaining 50 kWh or more of missed energy. While the, PV plus battery case, had a ≈ 100% chance of delivering the same amount of missed energy. 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. While the main power source, during normal operation, is the power grid. The major difference of this case, when comparing it with the previous ones, is that it provided results that had zero missed energy. Which means that the user would be completely impervious to power outages. However, as in 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 third approach obtained more satisfactory results, which leads to the conclusion that it is the more suitable solution for this type of application.

6.2 Future work

As a future investigation, it would be of particular interest, the installation of the physical devices. In order to understand if the optimal cases, provided by the developed model, have indeed a better performance than the suboptimal ones. Another possible line of progression, would be the integration of further sources of renewable power in the system, such as wind power or micro hydro power plants.
References


