# Power Demand Modeling and Reliability Analysis for Residential Nearly-Zero Energy Buildings

by

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Submitted to the Department of Electrical Engineering, Electronics,
Computers and Systems
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## Abstract

This thesis develops a power reliability-based methodology to be used in a computer tool that assesses the selection of the most convenient power distributed-generation system in residential buildings. To do this a building power demand model is implemented by considering the dwellings' energy consumption, the number of users per dwelling, the non-occupied periods of the inhabitants and the load's usage pattern between others aspects. Some study cases are carried out under different scenarios to validate the proposed methodology by studying key reliability indexes that provide relevant information to infer the feasibility of the selected distributed generation. The attained results were very promising as they revealed for every case which were the most suitable power generation configurations to be employed.

Thesis Supervisor: Pablo Arboleya Arboleya
Title: Associate Professor

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I want to thank all my family and friends, specially my wife and daughter, Lorena and Giuliana; for constantly encourage me to know and to live from higher regions of consciousness. Thank you for Being who You Are.

Every step given in my life is dedicated to the One Infinite Creator who lovely inspires me to make known the unknown.

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# Chapter 1

# Introduction

## 1.1 Introduction

Buildings account for around 40% of total energy consumption and 36% of CO2 emissions in Europe [1]. 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 [16].

The European Union Directive 2010/31/EU [40] 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 [2]. 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 necessary to create technical methodologies and 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 power reliability conditions. Therefore, it is crucial 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 accomplish the mentioned objective, it is crucial to develop a suitable power demand model for buildings to be later contrasted with their power generation. By doing this, it can be then performed relevant power reliability studies which will play a major role when assessing the selection of the best distributed generation arrangement. These mentioned analyses are the major goals of this master thesis.

## 1.2 Objectives

The main goals of this master thesis are:

- Analyze criteria and concepts regarding to nearly Zero-Energy Buildings and microgrid's power reliability.
- Study the state of the art for computer tools that assess the selection of distributed generation systems.
- Study power demand models for residential buildings.
- Development of a power demand model suitable to be used for power reliability analyses.
- Perform a Generating System Adequacy Assessment to evaluate the ability of the system generating capacity to satisfy the total system load.
- Validate under different scenarios the proposed methodology to perform power reliability studies for distributed generation systems in residential buildings.

### 1.2.1 Master Thesis Outline

This master thesis is divided into six chapters, with the following structure:
In Chapter 1, an introduction concerning the main objectives of the thesis is presented.
Chapter 2 presents the state of the art regarding the assessment in the selection of distributed generation systems. Firstly, the nearly Zero-Energy Buildings concept is introduced. Then, power reliability criteria to perform the analysis is explained. To conclude, existing computer tools used for the selection of renewable-distributed power generation systems is discussed.
In Chapter 3, a power demand model for residential buildings is developed by considering the dwelling's energy consumption, the number of users per dwelling, the non-occupied periods of the inhabitants and the load's usage pattern between others

aspects.

Chapter 4 focuses in the generating system adequacy assessment to perform the microgrid reliability analysis. A System State Duration Sampling Methodology is proposed.

In Chapter 5 study cases are carried out under different scenarios to validate the proposed methodology by studying key reliability indices that provide relevant information to infer the feasibility of the selected distributed generation.

Finally, Chapter 6 presents conclusions and future developments.

# Chapter 2

# State of the Art

## 2.1 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 [38] (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) [37] and its recast (Directive 2010/31/EU) [39]. 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 [50] 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 [47] and [32], 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 [11]:

- 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).

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 [31]. However, as indicated by Laustsen [25], 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 [10].

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 and power reliability concerns.

## 2.2 Power Reliability

Power system reliability is defined as the overall ability of a power system to perform its function [5]. It is composed of two main aspects which are system security and system adequacy [4]. Security relates to the ability of the system to respond to dynamic or transient disturbances arising within the system like the abrupt loss of major generation or/and transmission facilities which can lead to dynamic, transient, or voltage instability of the system. On the other hand, adequacy relates to the existence of sufficient facilities within the system to satisfy the consumer load demand or system operational constraints. These includes the facilities necessary to generate, transport and distribute energy to the consumer load points. Therefore, adequacy is associated with static conditions which do not include system dynamic and transient disturbances.

It is important to mention that most of the probabilistic techniques presently available for reliability evaluation are in the domain of adequacy assessment. The ability to assess security is therefore very limited due to the complexity associated with modeling the system in this case [8]. This is why most of the indices currently used are adequacy indices and not overall reliability indices.

### 2.2.1 Hierarchical Levels

The basic techniques for adequacy assessment can be categorized in terms of their application to segments of a complete power system. These segments can be defined as the functional zones of generation, transmission, and distribution [4]. Figure 2-1 shows how these segments are combined to form the different hierarchical levels which are to be used in the adequacy assessment. Hierarchical Level 1 (HL1) in only concerned with the generation facilities. Hierarchical Level 2 (HL2) includes both generation and transmission facilities while HL3 includes all three functional zones in an assessment of consumer load point adequacy.

In the present project we will focus in the adequacy assessment at the Hierarchical Level 1 as it is the one that satisfies the study's needs. In a generation system (HL1) study, the total system generation is examined to determine its adequacy to meet the total system load requirements. The basic concern is to estimate the generating capacity required to satisfy the system demand and to have sufficient capacity to perform corrective and preventive maintenance on the generating facilities. The transmission system and its ability to move the generated energy to the consumer load points is ignored in generating system adequacy assessment. The basic modeling approach [7] for an HLl study is shown in Figure 2-2.

Reliability studies, by the nature of the process that they represent, have a significant probabilistic content. There are two approaches to the solution of this probabilistic phenomenon: analytical and simulation methods. Analytical techniques [6] represent the system by analytical models and evaluate the indices from these models using mathematical solutions. Simulation methods, however, estimate the indices by simulating the actual process and random behavior of the system. This method,

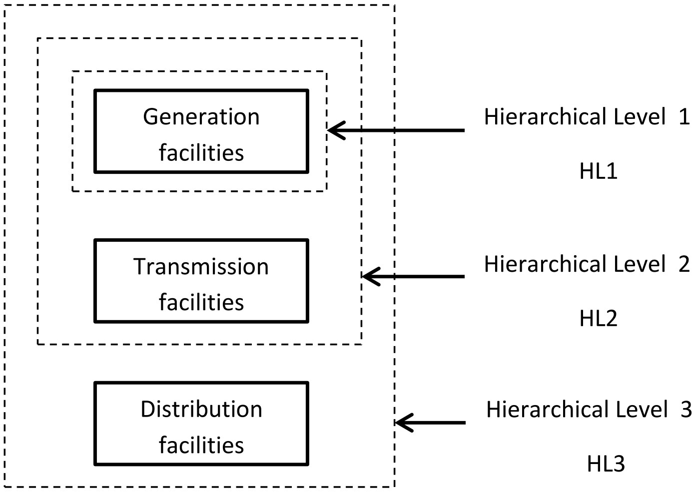


Figure 2-1: Hierarchical levels [4].

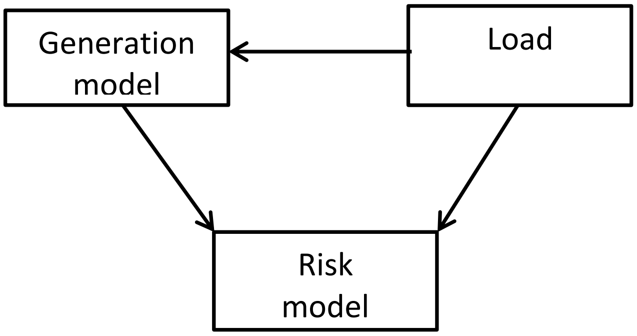


Figure 2-2: Conceptual tasks for HL1 evaluation [4].

therefore, treats the problem as a series of experiments. There are merits and demerits in both methods [14], nevertheless, when complex operating conditions are involved and/or the number of severe events is relatively large, Monte Carlo methods are often preferable [4]. This is the main reason why we will use the Monte Carlo criteria along this master thesis. Furthermore, Monte Carlo methods are between the most used simulation techniques.

## 2.3 Computer tools for assessing the selection of distributed generation systems

Nowadays, there are some tools that assess the selection of distributed generation systems with special focus in renewable energies. The ones most representative for being developed in renowned energy-planning institutions , for being highly cited in the technical literature and for being license-free are:

### 2.3.1 Web-Opt

The Distributed Energy Resources Web Optimization Service (Web-Opt) is an optimization tool to minimize the cost of operating on-site generation and combined heat and power (CHP) systems, either for individual customer sites or a microgrid, based on a one-hour time step [22]. WebOpt is based on the Distributed Energy Resources Customer Adoption Model (DER-CAM), a mixed integer linear programming (MILP) tool, developed at Berkeley Lab which is managed by the University of California (USA). Web-Opt assumes that the customer desires to install distributed generation to minimize the cost of energy consumed on site. Consequently, its purpose is to determine the technologies and capacity the customer is likely to install and to predict when the customer will be self-generating electricity or transacting with the power grid, and likewise when purchasing fuel or using recovered heat. Table 2.1 summarizes Web-Opt's inputs, outputs and assumptions.

### 2.3.2 HOMER

The Hybrid Optimization Model for Electric Renewables (HOMER) software was developed at the National Renewable Energy Laboratory (NREL) in the USA. It is a tool for designing and analyzing hybrid power systems, which can contain a variety of technologies. For either grid-tied or islanded-mode, HOMER helps determine how intermittent resources, such as wind and solar, can be optimally integrated into microgrids. The economic feasibility of a hybrid energy system and optimization of the

Table 2.1: Wep-Opt features, [26]

| **Inputs** | **Outputs** | **Assumptions** |
|---|---|---|
| Load Profiles: space heat, hot water, gas only, cooling, and electricity only. | Optimal combination of technologies and their capacities. | Decisions based on direct economic criteria. |
| Electricity and natural gas tariffs and rates. | Optimal operation schedule of the technologies. | Reliability and power quality benefits are not directly taken into account. |
| Capital plus operation and maintenance technology costs. | Cost data: total annual energy costs, upfront and annualized technology cost, utility electricity costs. | No decrease in efficiency of equipment over its lifetime. Also, start-up and other constraints are not included. |
| Characteristics of technologies: lifetime, efficiency, recoverable heat. | Other: total energy, emissions, utility electricity and natural gas consumption, specific technology production. | Economies of scale in Oper. and Maint. costs for multiple units of the same technology are not directly taken into account. |

system design are the ultimate goals in HOMER. It helps to mitigate the financial risk of a hybrid power system at the design process [23]. The model requires inputs such as technology options, component costs, and resource availability. The inputs are used to simulate different system configurations, and create a list of feasible configurations sorted by net present cost (NPC). HOMER is an hourly simulation model; it models system components, available energy resources, and loads on an hourly basis for one year. Energy flows and costs are assumed to be constant over any given hour. The user can enter in hourly data but HOMER can also synthesize hourly load resource data from monthly averages as well [26]. Table 2.2 exposes HOMER features.

HOMER simulates the operation of a system by making energy balance calculations for each of the 8760 hours in a year. For each hour, HOMER compares the electric and thermal load in the hour to the energy that the system can supply in that hour. For systems that include batteries or fuel-powered generators, HOMER also decides for each hour how to operate the generators and whether to charge or

Table 2.2: HOMER features, [26]

| **Inputs** | **Outputs** | **Assumptions** |
|---|---|---|
| Load profiles: electrical and thermal. | Optimal combination of technologies and capacities. | Decisions based on economic criteria |
| Component quantities: kW ratings, thermal ratings, and fuel ratings. | Sensitivity analysis, thermal output, and fuel consumption. | Energy flow is constant over each hour of the year. |
| Component costs: cost per kW, replacement cost, and operation and maintenance cost. | Net present cost analysis. | Analysis done over a year. |
| Characteristics of technologies: lifetime, efficiency, recoverable heat. | Effect of net present cost calculation. | It repeats the optimization process for each value of the input so that the effect of changes can be examined in the value on the results. |
| Energy resources: solar, diesel, natural gas, wind, hydro. | Total energy production. | It considers the system to be feasible if it can adequately serve the electric and thermal loads and satisfy any other constraints imposed by the user. |

discharge the batteries. If the system meets the load for the entire year, HOMER estimates the life cycle cost of the system, accounting for the capital, replacement, operation and maintenance, fuel and interest costs [19].

### 2.3.3 HYBRID2

Hybrid2 is a combined probabilistic/time series computer model developed at the U.S. National Renewable Energy Laboratory. It assists designers in sizing hybrid power systems and in selecting operating options on the basis of overall system performance and economics when site specific conditions and load profiles are known. Hybrid2 allows the user to consider a number of system configurations and operating strategies to optimize the system design [34].

The simulation models for hybrid power systems can be classified into two broad categories: logistical models and dynamic models [30]. Logistical models are used primarily for long-term performance predictions, for component sizing, and for providing input to economic analyses. Dynamic models are used primarily for components design, assessment of system stability, and determination of power quality. Hybrid2 is a logistical model, since it allows the user to determine long-term system performance while taking into consideration the effect of the short-term variability of the renewable resources. Hybrid2 is based on a combined time series and statistical approach. More specifically, Hybrid2 uses a time series approach to account for load and resource variations over intervals typically ranging from 10 minutes to one hour. Shorter term fluctuations within those intervals are dealt with by means of statistical techniques [34]. Table 2.3 exposes HYBRID2 main characteristics.

### 2.3.4 RETScreen

RETScreen is an Excel-based standardized renewable energy project analysis software developed by the Government of Canada. RETScreen is a decision-support tool designed to help decision makers and energy professionals to evaluate the financial viability of renewable energy, energy efficiency and cogeneration projects [12]. RETScreen models both new and conventional technologies, allowing for comparisons between technology options. The software can be used to evaluate benefits from both clean energy production from power generation projects and savings through energy efficiency projects, accounting for project costs, emission reductions, and financial risk.

This tool provides a common platform for both decision-support and capacity-building purposes. RETScreen can be used to evaluate the energy production, life-cycle costs and greenhouse gas emissions reduction for various renewable energy technologies. It is dedicated to the preparation of pre-feasibility studies without considering hybrid energy systems containing simultaneously renewable and conventional resources. Indeed, RETScreen consider simpler power generation models. For exam-

Table 2.3: HYBRID2 features

| **Inputs** | **Outputs** | **Assumptions** |
|---|---|---|
| Loads: primary, deferrable, optional and heating load. | Performance summary files: summary of the cumulative energy flows and fuel consumption during the simulation run. | Decisions based mainly in technical criteria |
| Site/resource: site parameters as well as time series data of wind, solar radiation and ambient temperature. | Economics summary file: net present value of total costs, levelized cost of energy, simple payback period, discounted payback period, internal rate of return, yearly cash flows, etc. | The dispatch options are based on decisions relating to how batteries and diesels will operate if included in the power system. |
| Power system topology and component quantities: Three-bus AC or single-bus DC grid. Power ratings and technical characteristics | The system variables include the power in every load,in each generator, into storage, conversion losses, the unmet load and the energy balance. | It does not consider optimization and sensitivity analysis modules. |
| Base case: The user can compare the demand being supplied by a diesel-only system against a renewable topology. | It simulates some important technical constraints, including bus voltage levels, intra-hour performance of components and complex diesel generator dispatch strategies. | It assumes a linear relationship between diesel generator set load and fuel consumption. |
| Parameters related to component costs and economic performance | It provides detailed dispatching results. | It considers that the wind speed, wind power, and load are all normally distributed over the time step |

Table 2.4: RETScreen features

| **Inputs** | **Outputs** | **Assumptions** |
|---|---|---|
| Site conditions: project location, latitude of project location, annual solar radiation (tilted surface), and annual average temperature. | Annual energy balance: renewable energy delivered, net greenhouse gas emission reduction. | Decisions based in economic criteria. |
| System characteristics: application type, nominal PV array power, PV module type, nominal PV module efficiency, slope of PV array, inverter capacity and average inverter efficiency, battery data, load data. | Project costs and savings: total initial costs, incentives/grants, periodic costs and credits, total annual costs, total annual savings. | It does not include optimization and sensitivity analysis modules. |
| Financial parameters: initial project costs, annual costs, annual savings or income and parameters for the economic evaluation of the project. | Yearly cash flows: pretax, after-tax, and cumulative yearly cash flows. | It uses international product data from 1000 suppliers. It also uses international weather data from 1000 ground monitoring stations. |
| - | Financial feasibility: internal rate of return, net present value, yeartopositive cash flow, simple payback, and profitability index. | It cannot evaluate systems with more than one renewable technology (e.g. PV and wind energy). |

ple, it only requires 1 point of wind speed data versus 8760 points of data for most hourly simulation models (e.g. HOMER) [19]. Table 2.4 exposes RETScreen features.

### 2.3.5 iHoga

iHOGA (improved Hybrid Optimization by Genetic Algorithms) is a software developed in C++ for the simulation and optimization of Hybrid Renewable Systems for generation of electrical energy (DC and/or AC) and/or Hydrogen. It was developed by the Electric Engineering Department of the University of Zaragoza (Spain).

Optimization is achieved by minimizing total system costs throughout the entire useful lifespan, when those costs are referred to or updated for the initial investment

(Net Present Cost, NPC). Optimization is therefore financial (mono-objective). However, the model allows multi-objective optimization, where additional variables may also be minimized: equivalent CO2 emissions or unmet load (energy not served), as selected by the user. Since all of these variables (cost, emissions, or unmet load) are mutually counterproductive in many cases, more than one solution is offered by the software, when multi-objective optimization is sought. Some of these solutions show better performances when applied to emissions or unmet load, whereas other solutions are best suited for costs. iHOGA allows the option of selling AC electric energy to the grid (surplus unused energy), purchasing AC electric energy to the grid (unmet load by the standalone system) or selling surplus hydrogen, produced in the electrolyzer and stored in the tank. Simulations are also possible for feasibility studies of zero-consumption renewable energy facilities connected to the grid [35]. Table 2.5 numerates iHOGA characteristics.

Each and every year in the useful life-cycle of the system is assumed to be equivalent to any other year within the study period. Thus, the system is simulated for one full year, for each combination of control variables and components. The results obtained for a 1-year simulation will then be the same for the whole of the useful life-cycle of the facility. Throughout this 1-year period, iHoga collects the variables to define the system behavior. This is based on the features of all system components, on control variables, on levels of energy demand, and on weather reports. The system is assumed to be semi-stationary, so that all system variables remain unchanged through any given 1-hour period [15].

### 2.3.6 Analysis of existing Tools

While the existing tools are quite useful and detailed in certain applications, none of them has successfully included a transparent power demand model for residential buildings and they haven't either included power reliability analysis which is crucial to select the best distributed-generation option. Therefore, these improvements would represent a new addition to the field.

Table 2.5: iHOGA features

| **Inputs** | **Outputs** | **Assumptions** |
|---|---|---|
| Define loads: AC or DC loads consumption | Optimal combination of technologies and capacities. | The sale to the AC grid can be of any excess energy or not exceeding the energy purchased annually or monthly (Net metering of energy, annual or monthly, with or without hourly periods). |
| Component quantities: kW ratings, and fuel ratings. | Sensitivity analysis | Optimization is available for all the different elements combinations, as well as for system control strategies |
| Site conditions: Hourly Solar irradiation, wind speed, hydraulic flow, hydrogen availability. | Net present cost calculation. | iHOGA models (components, financial calculations...) are highly accurate and detailed |
| Control strategies | Probability Analysis if requested | Variables are kept the same for any given 1-hour period |

# Chapter 3

# Power Demand Modeling for Residential Buildings

In order to suitably match the power demand requirements with the power generated by local renewable energy systems, it is essential to identify the pattern of energy uses of dwelling or apartments to predict the load profile for domestic buildings.

Two distinct approaches have been identified in the literature to model the residential energy consumption: the top-down and bottom-up approaches. Each technique relies on different levels of input information, different calculation or simulation techniques, and provides results with different applicability.

The top-down approach [46] treats the residential sector as a mere energy consumer and does not distinguish energy consumption due to individual end-uses. Top-down models determine the effect on energy consumption due to ongoing long-term changes or transitions within the residential sector, primarily for the purpose of determining supply requirements. Variables which are commonly used by top-down models include macroeconomic indicators (gross domestic product (GDP), employment rates, and price indices), climatic conditions, housing construction/demolition rates, and estimates of appliance ownership and number of units in the residential sector. The main drawback existent in this approach is the lack of detail regarding the energy consumption of individual end-uses and eliminates the capability of identifying key areas for improvements for the reduction of energy consumption.

On the other hand, the bottom-up approach [46] includes all models which use input data from the end-consumer level. Common input data to bottom-up models include dwelling properties such as geometry, equipment and appliances, climate properties, as well as indoor temperatures, occupancy schedules and equipment use. This high level of detail is a strong point in favor of bottom-up modeling and gives it the chance to be used to size renewable generation systems. As energy consumption is calculated, the bottom-up approach has the capability of determining the total energy consumption of the residential sector without relying on historical data. All this advantages are the reason why the bottom-up method has been considered for this project.

## 3.1 Domestic Load Profile

Some methodologies have been developed to create domestic power load profiles [20], [53], [36]. They vary between each other in the level of detail employed and the resolution time. One of the most accurate and consistent methods is the one developed in [42], where a 1-minute resolution method that considers also an occupancy model was performed. However, the major drawback of the highly-detailed models is that they are computer-intensive and not feasible to be employed for obtaining long-term reliability analysis which is the objective of this project. These reliability indices will be necessary to justify or not the installation of a particular renewable-distributed generation system. For these reasons, the approach presented in References [53] and [54] have been considered for being a simplified and representative method suitable to accomplish the mentioned goal. A one-hour resolution will be used in the model as it is the minimum resolution time when forecasting the building power generation.

The daily load profile shape will vary from day to day and apartment to apartment depending in the following factors:

1. Daily energy consumption.
2. Period of the house unoccupied during the day.
3. Individual consumption profile for every appliance.

### 3.1.1 Daily energy consumption

The daily energy consumption per dwelling primarily depends in the number of occupants. For every country, there are representative statistical studies that detail the yearly average energy consumption per home for different number of occupants. For the Spanish case, the main organizations providing key information regarding the energy consumption levels and patterns for end-users are the IDAE (Instituto para la Diversificación y Ahorro de la Energía) [49] and REE (Red Eléctrica de España) [51].

It must be mentioned that for the present project, space heating and hot water services haven't been considered to be provided by electrical means as in the nearly-zero energy building concept this kind of loads are supplied by high-efficient thermal systems as geothermal or solar-thermal installations.

Table 3.1 shows the typical yearly energy consumption (excluding space heating, hot water services and air conditioning) for Spanish dwellings. Similarly, it also details the air conditioning energy employed on summer. The numeric values in the Table have been inferred from [13].

Once this yearly energy consumption $E_{year}$ is selected (from the corresponding column in Table 3.1 and depending in the number of occupants), we can split this energy into the different days of the year. However, as [24] details, the energy consumption significantly varies between the different days throughout the week, being

Table 3.1: Typical energy consumption for a single dwelling in Spain.

| **Number of occupants** | **Typical yearly energy consumption in a single dwelling in kWh excluding space heating and hot water services** | **Typical seasonal (summer) energy consumption in air conditioning for a single dwelling in kWh** |
|---|---|---|
| 1 | 1200 | 300 |
| 2 | 2400 | 450 |
| 3 | 3250 | 550 |
| 4 | 3850 | 600 |
| 5 | 4500 | 650 |

Saturday the one with the biggest consumption, followed by Sunday (0.98 times Saturday) and the different weekdays (0.96 times Saturday). Bearing this in mind, the amount of daily energy consumption for any of the 365 days of the year can be found by using Equations 3.1 to 3.3:

$$E_{year} = 261 \cdot E_{weekday} + 52 \cdot E_{saturday} + 52 \cdot E_{sunday} \tag{3.1}$$

$$E_{sunday} = 0.98 \cdot E_{saturday} \tag{3.2}$$

$$E_{weekday} = 0.96 \cdot E_{saturday} \tag{3.3}$$

Where:
$E_{year}$= Energy consumed in a year.
$E_{weekday}$= Energy consumed in a week day from monday to friday.
$E_{saturday}$= Energy consumed in saturday.
$E_{sunday}$= Energy consumed in sunday.

On the other hand, the amount of seasonal air conditioning energy used is only split throughout summer days (from the June 1st until the August 31st). This means that the daily energy use for air conditioning is obtained by equally dividing this seasonal consumption by 91 which is the number of summer days (Equation 3.4).

$$E_{daily\_ac} = E_{seasonal\_ac}/91 \tag{3.4}$$

### 3.1.2 Unoccupied period

The usage pattern is related to the number of occupants and the occupied period. For example, when people are not at home, most appliances will not be used. For the daily appliance electricity profile, at night while the occupants sleep, very little power is used (stand by and fridge-freezer), then may wake up and have breakfast, leave the house during the morning and then return around mid-day for lunch. In the evening, the meal is cooked, television is watched, washer machines and dryers are used, etc.

The four most common scenarios of household occupancy pattern in Spain have been considered:

**Scenario 1** Unoccupied period is from 09:00 to 14:00. The occupants in this type of household may have a part-time job in the morning session.

**Scenario 2** Unoccupied period is from 14:00 to 19:00. The occupants in this type of household may have a part-time job in the afternoon session.

**Scenario 3** Unoccupied period is from 09.00 to 18.00. The occupants in the house have full-time job.

**Scenario 4** The house is occupied all the time. The family of this type of household may have minor children to take care of or retired members.

For weekend days, all dwellings will be considered to be under Scenario 4, this is not having an unoccupied period as it happens in most homes worldwide.

### 3.1.3 Usage hours for the different loads

Depending on the number of occupants and the occupancy pattern, the number of usage hours for every appliance has to be selected as Table 3.2 shows for one occupant for example. The daily usage hours for minor loads or appliances (video games consoles, radios, watches, chargers, etc.) named as "Others" in the Table, are randomly selected between 3, 4 or 5 hours. Additionally, the air conditioning load only takes place during summer days. Note that there are similar tables with different usage hours for 2 up to 5 occupants per dwelling (See Appendix A section). The numerical values in these tables for the different number of occupants have been conjectured from [33].

A special consideration has been placed to get the number of usage hours for the lighting system as the natural sunlight hours $D$ (known as day length) significantly varies for different latitudes. This is why the Complete Benefits Model (CBM), explained in [18], has been implemented to firstly obtain the day length ($D$) in hours for every day in the year (See Equations 3.5 to 3.7) and then to get the required number of hours where artificial lighting will be requested for the occupants in that particular day. Figure 3-1 exposes the number of natural light hours and the selection of artificial light hours during a year for northern latitude equal to 40.4° (Madrid/Spain Latitude).

$$\sigma = 0.2163108 + 2 \cdot \tan^{-1}[0.9671396 \cdot \tan(0.00860(J - 186))] \tag{3.5}$$

$$\mu = \sin^{-1}[0.39795 \cdot \cos\sigma] \tag{3.6}$$

$$D = 24 - \frac{24}{\pi} \cdot \cos^{-1}\left[\frac{\sin\frac{0.8333 \cdot \pi}{180} + \sin\frac{L \cdot \pi}{180} \cdot sin\mu}{\cos\frac{L \cdot \pi}{180} \cdot \cos\mu}\right] \tag{3.7}$$

Where:

$J$= Day of the year.

$L$= Latitude in degrees (°), positive if northern and negative if southern.

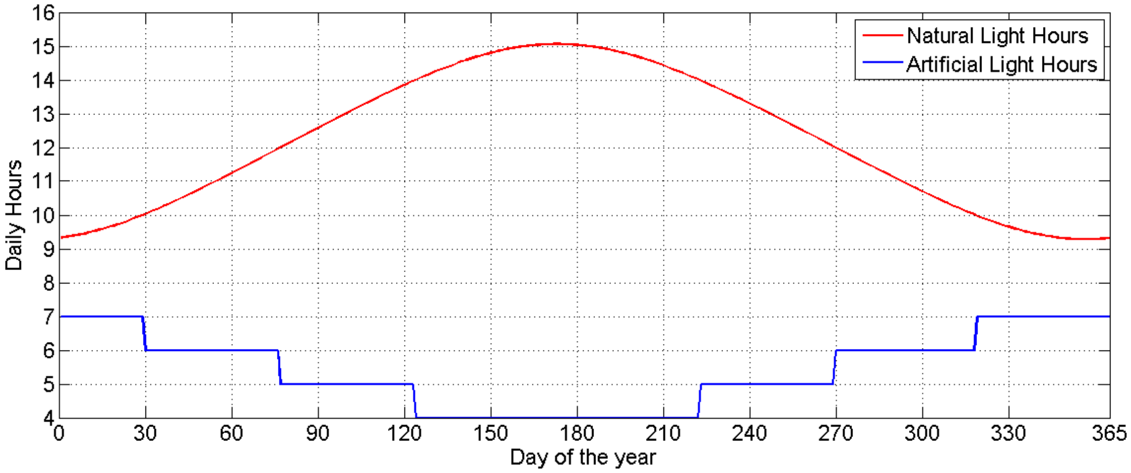


Figure 3-1: Artificial and Natural Light Hours throughout the year for $L$=43.53°.

Table 3.2: Usage hours for every load for one occupant.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Load** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **Cooker** | 3 | 3 | 2 | 3 |
| **Fridge** | 12 | 12 | 12 | 12 |
| **TV** | 6 | 6 | 4 | 8 |
| **Washer** | 1 | 1 | 1 | 1 |
| **Stand-by** | 24 | 24 | 24 | 24 |
| **Oven** | 1 | 1 | 1 | 1 |
| **PC** | 4 | 4 | 3 | 6 |
| **Dish Washer** | 1 | 1 | 1 | 2 |
| **Dryer** | 1 | 1 | 1 | 1 |
| **Others** | 3,4,5* | 3,4,5* | 2,3,4* | 4,5,6* |
| **Air conditioning** | 3** | 3** | 3** | 5** |

*Are randomly selected for every day

**Only during summer days

Table 3.3: Weightiness for the different hours of the day for the electric cooker.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Hour** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **1** | 0% | 0% | 0% | 0% |
| **2** | 0% | 0% | 0% | 0% |
| **3** | 0% | 0% | 0% | 0% |
| **4** | 0% | 0% | 0% | 0% |
| **5** | 0% | 0% | 0% | 0% |
| **6** | 0% | 0% | 0% | 0% |
| **7** | 7% | 7% | 12% | 2% |
| **8** | 17% | 17% | 52% | 5% |
| **9** | 7% | 7% | 12% | 17% |
| **10** | 0% | 1% | 0% | 5% |
| **11** | 0% | 1% | 0% | 3% |
| **13** | 0% | 7% | 0% | 3% |
| **13** | 0% | 17% | 0% | 3% |
| **14** | 0% | 7% | 0% | 5% |
| **15** | 7% | 0% | 0% | 5% |
| **16** | 7% | 0% | 0% | 5% |
| **17** | 17% | 0% | 0% | 15% |
| **18** | 1% | 0% | 0% | 2% |
| **19** | 1% | 0% | 4% | 2% |
| **20** | 1% | 0% | 4% | 2% |
| **21** | 17% | 17% | 22% | 16% |
| **22** | 7% | 7% | 12% | 5% |
| **23** | 4% | 4% | 3% | 1% |
| **24** | 1% | 1% | 1% | 1% |
| | 100% | 100% | 100% | 100% |

### 3.1.4 Consumption profile for the different loads

Now that the usage number of hours for every load has been acquired, the specific hours of the day where those loads are being used have to be settled. This is done by performing a weighted random selection between the 24 hours of the day, where every hour presents a specific heaviness. This hourly usage weightiness for an entire day is exposed in Table 3.3 for the electric cooker for example. There we can check that depending on the unoccupied period, the hours which are more common to be used for cooking have significant higher percentages than those hours which are less common to be employed for this activity. Every appliance/load presents its own hourly weighting percentages according to its pattern of use for the different unoccupied periods. The only exceptions to this rule are the Freezer and the Stand-by loads. For the Freezer, as it generally happens in a real one, it will be considered to alternately demand energy during one hour, not to request the following one and ask again for energy the coming hour and so on; repeating this cycle among the day. On the other hand, the daily energy related to Stand-by uses, due to its nature; will be equally divided for the 24 hours of the day. For the Spanish residential sector, [13] provides relevant information about the usage trend of different domestic loads.

Later, the daily individual energy usage for the different loads can be attained as a percentage of the daily energy consumption $E_{daily}$ (See Equation 3.8). These percentages (see second column in Table 3.4) have been inferred from [13]. Finally, the individual daily energy consumption for every load is equally split into its corresponding usage hours.

$$E_{daily\_loadX} = E_{daily} \cdot \%_{loadX} \tag{3.8}$$

### 3.1.5 Dwelling and Building Demand profile

For a single apartment, once the daily energy profiles for all the loads/appliances is obtained, all of them will be added to attain the dwelling demand profile. Furthermore, after acquiring the demand profile for all the dwellings (having each of them their particular behavior which depends in the number of occupants and unoccupied periods) we will add those profiles to finally get the daily building demand. This action is repeated for the 365 days of all the required simulation years.

To make it more clear, the attainment of the expected dwelling demand profile for the day 195th of the year (assuming to be Monday) for an apartment in Madrid/Spain (Latitude=$40.4^{o}$) having air conditioning (used only in summer), an unoccupied period from 9:00 to 18:00 and three occupants will be now exemplified.

Firstly, according to the unoccupied period and the number of occupants, we will get the number of usage hours for every appliance/load like in Table 3.2, but this time we will take the data for the case of having three occupants in the dwelling (See second column in Table 3.4). We also need to bear in mind that the usage lighting hours vary during the year as a function of the natural sunlight hours (day length) as it has been previously described. For the day 195th of the year, as it can be checked in Figure 3-1, we will consider the lighting loads to be used for 4 hours.

Next, from Table 3.1, the yearly energy consumption $E_{year}$ is taken. For this example case this is 3250 [kWh]. Then, by solving Equations 3.1 to 3.3, and considering to be Monday ($E_{daily} = E_{weekday}$), we find $E_{daily}$ equal to 8.826 [kWh]. Next, by using the percentages share with respect to $E_{daily}$, we can get the daily amount of energy consumed for every appliance/load as it is exposed in Table 3.4.

Similarly, we get the seasonal air conditioning energy $E_{seasonal\_ac}$ from Table 3.1 (550 [kWh]). As we are in a summer-day case, by means of Equation 3.4, $E_{daily\_ac}$ is found to be 6.043 [kWh].

After that, we obtain the amount of energy spent per hour for all the loads by simply dividing their daily consumption energy by their corresponding number of usage hours (See Table 3.4). Later, for all loads, we just need to attain the specific hours of the day were those usage hours take place. This is done by performing the weighted random selection between the 24 hours of the day. For this study case, the specific probability for every hour and load is shown in Table 3.5 (To see the loads' hourly probability tables for the other not-occupied periods, refer to Appendix A section). To graphically visualize the specific demand profiles for the different loads among the studied day, refer to Figures 3-2 and 3-3.

Table 3.4: Explanation of the daily demand profile for the different loads.

| **Load** | $\%_{loadX}$ **consumption respect to** $E_{daily}$ | **Daily Consumption [kWh]** | **Usage Hours** | **Energy use per active hour [kWh]** | **Active hours of the day obtained by weighted random sampling** |
|---|---|---|---|---|---|
| **Electric Cooker** | 21.76% | 1.920 | 3 | 0.640 | 7, 9, 21 |
| **Lighting** | 14.05% | 1.240 | 4 | 0.310 | 3, 6, 20, 21 |
| **Freezer** | 20.10% | 1.774 | 12 | 0.148 | 2, 4, 6, 8, ... , 24 |
| **TV** | 8.02% | 0.708 | 5 | 0.142 | 6, 21, 22, 23, 24 |
| **Washer** | 7.75% | 0.684 | 1 | 0.684 | 22 |
| **Stand-by** | 7.03% | 0.620 | 24 | 0.026 | 1, 2, 3, 4, ... , 24 |
| **Oven** | 5.45% | 0.481 | 1 | 0.481 | 9 |
| **PC** | 5.06% | 0.447 | 3 | 0.149 | 19, 21, 22 |
| **Dish washer** | 4.01% | 0.354 | 1 | 0.354 | 22 |
| **Dryer** | 2.17% | 0.192 | 1 | 0.192 | 24 |
| **Others** | 4.60% | 0.406 | 2 | 0.203 | 8, 24 |
| **TOTAL** | 100% | **8.826** | - | - | - |
| **Air Conditioner** | - | **6.043** | 5 | 1.209 | 1, 19, 20, 22, 24 |

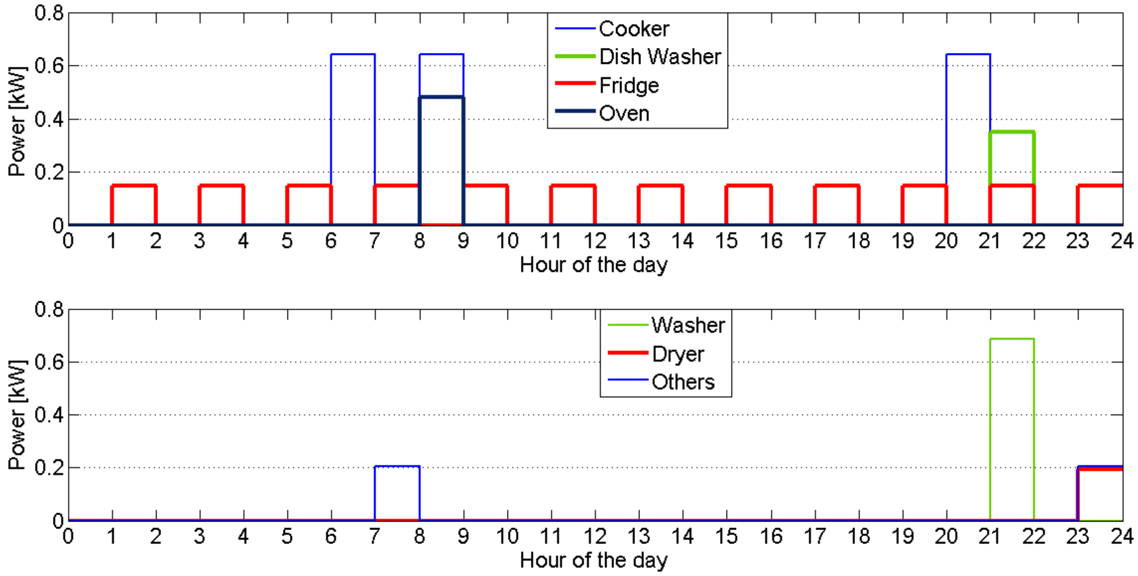


Figure 3-2: Daily demand profile for different loads.

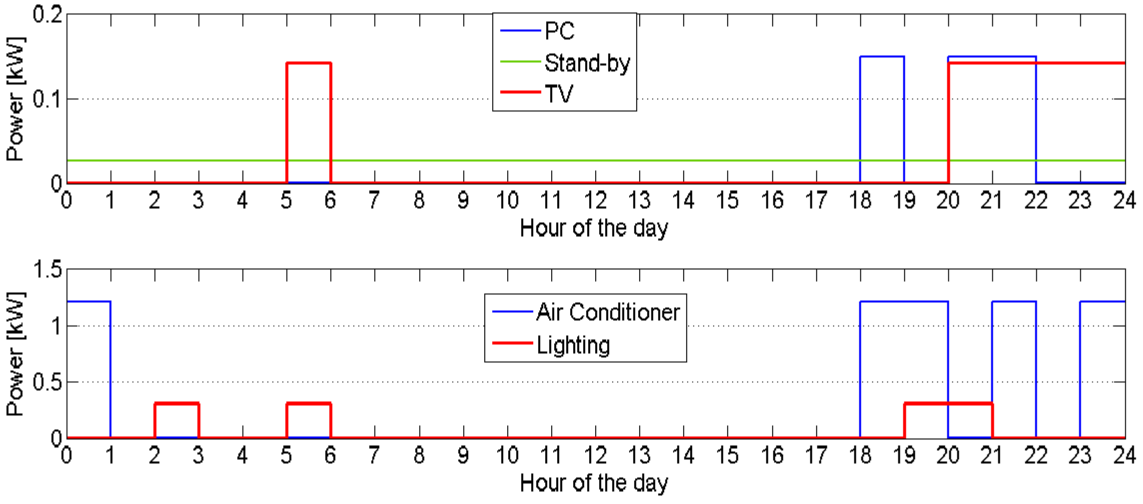


Figure 3-3: Daily demand profile for different loads.

Table 3.5: Hourly usage weightiness for an unoccupied period from 9:00 to 18:00 for the different loads.

| | **Appliance/load** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Hour** | **Electric Cooker** | **Lighting** | **TV** | **Washer** | **Oven** | **PC** | **Dish Washer** | **Dryer** | **Others** | **Air Conditioner** |
| **1** | 0% | 5% | 2% | 2% | 0% | 4% | 2% | 6% | 6% | 8% |
| **2** | 0% | 2% | 2% | 0% | 0% | 2% | 0% | 0% | 2% | 4% |
| **3** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 2% |
| **4** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **5** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **6** | 0% | 3% | 2% | 0% | 4% | 2% | 0% | 0% | 2% | 1% |
| **7** | 12% | 9% | 6% | 8% | 8% | 3% | 5% | 6% | 7% | 1% |
| **8** | 22% | 8% | 10% | 12% | 14% | 5% | 10% | 8% | 10% | 2% |
| **9** | 12% | 5% | 10% | 10% | 14% | 5% | 20% | 12% | 10% | 2% |
| **10** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **11** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **12** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **13** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **14** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **15** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **16** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **17** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **18** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **19** | 4% | 11% | 11% | 10% | 10% | 13% | 4% | 6% | 10% | 13% |
| **20** | 12% | 11% | 11% | 12% | 12% | 13% | 10% | 10% | 10% | 13% |
| **21** | 22% | 11% | 11% | 12% | 14% | 15% | 15% | 14% | 10% | 13% |
| **22** | 12% | 11% | 11% | 12% | 11% | 14% | 15% | 16% | 10% | 13% |
| **23** | 3% | 11% | 11% | 12% | 10% | 13% | 16% | 14% | 10% | 13% |
| **24** | 1% | 10% | 10% | 10% | 3% | 8% | 3% | 8% | 10% | 13% |
| | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Finally, if we sum all the loads' profiles, we get the daily demand profile for the dwelling (See Figure 3-4). This entire process must be repeated day after day so that the weekly and yearly demand profile are attained for the dwelling as in Figures 3-5 and 3-6 respectively. At last, to obtain the building power consumption, it is required to add all the dwellings' profiles (having each of them their specific pattern due to their particular characteristics). Figure 3-7 exposes the demand profile for a building consisting of five dwellings, having each of them the configuration detailed in Table 3.6.

Table 3.6: Building characteristics used to obtain Figure 3-7.

| **Dwellings** | **Occupants** | **Unoccupied Period** | **Air Conditioning** |
|---|---|---|---|
| ONE | 3 | 9:00 to 18:00 | YES |
| TWO | 2 | NO | YES |
| THREE | 1 | 14:00 to 19:00 | NO |
| FOUR | 4 | 9:00 to 14:00 | YES |
| FIVE | 4 | 9:00 to 18:00 | YES |

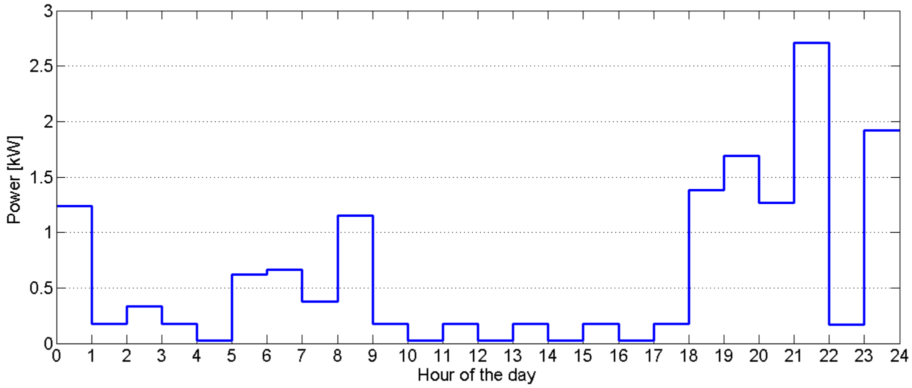


Figure 3-4: Dwelling's Daily demand profile for the example case.

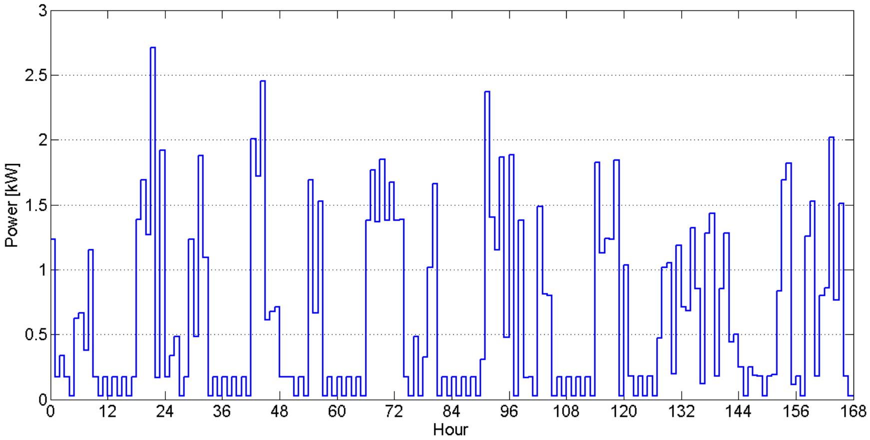


Figure 3-5: Dwelling's weekly demand profile for the example case.

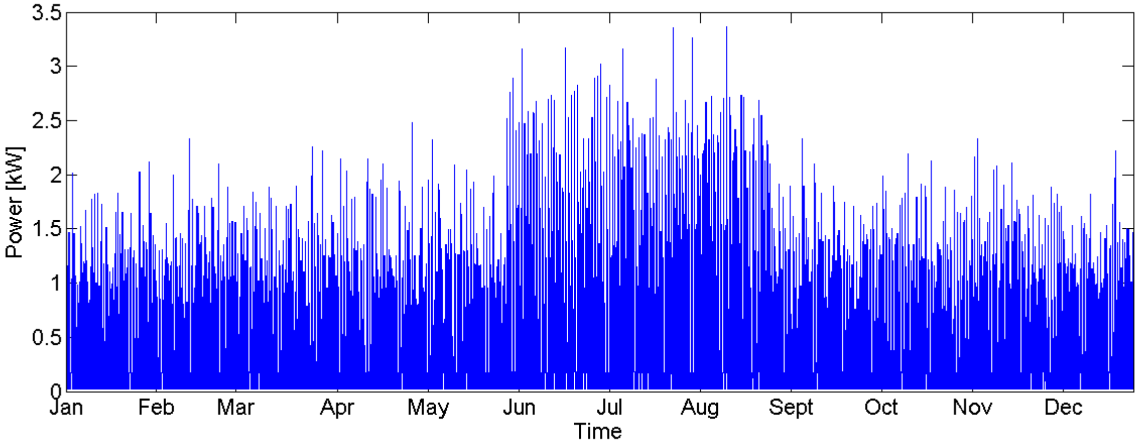


Figure 3-6: Dwelling's Yearly demand profile for the example case.

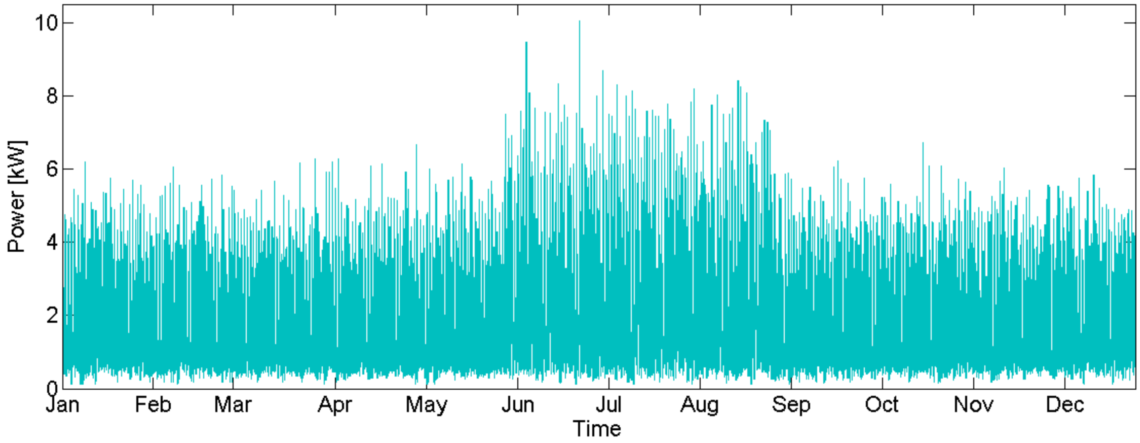


Figure 3-7: Power demand profile for a building like in Table 3.6.

# Chapter 4

# Microgrid Reliability Assessment

Microgrids comprise low voltage distribution systems with distributed generation (DG) devices (PV panels, wind turbines, micro-gas turbines, fuel cells, micro-hydro generators, diesel generators, etc.) together with storage equipment (batteries, energy capacitors and flywheels) and flexible loads [21]. Such systems can be operated in a non-autonomous way, if connected to the grid, or in an autonomous way, if disconnected from the main grid (islanded). Microgrid's main features (autonomy, flexibility, scalability and efficiency) can allow electrical companies to meet the growth of loads by adding new DG systems nearby to the user's site without expanding transmission lines and centralized power stations, which is more costly and time consuming [28]. Some kinds of DGs, such as wind turbines or photovoltaic generators, produce renewable power energy but have small unit capacity and are intermittent as they are dependent on weather conditions. Therefore, the power reliability impact on the use of DG systems in a microgrid is two-folded [48]. Some characteristics of the microgrid improve the system reliability indices, while others degrade the system reliability level [41]. For this reason, for a microgrid to provide steady and continuous electric power of high quality, great effort has to be done to assess its reliability performance.

## 4.1 Generating System Adequacy Assessment

Generating system adequacy assessment, which is performed at the Hierarchical Level 1 (explained at the Power Reliability Section in Chapter 2), is used to evaluate the ability of the system generating capacity to satisfy the total system load [4]. There are three basic Monte Carlo simulation methods in reliability evaluation [7]:

- **System state sampling:** In this method a system state depends in the combination of all components states and each component state can be determined by sampling the probability that the component appears in that state. The behavior of each component is described by a uniform distribution between [0,1].

- **System state duration sampling:** It is based in sampling the probability distribution of the component state duration. In this approach, chronological component state transition processes for all components are first simulated by sampling. The chronological system state transition process is then created by combination of the chronological component state transition processes.

- **System state transition sampling:** It focuses on state transition of the whole system instead of component states or component state transition processes.

The system state sampling can be called a non-sequential method because it considers each time point or system state independent of another. Contrary, state duration sampling and system state transition sampling are often called sequential methods because they advance time or system states sequentially. These three different techniques present benefits and drawbacks as Table 4.1 exposes and References [17] [52] [3] detail. The assessment performed in the present project will be conducted using the state duration sampling approach as it will permit the reliability indices with their statistic distributions to be easily calculated and also because chronological issues can be considered, which is very important as this will allow to incorporate weather and seasonal effects into the model [9]. It must be mentioned that this method, compared to the other two, usually requires a larger investment in computing time and effort; however, this is easily overcome with modern personal computers.

## 4.1.1 System State Duration Sampling Methodology

The state duration sampling methodology proposed in this project for the microgrid reliability assessment of nearly-Zero Energy Buildings (nZEB), consist of the following aspects:

### 4.1.1.1 Define the network topology and analysis limitations

First of all, all the distributed energy sources and loads at the nZEB microgrid will be assumed to be connected to a single bus which is connected to the grid distribution system at the Point of Common Coupling (PCC) at low voltage level as shown in Figure 4-1. The following limitations will be considered when performing the analysis:

- No failures (100% reliable) and no power losses will exist on buses, cables and power electronic devices in the microgrid. Very little error is committed with this assumption as properly sized wires for low voltage distribution in buildings present efficiencies higher than 98% [44] and commercial power converters have shown to achieve overall efficiencies beyond 96% [29].
- Upstream failures in the grid distribution system are neglected.
- The storage system will be assumed to have null power losses.
- No deterioration in output or efficiency during the lifetime of the equipment is considered.
- In a conventional distribution system without renewable DGs and microgrids, the minimum time unit of Monte Carlo simulation method is determined by the minimum value of the components' time to failure (TTF) or time to repair (TTR), which varies from several minutes to years according to the failure rate and repair rate [45]. However, when taking into consideration the time varying

Table 4.1: Features of Monte Carlo methods

| **Method** | **Advantages** | **Disadvantages** |
|---|---|---|
| **State sampling** | Sampling is simple (Only needed to generate uniformly distributed random number between [0,1].<br>Few basic reliability data required.<br>It can be generalized to sample states of other parameters in power system reliability evaluation. | It cannot be used by itself to calculate the actual frequency index. |
| **State duration sampling** | It can be easily used to calculate the actual frequency index.<br>Any state duration distribution can be easily considered.<br>The statistical probability distribution functions of the reliability indices can be calculated in addition to their expected values. | It requires more computing time and storage.<br>It demands parameters associated with all component state duration distributions. |
| **State transition sampling** | It can be used to calculate the exact frequency index without the need to sample the distribution function and storing chronological information as in the state duration sampling approach.<br>In the state sampling approach, $m$ random numbers are required to obtain a system state for an $m$-component system. This approach only requires a random number to produce a system state. | It only applies to exponentially distributed component state durations. |

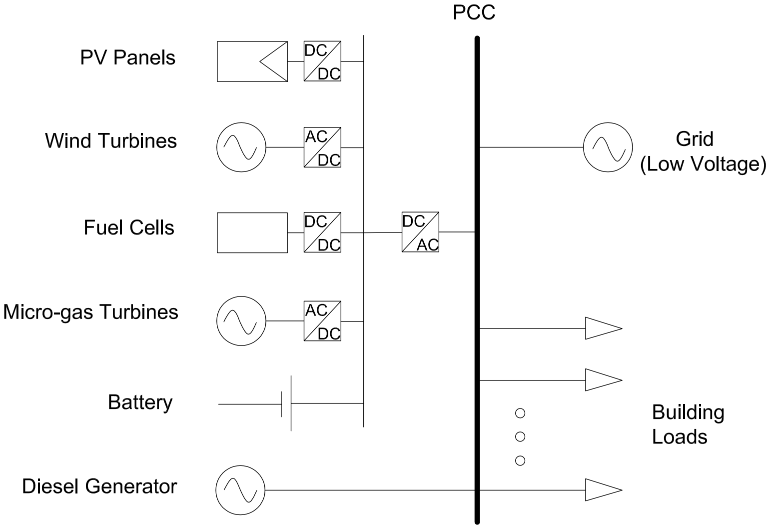


Figure 4-1: nZEB's microgrid topology

characteristic of renewable energy sources, an appropriate minimum time unit of simulation for weather conditions (solar radiation and wind speed) is chosen as an hour in this project.

#### 4.1.1.2 Attain the system available power margin

Obtain the hourly power generated from distributed energy sources (as reference [27] details) and the hourly power demanded by the building (considering the methodology exposed in Chapter 4). Then, superimpose both power profiles (generated and demanded) to obtain the system available margin (Figure 4-2). A positive margin denotes that the distributed system generation is sufficient to meet the system load, while a negative margin implies that the system load must be supplied either from the battery or from the grid.

#### 4.1.1.3 Use the 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

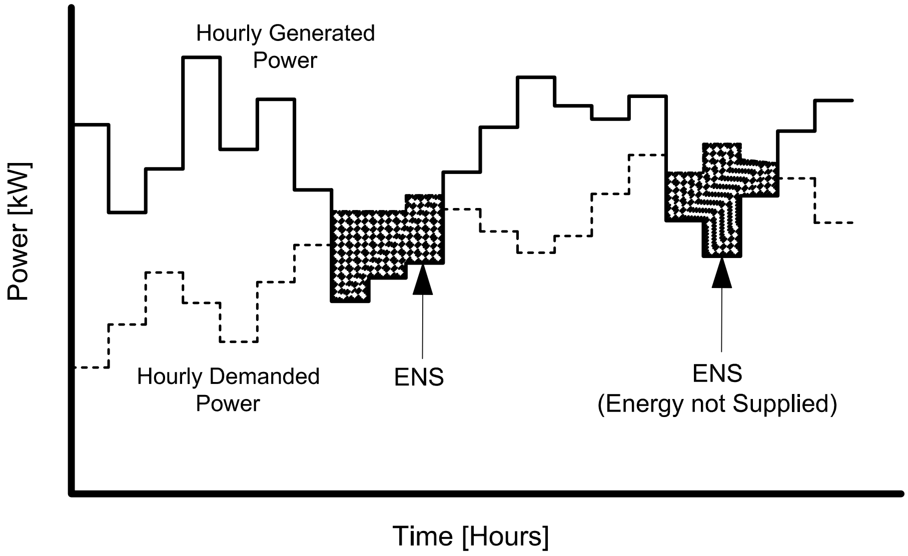


Figure 4-2: Available power margin attainment[4]

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 [55]. 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.

This means that, 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 nevertheless. The flowchart in Figure 4-3 details this procedure, while Table 4.2 explains the symbology employed in this flowchart.

The battery model will be very helpful to infer what is the actual interaction state with the grid; this is injecting power, receiving power or having no power interchange.

Table 4.2: Nomenclature used in Figure 4-3, [27].

| **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 | $E_{max}$ |
| Minimum 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) | $\Delta_{min}$ |

#### 4.1.1.4 Calculate reliability indices

For each sampled year $i$, by observing hourly the power margin and the grid interaction state, the loss of load duration ($LLD_i$) in hours, the loss of load occurrence

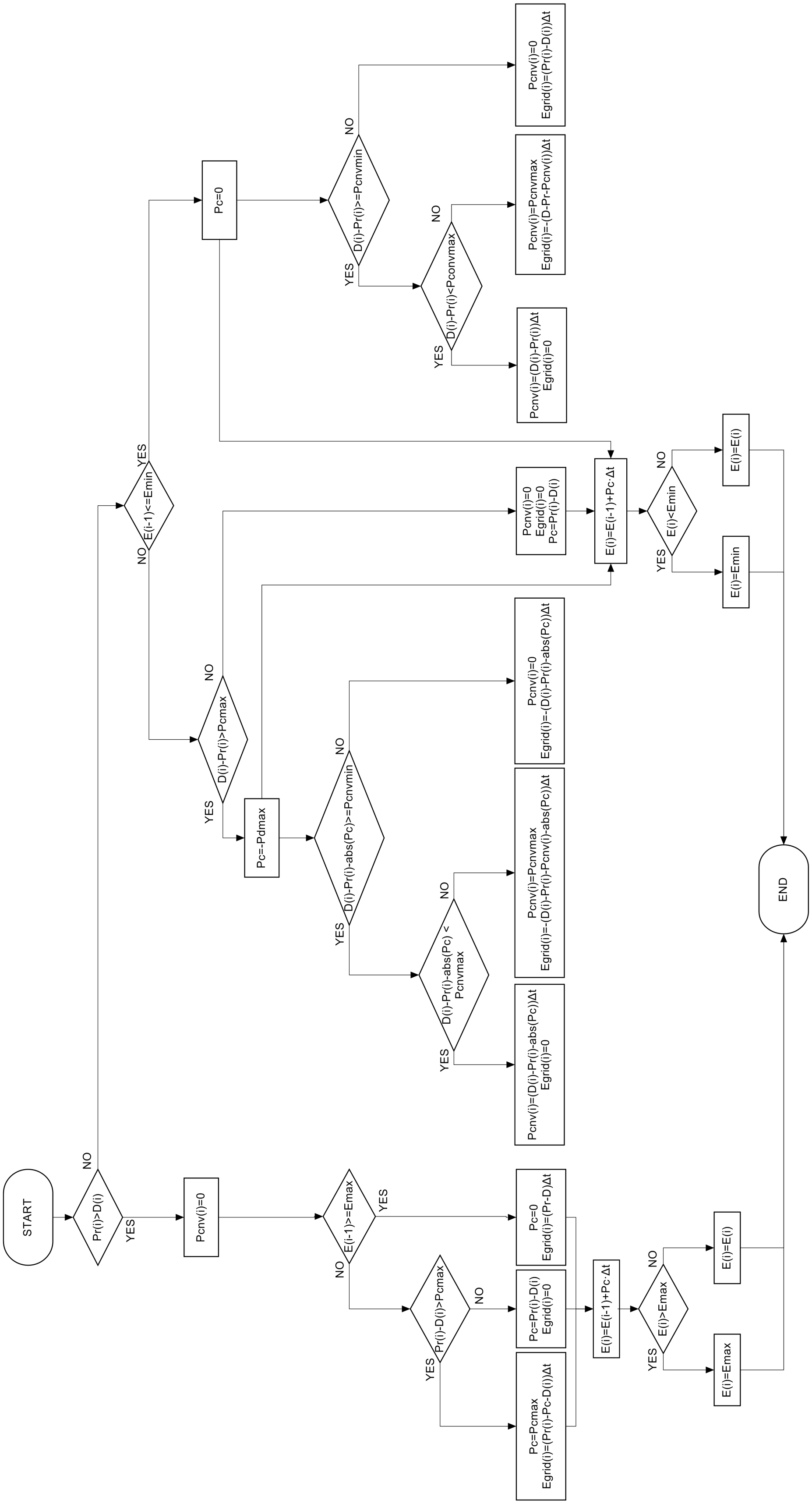


Figure 4-3: Battery model flowchart, [27]

($LLO_i$), and the energy not supplied ($ENS_i$) in kWh can be obtained. The reliability indices in $N$ sampling years therefore can be estimated using the following equations [4]:

**(1)** Loss of Load Expectation ($LOLE$), in hours/year

$$LOLE = \frac{\sum_{i=1}^{N} LLD_i}{N} \tag{4.1}$$

**(2)** Loss of Energy Expectation ($LOEE$), in kWh/year

$$LOEE = \frac{\sum_{i=1}^{N} ENS_i}{N} \tag{4.2}$$

**(3)** Loss of Load Frequency ($LOLF$), in occurrences/year

$$LOLF = \frac{\sum_{i=1}^{N} LLO_i}{N} \tag{4.3}$$

As we are using an hour as the minimum time unit in our model, the yearly number of occurrences in Equation 4.3 will be equal to the number of hours in Equation 4.2. Thus, the $LOLE$ and $LOLF$ magnitudes will be the same.

Additionally, the following three microgrid reliability indices proposed by [45] will be calculated. These indices refer to the microgid when it is working in islanded mode. For the present project, to be in islanded mode implies that the microgrid is self-autonomous and in that time period it doesn't take energy from the grid.

**(4)** Microgrid Islanded Operation Probability ($MIOP$) in p.u./year: The fraction of time in a year that the microgrid is self-autonomous and doesn't take energy from the grid.

$$MIOP = \frac{\sum_{i=1}^{N} \frac{\text{Microgrid hours in islanded mode}_\text{i}}{\text{Total Microgrid operations hours}_\text{i}}}{N} \tag{4.4}$$

**(5)** Island Load Shedding Expectation ($ILSE$) in kW/occurrence/year: The mean power that provokes a transition from self-autonomous state to power-intake from the grid state as the microgrid was not able to cover by itself all the required demand.

$$ILSE = \frac{\sum_{i=1}^{N} \frac{\text{Total kW load interrupted}_\text{i}}{\text{Total number of load interruption times}_\text{i}}}{N} \tag{4.5}$$

**(6)** Distributed Energy Penetration ($DEP$) in p.u./year: The percentage of the total demanded energy that is covered by the distributed generation systems in the microgrid in one year.

$$DEP = \frac{\sum_{i=1}^{N} \frac{\text{Annual kWh demand covered by distributed generation}_\text{i}}{\text{Total annual kWh electricity demand}_\text{i}}}{N} \tag{4.6}$$

It must be noted that the mean value obtained by Equations 4.1 to 4.6 are expectation estimates of the index over a period of $N$ sampling years. The variance of the estimate ($V$) for any of the previous reliability indices will be obtained by:

$$V = \sigma^2 = \frac{1}{N(N-1)} \sum_{i=1}^{N} (X_i - E(X))^2 \tag{4.7}$$

Where:

$E(X)$ is the estimated expectation of any index.

$X_i$ is the sample value of the index in year $i$.

#### 4.1.1.5 Define the convergence Criteria

Monte Carlo simulation is a fluctuating convergence process. As the simulation proceeds, the estimated indices will approach their ”real” values. The simulation should be terminated when the estimated reliability indices achieve a specified degree of confidence. The purpose of a stopping rule is to provide a compromise between the accuracy needed and the computational time effort. As noted in Section 1.4.3, the coefficient of variation $a$ is often used as the convergence criterion in Monte Carlo simulation. The coefficient of variation of an index is defined as

$$a = \frac{\sigma}{E(X)} \tag{4.8}$$

Being:

$E(X)$ the estimated expectation of any index. In our case it is the mean value of the index.

$\sigma$ the standard deviation of the estimated expectation obtained from Equation 4.7.

The coefficient of variation for the LOEE index has the lowest convergence speed compared to other indices [4]. This is why the LOEE's coefficient of variation will be used in this study as the convergence criterion in order to guarantee reasonable accuracy in the results. Achieving coefficients of variation lower than 2% represents admissible convergences in the simulations for most of the cases [43]. Figure 4-4, shows an example of the convergence process and the coefficient of variation evolution for the LOEE index.

#### 4.1.1.6 Use stopping rules to finish the simulation

Two stopping criteria will be used:

- The simulation will stop when the selected Coefficient of Variation (COV) is lower than the prespecified tolerance value.

- During simulation, if the coefficient of variation does not become lower than the prespecified tolerance value but a given number of maximum simulation years is achieved, the simulation will be also stopped. Then it is checked if the COV has an acceptable value. If not, the number of simulation years could be increased.

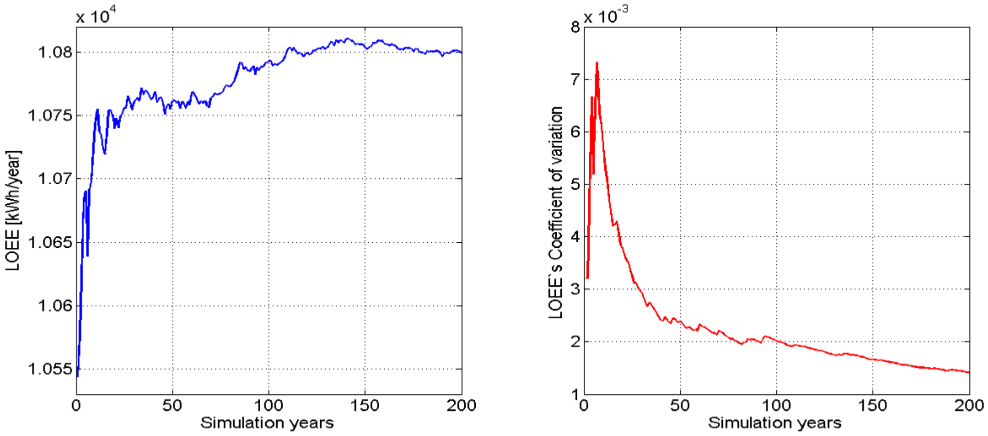


Figure 4-4: LOEE's convergence and coefficient of variation evolution

Finally, it must be mentioned that the Generating System Adequacy Assessment methodology and the power demand modeling detailed throughout this master thesis have been merged with the work developed in Reference [27] to create a computer tool (GenMIX v1.0 beta) that successfully assesses the selection of distributed generation systems in residential buildings considering reliability and economic concerns for the Spanish context. For more details about this software, refer to the Appendix B section.

# Chapter 5

# Study Cases

In this chapter, some study cases will be analyzed to validate the proposed methodology to quantitatively assess the selection of distributed generation systems in residential buildings by performing the generating system adequacy assessment procedure detailed in the previous chapter.

## 5.1 Case 1

This case studies the power reliability performance for a 5-dwelling residential building located in Madrid/Spain (Latitude=40.4°) which has installed 5 [kWp] of photovoltaic energy (See Figure 5-1) produced by 20 PV panels as Table 5.1 details. The different dwellings in the building will be assumed to consume as much energy as Table 3.1 specifies while the number of occupants per dwelling is exposed in Table 5.2.

### 5.1.1 Analysis 1

First of all, the way the reliability indices behave when varying the not-occupied periods of the inhabitants will be studied. Five conditions will be analyzed:

**Condition 1:** All the dwellings have a not-occupied period from 09:00 to 14:00.

**Condition 2:** All the dwellings have a not-occupied period from 14:00 to 19:00.

**Condition 3:** All the dwellings have a not-occupied period from 09:00 to 18:00.

**Condition 4:** All the dwellings are occupied all day long.

**Condition 5:** The dwellings have different not-occupied periods as Table 5.2 details.

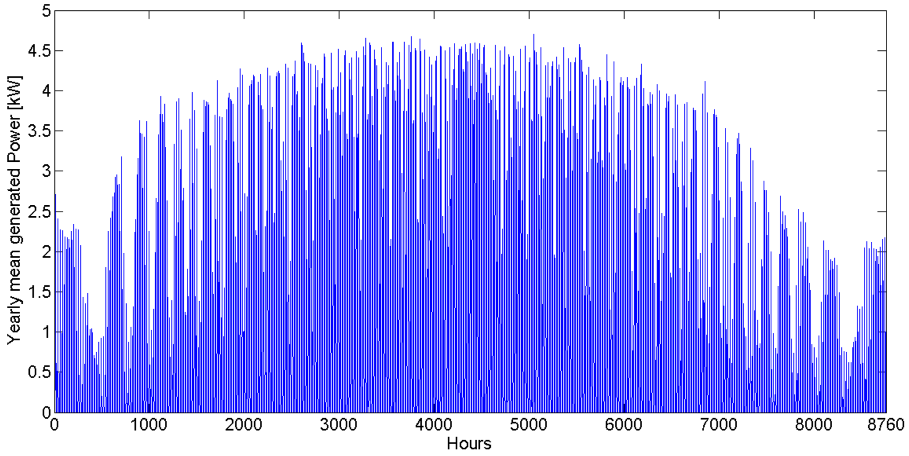


Figure 5-1: Yearly mean power generated in Case 1

Table 5.1: PV panels parameters used in Case 1

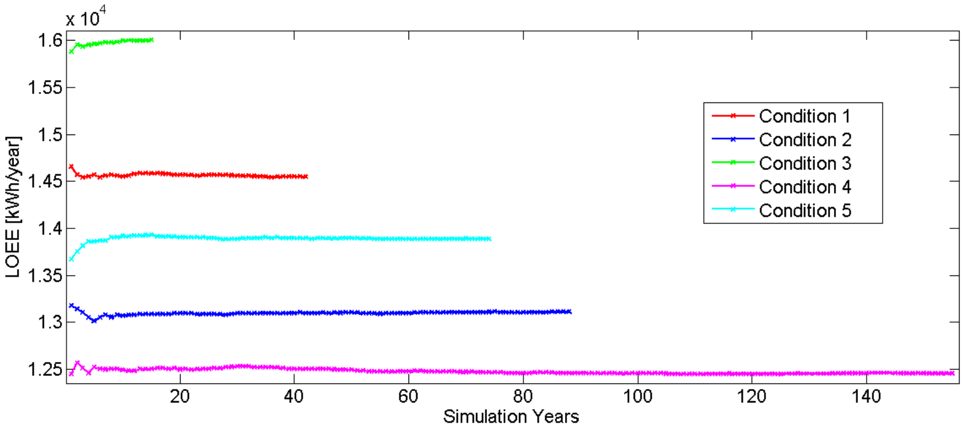
| | **PV Panel Parameters** | **Units** | **Value** |
|---|---|---|---|
| **PV Panel Specifications** | $P_{MPP}$ | W | 250 |
| | $V_{MPP}$ | V | 30.84 |
| | $I_{MPP}$ | A | 8.150 |
| | $V_{OC}$ | V | 37.26 |
| | $I_{SC}$ | A | 8.907 |
| | $K_V$ | mV/K | -0.4015% |
| | $K_I$ | mA/K | 0.0717% |
| | $N_{OT}$ | °C | 47 |
| **Location Data** | Latitude | Deg. | 40.4 |
| **Monte Carlo Two State Model** | $MTTF$ | Hours | 7500 |
| | $MTTR$ | Hours | 150 |

Table 5.2: Building characteristics

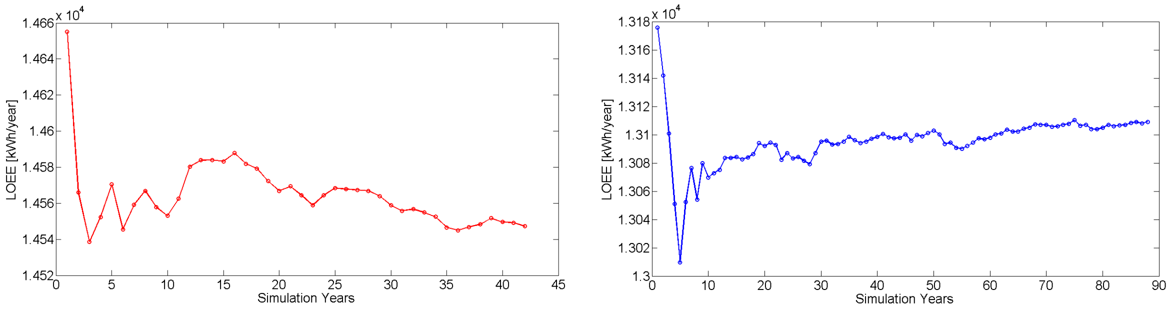
| **Dwelling** | **Occupants** | **Air Conditioning** | **Unoccupied Period for Condition 5 only** |
|---|---|---|---|
| ONE | 2 | YES | 9:00 to 14:00 |
| TWO | 4 | YES | 14:00 to 19:00 |
| THREE | 3 | YES | 09:00 to 18:00 |
| FOUR | 4 | YES | No |
| FIVE | 3 | YES | 09:00 to 18:00 |

The parameters of the battery employed for these analyses are given in Table 5.4 in the Battery 1 column. Figure 5-2 shows the convergence process for the Loss of Energy Expectation (LOEE) index for the different conditions while Figure 5-3 exposes the LOEE's coefficients of variation (COV) evolution until the convergence criteria was achieved; for this case the accepted COV was set to 0.1%. Additionally, Table 5.3 details the value of each reliability index for the last simulation year for every case.

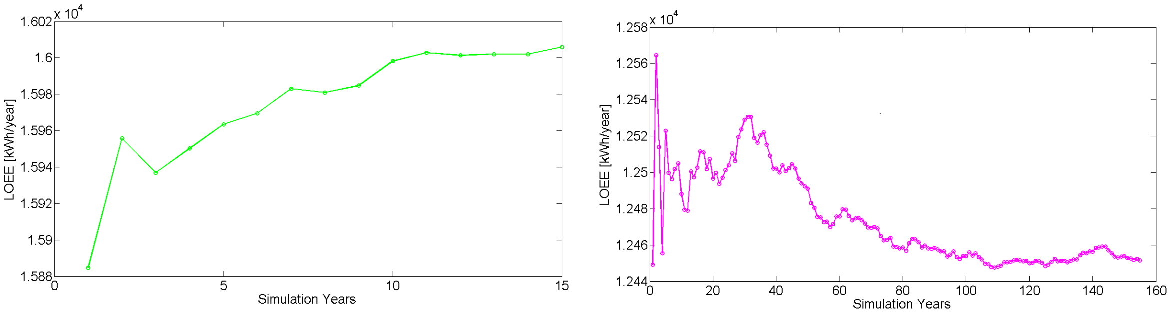
It can be checked that the situation having the worse LOEE behavior is Condition 3 (16006.0 [kWh/year]). This is a consequence of the inhabitants mostly demanding energy in hours where there is no solar radiation and thus deep energy extraction from the battery or the grid is needed as the ILSE index reveals (2.844 [kWh/occurrence/year]). Furthermore, the distributed energy penetration share (DEP index) in this situation is the lowest (0.172 [p.u./year]). On the other hand, Condition 4 presents the best LOEE (12451.5 [kWh/year]), ILSE (1.770 [kWh/occurrence/year]) and DEP (0.356 [p.u./year]) indices as a result of the occupants consuming energy throughout all the day. Therefore, this prevents the battery to be rapidly discharged. we can conclude that it is highly advisable for residential nearly Zero-Energy Buildings promoters to take into account demand-side management strategies to procure adequate power reliability results.



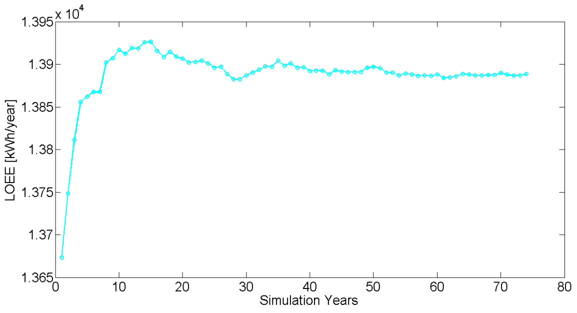
(a) Condition's comparison



(b) Condition 1 (c) Condition 2



(d) Condition 3 (e) Condition 4



(f) Condition 5

Figure 5-2: LOEE behavior for the different Conditions

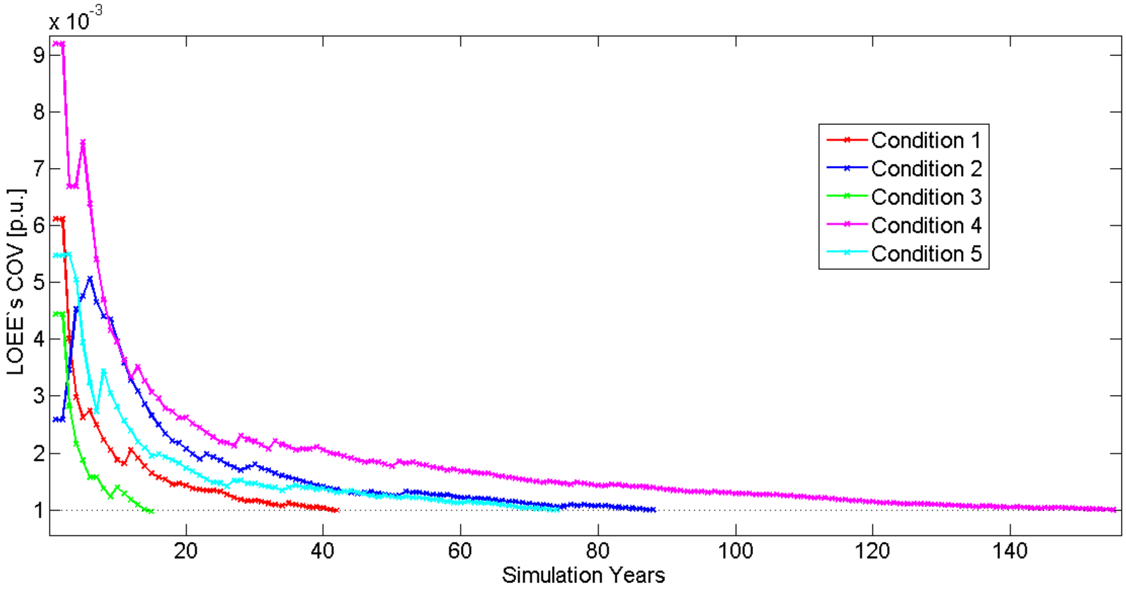


Figure 5-3: LOEE's COVs for the different conditions

Table 5.3: Reliability indices in the last simulation year for the different Conditions

| **Condition** | **Convergence** $[years]$ | **LOEE** $[\frac{kWh}{year}]$ | **LOLE** $[\frac{hours}{year}]$ | **MIOP** $[\frac{p.u.}{year}]$ | **ILSE** $[\frac{kW/occurrence}{year}]$ | **DEP** $[\frac{p.u.}{year}]$ |
|---|---|---|---|---|---|---|
| **1** | 42 | 14547.2 | 6506.3 | 0.257 | 2.235 | 0.248 |
| **2** | 88 | 13109.0 | 6156.7 | 0.297 | 2.129 | 0.322 |
| **3** | 15 | 16006.0 | 5626.5 | 0.357 | 2.844 | 0.172 |
| **4** | 155 | 12451.5 | 7032.7 | 0.197 | 1.770 | 0.356 |
| **5** | 74 | 13888.7 | 6313.8 | 0.279 | 2.199 | 0.282 |

### 5.1.2 Analysis 2

Now, for the building having not occupied periods as Table 5.2 shows, it will be analyzed how the system's power reliability behaves when varying the storage capacity in the battery as Table 5.4 details for six different battery sizes.

Table 5.4: Batteries parameters for Case 1 study

| | **Battery Parameters** | **Units** | **Battery 1** | **Battery 2** | **Battery 3** | **Battery 4** | **Battery 5** | **Battery 6** |
|---|---|---|---|---|---|---|---|---|
| **Battery Specifications** | Max. Charge Power | W | 1050 | 900 | 750 | 600 | 450 | 300 |
| | Max. Discharge Power | W | 1050 | 900 | 750 | 600 | 450 | 300 |
| | Capacity (Max. Energy) | Wh | 3500 | 3000 | 2500 | 2000 | 1500 | 1000 |
| | Min. Energy | Wh | 1050 | 900 | 750 | 600 | 450 | 300 |
| **Monte Carlo Two State Model** | $MTTF$ | Hours | 8500 | | | | | |
| | $MTTR$ | Hours | 50 | | | | | |

As Table 5.5 exposes, the bigger the battery capacity the better the reliability indices. Additionally, Figure 5-4 shows the lineal tendency existing for the LOEE index and the battery size for the studied range. However, it also should be noticed that very little improvement (612.8 [kWh]) is achieved even if varying the battery significantly from 1000[Wh] to 3500[Wh]. Therefore, for this study case, the battery size is not a key factor to considerably improve the reliability results.

Table 5.5: Reliability indices in the last simulation year when using different batteries

| **Battery Type** | **Convergence** $[years]$ | **LOEE** $[\frac{kWh}{year}]$ | **LOLE** $[\frac{hours}{year}]$ | **MIOP** $[\frac{p.u.}{year}]$ | **ILSE** $[\frac{kW/occurrence}{year}]$ | **DEP** $[\frac{p.u.}{year}]$ |
|---|---|---|---|---|---|---|
| **1** | 74 | 13888.7 | 6313.8 | 0.279 | 2.199 | 0.282 |
| **2** | 50 | 13976.5 | 6327.2 | 0.277 | 2.209 | 0.277 |
| **3** | 51 | 14114.6 | 6407.7 | 0.268 | 2.202 | 0.270 |
| **4** | 47 | 14237.9 | 6478.1 | 0.260 | 2.197 | 0.264 |
| **5** | 41 | 14351.4 | 6543.0 | 0.253 | 2.193 | 0.258 |
| **6** | 39 | 14501.5 | 6618.6 | 0.244 | 2.191 | 0.250 |

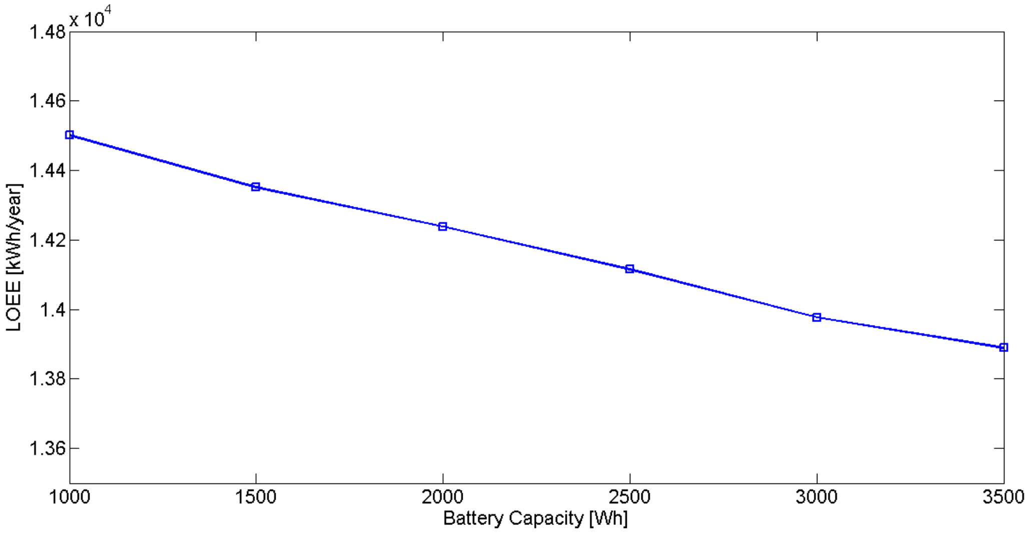


Figure 5-4: LOEE response when changing the battery capacity

### 5.1.3 Analysis 3

To finish this study case, now it will be analyzed how the reliability indices respond when the number of PV panels is varied. For this analysis Battery 1 is employed. Table 5.6 exposes the indices results after varying the number of PV panels from 10 to 50. As expected, the more the PV panels the better the indices. However, Figure 5-5 graphically denotes that for a particular photovoltaic system, if the power generation is excessively increased; no major power reliability improvements take place. To explain it better, it should be noted that when changing the number of PV panels from 10 to 20, the DEP index has an 8.1% gain. Nevertheless, when the number of PV panels is varied from 40 to 50, the DEP index only improves 2.1%. This is a consequence of the storage capacity saturation in the battery.

The analysis performed in this subsection makes clear the need to counterweight reliability aspects with economic constraints to have enough criteria for properly sizing the system's components.

Table 5.6: Reliability indices when varying the number of PV panels

| **Number of PV panels** | **Convergence** $[years]$ | **LOEE** $[\frac{kWh}{year}]$ | **LOLE** $[\frac{hours}{year}]$ | **MIOP** $[\frac{p.u.}{year}]$ | **ILSE** $[\frac{kW/occurrence}{year}]$ | **DEP** $[\frac{p.u.}{year}]$ |
|---|---|---|---|---|---|---|
| **10** | 30 | 15420.4 | 7178.0 | 0.180 | 2.148 | 0.203 |
| **20** | 42 | 13848.5 | 6288.8 | 0.282 | 2.202 | 0.284 |
| **30** | 46 | 13063.2 | 5902.5 | 0.326 | 2.213 | 0.324 |
| **40** | 64 | 12570.4 | 5691.5 | 0.350 | 2.208 | 0.350 |
| **50** | 46 | 12170.0 | 5528.7 | 0.368 | 2.201 | 0.371 |

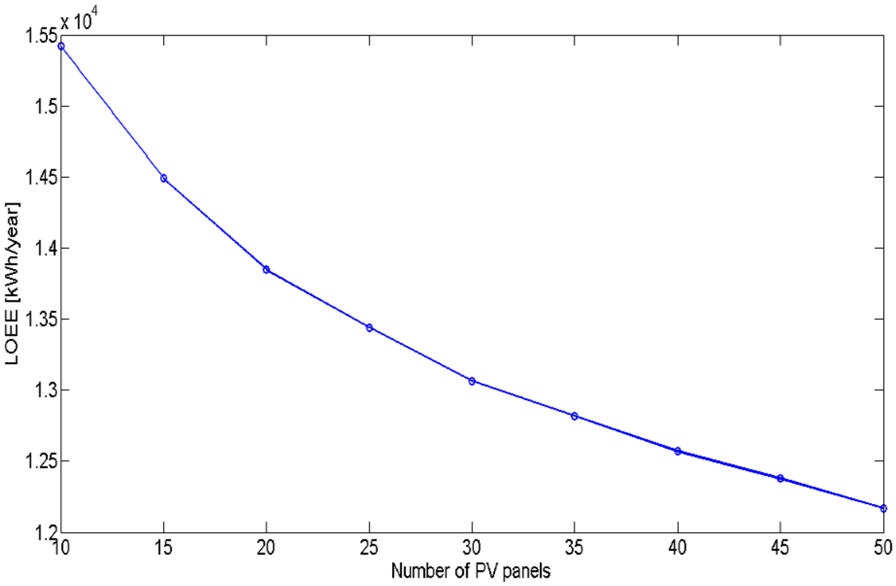


Figure 5-5: LOEE response when varying the number of PV panels

## 5.2 Case 2

A 20-dwelling residential building located in Barcelona/Spain (Latitude=41.1°) has the characteristics exposed in Table 5.10 and a power demand as in Figure 5-6. It has been decided to install a 20[kW] hybrid solar-wind power generation system in the building. Therefore, it is required to select the best hybrid combination in terms of power reliability concerns.

To produce electric energy, 5[kW] PV kits consisting of 20 panels as in Table 5.1 will be considered as well as 5[kW] wind turbine generators (WTG) having the characteristics detailed in Table 5.7. Hence, the possible hybrid combinations are listed in Table 5.8. Additionally, Table 5.9 exposes the characteristics of the employed battery.

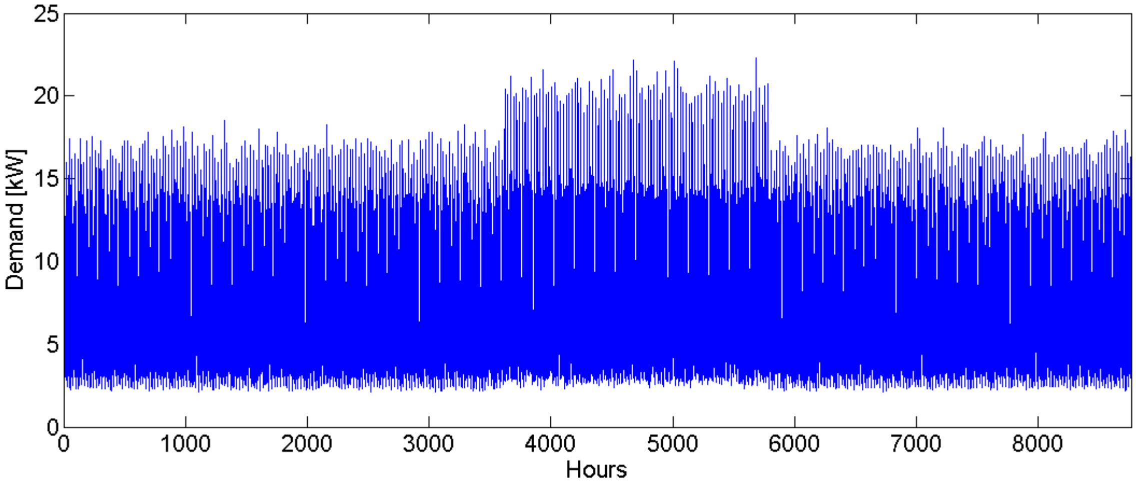


Figure 5-6: Demand profile for the building in Case 2

Table 5.7: Wind turbine generator parameters for Case 2

| | **WT Parameters** | **Units** | **Value** |
|---|---|---|---|
| **WTGS Characteristics** | Rated power | W | 5000 |
| | Rated speed | m/s | 12 |
| | Cut-in speed | m/s | 3.5 |
| | Cut-out speed | m/s | 14 |
| **Location Wind Speed** | Scale factor | m/s | 7 |
| | Shape factor | m/s | 1.60 |
| **Monte Carlo Two State Model** | $MTTF$ | Hours | 7500 |
| | $MTTR$ | Hours | 100 |

Table 5.8: Hybrid Solar-Wind power generation combinations for Case 2

| **Combination** | **Number of 5[kW] PV Kits** | **Number of 5[kW] WTGs** |
|---|---|---|
| **1** | 4 | 0 |
| **2** | 0 | 4 |
| **3** | 3 | 1 |
| **4** | 2 | 2 |
| **5** | 1 | 3 |

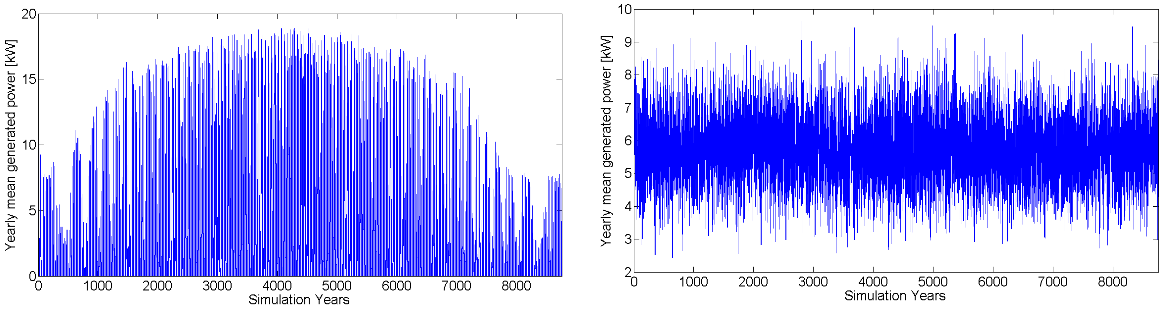
Table 5.9: Batteries parameters for Case 2 study

| | **Battery Parameters** | **Units** | **Value** |
|---|---|---|---|
| **Battery Specifications** | Max. Charge Power | W | 2100 |
| | Max. Discharge Power | W | 2100 |
| | Capacity (Max. Energy) | Wh | 7000 |
| | Min. Energy | Wh | 2100 |
| **Monte Carlo Two State Model** | $MTTF$ | Hours | 8500 |
| | $MTTR$ | Hours | 50 |

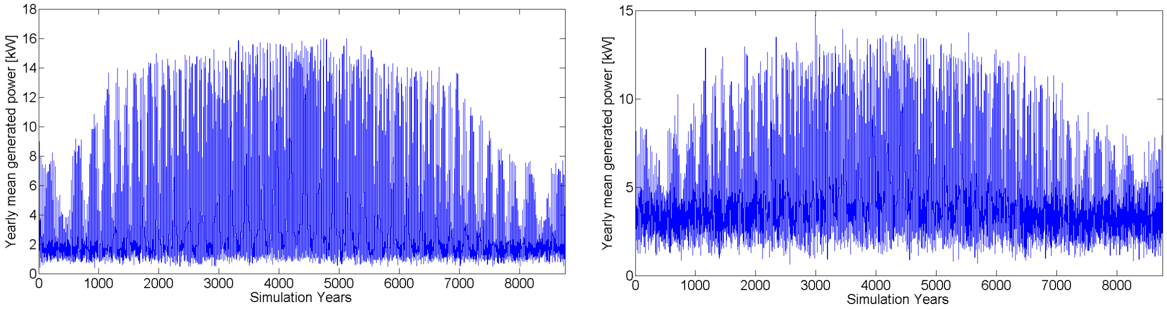
Table 5.10: Characteristics of a residential building for DG integration in Case 2 study

| **Dwelling** | **Number of Occupants** | **Not-Occupiep Period** | **Air Conditioning** |
|---|---|---|---|
| 1 | 1 | 9:00 to 18:00 | Yes |
| 2 | 1 | 14:00 to 19:00 | No |
| 3 | 1 | 09:00 to 18:00 | No |
| 4 | 1 | No | No |
| 5 | 2 | 9:00 to 18:00 | Yes |
| 6 | 2 | 14:00 to 19:00 | No |
| 7 | 2 | 09:00 to 18:00 | No |
| 8 | 2 | No | No |
| 9 | 3 | 9:00 to 18:00 | Yes |
| 10 | 3 | 14:00 to 19:00 | No |
| 11 | 3 | 09:00 to 18:00 | No |
| 12 | 3 | No | No |
| 13 | 4 | 9:00 to 18:00 | Yes |
| 14 | 4 | 14:00 to 19:00 | No |
| 15 | 4 | 09:00 to 18:00 | No |
| 16 | 4 | No | No |
| 17 | 5 | 9:00 to 18:00 | Yes |
| 18 | 5 | 14:00 to 19:00 | No |
| 19 | 5 | 09:00 to 18:00 | No |
| 20 | 5 | No | No |

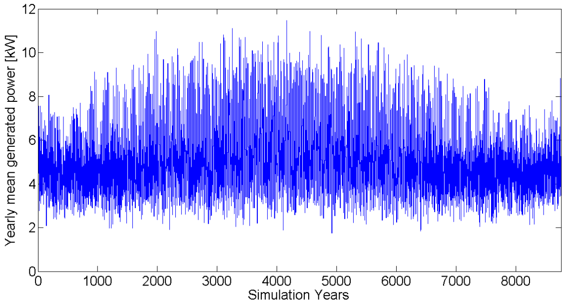
On the other hand, Figures 5-7 and 5-8 show the yearly mean generated power and the yearly mean energy into/from the grid respectively. For this last plot, positive values imply energy injection into the grid while negative values mean energy absorption from the grid.



(a) Combination 1 (b) Combination 2



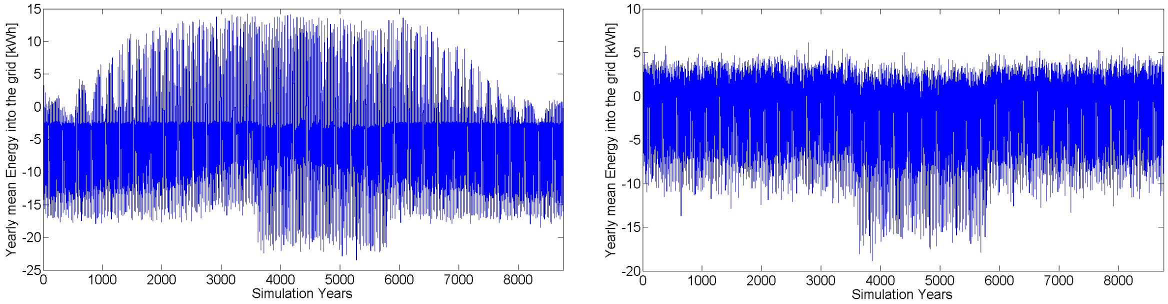
(c) Combination 3 (d) Combination 4



(e) Combination 5

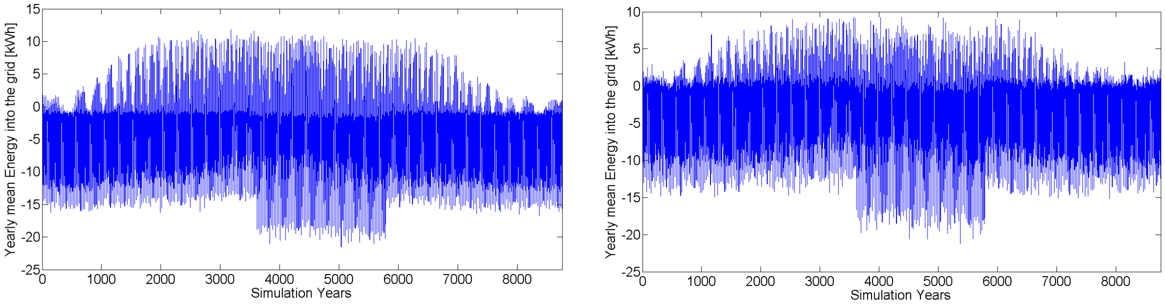
Figure 5-7: Yearly mean generated power for the different combinations.

For the reliability analysis, as the wind speed behavior is more stochastic than the solar radiation pattern, for simulation purposes the accepted tolerance for the COV for this Study Case was 0.3% which is still highly acceptable but higher than the one used for the Study Case 1 (0.1%). It also must be mentioned that if the



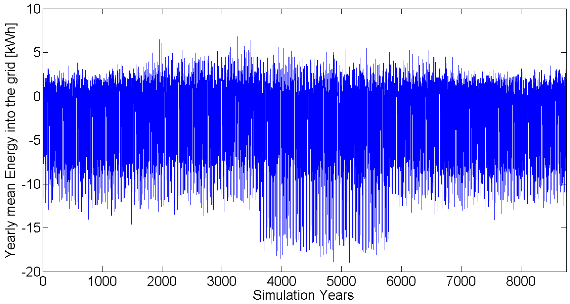
(a) Combination 1

(b) Combination 2



(c) Combination 3

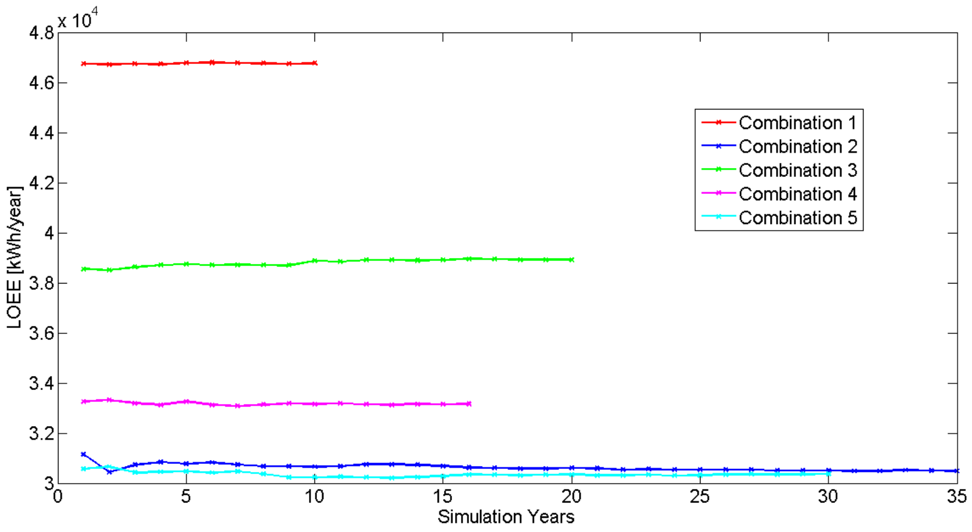
(d) Combination 4



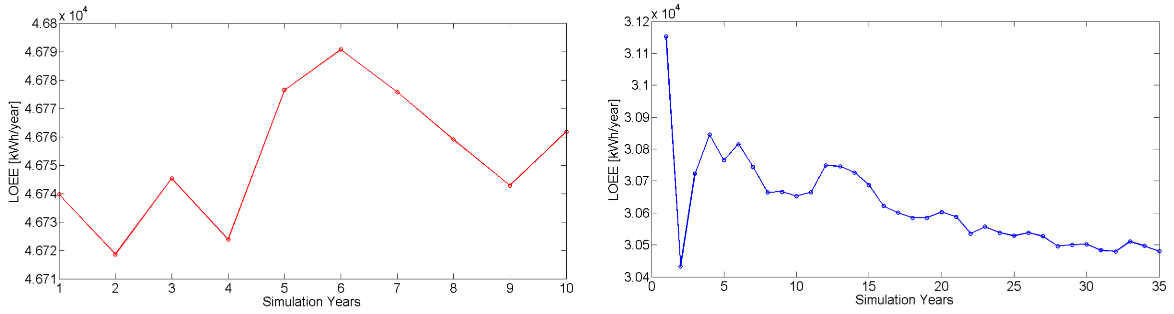
(e) Combination 5

Figure 5-8: Yearly mean Energy into/from the grid for the different combinations

COV rapidly achieves the required tolerance, the simulation is carried out for at least 10 years to ensure the attainment of representative results as for Combination 1 in Figure 5-10. Figure 5-9 exposes the LOEE index convergence process from the studied combinations while Table 5.11 details the results for the different reliability indexes. We can check that Combination 5 (1 5[kW]-PV Kit and 3 5[kW]-WTG) is the one having the best LOEE index (30358.3 [kWh/year]), therefore this is the most convenient option.

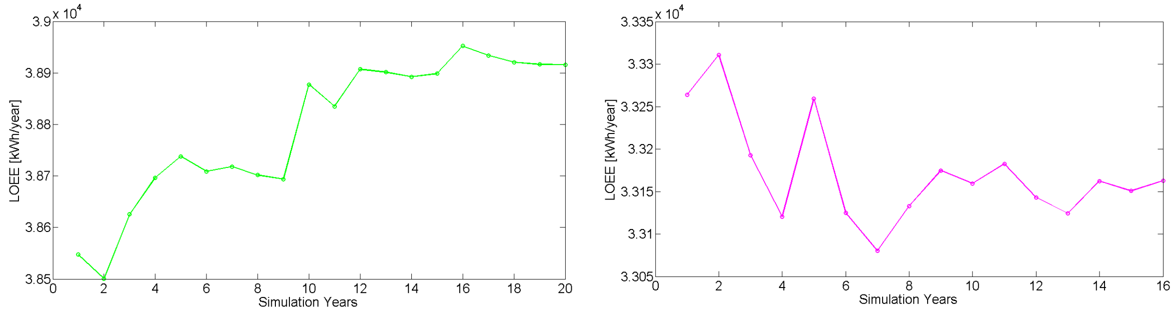


(a) Combination's comparison



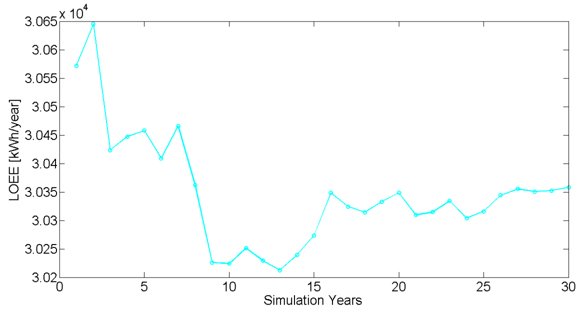
(b) Combination 1

(c) Combination 2



(d) Combination 3

(e) Combination 4



(f) Combination 5

Figure 5-9: LOEE behavior for the different combinations

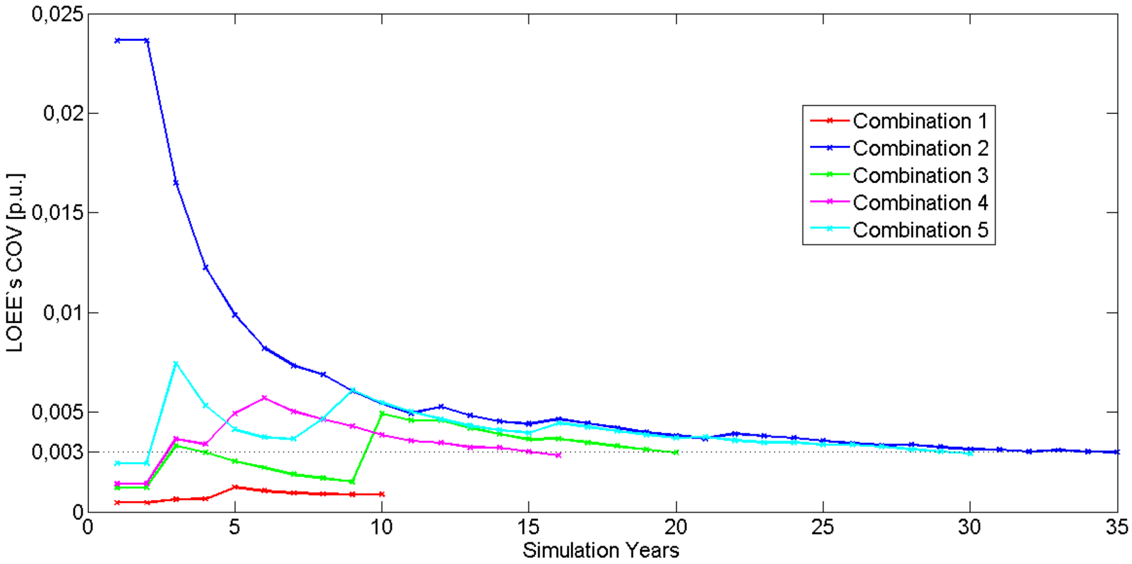


Figure 5-10: LOEE's COVs for the different combinations

Table 5.11: Reliability indices for Case 2 combinations

| **Combination** | **Convergence** $[years]$ | **LOEE** $[\frac{kWh}{year}]$ | **LOLE** $[\frac{hours}{year}]$ | **MIOP** $[\frac{p.u.}{year}]$ | **ILSE** $[\frac{kW/occurrence}{year}]$ | **DEP** $[\frac{p.u.}{year}]$ |
|---|---|---|---|---|---|---|
| **1** | ¡10 | 46761.8 | 6162.5 | 0.296 | 2.588 | 0.283 |
| **2** | 35 | 30479.9 | 5086.9 | 0.419 | 5.991 | 0.533 |
| **3** | 20 | 38916.0 | 5489.2 | 0.372 | 7.077 | 0.404 |
| **4** | 16 | 33162.7 | 4983.7 | 0.431 | 6.654 | 0.492 |
| **5** | 30 | 30358.3 | 4912.5 | 0.439 | 6.179 | 0.535 |

# Chapter 6

# Conclusions

- The need for development of computer tools and methodologies that assess the selection of distributed generation systems in residential buildings considering reliability and power demand models has been stated and justified in this master thesis.

- In the interest of properly sizing the power generation from distributed energy systems in residential buildings as a function of the demanded power, a simple but effective 1-hour resolution power demand model suitable to be used in power reliability analysis has been implemented. It considers the dwellings' energy consumption, the number of users per dwelling, the non-occupied periods of the inhabitants and the load's usage pattern between others aspects.

- A generating system adequacy assessment methodology for residential buildings has been developed to select the best distributed generation system. By doing this, relevant power reliability indices were attained. To guarantee reasonable accuracy in the results and decide if convergence was achieved in the simulation, the coefficient of variation (COV) for the Loss of Energy Expectation (LOEE) index was used as it has the lowest convergence speed compared to other indices. The attained results were very promising as they quantitatively revealed the most suitable power generation combination in terms of power reliability as in Study Case 2.

- To improve the reliability indexes, as Study Case 1 denoted, it is highly advisable for residential nearly Zero-Energy Buildings promoters to carefully study the not-occupied periods of the inhabitants or ultimately carry out demand-side management actions if possible. The higher the mismatch between the power generation and the demand, the worse the reliability performance.

- Reliability studies are very important to evaluate power generation systems, however it is crucial to counterweight reliability aspects with monetary constraints to have enough output information to properly decide the best distributed generation option.

- As a future development, it will be highly relevant to use viable optimization techniques to automatically provide the optimum generation system configurations rapidly and accurately. The employed optimization variables should compromise reliability, economic and environmental concerns.

# Appendix A

# Tables

Table A.1: Usage hours for every load for two occupants.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Load** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **Cooker** | 3 | 3 | 2 | 3 |
| **Fridge** | 12 | 12 | 12 | 12 |
| **TV** | 6 | 6 | 5 | 8 |
| **Washer** | 1 | 1 | 1 | 1 |
| **Stand-by** | 24 | 24 | 24 | 24 |
| **Oven** | 1 | 1 | 1 | 1 |
| **PC** | 4 | 4 | 3 | 6 |
| **Dish Washer** | 2 | 2 | 1 | 2 |
| **Dryer** | 1 | 1 | 1 | 1 |
| **Others** | 3,4,5* | 3,4,5* | 2,3,4* | 4,5,6* |
| **Air conditioning** | 3** | 3** | 3** | 5** |

*Are randomly selected for every day

**Only during summer days

Table A.2: Usage hours for every load for three occupants.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Load** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **Cooker** | 4 | 4 | 3 | 4 |
| **Fridge** | 12 | 12 | 12 | 12 |
| **TV** | 6 | 6 | 5 | 8 |
| **Washer** | 1 | 1 | 1 | 1 |
| **Stand-by** | 24 | 24 | 24 | 24 |
| **Oven** | 1 | 1 | 1 | 1 |
| **PC** | 4 | 4 | 3 | 6 |
| **Dish Washer** | 2 | 2 | 1 | 2 |
| **Dryer** | 1 | 1 | 1 | 1 |
| **Others** | 3,4,5* | 3,4,5* | 2,3,4* | 4,5,6* |
| **Air conditioning** | 4** | 4** | 4** | 5** |

*Are randomly selected for every day

**Only during summer days

Table A.3: Usage hours for every load for four occupants.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Load** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **Cooker** | 4 | 4 | 3 | 4 |
| **Fridge** | 12 | 12 | 12 | 12 |
| **TV** | 6 | 6 | 5 | 8 |
| **Washer** | 2 | 2 | 2 | 2 |
| **Stand-by** | 24 | 24 | 24 | 24 |
| **Oven** | 1 | 1 | 1 | 1 |
| **PC** | 4 | 4 | 3 | 6 |
| **Dish Washer** | 3 | 3 | 2 | 3 |
| **Dryer** | 2 | 2 | 2 | 2 |
| **Others** | 3,4,5* | 3,4,5* | 2,3,4* | 4,5,6* |
| **Air conditioning** | 4** | 4** | 4** | 5** |

*Are randomly selected for every day

**Only during summer days

Table A.4: Usage hours for every load for five occupants.

| | **Unoccupied Period** | | | |
|---|---|---|---|---|
| **Load** | **9:00 to 14:00** | **14:00 to 19:00** | **9:00 to 18:00** | **No** |
| **Cooker** | 5 | 5 | 4 | 5 |
| **Fridge** | 12 | 12 | 12 | 12 |
| **TV** | 7 | 7 | 6 | 9 |
| **Washer** | 2 | 2 | 2 | 2 |
| **Stand-by** | 24 | 24 | 24 | 24 |
| **Oven** | 1 | 1 | 1 | 1 |
| **PC** | 4 | 4 | 3 | 6 |
| **Dish Washer** | 3 | 3 | 2 | 3 |
| **Dryer** | 2 | 2 | 2 | 2 |
| **Others** | 3,4,5* | 3,4,5* | 2,3,4* | 4,5,6* |
| **Air conditioning** | 5** | 5** | 5** | 6** |

*Are randomly selected for every day

**Only during summer days

Table A.5: Hourly usage weightiness for an unoccupied period from 9:00 to 14:00 for the different loads.

| | **Appliance/load** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Hour** | **Electric Cooker** | **Lighting** | **TV** | **Washer** | **Oven** | **PC** | **Dish Washer** | **Dryer** | **Others** | **Air Conditioner** |
| **1** | 0% | 3% | 2% | 2% | 0% | 4% | 2% | 2% | 3% | 6% |
| **2** | 0% | 2% | 2% | 0% | 0% | 2% | 0% | 0% | 2% | 3% |
| **3** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **4** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **5** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **6** | 0% | 3% | 2% | 0% | 0% | 2% | 0% | 0% | 2% | 1% |
| **7** | 7% | 8% | 6% | 6% | 3% | 3% | 4% | 6% | 3% | 1% |
| **8** | 17% | 7% | 6% | 8% | 10% | 3% | 10% | 8% | 7% | 2% |
| **9** | 7% | 4% | 6% | 8% | 20% | 3% | 15% | 8% | 7% | 2% |
| **10** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **11** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **12** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **13** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **14** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **15** | 7% | 2% | 10% | 8% | 20% | 7% | 5% | 7% | 8% | 8% |
| **16** | 17% | 2% | 6% | 8% | 11% | 8% | 5% | 8% | 8% | 8% |
| **17** | 7% | 3% | 5% | 9% | 5% | 9% | 10% | 8% | 7% | 8% |
| **18** | 1% | 5% | 5% | 9% | 2% | 9% | 8% | 9% | 7% | 9% |
| **19** | 1% | 8% | 5% | 9% | 2% | 8% | 4% | 9% | 7% | 9% |
| **20** | 7% | 10% | 10% | 7% | 10% | 8% | 5% | 9% | 8% | 8% |
| **21** | 17% | 10% | 10% | 6% | 5% | 7% | 8% | 7% | 8% | 8% |
| **22** | 7% | 10% | 10% | 6% | 5% | 9% | 10% | 6% | 7% | 8% |
| **23** | 4% | 10% | 6% | 7% | 4% | 9% | 8% | 6% | 7% | 8% |
| **24** | 1% | 10% | 6% | 7% | 3% | 6% | 6% | 7% | 6% | 8% |
| | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Table A.6: Hourly usage weightiness for an unoccupied period from 14:00 to 19:00 for the different loads.

| | **Appliance/load** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Hour** | **Electric Cooker** | **Lighting** | **TV** | **Washer** | **Oven** | **PC** | **Dish Washer** | **Dryer** | **Others** | **Air Conditioner** |
| **1** | 0% | 5% | 2% | 2% | 0% | 4% | 2% | 3% | 3% | 6% |
| **2** | 0% | 2% | 2% | 0% | 0% | 2% | 0% | 2% | 2% | 3% |
| **3** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 1% | 1% | 1% |
| **4** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 1% | 1% | 1% |
| **5** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 1% | 1% | 1% |
| **6** | 0% | 3% | 2% | 0% | 0% | 2% | 0% | 2% | 2% | 1% |
| **7** | 7% | 9% | 6% | 6% | 2% | 3% | 4% | 3% | 3% | 1% |
| **8** | 17% | 8% | 6% | 8% | 8% | 5% | 4% | 6% | 6% | 2% |
| **9** | 7% | 5% | 6% | 8% | 8% | 5% | 8% | 7% | 7% | 2% |
| **10** | 1% | 3% | 5% | 9% | 4% | 6% | 10% | 6% | 6% | 3% |
| **11** | 1% | 2% | 5% | 9% | 4% | 6% | 10% | 6% | 6% | 3% |
| **12** | 7% | 2% | 6% | 9% | 4% | 6% | 5% | 6% | 6% | 4% |
| **13** | 17% | 2% | 10% | 9% | 20% | 8% | 5% | 8% | 8% | 6% |
| **14** | 7% | 2% | 5% | 6% | 10% | 6% | 10% | 6% | 6% | 6% |
| **15** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **16** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **17** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **18** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **19** | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| **20** | 7% | 11% | 10% | 8% | 10% | 9% | 7% | 7% | 7% | 12% |
| **21** | 17% | 11% | 10% | 8% | 13% | 9% | 10% | 9% | 9% | 12% |
| **22** | 7% | 11% | 10% | 6% | 10% | 9% | 13% | 9% | 9% | 12% |
| **23** | 4% | 11% | 6% | 6% | 4% | 9% | 8% | 9% | 9% | 12% |
| **24** | 1% | 10% | 6% | 6% | 3% | 8% | 4% | 8% | 8% | 12% |
| | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

Table A.7: Hourly usage weightiness when the dwelling is occupied all day long.

| | **Appliance/load** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Hour** | **Electric Cooker** | **Lighting** | **TV** | **Washer** | **Oven** | **PC** | **Dish Washer** | **Dryer** | **Others** | **Air Conditioner** |
| **1** | 0% | 4% | 2% | 2% | 0% | 4% | 2% | 2% | 4% | 4% |
| **2** | 0% | 1% | 1% | 0% | 0% | 2% | 0% | 2% | 2% | 3% |
| **3** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **4** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **5** | 0% | 1% | 1% | 0% | 0% | 1% | 0% | 0% | 1% | 1% |
| **6** | 0% | 2% | 1% | 0% | 4% | 2% | 0% | 0% | 2% | 1% |
| **7** | 2% | 4% | 5% | 8% | 8% | 3% | 2% | 2% | 4% | 1% |
| **8** | 5% | 5% | 5% | 12% | 14% | 4% | 3% | 3% | 6% | 2% |
| **9** | 17% | 6% | 7% | 10% | 14% | 5% | 4% | 3% | 6% | 2% |
| **10** | 5% | 3% | 4% | 0% | 0% | 6% | 10% | 4% | 4% | 2% |
| **11** | 3% | 2% | 4% | 0% | 0% | 7% | 4% | 7% | 4% | 2% |
| **12** | 3% | 2% | 3% | 0% | 0% | 6% | 3% | 9% | 4% | 3% |
| **13** | 3% | 2% | 4% | 0% | 0% | 5% | 3% | 9% | 4% | 5% |
| **14** | 5% | 2% | 7% | 0% | 0% | 3% | 6% | 8% | 6% | 5% |
| **15** | 5% | 2% | 4% | 0% | 0% | 4% | 10% | 5% | 6% | 6% |
| **16** | 15% | 2% | 4% | 0% | 0% | 5% | 15% | 6% | 5% | 6% |
| **17** | 5% | 2% | 4% | 0% | 0% | 6% | 4% | 7% | 4% | 7% |
| **18** | 2% | 3% | 4% | 0% | 0% | 7% | 2% | 7% | 4% | 7% |
| **19** | 2% | 10% | 4% | 10% | 10% | 6% | 2% | 4% | 6% | 7% |
| **20** | 5% | 10% | 9% | 12% | 12% | 4% | 4% | 4% | 6% | 7% |
| **21** | 16% | 10% | 9% | 12% | 14% | 4% | 8% | 4% | 6% | 7% |
| **22** | 5% | 10% | 9% | 12% | 11% | 4% | 10% | 5% | 6% | 7% |
| **23** | 1% | 9% | 4% | 12% | 10% | 4% | 6% | 5% | 4% | 7% |
| **24** | 1% | 6% | 3% | 10% | 3% | 6% | 2% | 4% | 4% | 6% |
| | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |

# Appendix B

# Computer Tool: GenMIX v1.0 beta

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.

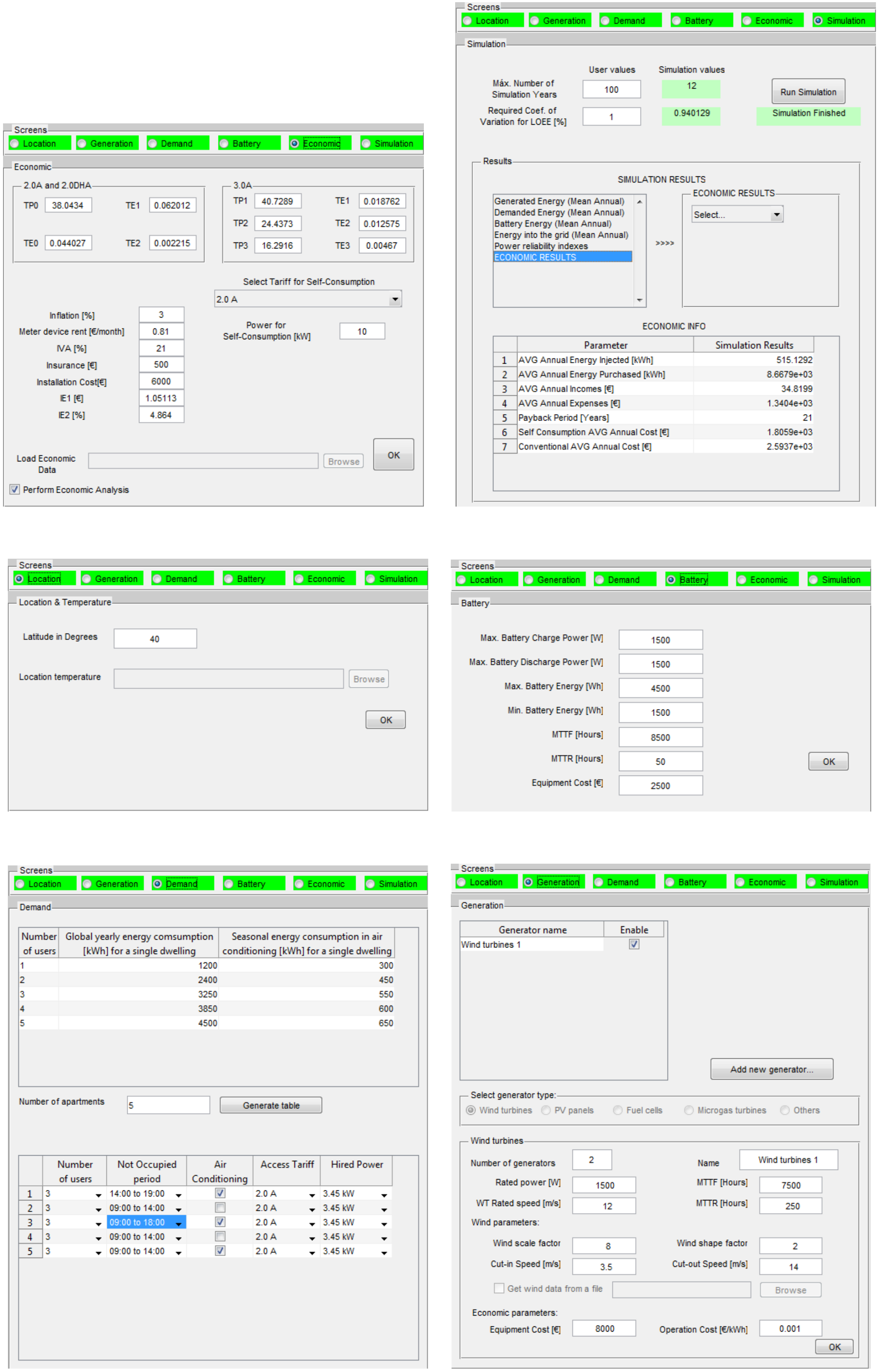
**Demand Panel.** In this panel the user configures the power demand characteristics of the different dwellings for the studied building as well as the mean annual energy demand requirements.

**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 B-1 exposes the different GUI panels while Figure B-2 presents a general overview of the entire GUI.



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

SIMULATION RESULTS

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

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:

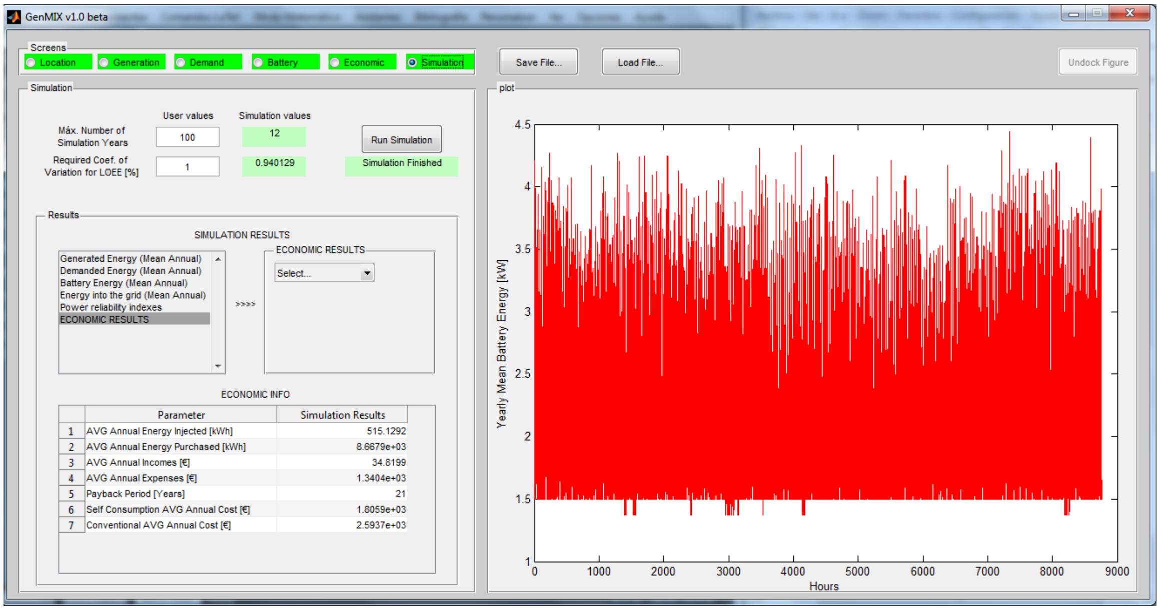
Wind scale factor 8
Wind shape factor 2
Cut-in Speed [m/s] 3.5
Cut-out Speed [m/s] 14

☐ Get wind data from a file

Economic parameters:

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

Figure B-1: GUI's different panels



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

Simulation Finished

SIMULATION RESULTS

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

ECONOMIC RESULTS

Select...

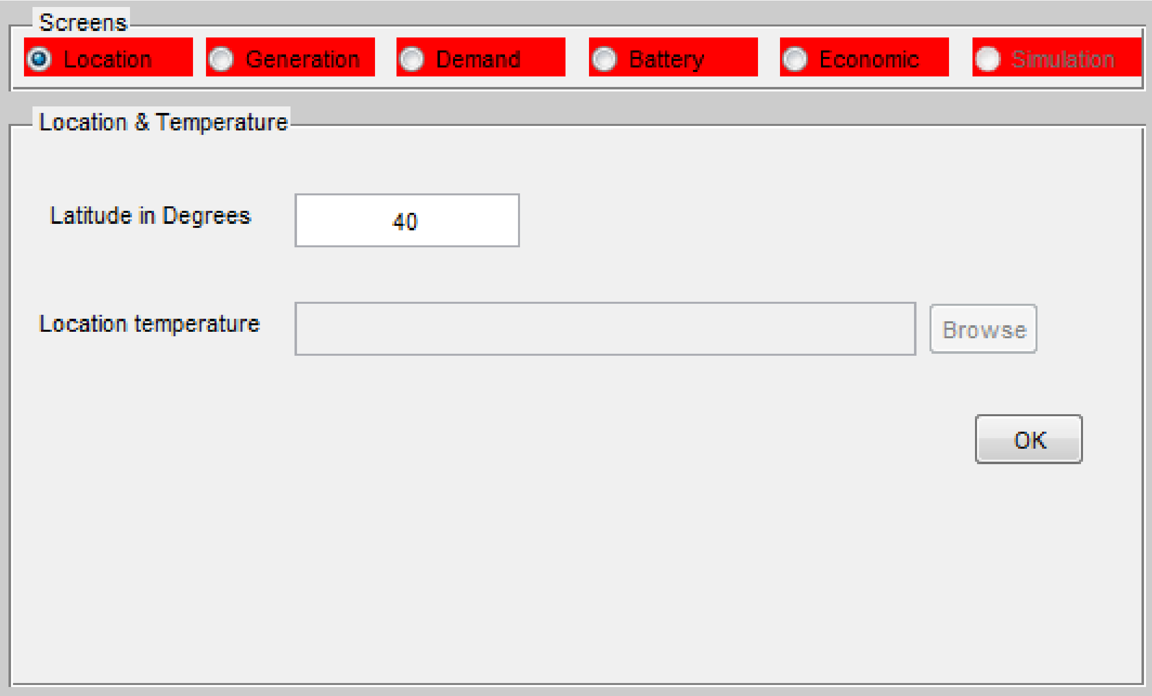
ECONOMIC INFO

| | 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 |

Figure B-2: General GUI layout

## B.1 Quick User Guide

Once we open the program, at the beginning the name's background of the different GUI's panels are colored in red (See Figure B-3), implying that the user requires to appropriately input the required information in all these panels to be allowed to perform simulations. Once the different fields in each panel are correctly filled, the background's name of the particular panel is colored in green.



Latitude in Degrees 40

Figure B-3: GUI's panels when starting the program

### B.1.1 Location Panel

In the "Location" panel (See Figure B-3), the user has to enter the Location's latitude in degrees (positive if northern and negative if southern). In future versions of the program, the user will have the chance to add his own location's temperature file which will contain the mean hourly temperature values for an entire year (8760 values). The latitude datum is specially used in the PV panel model for power generation and in the power demand model for the obtaining the air conditioner's usage hours. After typing the desired location's temperature and pressing the OK button, the background's name of the Location panel is colored in green.

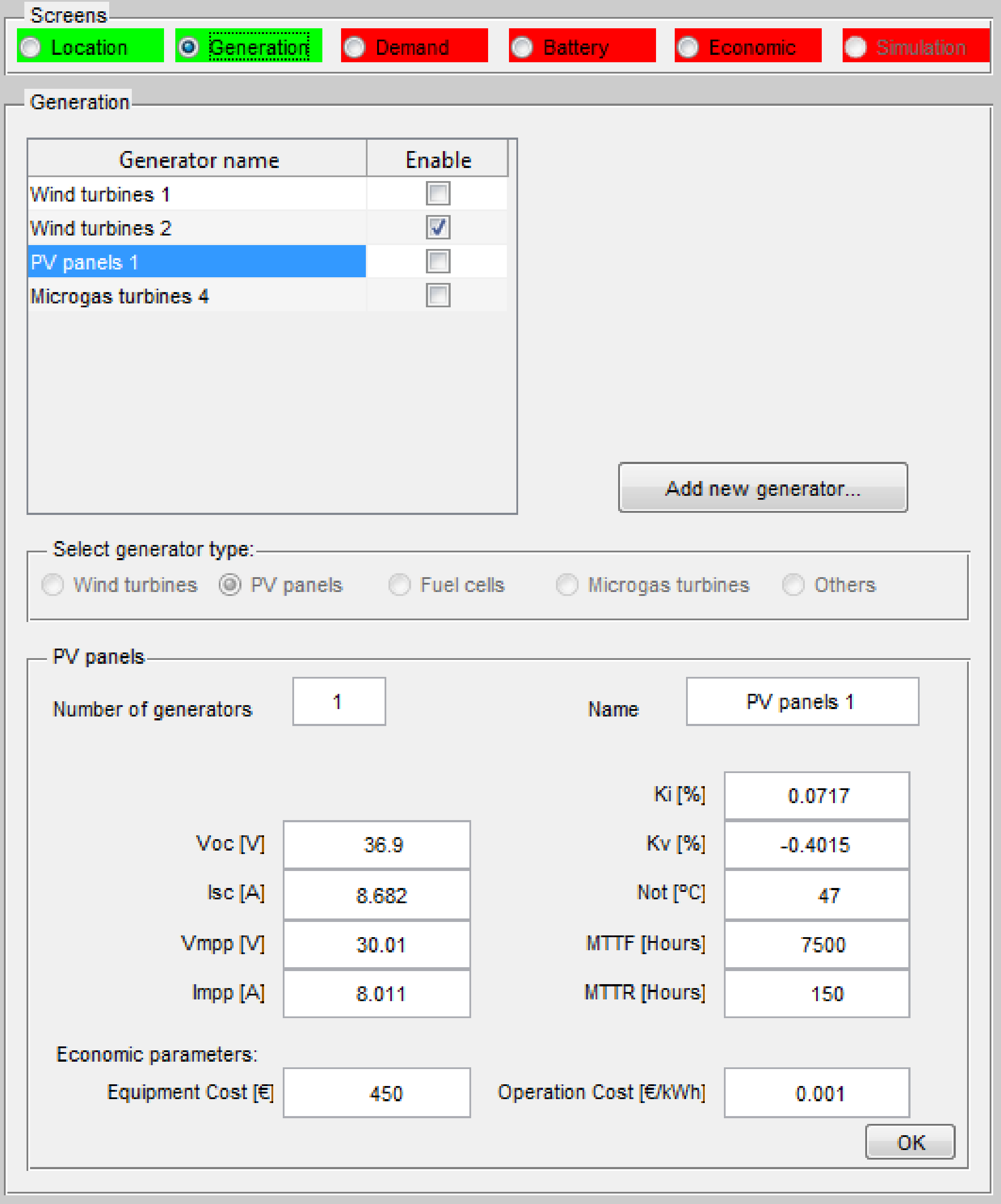
### B.1.2 Generation Panel

In the "Generation" panel (See Figure B-4), the first thing we have to do is pressing the "Add new generator" button. When doing this, we can choose between five different power generators: Wind Turbines, PV panels, Fuel Cells, Microgas Turbines and Others. Each generator type has its own parameters to be filled as Tables B.1 to B.3 detail.

After filling all the required parameters for each generator, a click in the "OK" button at the bottom of the window has to be done to load the generator type and configuration in the Generators List at the top-left side of the panel. Between this list, we have to select the generators we want to be considered when performing the simulation. This is done by clicking in the corresponding check box from every generator. Note that the "Generation" panel information is considered to be correctly filled (its background's name turns to green) when at least one generator from the list is activated.

### B.1.3 Demand Panel

This panel (See Figure B-5) consists of two sections. In the first section (located in the upper area), the user has to fill from one to five inhabitants per apartment; the total yearly energy consumption for the different dwelling's loads and the seasonal air conditioner energy consumption, both data in [kWh]. To generate the second section (located in the bottom area), the user firstly has to input the number of apartments in the building and then make a click in the "Generate Table" button. Then, a table appears. In this table, for the different apartments in the building; the user has to insert the number of inhabitants, the not-occupied period, the air conditioner existence, the access tariff and the hired power. For more information related to the access tariff and hired power terms, see reference [27].



Screens

○ Location ● Generation ○ Demand ○ Battery ○ Economic ○ Simulation

Generation

| Generator name | Enable |
|---|---|
| Wind turbines 1 | ☐ |
| Wind turbines 2 | ☑ |
| PV panels 1 | ☐ |
| Microgas turbines 4 | ☐ |

Select generator type:

○ Wind turbines ● PV panels ○ Fuel cells ○ Microgas turbines ○ Others

PV panels

Number of generators: 1

Name: PV panels 1

Voc [V]: 36.9
Isc [A]: 8.682
Vmpp [V]: 30.01
Impp [A]: 8.011
Ki [%]: 0.0717
Kv [%]: -0.4015
Not [ºC]: 47
MTTF [Hours]: 7500
MTTR [Hours]: 150

Economic parameters:

Equipment Cost [€]: 450
Operation Cost [€/kWh]: 0.001

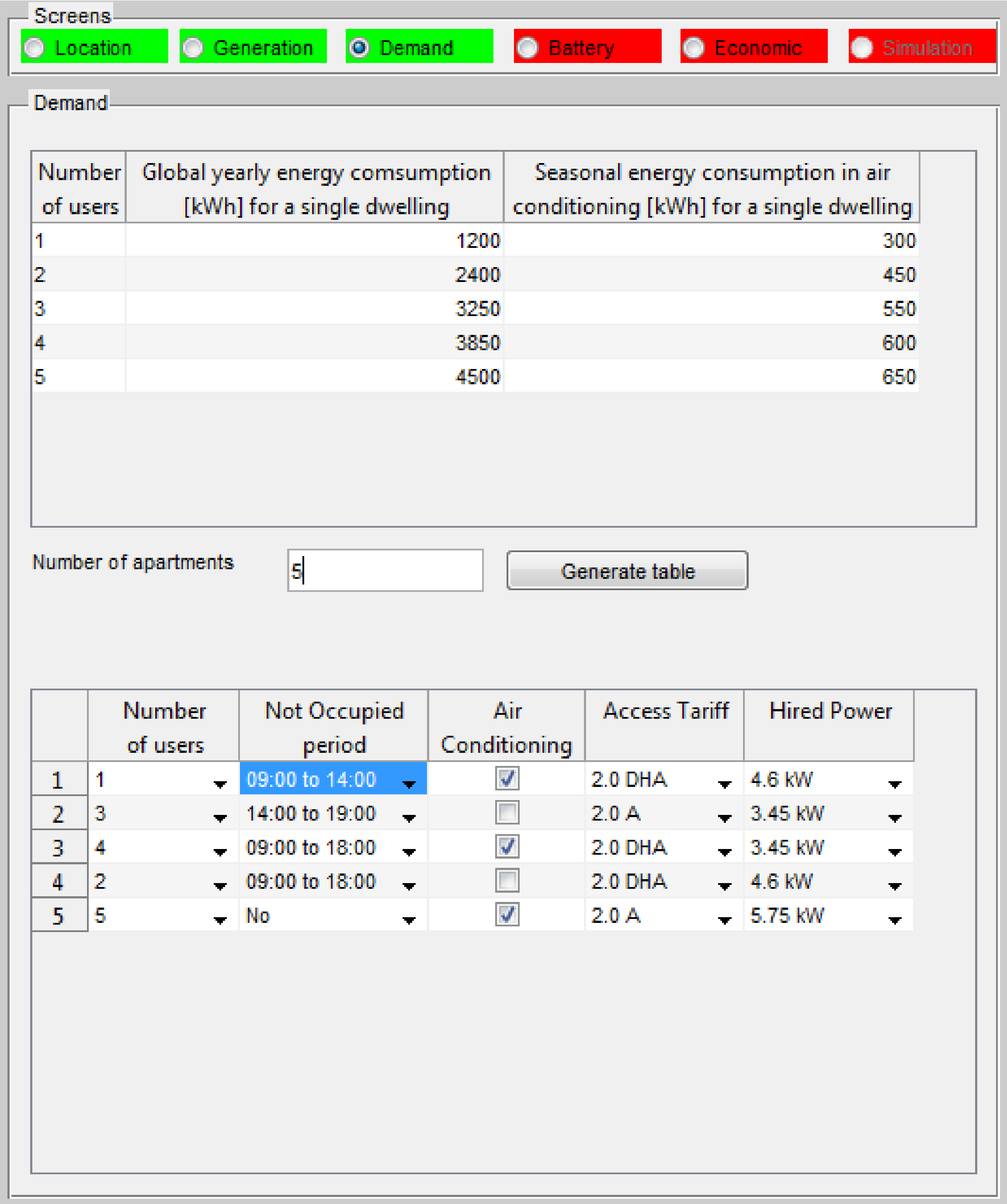
Figure B-4: GUI's generation panel

Table B.1: Wind turbine generation system parameters

| | **WTG Parameters** | **Units** | **Explanation** |
|---|---|---|---|
| **WTGS Characteristics** | Number of generators | u. | Number of WTGs (having the same characteristics) inside the generation group. |
| | Name | - | Generation group name. |
| | Rated power | W | Nominal wind turbine generator's power. |
| | Rated speed | m/s | Wind speed to produce nominal power. |
| | Cut-in speed | m/s | Wind speed where power production begins. |
| | Cut-out speed | m/s | Wind speed where power production stops. |
| **Location's Wind Speed** | Scale factor | m/s | Wind speed scale factor ($c$) from the Weibull probability distribution function. |
| | Shape factor | m/s | Wind speed shape factor ($k$) from the Weibull probability distribution function. |
| **Monte Carlo Model** | $MTTF$ | Hours | Mean Time to Failure. |
| | $MTTR$ | Hours | Mean Time to Repair. |
| **Economic data** | Equipment cost | euro | WTG group price including power electronics, cabling and protections. |
| | Operating cost | euro/ kWh | Related costs for the machine to work properly |

Table B.2: PV generation system parameters

| | **WTG Parameters** | **Units** | **Explanation** |
|---|---|---|---|
| **PV Panel Characteristics** | Number of generators | u. | Number of PV panels (having the same characteristics) inside the generation group. |
| | Name | - | PV group name. |
| | $V_{OC}$ | V | Open Circuit voltage |
| | $I_{SC}$ | A | Short-circuit current |
| | $V_{MPP}$ | V | PV panel Maximum power point voltage |
| | $I_{MPP}$ | A | Maximum power point current |
| | $K_I$ | mA/K | Temperature factor of the short-circuit current in terms of ampere per Celsius degree. |
| | $K_V$ | mV/K | Open-circuit voltage temperature factor in terms of volt per Celsius degree |
| | $N_{OT}$ | ºC | Normal operating temperature |
| **Monte Carlo Model** | $MTTF$ | Hours | Mean Time to Failure. |
| | $MTTR$ | Hours | Mean Time to Repair. |
| **Economic data** | Equipment cost | euro | PV generation group price including power electronics, cabling and protections. |
| | Operating cost | euro/ kWh | Related costs for the PV group to work properly |



Screens

○ Location ○ Generation ● Demand ○ Battery ○ Economic ○ Simulation

Demand

| 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 | 1 | 09:00 to 14:00 | ☑ | 2.0 DHA | 4.6 kW |
| 2 | 3 | 14:00 to 19:00 | ☐ | 2.0 A | 3.45 kW |
| 3 | 4 | 09:00 to 18:00 | ☑ | 2.0 DHA | 3.45 kW |
| 4 | 2 | 09:00 to 18:00 | ☐ | 2.0 DHA | 4.6 kW |
| 5 | 5 | No | ☑ | 2.0 A | 5.75 kW |

Figure B-5: GUI's demand panel

Table B.3: Fuel cell, Microgas Turbine and Other Generators' parameters

| | **Generator Parameters** | **Units** | **Explanation** |
|---|---|---|---|
| **Generator Characteristics** | Number of generators | u. | Number of generators (having the same characteristics) inside the generation group. |
| | Name | - | Generation group name. |
| | Rated power | W | Nominal generator power |
| | Minimum power | W | Minimum generator power production |
| **Monte Carlo Model** | $MTTF$ | Hours | Mean Time to Failure. |
| | $MTTR$ | Hours | Mean Time to Repair. |
| **Economic data** | Equipment cost | euro | Generation group price including power electronics, cabling and protections. |
| | Operating cost | euro/ kWh | Related costs for the generation group to work properly |

### B.1.4 Battery Panel

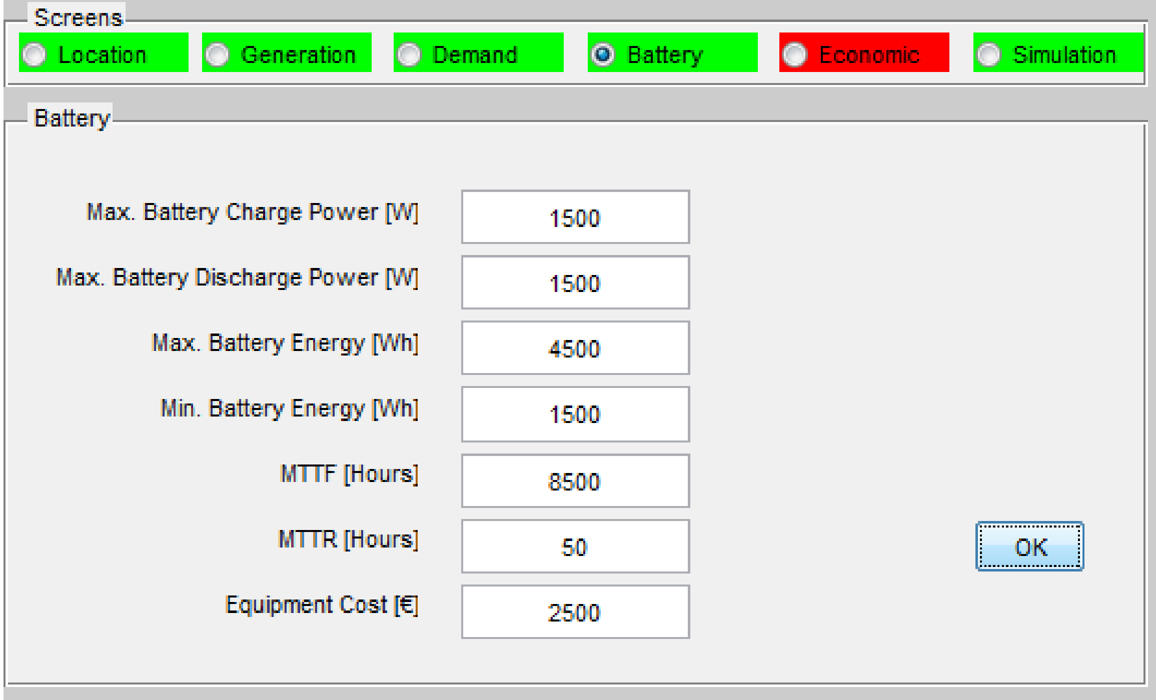
In this panel (See Figure B-6), the energy storage system parameters detailed in Table B.4 have to be filled. If all these required fields are opportunely inserted, the panel's name background is colored in green. Furthermore, if the data of the previous panels were also successfully added (having their panel's name background a green color), the Simulation Panel is then activated. This is because the information request for the Economic Panel is not mandatory to perform simulations. In this case, the program will only perform power reliability analyses.

### B.1.5 Economic Panel

This panels (See Figure B-7) demands information to study the economic viability of the studied distributed generation system. The user has to feed in, for the conventional consumption analysis, the dwellings' power and energy terms for the Spanish

Table B.4: Battery parameters

| | **Generator Parameters** | **Units** | **Explanation** |
|---|---|---|---|
| **Generator Characteristics** | Max. Battery Charge Power | W | Maximum charging power that the battery is able to withstand. |
| | Max. Battery Discharge Power | W | Maximum discharging power that the battery is able to withstand. |
| | Max. Battery Energy | Wh | Maximum energy that the battery is able to store without decreasing its lifespan. |
| | Min. Battery Energy | Wh | Minimum energy that the battery is able to store without decreasing its lifespan. |
| **Monte Carlo Model** | $MTTF$ | Hours | Mean Time to Failure. |
| | $MTTR$ | Hours | Mean Time to Repair. |
| **Economic data** | Equipment cost | euro | Storage system price including power electronics, cabling and protections. |
| | Operating cost | euro/ kWh | Related costs for the battery to work properly |



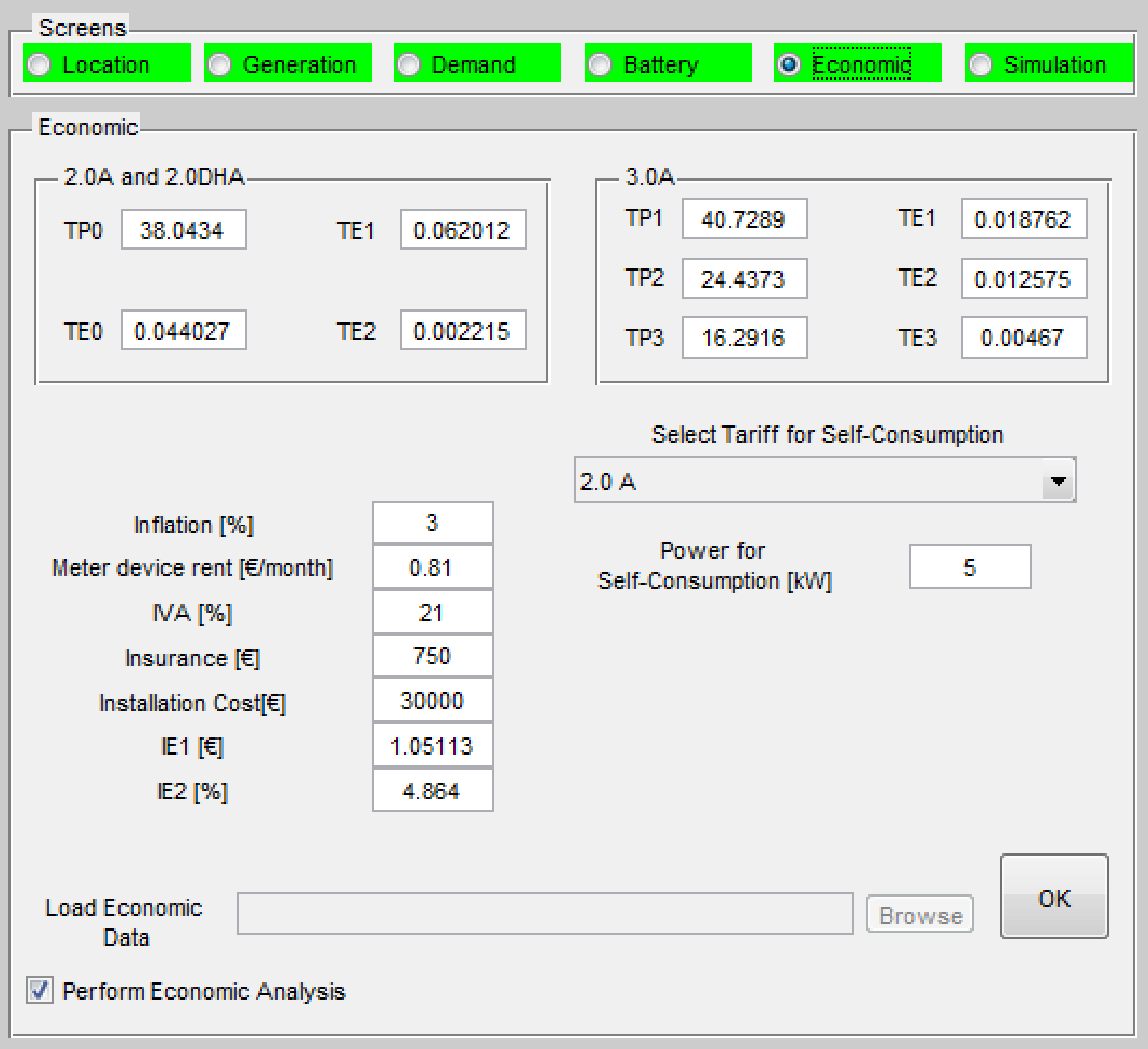
Max. Battery Charge Power [W]: 1500
Max. Battery Discharge Power [W]: 1500
Max. Battery Energy [Wh]: 4500
Min. Battery Energy [Wh]: 1500
MTTF [Hours]: 8500
MTTR [Hours]: 50
Equipment Cost [€]: 2500

Figure B-6: GUI's battery panel

access tariffs 2.0A, 2.0DHA and 3.0A. For the self-consumption study, the building's access tariff and the hired power have to be also selected. Additionally, the user is required to insert: the inflation (%), the meter device rent (euro/month), the IVA (%), the yearly insurance cost (euro), the generation system installation cost (euro) and the electrical taxes. For detailed information about the previous parameters, see Reference [27]. For the program to consider the economic analysis during simulation, the check box button at the bottom-left of the panel has to be selected.

### B.1.6 Simulation Panel

To perform a simulation, on the upper area of the panel the user firstly has to insert the maximum number of simulation years and the required Coefficient of Variation (COV) as a percentage (See Figure B-8). Then, to begin the simulation, the "Run Simulation" button has to be pressed. The simulation will stop when the selected COV is lower than the required tolerance value. If the COV does not become lower than the prespecified value but the maximum number of simulation years is achieved,



○ Location ○ Generation ○ Demand ○ Battery ● Economic ○ Simulation

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

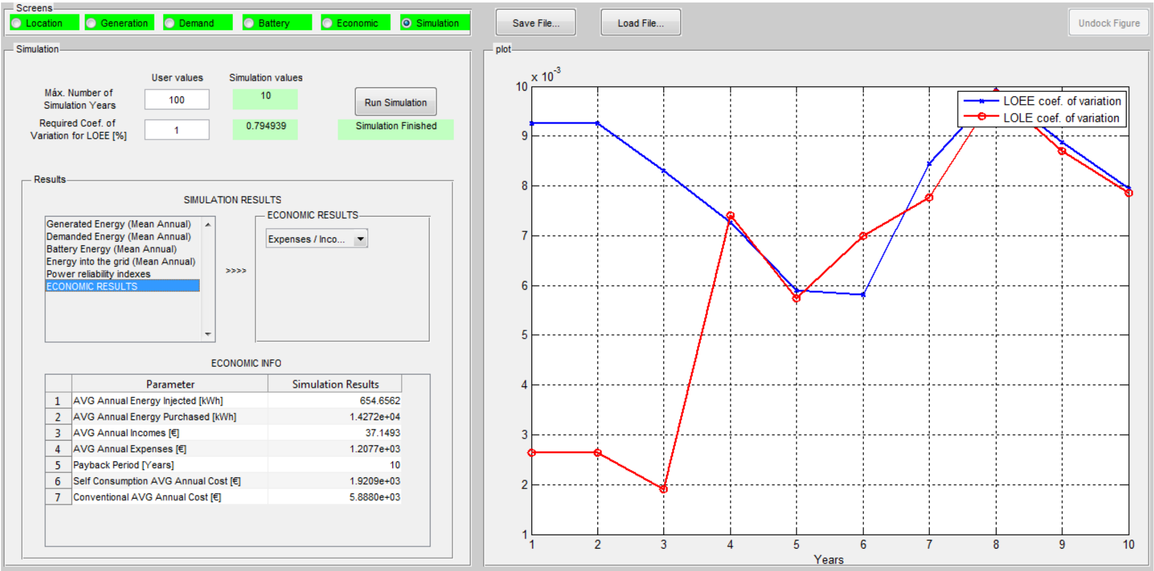
Power for Self-Consumption [kW]: 5

| | |
|---|---|
| Inflation [%] | 3 |
| Meter device rent [€/month] | 0.81 |
| IVA [%] | 21 |
| Insurance [€] | 750 |
| Installation Cost[€] | 30000 |
| IE1 [€] | 1.05113 |
| IE2 [%] | 4.864 |

Load Economic Data

☑ Perform Economic Analysis

Figure B-7: GUI's economic panel



| | User values | Simulation values |
|---|---|---|
| Máx. Number of Simulation Years | 100 | 10 |
| Required Coef. of Variation for LOEE [%] | 1 | 0.794939 |

Simulation Finished

ECONOMIC INFO

| | Parameter | Simulation Results |
|---|---|---|
| 1 | AVG Annual Energy Injected [kWh] | 654.6562 |
| 2 | AVG Annual Energy Purchased [kWh] | 1.4272e+04 |
| 3 | AVG Annual Incomes [€] | 37.1493 |
| 4 | AVG Annual Expenses [€] | 1.2077e+03 |
| 5 | Payback Period [Years] | 10 |
| 6 | Self Consumption AVG Annual Cost [€] | 1.9209e+03 |
| 7 | Conventional AVG Annual Cost [€] | 5.8880e+03 |

Figure B-8: GUI's simulation panel

the simulation will also be stopped. In addition, if the COV rapidly achieves the desired value, the simulation is carried out for at least 10 years to ensure the attainment of representative results.

Once the simulation is finished, the "Results" sub-panel appears. It gives the user the chance to visualize the building's performance regarding to the mean annual generated energy, demanded energy, battery energy, energy into the grid and power reliability analysis. If the economic analysis was activated in the "Economic" panel, the economic results can be also observed. The mentioned results are presented in the right-side plot panel (See Figure B-8).

Additionally, the user has the chance to load and save the entire simulation file containing all the inserted information and the output results by using the corresponding buttons located above the plot panel.

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