Computer Tool for Power Generation Modeling and Economic Analysis for Nearly-Zero Energy Buildings

by

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Submitted to the Department of Electrical Engineering, Electronics,
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Abstract

In this thesis, I developed a computer tool which is able to simulate the electrical energy generation of different generators, such as wind turbines, PV panels, fuel cells or micro turbines, for their employment in residential buildings for self-consumption. This involved the development of the mathematical models, as well as the estimation of some weather conditions such as wind profiles and solar radiation. In addition, the economic analysis, which consists on the comparison between the traditional energy purchase and self-consumption, has been also performed. This thesis is part of a project that also covers the demand modeling and the power reliability analysis of the system. The computer tool has been succesfully tested, by simulating different study cases, obtaining good representative results.

Thesis Supervisor: Pablo Arboleya Arboleya
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Chapter 1

Introduction and Objectives

Buildings account for around 40% of total energy consumption and 36% of CO2 emissions in Europe [12]. Therefore, the reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures which are needed to reduce energy dependency and greenhouse gas emissions. The mitigation potential of emissions from buildings is important and as much as 80% of the operational costs of standard new buildings can be saved through integrated design principles, often at no or little extra cost over the lifetime of the facilities [29]. The European Union Directive 2010/31/EU [38] related to the the energy performance of buildings (EPBD) demands that “Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings”. In the directive, “nearly zero-energy building” (nZEB) is defined as a building that has a very high energy performance. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby.

These requirements to move towards very low-energy buildings will trigger a deep market transformation not only in this sector but also in others, most notably the power sector, as over half of all electricity consumed today is used in buildings. Electricity savings in buildings will have significant benefits for the power sector, permitting to reduce the investment in generation and distribution assets and thus allowing electrical companies to increase their clients without significant network expansions or high investments in new power plants.

As a consequence, it is crucial to develop technical tools that enable the quantification and analysis of the environmental, economic and reliability merits or defects of using renewable-distributed power generation systems in buildings. However, due to the intermittence on the use of renewable energies when trying to reduce or avoid the grid electricity consumption, it is often difficult to determine which is the most appropriate array of technologies to implement. For instance, for a particular scenario, after considering location, environmental and supply constraints and given a certain budget; there are a huge number of combinations of renewable generation systems that could be used alone or simultaneously (wind, solar, fuel cells, biomass, etc.). Nevertheless, to take the best advantage of the investment, it is a key aspect to identify which specific distributed generation configuration provides the best reliability and monetary expectations. Hence, the main purpose of this project is to develop a software tool to successfully assess professionals, promoters or companies in the selection of the best renewable-distributed generation-mix suitable to be installed in residential buildings considering technical, economic and reliability aspects. To achieve this goal, firstly, it is necessary to analyze basic concepts and criteria regarding to nearly-zero energy buildings, distributed generation and power reliability.

1.1 Nearly-Zero Energy Buildings

The buildings in which we live need to be safe, functional and comfortable, as well as functionally integrated into our urban areas. At the same time, they need to be increasingly energy efficient and environmentally friendly. Meeting all these needs means coming face to face with the building sector as it unfortunately stands today: highly diverse, critically fragmented and with significant inertia to change. For this reason and with the aim of fulfilling the Europe 2020 targets [39] (have a 20% of final energy consumption from renewables and increase energy efficiency by 20% by 2020), the European legislation has set out a cross-sectional framework of ambitious targets for achieving high energy performances in buildings. Key parts of this European regulatory framework are the Energy Performance of Buildings Directive 2002/91/EC (EPBD) [27] and its recast (Directive 2010/31/EU) [28]. This recast demands that "Member States shall ensure that by 31 December 2020 all new buildings are nearly zero-energy buildings; and after 31 December 2018, new buildings occupied and owned by public authorities are nearly zero-energy buildings". The guidance by the EPBD recast is on a general level. In the directive, "nearly zero-energy building" (nZEB) is defined as a building that has a very high energy performance.

In response to this challenge, the building design and research community have started to develop efficient nZEB buildings [42] that, on an annual basis, draw from outside sources an amount of energy that is equal to, or a little higher than, the energy produced on site from renewable energy sources.

A nZEB building can be dependent or independent of the electrical grid. As discussed by [41] and [37], with the current technology, a grid disconnected nZEB is difficult to implement, both from an economical and technical viewpoint, due to the seasonal mismatch between energy demand and renewable energy supply and also because the need for large storage capacity. In the off-grid approach, the excess of renewable energy collected in the summer is wasted and cannot be used to balance energy needs during the winter period. On the other hand, on a grid connected nZEB any surplus in electricity production is injected into the grid, conversely, when production is insufficient, the building draws from the grid; making the grid connected configuration the most versatile and reliable. An ideal nZEB should have the following features [23]:

- Present low building related energy needs (adequate use of natural light and ventilation, have better performance of the building envelope, present optimal passive heating and cooling).
- Have efficient building energy systems (including domestic appliances).
- Have adequately sized renewable energy systems that are connected to a flexible energy infrastructure (the electrical grid must be able to exchange energy with the building).

Size		**Power Rating**
Micro	Distributed Generation	1 W to 5 kW
Small	Distributed Generation	5 kW to 5 MW
Medium	Distributed Generation	5 MW to 50 MW
Large	Distributed Generation	50 MW to 300 MW

Table 1.1: Distributed generation categorization [13].

Nevertheless, it is important to mention that the most logical path towards the ”nearly-zero goal” is firstly to reduce the energy demands by means of energy efficient technologies, and secondly to utilize the renewable energy sources (RES) to supply the remaining energy [36]. However, as indicated by Laustsen [33], a nZEB can also be a traditional building supplied with very large renewable energy systems, and if these systems deliver the same amount of energy over a year as the energy use in the building, the goal of ”zero energy” is still met. This may be the initial case of existing buildings that are moving to a greener path for instance. It also should be noticed that the allowed minimum energy demand requirement for any nZEB depends very much on its local context and building type [21].

Regarding the renewable sources, they can either be available on the site, e.g., sun or wind, or need to be transported to the site as biomass or hydrogen to be later used by micro-gas turbines and fuel cells respectively. Note that for a particular nZEB and given a fixed budget, there is a large amount of combinations for possible renewable generation systems that could be implemented. Therefore, the main purpose of this project is to provide nZEB designers and promoters with a computer tool that assesses the selection of the best renewable-distributed generation-mix considering technical, economic and reliability concerns.

1.2 Distributed Generation

There are several different definitions regarding *D*istributed Generation which are used as well in literature and in practice. This can yield to confusion as these definitions are often subjected to the power ratings or the generators size, factors that may vary for each appliance. After doing some research, it can be assumed that one of the most accepted definitions for distributed generation, is the one proposed by Professor Thomas Ackerman [13]:

"Distributed generation is an electric power source connected directly to the distribution network or on the customer site of the meter."

This definition of distributed generation does not define the rating of the generation source, as the maximum rating depends on the local distribution network conditions. However, it is advisable to categorize distributed generation systems according to the different power ratings, as shown in Table 1.1. In addition, the definition of distributed generation does neither define the size of the power delivery area, the penetration, the ownership nor the kind of operation of these kind of distributed resources. It cannot be assumed, as it is often done, that distributed generation stands for local power delivery, low system penetration, independent ownership and special operation.

Professor Ackerman here proposes the differentiation between some common situations, which may also create confusion as there are not standardized definitions. For example, if the power output of distributed generation is used only within the local distribution network, he suggests the term *embedded distributed generation*. And if the distributed generation source is not centrally dispatched, he claims it should be called: *not centrally dispatched distributed generation*.

1.3 Self-Consumption

Self-consumption is the name that defines those facilities in which electrical energy generation and consumption are simultaneously present, in such a way that the produced energy can be consumed near, or just at, the generation point. These kind of facilities can be isolated or connected to the electrical utility system. In case of being isolated, self-consumption facilities are not connected to the utility grid, since they are self-sufficient and do not need grid services. In contrast, self-consumption facilities can be connected to the utility grid to use it as back up, in a way that the facility is able to inject energy into the grid, or take it, depending on the consumption needs. This second case presents an important advantage with respect to the isolated facilities, and it is the guarantee of electrical energy supply in appropriate conditions all the time, aspect that is not possible in isolated systems. In this second scenario, the role of the distributor is crucial to guarantee a high reliability and power quality standard. New business models will be created for the distributor like for instance the ones based in the coordinated operation in this kind of facilities to guaranty the distribution network adequacy assessment.

Since the employed technologies for self-consumption are usually intermittent and non-predictable (renewable energies such as wind or sun, that depend on weather conditions and as a result they have intrinsic characteristics that impede their dispatchability), the connection to a distribution grid is necessary to guarantee the service reliability.

The inclusion of self-consumption facilities in the electrical system means a big change in the actual model, and it has many consequences at different levels. From a technical point of view, the the installation of self-consumption facilities may result in a reduction of grid losses, since the generation units are closer to the consumption points. On the other hand, self-consumption models disturb the configuration and the traditional modes of operation of the electrical system, since they mean the presence of new generation units at locations where there were only consumers. This fact implies the transformation of the centralized generation pattern and unidirectional power flows in the lines, into a new distributed generation scenario and bidirectional line power flows. This means a huge change in the electrical system, that could derive in harmful consequences for the system safety and reliability, if there is no previous adaptation of the electrical system, to assure the coordinated and compatible introduction of the new generation within the existing electrical utilities. As a result, the introduction and development of self-consumption should be accompanied by a rigorous study, that assures the establishment of this new model treatment and the quality and sustainability levels of the electrical system are maintained.

1.4 Monte Carlo Method

Two main possibilities can be considered when Monte Carlo methods [17] are applied to power systems reliability evaluation. These methods are named as sequential and non-sequential techniques [19][20].

The non-sequential technique, as well as the analytical approach, is usually restricted to the evaluation of expected values and, sometimes, to a limited range of system parameters. Hence, it is often required to know the likely range of the reliability indices, the probability of a certain value being exceeded, and similar parameters. These can only be assessed if the probability distribution function related to the index is previously known, and this is not often achieved with an analytical approach. In such situations, sequential simulation can be employed.

In contrast, in sequential simulation, each subsequent system state sample is related to the previous set of system states. This results in a sequential time evolution of the system behaviour, which provides a wide range of reliability indices to be evaluated [15]. Sequential simulation is very useful when the historical evolution of the system partially determines the state of the system at any given time. It can be assumed that, nowadays, sequential simulation is the only realistic choice available to develop the distributions associated with the system index mean values [18].

1.4.1 Methods in Reliability Evaluation

A fundamental parameter in reliability evaluation is the mathematical expectation of a given reliability index. Salient features of the Monte Carlo method for reliability evaluation therefore can be discussed from an expectation point of view.

Let Q denote the unavailability (failure probability) of a system and x_i be a zero-one indicator variable which states that

$x_i = 0$ if the system is in the up state

$x_i = 1$ if the system is in the down state

The estimate of the system availability is given by:

$$\bar{Q} = \frac{1}{N}\sum_{i=1}^{N} x_i \tag{1.1}$$

where N is the number of system state samples.

The unbiased sample variance is:

$$V(x) = \frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{Q})^2 \tag{1.2}$$

When the sample size is large enough, equation (1.2) can be approximated by:

$$V(x) = \frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{Q})^2 \tag{1.3}$$

Because x_i is a zero-one variable, it follows that:

$$\sum_{i=1}^{N} x_i^2 = \sum_{i=1}^{N} x_i \tag{1.4}$$

Substituting equations (1.1) and (1.4) into equation (1.3) yields to:

$$V(x) = \frac{1}{N}\sum_{i=1}^{N} x_i^2 - \frac{1}{N}\sum_{i=1}^{N} 2\cdot x_i\bar{Q} + \frac{1}{N}\sum_{i=1}^{N}\bar{Q}^2 = \bar{Q} - 2\cdot\bar{Q}^2 + \bar{Q}^2 = \bar{Q} - \bar{Q}^2 \tag{1.5}$$

It is important to note that equation (1.1) gives only an estimate of the system unavailability. The uncertainty around the estimate can be measured by the variance of the expectation estimate:

$$V(\bar{Q}) = \frac{1}{N}V(x) = \frac{1}{N}(\bar{Q} - \bar{Q}^2) \tag{1.6}$$

The accuracy level of Monte Carlo simulation can be expressed by the coefficient of variation, which is defined as:

$$a = \frac{\sqrt{V(\bar{Q})}}{\bar{Q}} \tag{1.7}$$

Substitution of equation (1.6) into equation (1.7) gives:

$$a = \sqrt{\frac{1-\bar{Q}}{N\bar{Q}}} \tag{1.8}$$

Equation (1.8) can be rewritten as:

$$N = \frac{1-\bar{Q}}{a^2\bar{Q}} \tag{1.9}$$

Equation (1.9) indicates two important points:

1. For a desired accuracy level a, the required number of samples N depends on the system unavailability but is independent of the size of the system. Monte Carlo methods are therefore suited to large-scale system reliability evaluation. This is an important advantage of Monte Carlo methods compared to analytical enumeration techniques for reliability evaluation.

2. The unavailability (failure probability) in practical system reliability evaluation is usually much smaller than 1.0. Therefore,

$$N = \frac{1}{a^2\bar{Q}} \tag{1.10}$$

This means that the number of samples N is approximately inversely proportional to the unavailability of the system. In other words, in the case of a very reliable system, a large number of samples is required to satisfy the given accuracy level.

1.4.2 Efficiency of Monte Carlo methods

The same problem can be solved by different Monte Carlo techniques. These include different random number generation methods, different sampling approaches, and different variance reduction techniques, among others. It is thus sometimes required to compare the efficiency of different Monte Carlo methods.

Suppose two Monte Carlo methods, which provide the same expectation estimates of the reliability index, are used to evaluate the same system. Let t_1 and t_2 denote computing times and σ_1^2 and σ_2^2 be the variances of the reliability index for the two methods, respectively. If the ratio

$$\eta = \frac{t_1\sigma_1^2}{t_2\sigma_2^2} < 1 \tag{1.11}$$

then the first method can be considered to be more efficient than the second method. The efficiency of the Monte Carlo method depends not only on the number of required samples, but also on the computing time multiplied by the variance of the estimate.

In conducting reliability evaluation of power systems using Monte Carlo methods, the computing time and the variance are directly affected by the selected sampling techniques and system analysis requirements.

1.4.3 Convergence characteristics

- **Convergence process.** Monte Carlo simulation creates a fluctuating convergence process and there is no guarantee that a few more samples will definitely lead to a smaller error. It is true, however, that the error bound or the confidence range decreases as the number of samples increases.

- **Convergence accuracy.** The variance of the expectation estimate is given by equation (1.6). The standard deviation of the estimate can be obtained as follows:

$$\sigma = \sqrt{V(\bar{Q})} = \frac{\sqrt{V(x)}}{\sqrt{N}} \tag{1.12}$$

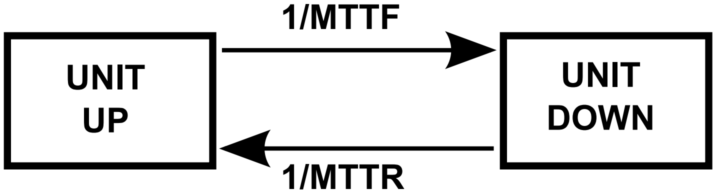

Figure 1-1: Two-state model for a base load unit.

- **Convergence criteria.** The coefficient of variation shown in equation (1.7) is often used as the convergence criterion in Monte Carlo simulation. In power system reliability evaluation, different reliability indices have different convergence speeds. It has been found that the coefficient of variation of the Expected Energy Not Supplied (EENS) index has the lowest rate of convergence. This coefficient of variation should therefore be used as the convergence criterion in order to guarantee reasonable accuracy in a multi-index study.

1.4.4 Two-State Model

A conventional two-state model for a base load unit is shown in Figure 1-1 in which both the operating and repair times are exponentially distributed. In this figure, $MTTF$ is the mean time to failure and $MTTR$ the mean time to repair. Sampling values of the TTF (time to failure) and the TTR (time to repair) can be obtained by drawing random variates following the exponential distributions with parameters $\lambda = 1/MTTF$ and $\mu = 1/MTTR$, respectively, i.e.,

$$TTF = -MTTF \cdot \ln U \tag{1.13}$$

$$TTR = -MTTR \cdot \ln U' \tag{1.14}$$

where U and U' are two uniformly distributed random number sequences between [0, 1]. An up-and-down cycle of a two-state unit can be generated starting from an initial state by sampling values of the TTF and TTR, as shown in Figure 1-2.

In this project, the Monte Carlo two-state model is applied to estimate the reliability of using different kinds of electrical generators, for their appliance in residential buildings suitable for self-consumption. The simple two-state model explained above, can be directly applied to obtain the power generated by conventional generators, since their fuel source is stable and does not depend on external factors. In contrast, when talking about unstable resource generators, as wind turbines and photovoltaic modules, this two-state model is combined with the electrical output power models defined for each case. Figures 1-3 and 1-4 illustrate how the reliability models, of a wind turbine and a photovoltaic module, respectively, are obtained by means of the two-state model [26]. Detailed explanations of the models illustrated in these figures will be given later.

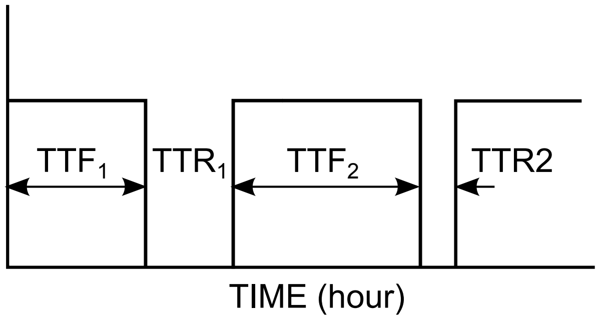

Figure 1-2: Up-down cycle of a two-state unit.

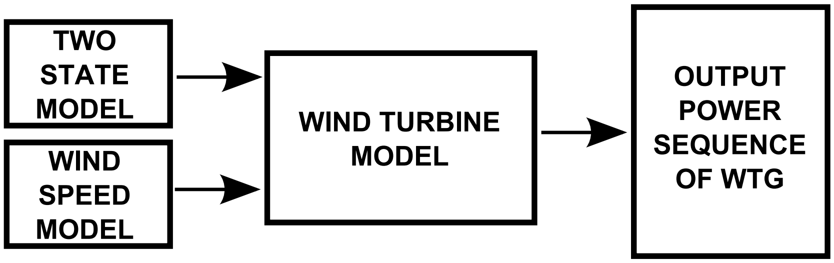

Figure 1-3: Wind turbine generator reliability model.

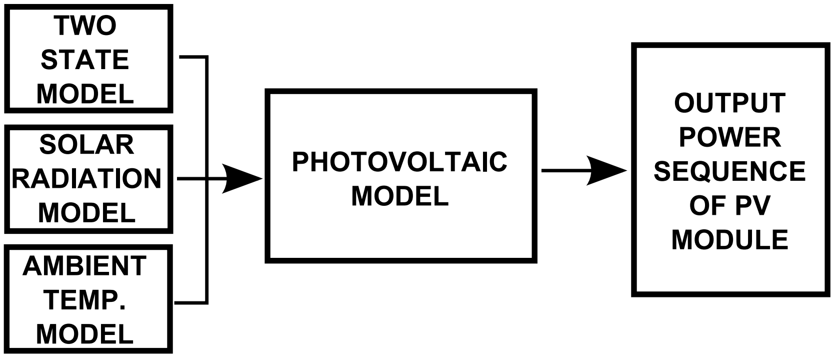

Figure 1-4: Photovoltaic module reliability model.

1.5 Objectives

The main objective of this project is to develop a software tool to successfully assess professionals, promoters or companies in the selection of the best renewable-distributed generation-mix suitable to be installed in residential buildings considering technical, economic and reliability aspects.

To fulfill the mentioned goal, the following activities will be developed:

1. Discussion and implementation of renewable/distributed power generation models.
2. Discussion and implementation of a power demand model for residential buildings.
3. Discussion and implementation of an energy storage model for distributed generation.
4. Analyze the grid energy exchange for renewable/distributed generation systems in residential buildings.
5. Evaluate and validate the developed computer tool to assess the power generation-mix in residential buildings performing power reliability and economic analyses for study cases.

Chapter 2

Power Generation Modeling

2.1 Overview

Due to the intermittency existing when producing electric energy with fully or hybrid renewable generation systems, different considerations must be taken into account to precisely forecast the expected output power for any particular configuration that a building may use to procure significant self-produced generation. In this chapter, different models for the most common renewable-distributed generation devices used in buildings are presented. These are photovoltaic panels, wind turbines, fuel cells, micro gas turbines and diesel generators.

2.2 Photovoltaic Model

The fundamental issue regarding the design of any solar energy generation system, is the knowledge of solar radiation data at the location of interest. The average distribution of solar radiation during the day, provides the basis for estimating instantaneous solar radiation from the available data, which is commonly given by averages of daily isolation. Accurate estimations of hourly solar radiation are an important part of the design of solar energy devices. However, it is very common that no hourly radiation values are available at the desired location. There are several methods which allow obtaining very accurate values for hourly solar radiation. Within these techniques, there are three that can be highlighted over the rest. The Liu and Jordan method [35], evaluates the distribution of total radiation on a horizontal surface over a day, correlating the ratio of hourly to daily radiation with the local day length and hour angle. Collares-Pereira and Rabl [25] developed an analytical expression, for hourly to daily global radiation ratio, in terms of sunset hour angle. Another method for estimating hourly solar radiation was developed by Al-Sadah [14], this method correlates the solar radiation with the local time of day. The method chosen to implement this photovoltaic model is developed in [31], based on the American Society of Heating Refrigeration and Air-conditioning Engineers (ASHRAE) model, which correlates the hourly solar radiation with the zenith angle. Independently from the method, there are some constants that need to be always calculated. These are the solar declination angle, the sunset hour angle, and the hour angle for the midpoint of the hour for which the calculation will be made. The equations for hourly solar radiation are given as:

$$S = S_b + S_d \tag{2.1}$$

$$S_b = A \cdot S_N \cdot cos(\theta_Z) + B \tag{2.2}$$

$$S_N = C \cdot \mathrm{e}^{[-\frac{D}{cos(\theta_Z)}]} \tag{2.3}$$

$$S_d = E \cdot S_N + F \tag{2.4}$$

Where:

S = Total hourly radiation.

S_b = Hourly beam radiation.

S_d = Hourly diffusse radiation.

S_N = Hourly beam radiation in direction of rays.

$A\ B\ C\ D\ E\ and\ F$ are constants given in Table 2.1.

θ_Z = Zenith angle

Months	**A**	**B**	**C**	**D**	**E**	**F**
January	1.259	73.51	1175	0.7850	0.3313	51.03
February	1.117	65.99	1382	0.8464	0.3061	71.55
March	1.003	79.68	1636	0.9669	0.2900	64.18
April	0.889	105.7	1810	1.1050	0.3030	88.4
May	0.9142	80.38	1777	1.1740	0.3579	98.47
June	0.9113	29.84	1038	1.1560	0.7719	84.17
July	1.407	50.20	602	1.1190	1.4670	73.19
August	0.9036	31.19	531	1.0230	1.6480	56.72
September	0.9618	42.15	816	0.9955	0.9439	55.21
October	1.069	56.60	1103	0.9955	0.4878	48.69
November	1.176	60.29	1370	0.8599	0.2748	57.16
December	1.186	70.85	1189	0.7876	0.3405	49.92

Table 2.1: Correlation constants for present model [31].

2.2.1 Zenith angle

The solar zenith angle is the angle measured from directly overhead to the geometric centre of the sun's disc, using a horizontal coordinate system. It is calculated as:

$$cos(\Theta_Z) = sin(\Phi) \cdot sin(\delta) + cos(\Phi) \cdot cos(\delta) \cdot cos(\omega) \qquad (2.5)$$

Where:

ϕ = Latitude of the location.

δ = Solar declination angle.

ω = Hour angle for the midpoint of the hour for which the calculation is made.

2.2.2 Solar declination angle

The solar declination angle is the angle between the equator and a line drawn from the centre of the Earth, to the centre of the sun. It varies seasonally due to the tilt of the Earth on its rotation axis and the rotation of the Earth around the sun. Since the Earth is tilted by 23.45^o, the declination angle varies between plus and minus this value, becoming equal to 0^o at the spring and autumn equinoxes. The declination angle

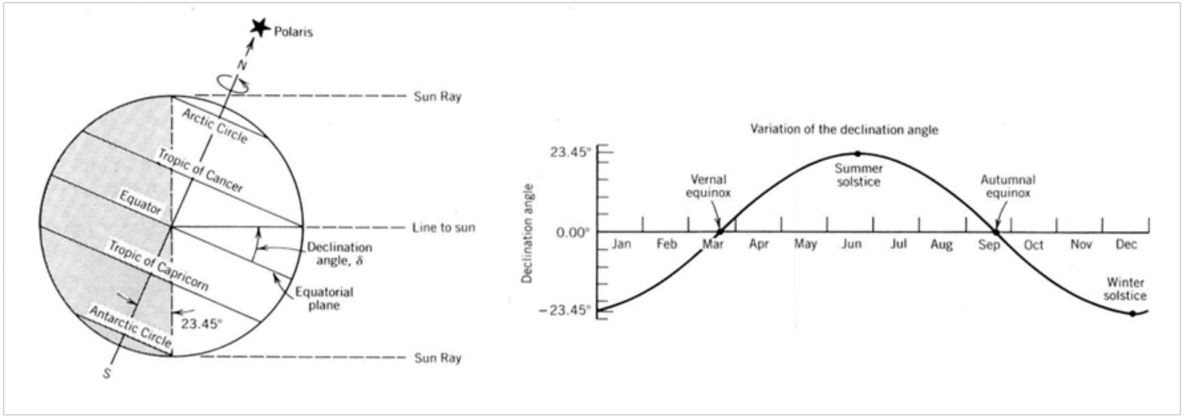

Figure 2-1: Solar declination angle.[1]

can be calculated as indicated in (2.6).

$$\delta = 23.45^{o} \cdot sin[\frac{360}{365} \cdot (d - 81)] \tag{2.6}$$

Where:

d = Day of the year.

Figure 2-1 illustrates the solar declination angle variation during a year and the Earth in the summer solstice position, when $\delta = 23.45^{o}$.

2.2.3 Sunset hour angle

The hour angle is the angular displacement of the local meridian of the east from the west due to the rotation of the Earth on its axis at 15° per hour. The sunset equation, as given in (2.7), can be used to derive the time of sunrise and sunset for any solar declination and latitude, in terms of local solar time when sunrise and sunset actually occur.

$$cos(\omega_s) = -tan(\Phi) \cdot tan(\delta) \tag{2.7}$$

Where:

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[1] www.powerfromthesun.net

ω_s = Hour angle at either sunrise, when it takes negative value, or sunset, when it takes positive value.

2.2.4 Weather modeling

It is obvious that the weather is not equal every day, so it is a key element to generate the chronological solar radiation to somehow estimate what the weather will be like every day of the year. To simulate these meteorological data the Markov chain model is used. It is a mathematical system that undergoes transitions from one state to another on a state space. It is a random process usually in which the next state depends only on the current state and not on the sequence of events that preceded it.

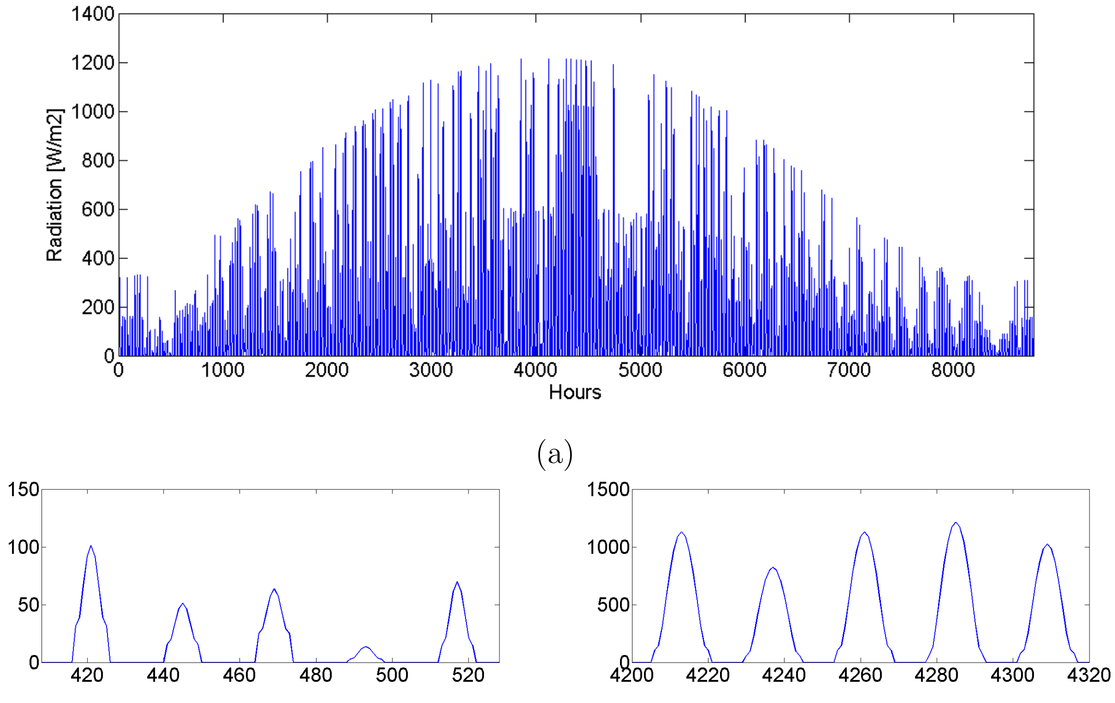
To develop the Markov chain three different weather types are considered, these are: 1) Sunny day, 2) Light raining day and 3) Heavy raining day. If the day is type 1 the radiation output is the 100% of the value obtained with the radiation estimation model, if the day is type 2 it will be the 50%, and if it is type 3 the radiation will be the 10%. With this criterion a probability matrix $P_{d,d+1}$ is built:

$$P_{d,d+1} = \begin{bmatrix} p_{11} & p_{12} & p_{13} \\ p_{21} & p_{22} & p_{23} \\ p_{31} & p_{32} & p_{33} \end{bmatrix} = \begin{bmatrix} 0.80 & 0.19 & 0.01 \\ 0.36 & 0.58 & 0.06 \\ 0.16 & 0.67 & 0.17 \end{bmatrix} \tag{2.8}$$

The matrix above contains the transition probabilities p_{ij} from a state i at a day d to a state j at a day $d+1$. The daily weather sequences are generated following the next steps [40]:

1. A cumulative probability transition matrix Pc is obtained by summing cumulatively along each row of $P_{d,d+1}$.
2. An initial state is randomly set.
3. A uniform random value between 0 and 1 is generated and compared with the elements in row i of P_c to define the next state.
4. Step 3 is repeated as many times as number of days.

Figure 2-2 (a) plots the obtained results for the estimated hourly solar radiation using the method proposed in [31], for a location with latitude equal to 43.53°, during a year. It can be appreciated that the radiation is greater during the second and third quarters of the year, as the location is on the north hemisphere. In Figure 2-2 (b)-(c) the solar hourly radiation obtained for 5 five consecutive days, in winter and summer respectively, is illustrated. The difference can be appreciated with a quick look as the radiation level is higher in the summer plot. But this is not the only difference, in winter most of the days are rainy or cloudy while in summer it is sunny most of the time, this can be also noticed due to the fact that in (b) there are no peaks corresponding to sunny day, all of them match the shape of a light raining or heavy raining day. By contrast, in (c) most of the peaks correspond to sunny days.



(a)

(b)

(c)

Figure 2-2: Estimated hourly solar radiation during (a) a year (b) five consecutive winter days and (c) five consecutive summer days.

2.2.5 PV system modeling

Once the theoretical basis for the hourly solar radiation estimation is stated, it is possible to develop the design of the photovoltaic energy system. Also ambient temperature plays a crucial role in PV generation systems but, it is by far more complex to estimate than the radiation. Hence, ambient temperature will be taken from historical data as this information is easily available on the reports from meteorological and statistical institutions.

In PV systems modeling, it is necessary to get the current-voltage characteristic, which can be obtained by the following equations [43].

$$T_C = T_A + \frac{S \cdot (N_{OT} - 20)}{0.8} \tag{2.9}$$

$$I = S \cdot [I_{sc} + K_I \cdot (T_C - 25)] \tag{2.10}$$

$$V = V_{OC} - K_V \cdot T_C \tag{2.11}$$

Where:

T_C = Temperature of the solar cell.

T_A = Ambient temperature.

N_{OT} = Normal temperature of operation of the solar cell, provided by the manufacturer.

I = Current through the solar cell.

I_{SC} = Short-circuit current, provided by the manufacturer.

K_I = Temperature factor of the short-circuit current in terms of ampere per Celsius degree, provided by the manufacturer.

V = Voltage across the solar cell.

V_{OC} = Open-circuit voltage, provided by the manufacturer.

K_V = Open-circuit voltage temperature factor in terms of volt per Celsius degree, provided by the manufacturer.

The next step required to evaluate the output power of a PV module is the calculation of the fill factor, FF [32], which is a parameter which in conjunction with V_{OC} and I_{SC} determines the maximum power from a solar cell. It is a key parameter for evaluating the performance of solar cells, defined as the ratio of the maximum power from the solar cell to the product of V_{OC} and I_{SC}. Graphically, it is the area of the largest rectangle which will fit in the IV curve of the solar cell, Figure 2-3.

$$FF = \frac{V_{MPP} \cdot I_{MPP}}{V_{OC} \cdot I_{OC}} \tag{2.12}$$

Where:

V_{MPP} = Voltage at the maximum power point.

I_{MPP} = Current at the maximum power point.

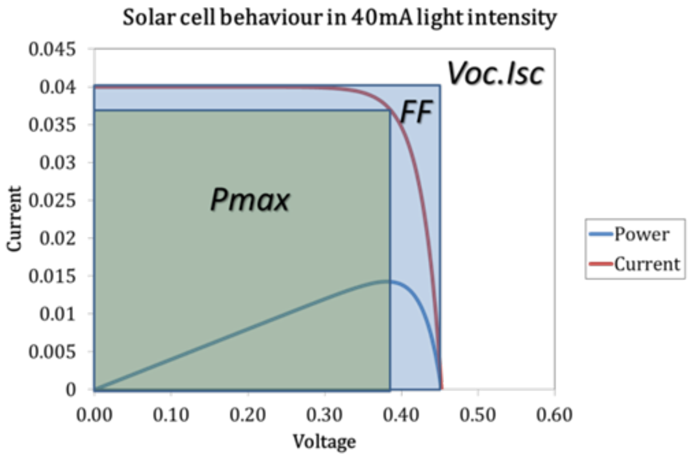


Figure 2-3: Fill Factor.[2]

The electrical power generated by a PV array constituted of N modules can be obtained as indicated in (2.13).

$$P_{PV} = N \cdot FF \cdot V \cdot I \tag{2.13}$$

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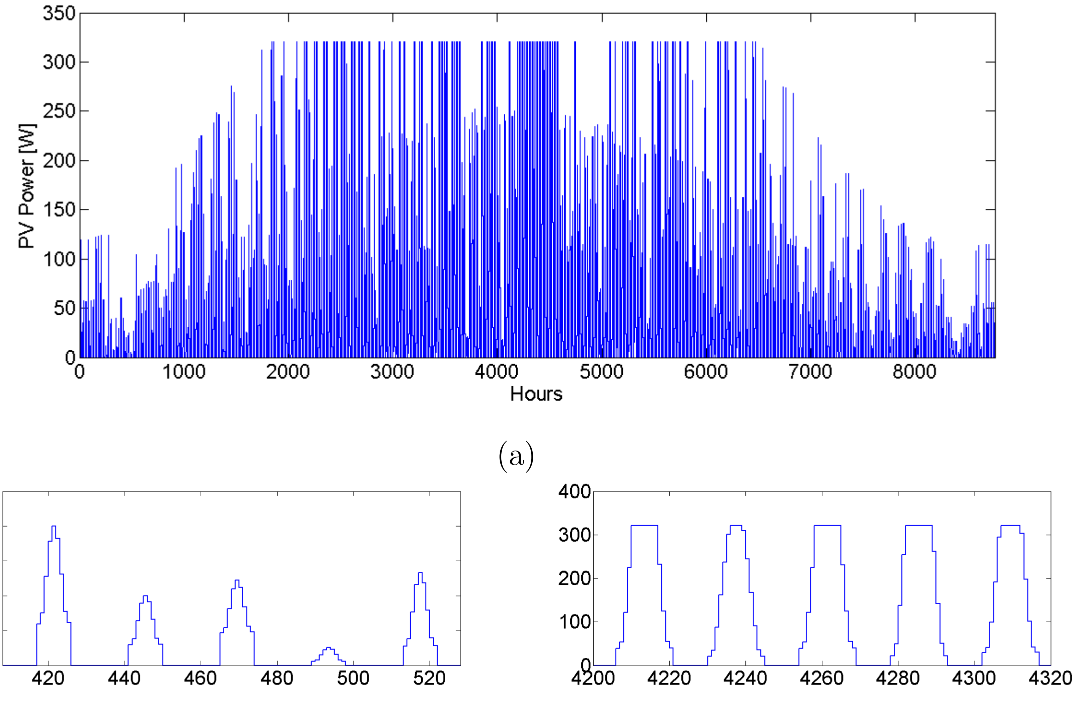
[2] http://mehran005.blogspot.com.es/2012/04/pv-solar-cell-simulation.html

	PV Panel Parameters	**Units**	**Value**
PV Panel Specifications	P_{MPP}	W	320
	V_{MPP}	V	54.7
	I_{MPP}	A	5.86
	V_{OC}	V	64.8
	I_{SC}	A	6.24
	K_V	mV/K	-176.6
	K_I	mA/K	3.5
	N_{OT}	°C	45
Location Data	Latitude	Deg.	43.55
Monte Carlo Two State Model	$MTTF$	Hours	8000
	$MTTR$	Hours	100

Table 2.2: PV panel parameters used in Figures 2-4 and 2-5.



(a)

(b)

(c)

Figure 2-4: Estimated hourly PV power during (a) a year (b) five consecutive winter days (c) five consecutive summer days.

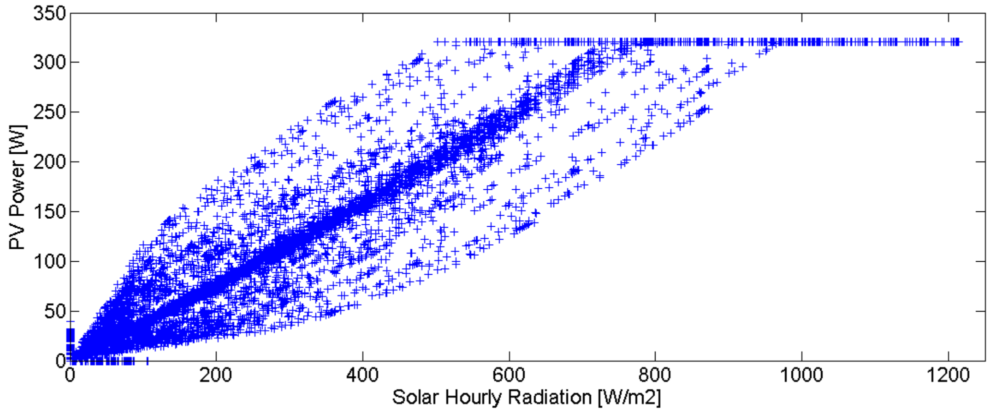


Figure 2-5: PV panel power curve as a function of solar hourly radiation.

It is now possible to obatin the output power of the PV system, as it was shown in Figure 1-4. The hourly output power of a PV panel during a year, considering the parameters stated in Table 2.2, is illustrated in Figure 2-4 (a) while Figure 2-5 plots the PV panel power curve as a function of solar hourly radiation. Figure 2-4 (b)-(c) plots the hourly output power of a PV panel during five consecutive days, in winter and summer respectively. This power curve corresponds to the solar hourly radiation mentioned before and illustrated in Figure 2-2.

2.3 Wind Turbine Generator Model

There are two main factors which determine the output power of a whole wind energy conversion system. These are the wind speed distribution of a selected location where the wind turbine will be installed and the output power curve of the chosen wind turbine.

2.3.1 Wind speed distributions

Weibull distribution function (2.14) has been utilized to simulate the hourly wind speed. The hourly wind speed can be obtained from (2.15), in which the shape factor k and the scale factor c of the Weibull distribution were defined by doing some statistical analysis from the historical wind speed data [22]. It is also a common practice to obtain those

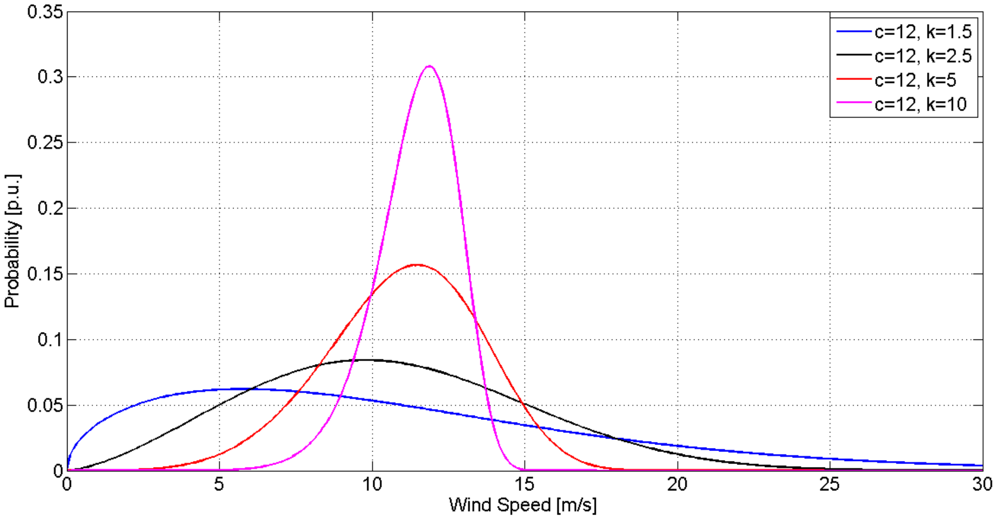


Figure 2-6: Weibull probability density function for different shape factor values.

two factors directly from meteorological stations.

$$F_v = 1 - \mathrm{e}^{[-(\frac{v}{c})^k]} \tag{2.14}$$

$$v = c \cdot [-\ln(u)]^{1/k} \tag{2.15}$$

Where:

F_v = The cumulative distribution function for the Weibull distribution.

v = Wind speed.

u = Random value between 0 and 1 for wind speed calculation.

To have a better idea about the wind behavior tendency when using the Weibull Density Function, Figure 2-6 exposes different Weibull probability plots by keeping constant the c factor and varying k to different values.

2.3.2 Wind turbine model

Generally, for a typical wind turbine, the output power characteristic can be assumed in such a way that it starts power generation at the cut-in wind speed, then the output power increases linearly as the wind speed does from the cut-in to the rated speed, and the rated power is produced when the wind speed varies from the rated to the cut-out wind speed, at which the wind turbine will be shut down for safety implications. Based on the assumptions above, the most simplified model to simulate the output power of a wind turbine can be described as:

$$P_w(v) = \begin{cases} 0 & 0 \leq v \leq v_{ci} \\ P_{rated} \cdot \dfrac{v - v_{ci}}{v_r - v_{ci}} & v_{ci} \leq v \leq v_r \\ P_{rated} & v_r \leq v \leq v_{co} \\ 0 & v_{co} \leq v \end{cases} \tag{2.16}$$

Where:

$P_w(v)$ = Output power associated with the wind speed.

P_{rated} = Turbine rated power.

v_{ci} = Turbine cut-in speed.

v_{co} = Turbine cut-out speed.

v_r = Turbine rated speed.

Depending on different values for the previously mentioned parameters, different output power performance curves will be attained for the chosen wind generators. Figure 2-7 exposes the hourly wind turbine generator output power in a single year for a particular simulation considering the different parameters detailed in Table 2.3. Additionally, Figure 2-8 corroborates for this case the expected output power curve for the wind turbine as a function of the wind speed.

	WT Parameters	**Units**	**Value**
Wind Turbine Power Curve	Rated power	W	1000
	Rated speed	m/s	12
	Cut-in speed	m/s	3
	Cut-out speed	m/s	24
Wind Speed	Scale factor	m/s	12
	Shape factor	m/s	2
Monte Carlo Two State Model	$MTTF$	Hours	6200
	$MTTR$	Hours	100

Table 2.3: Wind turbine generator system parameters used in Figures 2-7 and 2-8.

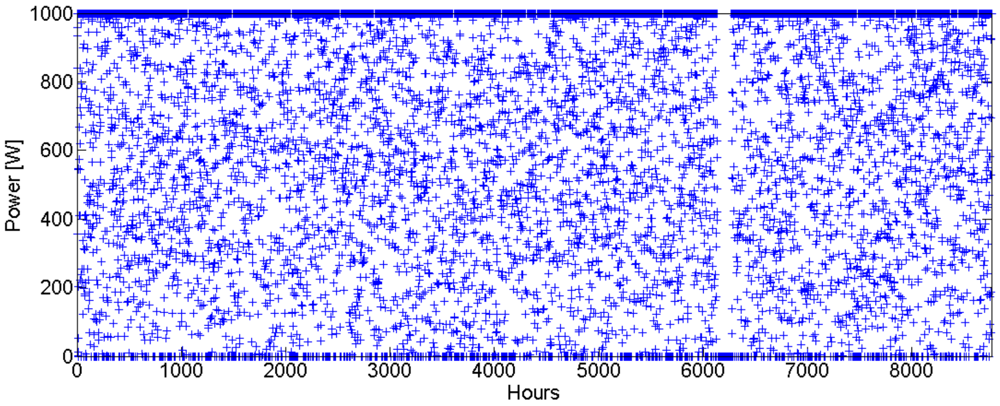


Figure 2-7: Hourly wind turbine generator power for a single year.

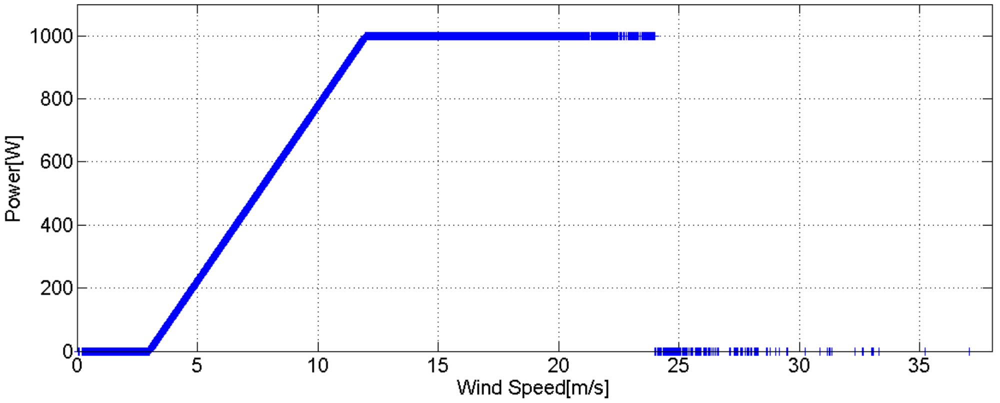


Figure 2-8: Wind turbine power curve as a function of the wind speed.

It may be noticed in Figure 2-7 that nearby the hour 6000, the power is equal to zero for significant hours. This null power is also the result of a failure provoked by the

Monte-Carlo reliability criterion. Additionally, in Figure 2-8, it can be observed that for some wind velocities superior to the cut-in speed up to the cut-out speed, we have zero power delivered. These null power samples occurs when having enough wind speed but the wind turbine being not available due to the existence of the mentioned Monte-Carlo failure state. For wind speeds superior to the cut-out limit and due to safety implications of the wind turbine, the power is set to zero as it is done in real systems.

2.4 Conventional Generators Modeling

Even though self-consumption is supposed to be a more sustainable way of producing energy, it may be necessary to count on some conventional generation back up when renewable energy is not enough to satisfy the demand, or when the building power system designer wants to reduce the grid dependence. Among the most widely employed generators in distributed generation, fuel cells and micro turbines are the most suitable for the appliance that this project is proposing. A brief description of these small-scale generators will be given next.

Fuel cells

An entirely different approach to the production of power from fossil fuel is to use a fuel cell, essentially a chemically powered battery, which produces DC current when supplied with hydrogen (or a fossil fuel containing hydrogen) and oxygen (air). Fuel cells are quite different from all other fossil-fuel powered energy types. They have no moving parts (except for auxiliary systems), they are silent, their pollution is minimum if operated properly, and they have potential fuel efficiencies far beyon the most advanced reciprocating piston or gas turbine generators [34].

However, not everything is as good as it seems and there are also some factors which are of concern. They are expensive, the produce high-current/low-voltage DC power, which requires a DC/AC converter and filter system to turn it into AC, and they require special maintenance which can only be carried out by highly qualified technicians.

Summarizing, a fuel cell is a device which has a positive electrode (anode) and a negative one (catode) and generates electricity by a chemical reaction. The output DC power of the fuel cell is converted using DC/AC inverter in order to connect it to the grid, as shown in Figure 2-9 [30].

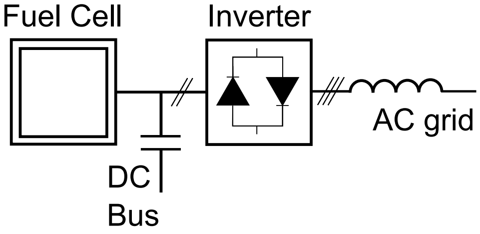


Figure 2-9: Fuel cell system.

Micro Turbines

Gas turbine genrators use a turbine spun by the gases of combustion to rotate an electric generator. Traditional utility type gas turbine generators are too large for distributed and dispersed applications. But smaller turbine generators are available in sizes that fit distributed generation needs and that might work well for dispersed residential applications, these are called mini and micro turbines respectively. Gas turbine generators have disctinctly different size, fuel, efficiency, and operating characteristics that in many situations give them considerable advantages with respect to other types of DG.

Micro turbines were mostly designed originally for vehicular application, as for small hellicpoters, buses, and similar applications. Most micro turbines are aimed squarely at dispersed, cuustomer-site applications, and not as units to be installed on the utility system [34].

The basic principle of operation of gas micro turbines consist on an AC high frequency generator, that cannot be directly connected to the power system. Generated voltage is first rectified and a DC/AC inverter is employed to connect it to the grid as shown in Figure 2-10 [24].

Parameters	Units	Value
Rated power	W	1000
Minimum power	W	250
MTTF	Hours	7500
MTTR	Hours	150

Table 2.4: Fuel cell parameters used in Figure 2-11.

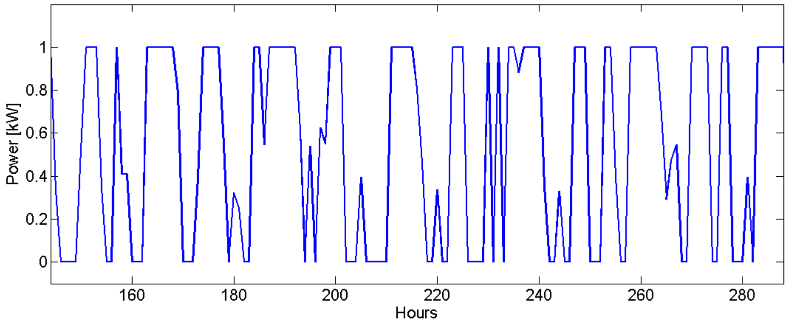


Figure 2-11: Output power of a backup fuel cell during six consecutive days.

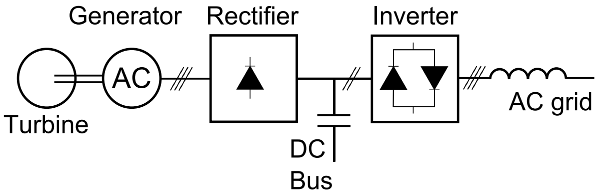


Figure 2-10: Micro gas turbine system.

So in order to develop the mathematical model of the conventional generators (micro gas turbines, fuel cells and other generators), it is assumed that these units will only be started up, when the demand surplus is within a minimum power and the rated power, so as to guarantee maximum efficiency. In addition, since their fuel supply is constant, they all can be considered to behave according to Monte Carlo reliability technique (See Figures 1-1-1-2 and Equations (1.13)-(1.14)) by only defining representative MTTF and MTTR indices. For instance, Figure 2-11 shows the output power during six consecutive days for a fuel cell, which has been simulated as backup for a wind turbine generator, with the parameters stated in Table 2.4. It can be easily appreciated that this fuel cell, is only supplying power within its minimum and rated values.

Chapter 3

Energy Storage Model

3.1 Overview

Electrical power generated by the sun or wind, and actual power consumption unlikely match. The result is feedback of power into the grid when excess power is generated, and power needed from the grid when power generation is insufficient.

As more solar and wind power comes on line, it becomes increasingly difficult, and expensive, to ensure stability of the grid. Intermediate energy storage is therefore rapidly becoming an essential tool to keep power fluctuations on the grid within manageable limits. Moreover, as feed-in tariffs are decreasing, the business case for a home energy storage system that increases self-consumption becomes more solid every day.

The usage of conventional generators to back up the wind and solar energy systems, in case these are not able to cover the demand, requires special care in order to avoid the supply of non renewable energy to the grid. In addition, the battery will never be fed by conventional generators, as it would result in extra unnecessary operation costs.

3.2 Battery Model

Unlike fossil fuels, which are sources of energy that can be easily stored and transported, renewable forms of energy are intermittent and unreliable. This is why batteries are required to store energy when solar and wind power generation is abundant in order to later use that surplus when renewable production is scarce.

In the past decades, researchers have presented a lot of different battery models. Most of them are complex in terms of the expressions and number of parameters employed. Moreover, many of the parameters are determined through extensive experimentation. Consequently, these models tend to be used to assess the theoretical performance of battery designs and are not viable for assessing power reliability studies in renewable generation systems. For this reason, due to practical and simulation time constraints and still accomplishing acceptable accuracy; the battery energy storage will be only limited by its maximum power charge-discharge rates and its maximum-minimum state of charge.

Simplifying, when the power from distributed generation is higher than the building demand, the battery will be charged unless its maximum state of charge has been achieved, the surplus will be injected into the grid. In contrast, if the demand is higher than the generated power, the battery will be discharged to deliver energy to the building unless the minimum state of charge is reached, if so, the system will request energy from the grid.

This is an overview of the process. In the next section, it will be explained in detail and illustrated with the flowchart.

3.3 Grid Energy Exchanges and Flowchart

In case the battery (and the conventional back up if exists) is not able to cover the demand surplus, the grid will supply the required energy to satisfy the demand. This scenario will minimize the impact of these buildings in the distribution network.

The battery operation will be done in coordination, with the rest of dispatchable generators in the building, in such a way that if the actual renewable energy at a time i, is greater than the demand at the same time, there is no need to start up the convenvtional back up or to take energy from the grid. The surplus will be stored in the battery while it is possible, and once the state of charge reaches the maximum, the energy excess will be injected to the grid.

Problems appear when the actual renewable generation is not enough to cover the demand. In this case, the first option is to take energy from the battery while the state of charge is above the lower limmit. If this is insufficient, the conventional generation back up will be started up if possible. And as a last resource, if the support of the battery and the conventional generators is not enough to satisfy the demand, the remaining energy will be taken from the grid. There are also some considerations to be taken into account in this process, which are listed below.

- The battery will be charged or discharged only when its energy level is within the limits.

- To start up the conventional back up, the energy deficit must be greater than a minimum amount which is stated by the user. Otherwise, it will not be worth to use the generators to supply a little amount of energy.

- In case there are different types of conventional generators, the ones with lower operation costs will be started up first.

- The conventional back up is only employed to help covering the instantaneous demand. It will never be used to inject energy neither into the grid nor into the battery.

- Only if there is no choice, energy will be taken from the grid to cover the demand. The process can be more easily seen looking at the flowchart in Figure 3-1. Table 3.1 defines the nomenclature used in the mentioned flowchart.

Variable	**Abbreviation**
Actual renewable power	P_r
Actual conventional power	P_{cnv}
Maximum conventional power	P_{cnvmax}
Minimum conventional power	P_{cnvmin}
Actual demanded power	D
Maximum battery power charge	P_{cmax}
Maximum battery power discharge	P_{dmax}
Actual battery power charge	P_c
Maximum battery energy	E_{max}
Miniimum battery energy	E_{min}
Actual battery energy status	E_i
Previous hour battery energy status	E_{i-1}
Energy into (+) from (-) the grid	E_{grid}
Time interval (1 hour)	Δ_{min}

Table 3.1: Nomenclature used in Figure 3-1.

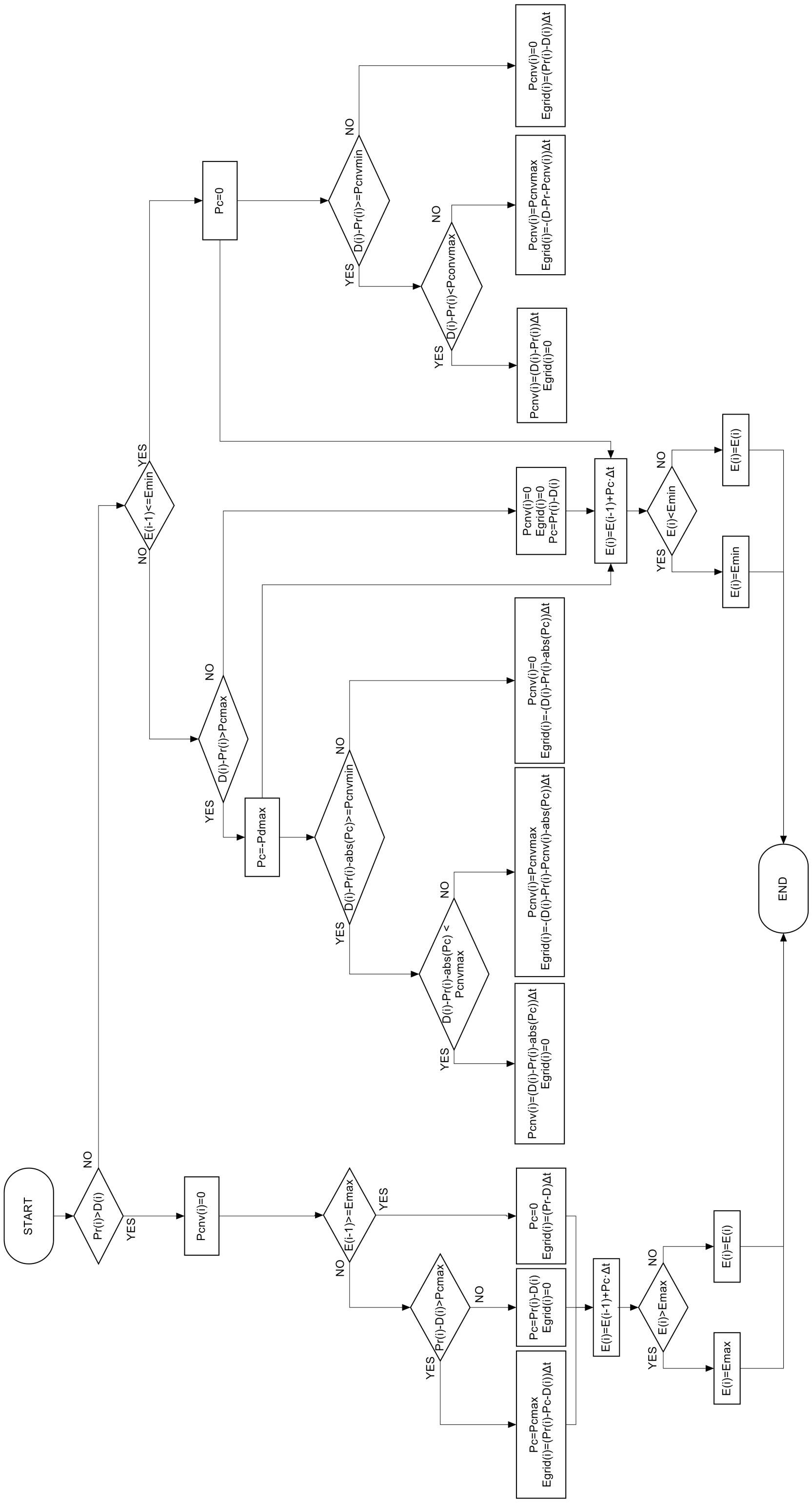


Figure 3-1: Battery model flowchart.

Chapter 4

Economic Analysis

4.1 Overview

The economic analysis consists of the comparison between the traditional energy purchase from the electrical grid, and the costs that self-consumption would involve.

For the case of the traditional energy purchase, two possible access tariffs for low voltage users are considered. These are the tariffs 2.0A and 2.0DHA, which are access tariffs for voltage below 1kV and power below 10kW, it can be assumed that nearly the total of domestic users have a hired tariff within these values. It is not possible to perform an exact estimation of how much would be the energy price in the future, because both the power term and the energy term, are periodically reviewed and modified by means of new Royal Decrees. Hence, once the average yearly cost is estimated, an annual inflation will be considered.

For the estimation of the self-consumption costs some possible scenarios must be taken into account. The idea is to self-generate as much energy as possible and when the production is greater than the demand, the exceeding power will be stored in batteries while these are within the expected levels of charge. But, at some certain moments, it might occur that the system is not able to keep storing energy because the batteries are fully loaded, in this case, the exceeding energy must be injected into the grid, taking into account the corresponding access toll for generators and the price at which this energy will be sold. In contrast, appears the situation in which the self-generated energy is not enough to satisfy the demand. At this point, the required energy will be taken from the batteries while their charge is over the lowest allowed level, but if it is not possible to take this energy from the batteries it must be taken from the grid. For the last situation, the building will be considered as a whole customer who will buy the energy according to the corresponding access tariff, in this case the 3.0A, which is a low voltage access tariff for hired powers greater than 15kW. It has been also considered the possibility of studying the reliability of the system in a single country house. In this case, the tariff 3.0A may be unsuitable as it is for big powers, hence the user will be allowed to choose within the tariffs 2.0A and 2.0DHA also for the self-consumption scenario.

It must be cleared up that it is not possible to consider the net-balance scenario in this project, since this modality is exclusively for self-consumption users who only use solar generation systems.

4.2 Traditional Energy Purchase

The process to estimate the energy purchase costs is simple. A building with a number of apartments, n, is considered. Each one of these apartments has one of the access tariffs mentioned before, 2.0A or 2.0DHA, and a hired base power which will be associated to the power term. The energy consumed by each apartment comes from the *Domestic Load Profile* developed in the Thesis by Edwin Xavier Domínguez Gavilanes, and it is related to the energy term. It must be kept in mind that the fact of simulating a number of years, y, is not a projection to the future, it is the same year simulated y times, which will provide the average cost per year.

4.2.1 Access tariffs structure

According to the article 17 of the Law 54/1997, [1], the access tariffs to the electrical grid will be unique in the whole national territory and will not include any kind of taxes. Furthermore, they will take into account the specialties by voltage levels and the features of hourly and power related consumption.

The structure of these tariffs is currently described in the Royal Decree 1164/2001 [6], taking into account the additional disposition of the Order ITC/1723/2009 [4], related to the access tariff 2.0A. The conditions for its application are described in the same Royal Decree, being completed with the Royal Decree 1955/2000 [10], and the Royal Decree 1435/2002 [7]. The tariff 2.0DHA is the same as the 2.0A but with two ratable periods per day. These periods are described in Table 4.1.

Additionally, the new hours of application of these tariffs are contained in the Order ITC/2794/2007 [5].[1]

Power term

For each one of the ratable periods applicable to the tariffs, an amount of power will be hired, applicable during the whole year. The power billing term, will be the resultant sum of multiplying the hired power, on each ratable period by the corresponding power term 4.1.

In the case of the access tariff 2.0DHA, although it has two ratable periods, there is only one existing power term, which is the same as for the tariff 2.0A.

$$T_P = \sum_i P_{hi} \cdot T_{Pi} \tag{4.1}$$

Where:

T_P = Power billing term in €.

P_{hi} = Hired power in kW.

T_{Pi} = Power term in €/kW/year.

Active energy term

The energy billing term, will be the resultant sum of multiplying the consumed and metered energy on each ratable period, by the price of the corresponding energy term.

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[1] http://www.minetur.gob.es

The energy billing term will be charged monthly, including the consumed energy corresponding to each ratable period. There are three different energy terms within the tariffs 2.0A and 2.0DHA, one for the first tariff, T_{E0}, and two for the second tariff, one per each ratable period, T_{E1} and T_{E2}.

$$T_E = \sum_i E_i \cdot T_{Ei} \tag{4.2}$$

Where:

T_E = Energy billing term in €.

E_i = Consumed and metered energy for each period in kWh.

T_{Ei} = Energy term in €/kWh.

Reactive energy term

Applicable to the access tariffs 3.0A, 3.1A and the 6.X tariffs. It requires the permanent installation of a reactive energy meter. It is applicable always the reactive energy consumption overpasses the 33% of the active energy consumption.

$$T_R = \sum_i Q_i \cdot T_{Ri} \tag{4.3}$$

Where:

T_R = Reactive energy billing term in €.

Q_i = Reactive energy in kVAr.

T_{Ri} = Reactive energy term in €/kVAr.

Electric Tax

The Electrical Tax, appeared in the article 7 of the Law 66/1997 [2]. Its creation was justified as a new figure within the Special Taxes, and it can be calculated, in €, as indicated in Equation (4.4).

$$IE = 1.05113 \cdot 4.864\% \cdot (T_P + T_E + Penalties + T_R + rents) \tag{4.4}$$

Where:

IE = Electrical tax in €.

$Penalties$ = Costs related to the consumption of more energy than hired in €.

T_{Ri} = Costs due to the rent of metering devices in €.

IVA

As always, the 21% corresponding to the IVA must be applied.

$$IVA = 21\% \cdot (T_P + T_E + Penalties + T_R + rents + IE) \tag{4.5}$$

Electric bill

The electric bill is calculated, as follows, once all the previous terms and taxes have been cleared out.

$$Bill = T_P + T_E + Penalties + T_R + rents + IE + IVA \tag{4.6}$$

Time discrimination

The access tariffs, besides voltage and hired power, include time discrimination within the different time periods. The discrimination can be made of 2, 3 or 6 periods. It is applied to both the power and energy terms, but it also can be applied to both the standard loss and the pay per capacity coefficients.

Within the access tariffs considered in this paper, tariffs 2.0 DHA and 3.0 A are affected by time discrimination, resulting in two different periods. Table 4.1 shows how these periods are distributed depending on the season.

	Winter			**Summer**		
Acces Tariff	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
2.0 DHA **2.1 DHA**	12:00-22:00	22:00-12:00	-	13:00-23:00	23:00-13:00	-
2.0 DHS **2.1 DHS**	13:00-23:00	23:00-01:00 07:00-13:00	01:00-07:00	13:00-23:00	23:00-01:00 07:00-13:00	01:00-07:00
3.0 A	18:00-22:00	22:00-00:00 08:00-18:00	00:00-08:00	11:00-15:00	15:00-00:00 08:00-11:00	00:00-08:00

Table 4.1: Time Discrimination.

4.3 Self-Consumption

The main costs related to the self-consumption are those regarding the installation and maintenance of the self-generation system, as the idea is to avoid as much as possible the energy exchanges with the grid. Unfortunately, it is impossible to be completely independent from the electrical grid, as sometimes it will be necessary to take some energy from it to help satisfying the demand, and sometimes the situation will be the opposite, the self-generated energy will be much greater than the demand and it will be required to inject the excess into the grid.

The economic issue regarding the energy exchanges with the grid is probably the most complicated part of this work, due to the legislation involving the energy exchanges between the grid and self-generation users, is still unclear. Hence, this project is being developed based on a future vision in order to find reliable alternatives that can yield to more sustainable energy generation, management and consumption.

4.3.1 Installation, maintenance and operation costs

The installation costs are those involving the price of the generators to be installed, as well as the labor costs and legal permits. These costs will be inputted in the design tool by the user. In order to perform an economic analysis some cases of study are considered, for which these costs differ from one to another.

The maintenance costs are meant to be a fixed amount which can be considered as some kind of insurance, which will cover the expenses involving periodical revisions and reparation due to possible failures in the generators.

The operation costs are associated with the fuel consumption of each generator, so they only affect to the fuel cell or the micro gas turbine, as the wind turbines and the photovoltaic panels are not related to these costs.

4.3.2 Energy exchanges with the grid

As mentioned before, the self-consumption means that sometimes it will be necessary to inject the exceeding energy into the grid, and sometimes the energy must be taken from the grid to satisfy the demand.

Exceeding energy sale

The energy sale must be performed only when it is not possible to store the self-generated surplus, due to the battery level of charge is at the upper limit. The legal regulations regarding this situation are still undefined, some options are being considered but still there is not one final decision. A few years ago, the draft of the Royal Decree 1699/2011 [9], defined as net balance supply modality those systems able to compensate the energy balances in an instantaneous or delayed way, that allow the consumers the individual energy production for their own use in order to fit together their production and demand curves.

With this system, an installation will produce energy for its self-consumption always the demand exists. If the demand is higher, the energy will be taken from the grid, and when the demand is lower than the produced energy, this surplus will be injected into the grid.

However, the scenario mentioned above did not come out at all. Hence, this creates the need of searching for alternatives. This paper suggests nZEBs to be connected to the grid as a whole small distributed generation system.

By means of the Royal Decree Law 14/2010 [11], an access toll for special and ordinary regime generators was created. This Royal Decree Law did not develop the application mechanism, for this reason the application of this toll did not come out until the publication of the Royal Decree 1544/2011 [8]. The amount to be paid by the generators since 1^{st} of January 2011 is 0.5 €/MWh.[2]

Energy purchase for self-consumption

As mentioned in the previous point, nearly zero-energy buildings are considered as a whole small distributed energy generation system and, in the same way, they are considered as a whole when energy purchase from the grid is needed. This differs from what was explained when talking about traditional energy purchase, where each customer was associated to an access tariff. Here, the purchase energy is intended to be as low as possible, so it makes no sense to take into account the different access tariffs that all the customers in a building may have hired. Hence, to calculate the costs related to the energy purchase for self-consumption, in a residential building, an access tariff is considered for the whole building. This tariff is the 3.0A, which is a low voltage tariff for hired powers greater than 15kW and with three ratable periods as indicated in Table 4.1. If the study case is about a single country house, or any other small building which may consume few energy, the user is also given the chance to select the tariff 2.0A or 2.0DHA for the self-consumption scenario. As in the case of the traditional energy purchase, once the average yearly cost is calculated the corresponding annual inflation will be applied.

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[2] http://www.cne.es/cne/doc/publicaciones/cne_cp_metodologia_asignacion.pdf

Chapter 5

Computer Tool: GenMIX v1.0 beta

5.1 Developed Computer Tool

A Graphical User Interface (GUI) in Matlab© has been developed to assess the selection of the best renewable-distributed generation-mix suitable to be installed in residential buildings. The software has been named as "GenMIX v1.0 beta" as it is in a development stage. It has taken into account key technical, economic and reliability aspects so that it becomes a useful computer tool to be used by nearly zero-energy buildings promoters. GenMIX has been designed to be user-friendly and easily permit users to input all the required information to achieve representative simulation results that will help to decide the most appropriate configuration for the distributed power generation in buildings. There are six different panels in the GUI which allow the user to introduce the simulation data, these are:

Location Panel. It requests the location latitude to be employed for the power generation and demand models. Optionally, the user can select its own file containing the location's hourly temperature which is important to predict PV panels output power.

Generation Panel. It permits the user to create his own distributed generation combinations by allowing him to parameterize wind turbine, photovoltaic, fuel cell and micro-gas generators.

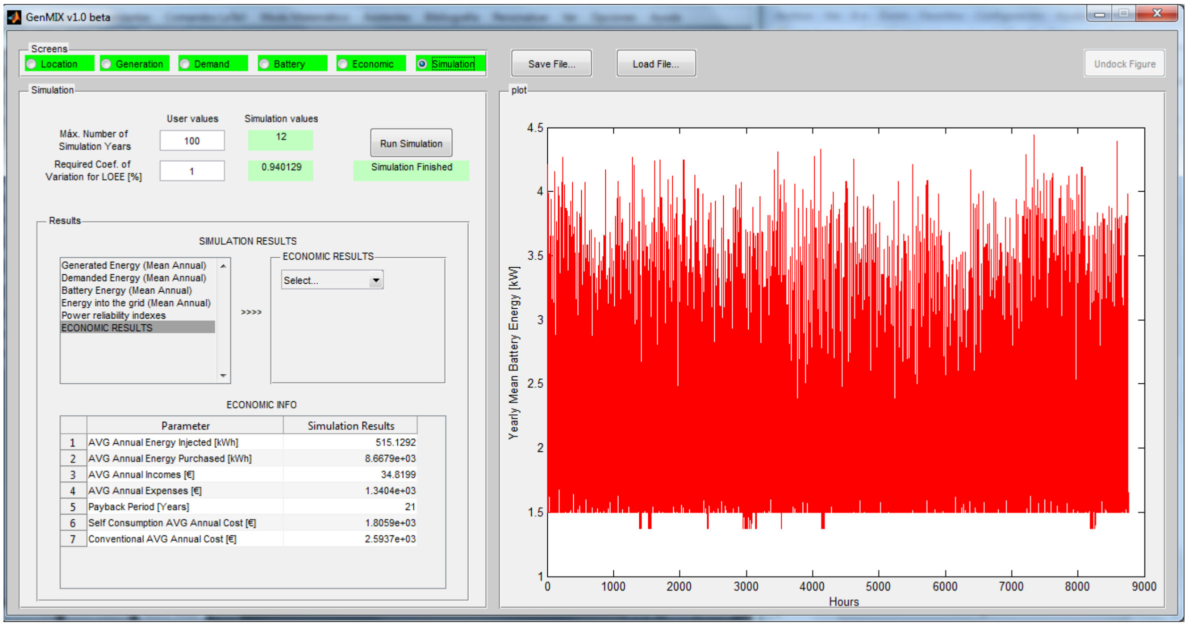
Demand Panel. In this panel the user configures the power demand characteristics of the different dwellings for the studied building as well as the mean annual energy demand requirements.

Battery Panel. The system's energy storage features is entered in this panel.

Economic Panel. All the economic information regarding to access tariffs, taxes and self-consumption parameters is inserted in this panel.

Simulation Panel. This panel allows the user to define his acceptable convergence tolerance and the maximum number of simulation years if convergence is not achieved. Additionally, when a simulation finishes, it permits the user to display in a plot panel different technical, reliability and economic information about the simulation results.

The software also permits the user to save and load his simulation files with their corresponding simulation results. Figure 5-1 exposes the different GUI panels while Figure 5-2 presents a general overview of the entire GUI.

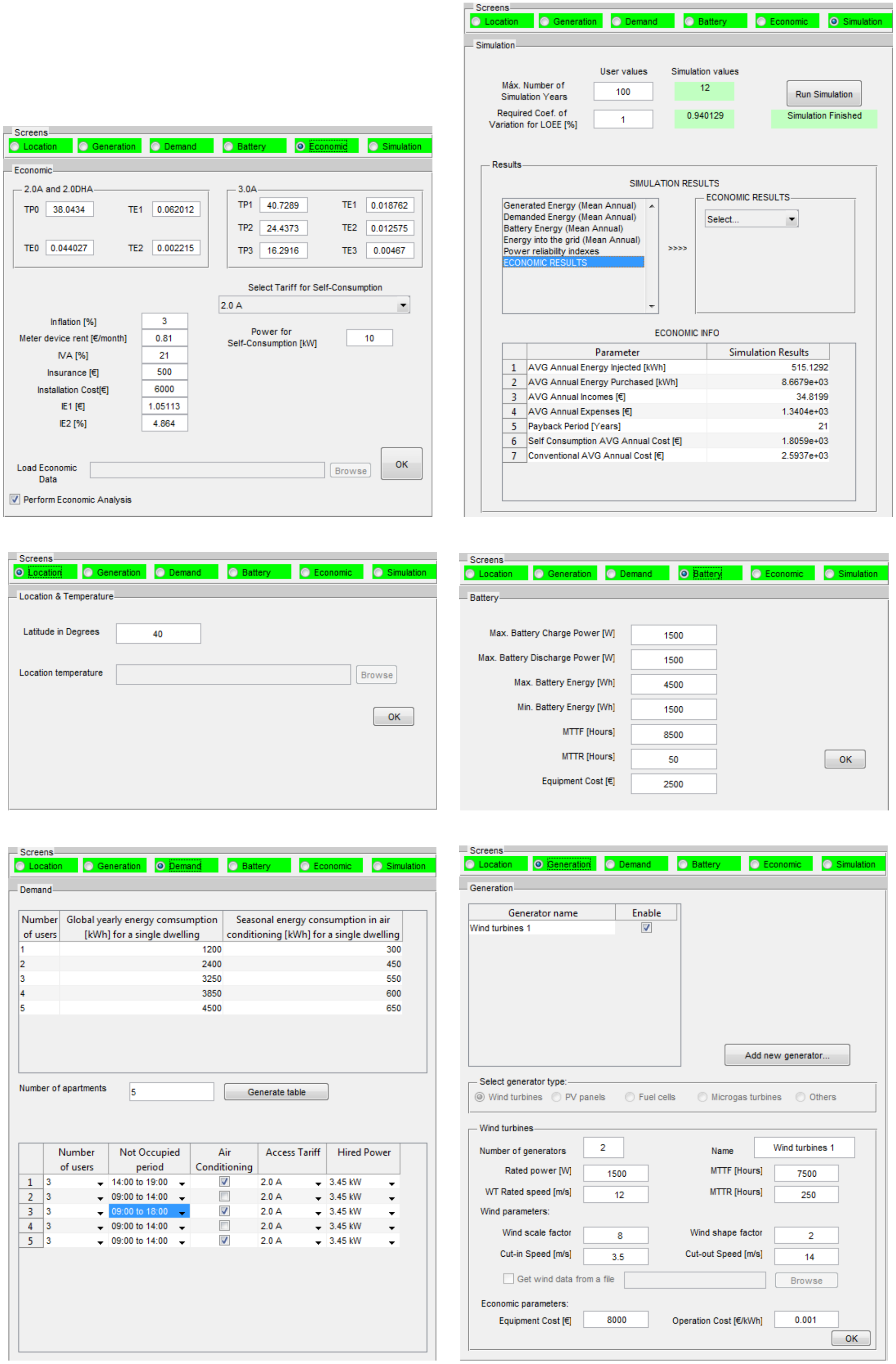


	User values	Simulation values
Máx. Number of Simulation Years	100	12
Required Coef. of Variation for LOEE [%]	1	0.940129

Simulation Finished

	Parameter	Simulation Results
1	AVG Annual Energy Injected [kWh]	515.1292
2	AVG Annual Energy Purchased [kWh]	8.6679e+03
3	AVG Annual Incomes [€]	34.8199
4	AVG Annual Expenses [€]	1.3404e+03
5	Payback Period [Years]	21
6	Self Consumption AVG Annual Cost [€]	1.8059e+03
7	Conventional AVG Annual Cost [€]	2.5937e+03

Figure 5-2: General GUI layout



2.0A and 2.0DHA

TP0 38.0434
TE1 0.062012
TE0 0.044027
TE2 0.002215

3.0A

TP1 40.7289
TE1 0.018762
TP2 24.4373
TE2 0.012575
TP3 16.2916
TE3 0.00467

Select Tariff for Self-Consumption: 2.0 A

Power for Self-Consumption [kW]: 10

Inflation [%]: 3
Meter device rent [€/month]: 0.81
IVA [%]: 21
Insurance [€]: 500
Installation Cost[€]: 6000
IE1 [€]: 1.05113
IE2 [%]: 4.864

Load Economic Data:

☑ Perform Economic Analysis

	User values	Simulation values
Máx. Number of Simulation Years	100	12
Required Coef. of Variation for LOEE [%]	1	0.940129

Simulation Finished

Generated Energy (Mean Annual)
Demanded Energy (Mean Annual)
Battery Energy (Mean Annual)
Energy into the grid (Mean Annual)
Power reliability indexes
ECONOMIC RESULTS

ECONOMIC INFO

	Parameter	Simulation Results
1	AVG Annual Energy Injected [kWh]	515.1292
2	AVG Annual Energy Purchased [kWh]	8.6679e+03
3	AVG Annual Incomes [€]	34.8199
4	AVG Annual Expenses [€]	1.3404e+03
5	Payback Period [Years]	21
6	Self Consumption AVG Annual Cost [€]	1.8059e+03
7	Conventional AVG Annual Cost [€]	2.5937e+03

Latitude in Degrees: 40
Location temperature:

Max. Battery Charge Power [W]: 1500
Max. Battery Discharge Power [W]: 1500
Max. Battery Energy [Wh]: 4500
Min. Battery Energy [Wh]: 1500
MTTF [Hours]: 8500
MTTR [Hours]: 50
Equipment Cost [€]: 2500

Number of users	Global yearly energy comsumption [kWh] for a single dwelling	Seasonal energy consumption in air conditioning [kWh] for a single dwelling
1	1200	300
2	2400	450
3	3250	550
4	3850	600
5	4500	650

Number of apartments: 5

	Number of users	Not Occupied period	Air Conditioning	Access Tariff	Hired Power
1	3	14:00 to 19:00	☑	2.0 A	3.45 kW
2	3	09:00 to 14:00	☐	2.0 A	3.45 kW
3	3	09:00 to 18:00	☑	2.0 A	3.45 kW
4	3	09:00 to 14:00	☐	2.0 A	3.45 kW
5	3	09:00 to 14:00	☑	2.0 A	3.45 kW

Generator name	Enable
Wind turbines 1	☑

Select generator type: ● Wind turbines ○ PV panels ○ Fuel cells ○ Microgas turbines ○ Others

Wind turbines

Number of generators: 2
Name: Wind turbines 1
Rated power [W]: 1500
MTTF [Hours]: 7500
WT Rated speed [m/s]: 12
MTTR [Hours]: 250

Wind parameters:

Wind scale factor: 8
Wind shape factor: 2
Cut-in Speed [m/s]: 3.5
Cut-out Speed [m/s]: 14

☐ Get wind data from a file

Economic parameters:

Equipment Cost [€]: 8000
Operation Cost [€/kWh]: 0.001

Figure 5-1: GUI’s different panels

Chapter 6

Study Cases

6.1 Case 1

This case studies the feasibility of installing a PV generation system for self consumption, in a rural house in Almería/Spain (Latitude=36.5°). The analysis performed consists in the comparison between two different real PV kits employed for self consumption, using two different storage systems. This analysis gives both reliability and economic results, which is expected to be analyzed in real situations.

The details of the country house are given in Table 6.1, while Figure 6-1 plots the yearly mean consumption profile. It has been considered that this house presents a yearly electric energy consumption of 4500 [kWh] and it is occupied by a family who works the ground, and have decided to install a PV generation system in their property, this is why the house is supposed to be occupied all the time. Also, as most Almería's dwellings, it has been consider the usage of air conditioner during summer.

Table 6.2 details the parameters of both kinds of PV panels that will be considered for the simulation. The first simulation will be carried out using a commercial kit composed by eleven panels like Panel 1, while the second commercial kit consists of ten panels like Panel 2. The mean annual output power obtained for each kit is illustrated in Figure 6-2.

Building Type	**Nº of Occupants**	**Not Occupied Period**	**Air Conditioning**	**Acces Tariff**	**Hired Power**
Country House	5	No	Yes	2.0 DHA	9.2 kW

Table 6.1: Characteristics of a country house for PV self consumption in Almería

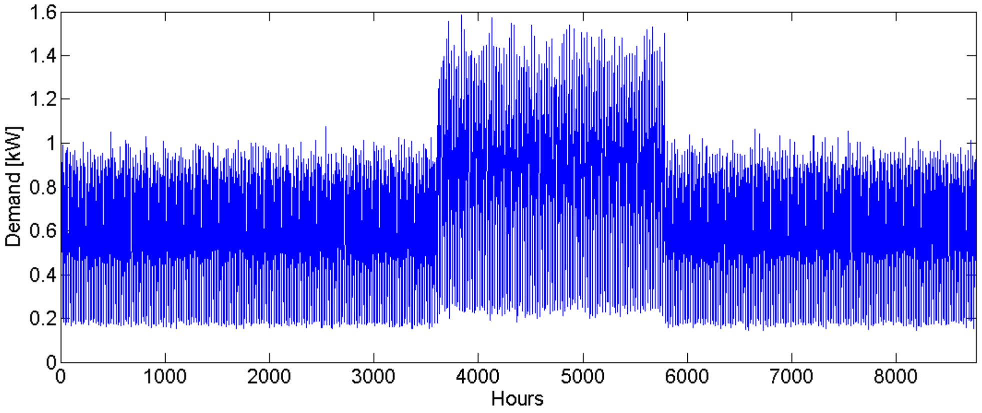
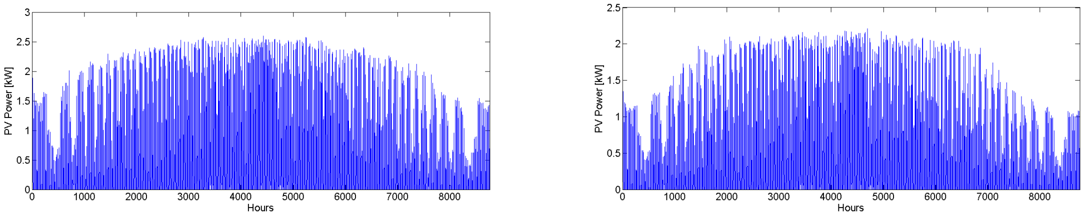


Figure 6-1: Demand profile of a country house for PV self consumption in Almería.

On the other hand, the parameters of the batteries that will be used in this simulation are given in Table 6.3. These batteries will be used within the two different PV kits detailed before in order to see how the reliability and economic results vary. This implies four different scenarios as Table 6.4 states:

Figure 6-3 plots the energy flow into the battery for each one of the scenarios listed before.



(1) (2)

Figure 6-2: PV generation for self consumption in a country house in Almería.

PV Panel Parameters	**Units**	**Value**	
		Panel 1	Panel 2
P_{MPP}	W	240	240
V_{MPP}	V	30.01	30
I_{MPP}	A	8.011	8
V_{OC}	V	36.90	36.90
I_{SC}	A	8.682	8.52
K_V	mV/K	-0.4015	-0.329
K_I	mA/K	0.0717	0.038
N_{OT}	°C	47	25
Number of Panels		11	10
Cost	€	4985	2950
Latitude	Deg.	36.5	
$MTTF$	Hours	7500	
$MTTR$	Hours	150	

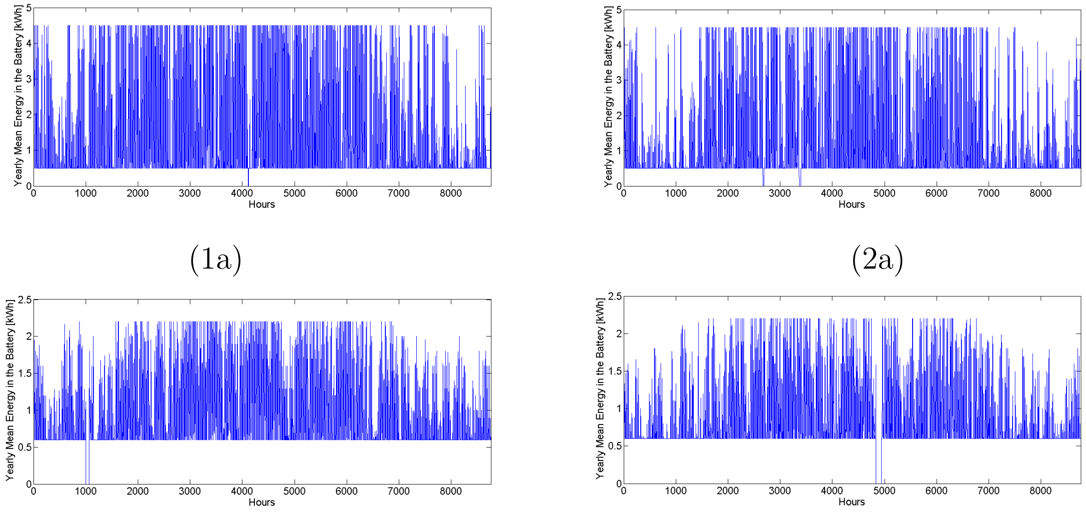
Table 6.2: PV panel parameters for self consumption in a country house in Almería.

Units		**Value**	
		Battery 1	Battery 2
Max. Charge Power	W	1000	200
Max. Discharge Power	W	1000	200
Max. Energy	Wh	4500	2200
Min. Energy Power	Wh	500	600
Cost	€	1000	600
$MTTF$	Hours	8500	
$MTTR$	Hours	50	

Table 6.3: Battery parameters for a simulation in a country house in Almería.

	PV Kit 1	**PV Kit 2**
Battery 1	Scenario 1a	Scenario 2a
Battery 2	Scenario 1b	Scenario 2b

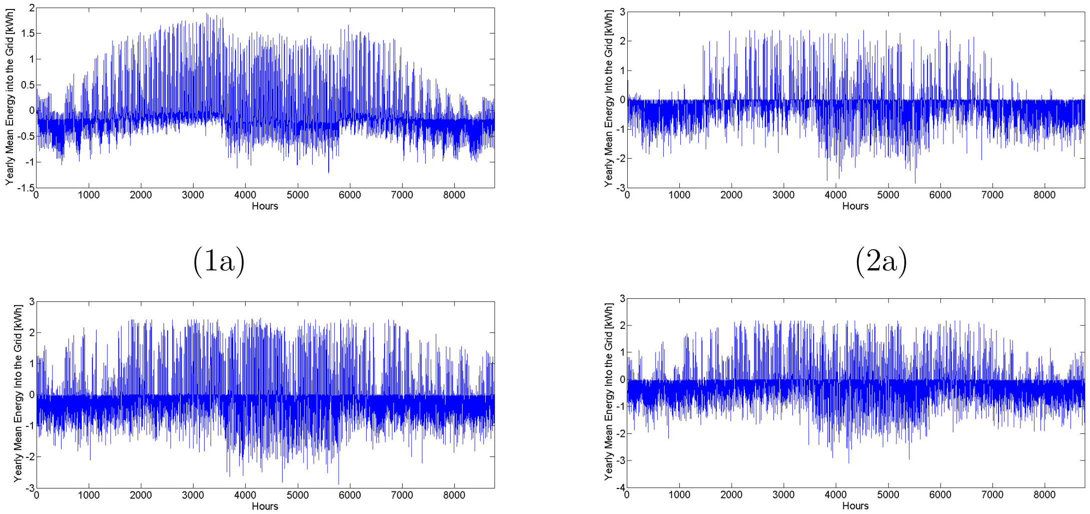
Table 6.4: Scenarios for Case Study 1



(1a) (2a)

(1b) (2b)

Figure 6-3: Energy flow in the battery for self consumption in a country house in Almería for the different scenarios.



(1a) (2a)

(1b) (2b)

Figure 6-4: Grid energy flow for self consumption in a country house in Almería

The energy exchanges with the grid, for each one of the scenarios mentioned before, are shown in Figure 6-4. When the curve takes positive value means that the energy surplus is being injected into the grid, otherwise, negative values mean that the generation is not enough and the grid is supplying the necessary energy to cover the demand. In the mentioned figure it can be noticed that when Battery 1 is used, (1a) and (2a), the energy taken from the grid is lower, fact that will result in economic saving.

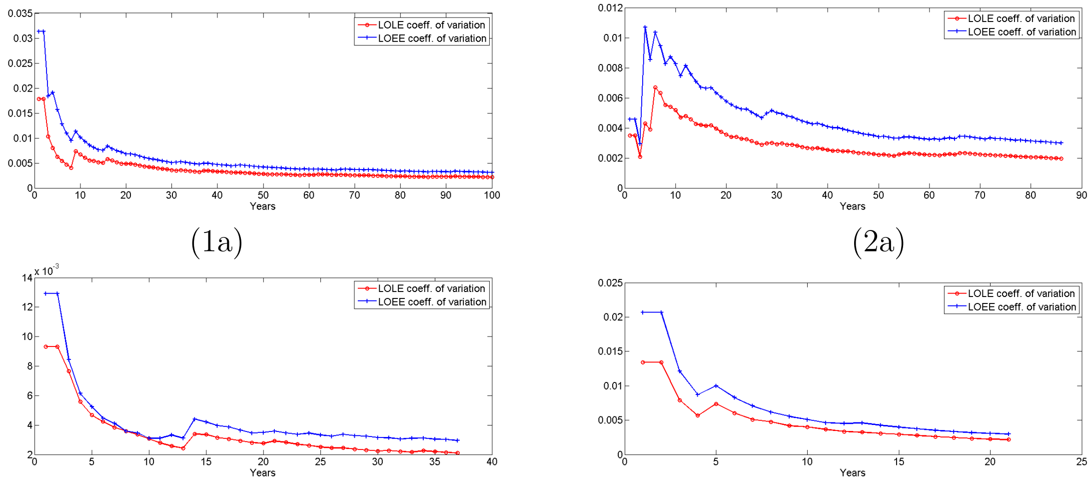
6.1.1 Reliability Results

Figure 6-5 plots the Loss of Energy Expectaction (LOEE) and the Loss of Load Expectation (LOLE) indices for each case. It can be checked that using bigger storage devices increases the reliability of the system. Independently on the battery used, both LOEE and LOLE are better when PV kit 1 is used (Scenarios 1a and 1b) as it provides more energy than the PV kit 2.

From the different scenarios considered in this study case, it can be stated that the most reliable is the one in which the PV kit 1 was used within Battery 1. In addition, taking a look at plots (1b) and (2a), it can be proved that the battery change has more impact in the reliability of the system than changing the PV kits, since the indices in plot (2a), which correspond to PV kit 2 and Battery 1, are lower than the indices in plot (1b), which are related to PV kit 1 and Battery 2.

Figure 6-6 plots the evolution of the coefficients of variation of the LOEE and LOLE indices for each scenario. A tolerance equal of 0.3% was used to determine if the system achieved convergence. Due to simulation constraints, the maximum number of simulation years has been set to 100. It can be noticed that in Scenario 1a the system didn't achieve the desired convergence of 0.3% within the maximum simulation years, however the final convergence value at the year 100 was 0.37%, which is highly acceptable.

Table 6.5 shows the value of each reliability index for the last simulation year. It can be appreciated that Scenario 1a is the most grid-independent case and it presents the best reliability indices not only for LOEE and LOLE, but also for the Distributed Energy Penetration (DEP), Microgrid Island Operation Probability (MIOP) and Island Load Shedding Expectation (ILSE) indices.



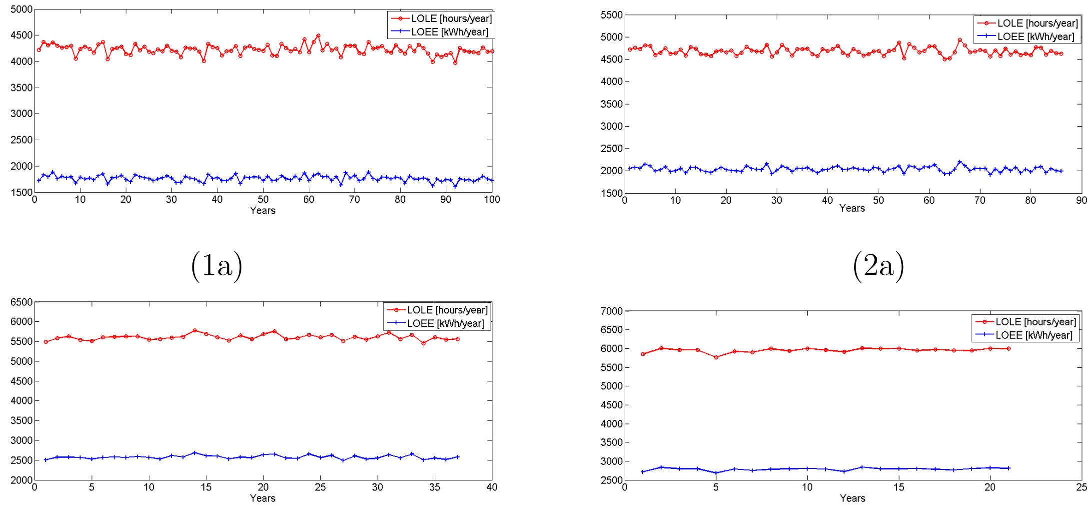
(1a)

(2a)

(1b)

(2b)

Figure 6-6: Coefficients of variation of LOEE and LOLE for PV self consumption in a country house in Almería.



(1a)

(2a)

(1b)

(2b)

Figure 6-5: LOEE and LOLE indices for PV self consumption in a country house in Almería.

6.1.2 Economic Results

This section consists of the comparison between the economic results for the different scenarios. The economic data regarding the power and energy terms, has been taken

Scenario	**LOEE** [kWh/year]	**LOLE** [hours/year]	**MIOP** [p.u./year]	**ILSE** [kW/occurrence/year]	**DEP** [p.u./year]
1a	1727	4197	0.5290	0.4115	0.6647
1b	2579	5564	0.3648	0.4635	0.4992
2a	1987	4629	0.4769	0.4293	0.6142
2b	2811	5993	0.3159	0.4691	0.4541

Table 6.5: Reliability indices in the last year of simulation for the country house in Almería.

according to the Order IET/107/2014 [3], which states the latest review of the access tariffs of electrical energy, see Table 6.6. To obtain the economic results for self consumption, it has been considered that the user has hired the acces tariff 2.0A and 3.45 kW of power. Table 6.7 details the year-one investment (fixed costs) that was made for each scenario. Additionally, to obtain the income due to sold energy, it will be assumed to be paid 0.05€ for every kWh injected into the grid. The installation cost is assumed to be the 45% of the total cost of the equipment, while the maintenance costs have been set to 10%. The variable costs subjected to inflation are indicated in Table 6.8, and the results are given in Table 6.9.

Access	**TP [€/kW/year]**			**TE [€/kWh]**		
Tariff	**P1**	**P2**	**P3**	**P1**	**P2**	**P3**
2.0 A	38.043426	-	-	0.044027	-	-
2.0 DHA	38.043426	-	-	0.062012	0.002215	-
3.0 A	40.728885	24.437330	16.29155	0.018762	0.012575	0.004670

Table 6.6: Active power and energy terms according to latest review.

Scenario	**PV Kit** [€]	**Battery** [€]	**Installation Cost [€]**	**Maintenance Costs [€]**	**Total Investment [€]**
1a	4985	1000	2693.25	598.5	9276.75
1b	4985	600	2513.25	558.5	8656.75
2a	2950	1000	1777.5	395	6727.5
2b	2950	600	1597.5	355	5502.5

Table 6.7: Detail of the year-one investment for each scenario for PV self consumption in a country house in Almería.

Inlfation [%]	**Meter Device Rent** [€/month]	**IVA** [%]	**IE1** [€]	**IE2** [%]
3	0.81	21	1.05113	4.864

Table 6.8: Variable costs for PV self consumption in a country house in Almería.

	Scenario 1a	**Scenario 1b**	**Scenario 2a**	**Scenario 2b**
AVG Annual Energy Injected [kWh]	1427	2147	730.88	1294
AVG Annual Energy Purchased [kWh]	1687	2425	1968	2622
AVG Annual Incomes [€]	87.58	131.76	44.15	76.96
AVG Annual Expenses [€]	339.42	390.67	353.31	391.77
Payback Period [Years]	19	17	12	11
Self Cons. Annual Bil Maintenance Costs [€]	877.08	826.14	712.68	672.90
Conventional Annual Bill Cost [€]	1351.50	1308.80	1209.20	1190.50

Table 6.9: Economic results for PV self consumption in a country house in Almería.

As mentioned before, using bigger storage devices (scenarios 1a and 2a), means lower grid interaction. This results in a reduction on the expenses due to energy purchasing, but also the incomes due to the sell of energy surplus to the grid are lower. However, as the simulations show, the most critical issue that affects the payback period is the initial investment, and not the amount of sold or bought energy. Therefore we have a counterbalance, the Scenario which presents the best reliability performance is the one that has the longest payback period.

It also can be appreciated that installing self consumption systems like the ones proposed here, yields to significant economic saving on the electric bill. In addition, the self consumption costs indicated in Table 6.9, include not only the electrical bill but also

the maintenance costs of the system. This means that the scenarios which provide more saving in the electrical bill are scenarios 1a and 1b, even though they suppose higher annual cost due to their higher investment and maintenance costs.
To close, when looking both reliability and economic criteria, it can be cleared up that making a higher investment may result in better reliability aspects, but this will increase the payback period, which is surely the most important aspect that will yield a user to choose one system or another.

6.2 Case 2

The owner of a rural farm in Malpica de Bergantinos (Latitude=43.1°) in Galicia/Spain wants to take advantage of the abundant wind existing in the region to produce electricity. By looking into his electricity bills it is inferred that his yearly electric energy consumption is 4350 [kWh]. The details of the house are exposed in Table 6.10 while Figure 6-7 shows the mean annual consumption in the farm. Therefore, it is needed to select the best wind turbine generator and battery combination to take the best advantage of the initial investment.

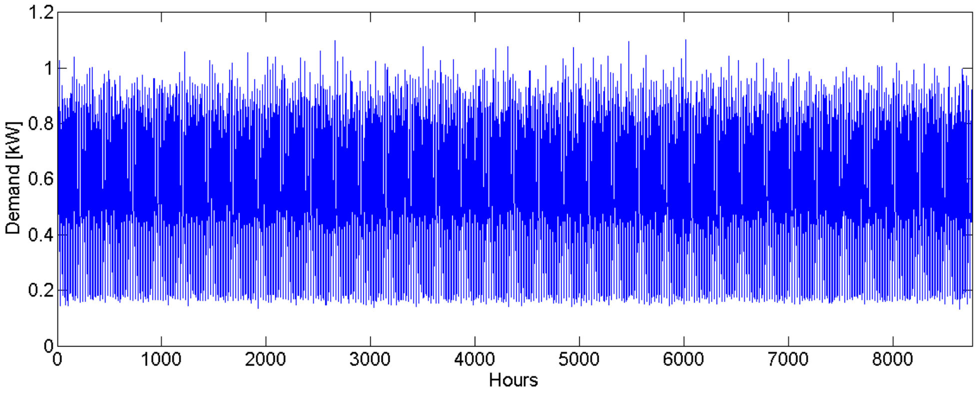


Figure 6-7: Mean yearly demand profile for Malpica's rural farm.

Considering the existing power demand for the rural farm, three commercial wind turbine generation systems with two distinct batteries will be analyzed so that the best configuration is selected. The parameters considered for the Wind Turbine Generation

Building Type	**N^o of occupants**	**Not Occupied Period**	**Air Conditioning**	**Access Tariff**	**Hired Power**
Rural house	4	No	No	2.0 A	4.6 kW

Table 6.10: Building specifications for a simulation case in Malpica-Spain.

WT Parameters	**Units**	**WTGS 1**	**WTGS 2**	**WTGS 3**
N^o of Wind Turbines		1	1	2
N^o of Wind Turbines	u	1	1	2
Rated power	W	3000	1500	1000
Rated speed	m/s	12	12	13
Cut-in speed	m/s	3.5	3.5	3
Cut-out speed	m/s	14	14	15
Scale factor	m/s	8.9	8.9	8.9
Shape factor	m/s	1.68	1.68	1.68
$MTTF$	Hours	7500	7500	7500
$MTTR$	Hours	100	100	100

Table 6.11: Wind turbine generators parameters for Malpica's rural farm.

Systems (WTGS) and the batteries are detailed in Tables 6.11 and 6.12 respectively. Table 6.13 exposes the different scenarios to be considered. The mean annual output power obtained for each WTGS is shown in Figure 6-9 while Figure 6-8 exposes the mean yearly energy interchange with the grid for the different scenarios.

6.2.1 Reliability Results

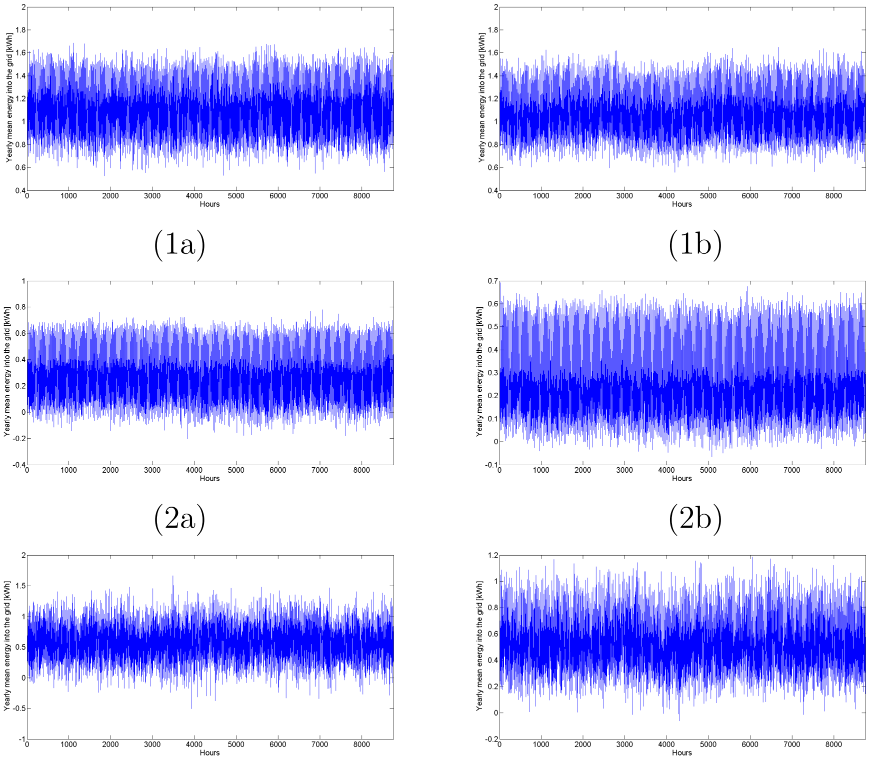
By looking to Figure 6-10 and Table 6.14, it can be observed that the use of the battery with bigger capacity (Scenarios 1b, 2b and 3b) significantly improves the reliability indices. Despite the fact that Scenario 3b is not the one that has the biggest amount of nominal power installed, it is the one which presents the best reliability results.

Battery Parameters	**Units**	**Value**	
		Battery 1	**Battery 2**
Max. Charge Power	W	400	800
Max. Discharge Power	W	400	800
Max. Energy	Wh	1280	2580
Min. Energy Power	Wh	400	800
Cost	€	1300	1500
$MTTF$	Hours	8500	
$MTTR$	Hours	50	

Table 6.12: Batteries' parameters for self consumption for Malpica's rural farm.

	Battery 1	**Battery 2**
WTGS 1	Scenario 1a	Scenario 1b
WTGS 2	Scenario 2a	Scenario 2b
WTGS 3	Scenario 3a	Scenario 3b

Table 6.13: Scenarios for Malpica's rural farm.

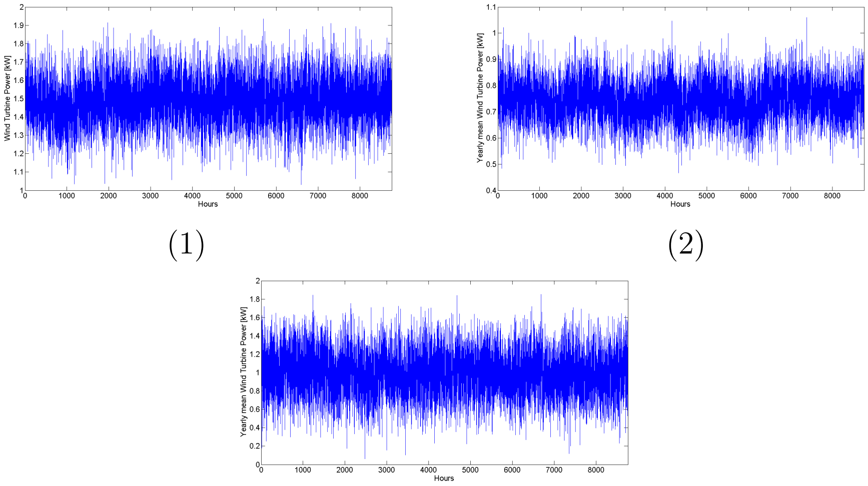


(1a) (1b)

(2a) (2b)

(3a) (3b)

Figure 6-8: Mean Energy into the grid for the different scenarios for Malpica's rural farm.



(1) (2)

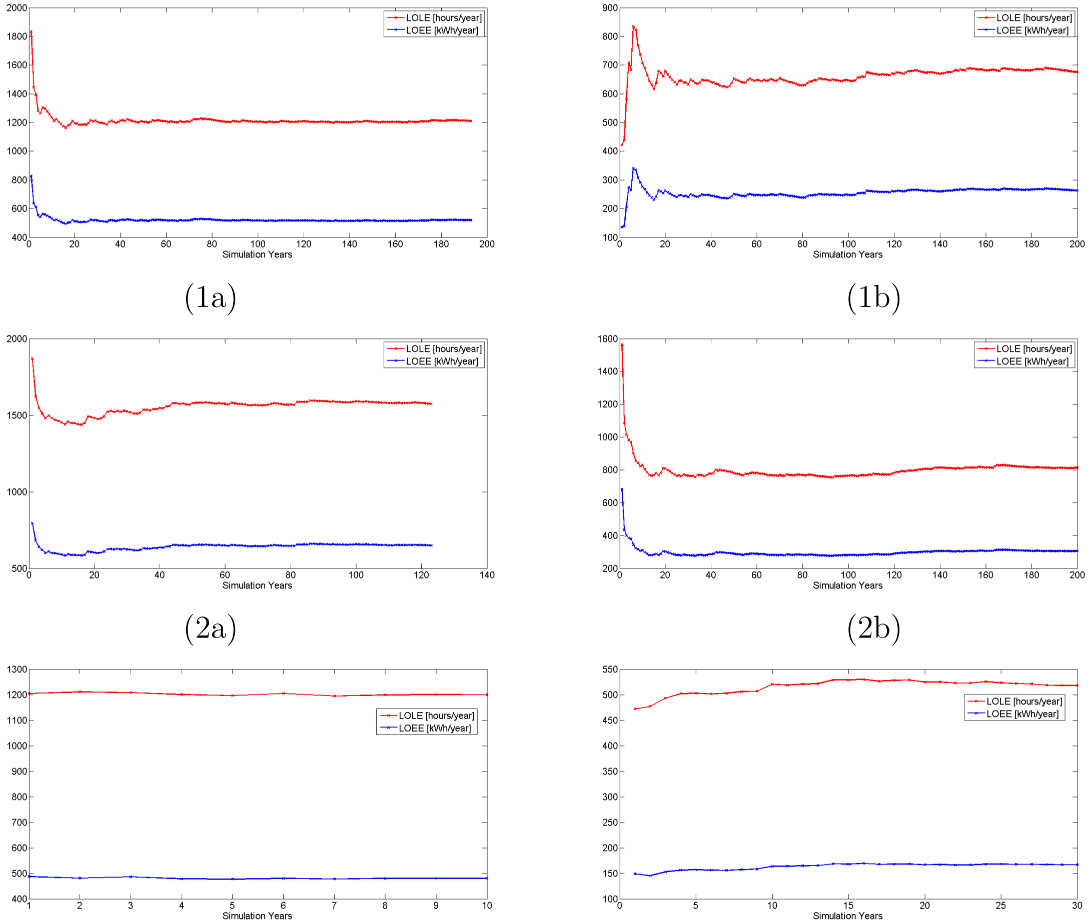
(3)

Figure 6-9: Output Power of the different WTGS for Malpica's rural farm.

Scenario	LOEE [kWh/year]	LOLE [hours/year]	MIOP [p.u./year]	ILSE [kW/occurrence/year]	DEP [p.u./year]
1a	519	1210	0.8619	0.4251	0.8808
1b	263	676	0.9228	0.3687	0.9396
2a	649	1574	0.8203	0.4098	0.8508
2b	305	814	0.9071	0.3606	0.9298
3a	480	1200	0.8631	0.4000	0.8897
3b	167	518	0.9409	0.3214	0.9617

Table 6.14: Reliability indices in the last year of simulation for the different scenarios for Malpica's rural farm.

As the wind speed behavior is more stochastic than the solar radiation pattern, the accepted coefficient of variation value for this Study Case was 2% which is bigger than the one used for the Study Case 1 (0.3%). Nevertheless, as Figure 6-11 shows for Scenarios 1b and 2b, after simulating up to a predefined simulation years limit (200); the LOEE's coefficient of variation was only a little lower than 4% which was still considered as acceptable.

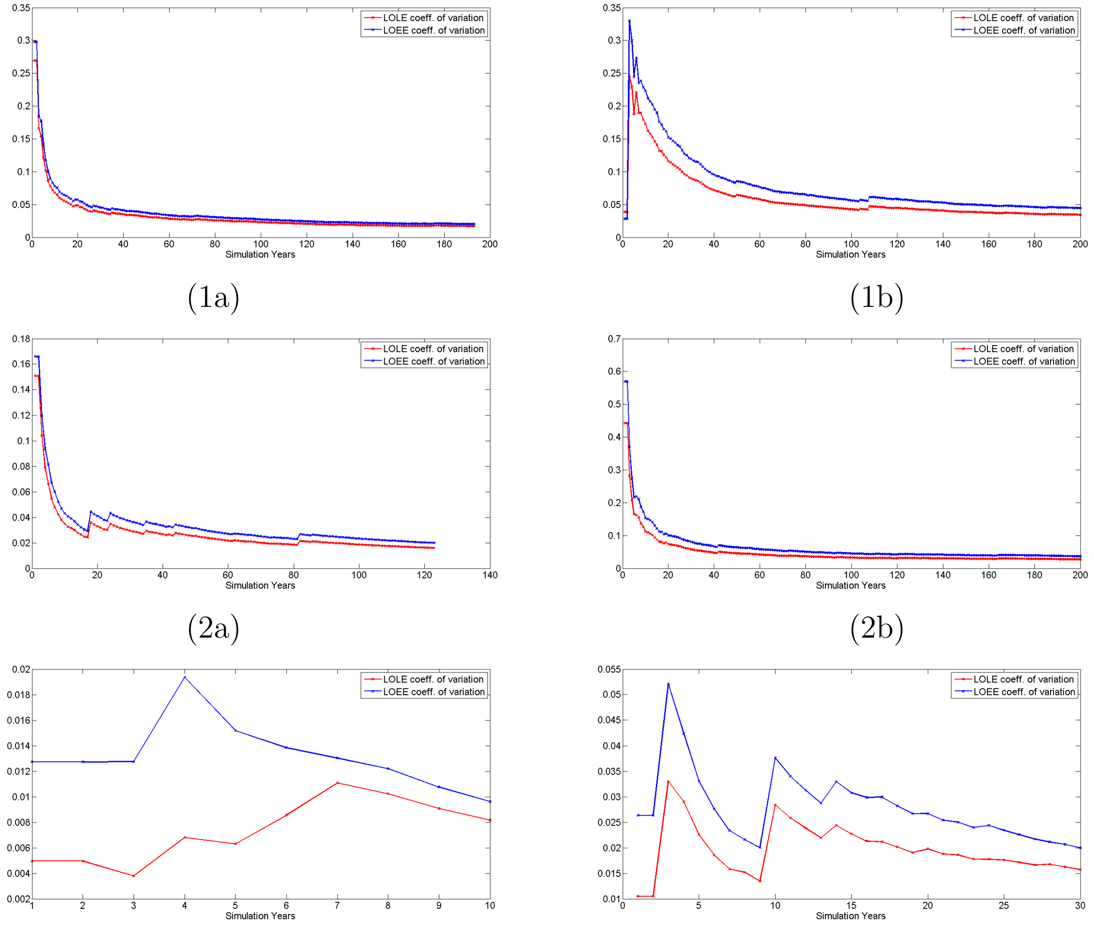


(1a) (1b)

(2a) (2b)

(3a) (3b)

Figure 6-10: LOEE and LOLE indices for the different scenarios for Malpica's rural farm.



(1a) (1b)

(2a) (2b)

(3a) (3b)

Figure 6-11: LOEE and LOLE coefficients of variation for the different scenarios for Malpica's rural farm.

Scenario	**Wind Turbine** [€]	**Battery** [€]	**Installation Costs [€]**	**Maintenance Costs [€]**	**Total Investment [€]**
1a	9495	1300	4857.75	1079.5	16732.25
1b	9495	1500	4947.75	1099.5	17042.25
2a	7495	1300	3957.75	879.5	13632.25
2b	7495	1500	4047.75	899.5	13942.25
3a	6995	1300	3732.75	829.5	12857.25
3b	6995	1500	3822.75	849.5	13167.25

Table 6.15: Detail of the year-one investment for each scenario for Malpica's rural farm.

6.2.2 Economic Results

Using the same economic assumptions as in the Study Case 1 (considering the figures in Tables 6.6 and 6.8), and employing investment costs as in Table 6.15; the economic results obtained for this Study Case are exposed in Table 6.16. Scenarios 2a and 2b are totally discarded for having the biggest payback periods. Scenario 1a, which is the one with the biggest investment, presents the best payback period (22 years). However, it would be very advisable to consider Scenario 3a as its payback period (24 years) is still good bearing in mind the fact that it is the case having the lowest initial investment.

6.3 Case 3

This case will study the reliability and economic aspects of installing a distributed generation system, mainly based on renewable energies, in a twenty-dwelling residential building in Madrid/Spain. The characteristics of the dwellings that compose the building are given in Table 6.17, while Figure 6-12 plots the demand profile.

The promoter of the project has decided to install up to 20kW of distributed generation, but he needs to clear up which solution is the most balanced within reliability and economic concerns. Hence, three different scenarios with different energy sources will be compared to determine which generation system is the most suitable for this application. These scenarios are the following:

The DG system in the first scenario, consists of four PV kits of 5 kW each, composed by twenty panels as Panel 1 in Table 6.2, with the difference now that the cost per kit is 8500€. On the other hand, Table 6.19 details the characteristics of the fuel cell that will

	Scenario 1a	Scenario 1b	Scenario 2a	Scenario 2b	Scenario 3a	Scenario 3b
AVG Annual Energy Injected [kWh]	10071	9697	2781	2451	5213	4776
AVG Annual Energy Purchased [kWh]	0	0	19	1	15	0
AVG Annual Incomes [€]	1111.30	1087.80	375.42	348.48	594.50	562.97
AVG Annual Expenses [€]	248.87	252.98	306.23	320.80	258.37	265.87
Payback Period [Years] Energy Injected [kWh]	22	23	34	37	24	26
Self-Consump. Annual Bill +Maintenance Costs [€]	224.06	271.57	812.67	874.02	497.10	555.94
Conventional Annual Bill [€]	973.37	989.47	1190.70	1254.22	1005.9	1039.8

Table 6.16: Economic results for the different scenarios for Malpica's rural farm.

Dwellinf	Number of Occupants	Not Occupied Period	Air Conditioning	Acces Tariff	Hired Power [kW]
1	1	9:00 to 18:00	Yes	2.0 DA	3.45
2	1	14:00 to 19:00	No	2.0 DA	3.45
3	1	09:00 to 18:00	No	2.0 DA	3.45
4	1	No	No	2.0 DA	3.45
5	2	9:00 to 18:00	Yes	2.0 DA	3.45
6	2	14:00 to 19:00	No	2.0 DA	3.45
7	2	09:00 to 18:00	No	2.0 DA	4.6
8	2	No	No	2.0 DA	4.6
9	3	9:00 to 18:00	Yes	2.0 DA	5.75
10	3	14:00 to 19:00	No	2.0 DA	5.75
11	3	09:00 to 18:00	No	2.0 DA	6.9
12	3	No	No	2.0 DA	6.9
13	4	9:00 to 18:00	Yes	2.0 DHA	8.05
14	4	14:00 to 19:00	No	2.0 DHA	8.05
15	4	09:00 to 18:00	No	2.0 DHA	8.05
16	4	No	No	2.0 DHA	8.05
17	5	9:00 to 18:00	Yes	2.0 DHA	9.2
18	5	14:00 to 19:00	No	2.0 DHA	9.2
19	5	09:00 to 18:00	No	2.0 DHA	9.2
20	5	No	No	2.0 DHA	9.2

Table 6.17: Characteristics of a residential building for DG integration in Madrid.

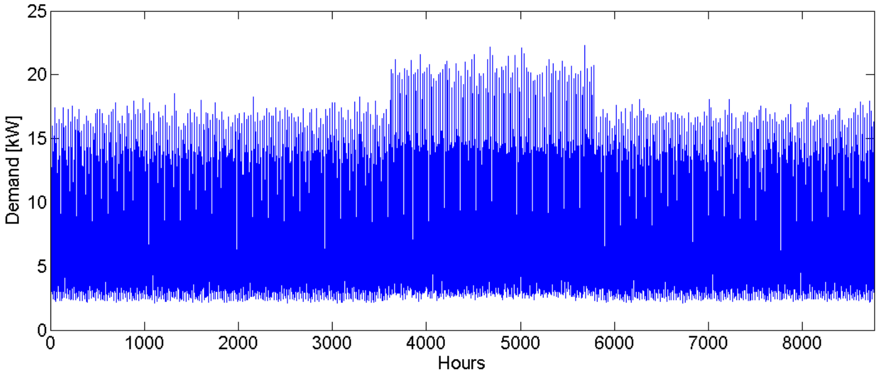


Figure 6-12: Demand profile of a residential building for DG integration in Madrid.

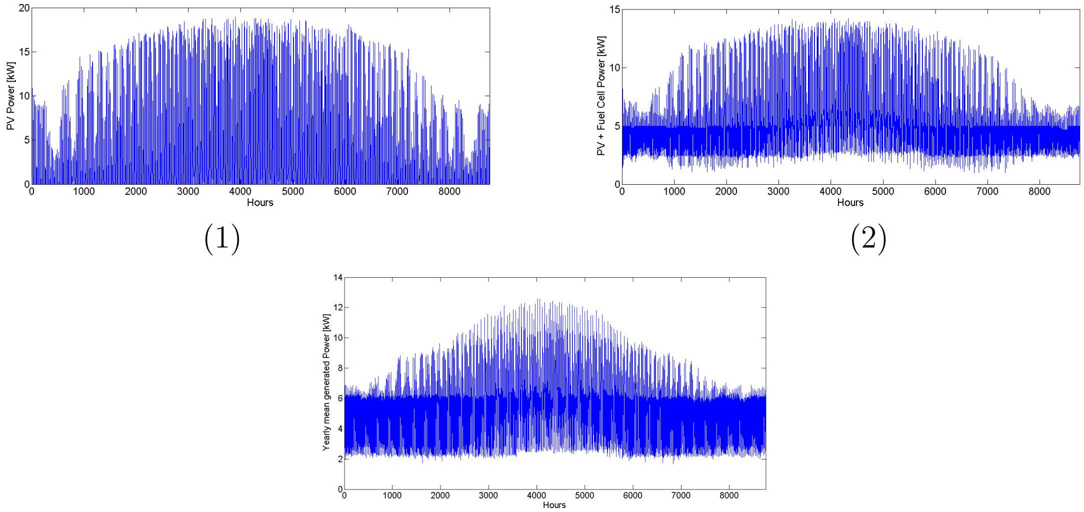
	Number of 5kW PV Kits	**Number of 5kW Fuel Cells**	**Number of 3kW WTGS**
Scenario 1	4	-	-
Scenario 2	3	1	-
Scenario 3	2	1	1

Table 6.18: Scenarios for Case Study 3

be used in Scenarios 2 and 3 while Table 6.11 provides the specifications of the 3-kW wind turbine employed for scenario 3. Figure 6-13 plots the mean power generation for each scenario. The parameters of the energy storage system are detailed on Table 6.20, while Figure 6-14 illustrates the mean energy state in the battery for each scenario, and the energy exchanges with the grid are plotted in Figure 6-15.

Fuel Cell Parameters	**Units**	**Value**
Rated Power	W	5000
Minimum Power	W	1000
Cost	€	16355
Operation Cost	€/kWh	0.08
MTTF	Hours	7500
MTTF	Hours	100

Table 6.19: Fuel cell parameters for a DG system in a residential building in Madrid.



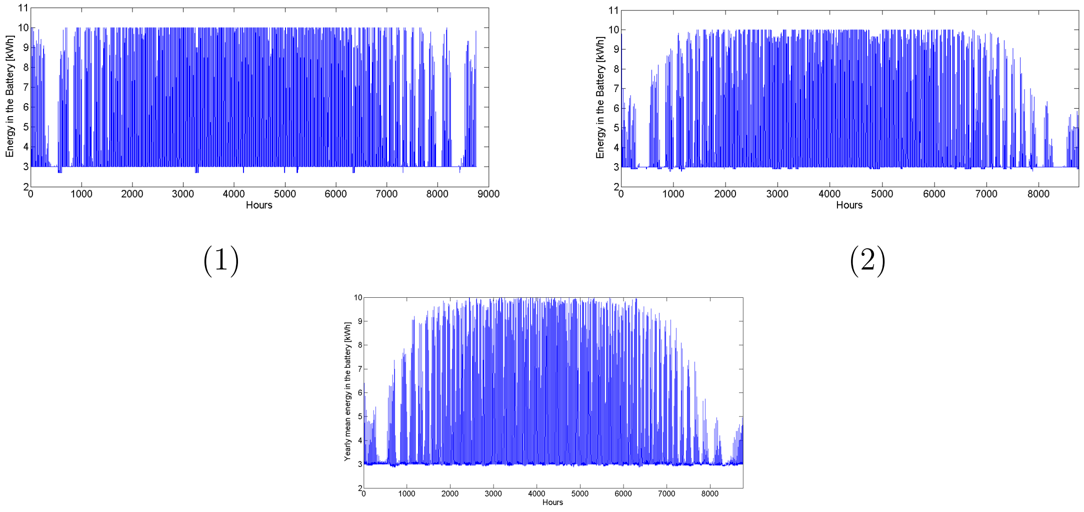
(1) (2)

(3)

Figure 6-13: Power generation for each scenario.

Battery Parameters	**Units**	**Value**
Max. Charge Power	W	3000
Max. Discharge Power	W	3000
Max. Energy	Wh	10000
Min. Energy Power	Wh	3000
Cost	€	4000
$MTTF$	Hours	8500
$MTTR$	Hours	50

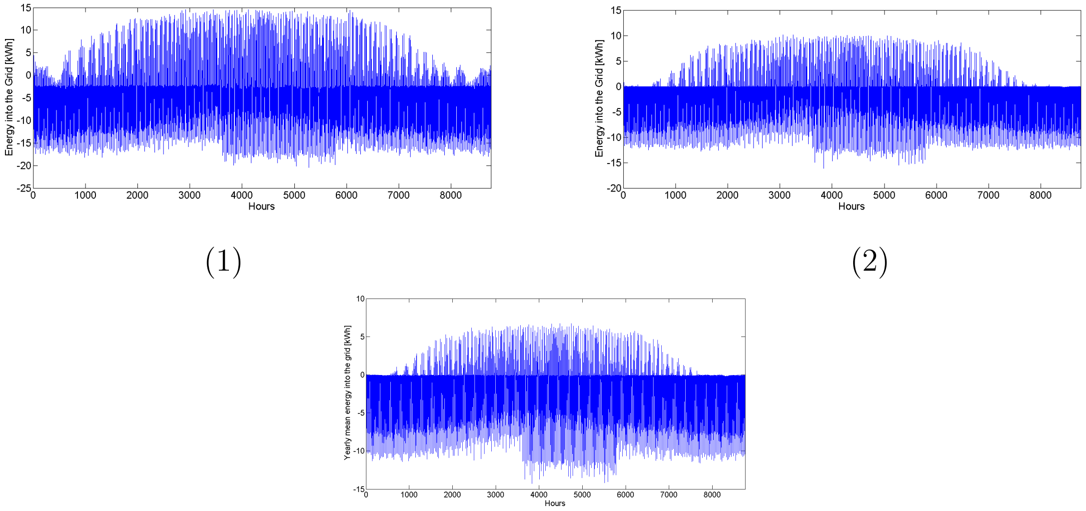
Table 6.20: Battery parameters for a DG system in a residential building in Madrid.



(1) (2)

(3)

Figure 6-14: Battery energy flow for DG integration in a residential building in Madrid.



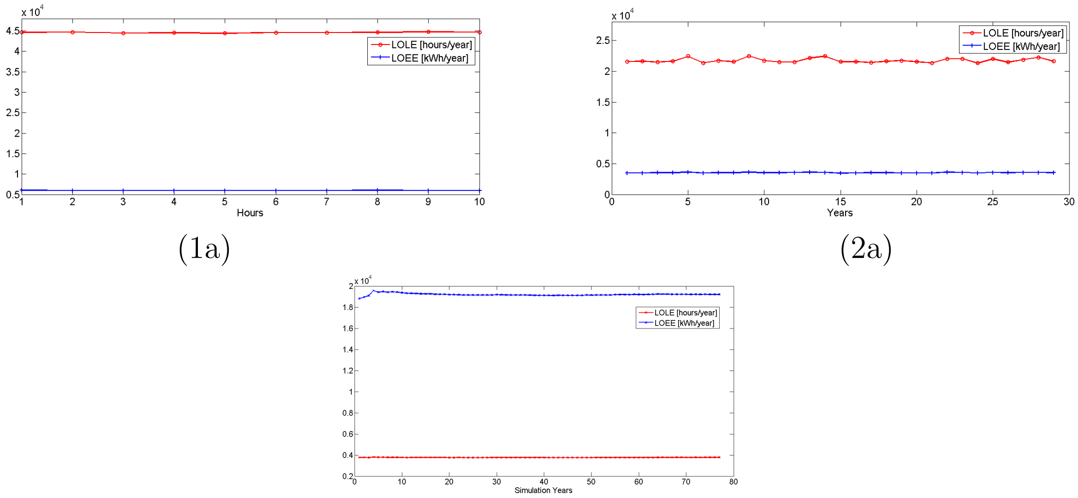
(1) (2)

(3)

Figure 6-15: Grid energy flow for DG integration in a residential building in Madrid.

6.3.1 Reliability Results

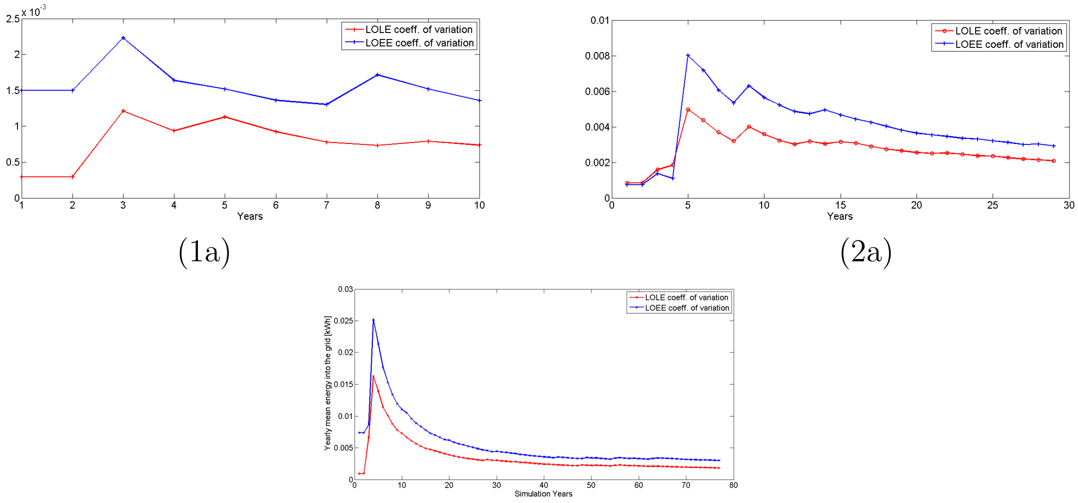
Figure 6-16 plots the behavior of the LOEE and LOLE indices meanwhile Figure 6-17 plots the evolution of the coefficients of variation for these indices for each scenario. A tolerance equal to 0.3% was used to determine if the system achieved convergence.



(1a) (2a)

(3)

Figure 6-16: LOEE and LOLE indices for DG integration in a residential building in Madrid.



(1a) (2a)

(3)

Figure 6-17: Coefficients of variation of LOEE and LOLE for DG integration in a residential building in Madrid.

Scenario	**LOEE [kWh/year]**	**LOLE [hours/year]**	**MIOP [p.u./year]**	**ISLE [kW/occurrence/year]**	**DEP [p.u./year]**
1	44679	5997	0.3154	7.4501	0.2947
2	21623	3540	0.5959	6.1483	0.6564
3	19200	3773	0.5693	5.0987	0.6969

Table 6.21: Reliability indices in the last year of simulation for the residential building in Madrid.

	Scenario 1	**Scenario 2**	**Scenario 3**
AVG Annual Energy Injected [kWh]	14388	8086	4181
AVG Annual Energy Purchased [kWh]	44567	21749	19170
AVG Annual Incomes [€]	791.67	488.48	399.33
AVG Annual Expenses [€]	3084.20	2955.25	2860.80
Payback Period [Years]	8	14	13
Self Consumption Annual Bill Maintenance Costs [€]	6100.5	9478.60	8866.59
Conventional Annual Bill Cost [€]	13349	14657	14427.82

Table 6.22: Economic results for DG integration in a residential building in Madrid.

6.3.2 Economic Results

Similar economic assumptions as the one used for the previous cases have been taken into account. To obtain the economic results for self consumption, it has been considered that the user has hired the access tariff 3.0A with 20 kW of power. Table 6.23 details the year-one investment for each scenario. The installation cost is assumed to be the 45 % of the total cost of the equipment, while the annual maintenance costs have been set to 10%. The variable costs subjected to inflation are the same as those indicated in Table 6.8.

Scenarios 2 and 3 present the best reliability results (See Table 6.21) as a consequence of having the biggest investments (See Table 6.23). This fact, however, provokes the payback period to significantly increase (See Table 6.22). Therefore, in monetary terms, it is advisable to install the distributed generation configuration from Scenario 1 for having an attractive payback period of 8 years with a reduced initial investment.

Scenario	**PV Kit**	**Fuel Cell**	**Wind Turb.**	**Battery**	**Installation**	**Maintenance**	**Total Investment**
	[€]	[€]	[€]	[€]	[€]	[€]	[€]
1	8500x4	-	-	4000	17100	3800	58900
2	8500x3	16355	-	4000	20634.75	4585.5	71075.25
3	8500x2	16355	9495	4000	21802.5	4685	73337.5

Table 6.23: Detail of initial investment for each scenario for DG integration in a residential building in Madrid.

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