FINAL DEGREE PROJECT

Degree in Energetic Engineering

ENERGY-LEVEL SIMULATOR FOR MICRO-GRIDS

Volume I

Technical Report

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Resum

El present treball pretén aportar una eina per a l'anàlisi de les Micro Xarxes Intel·ligents a nivell de polítiques energètiques i gestió de fluxos de potència. Es presenta l'eina com un simulador desenvolupat en Matlab que permet implementar una gran varietat d'algoritmes de gestió tenint en compte un ampli ventall de variables. El nivell de flexibilitat és elevadíssim podent-se integrar en l'algoritme diferents nivells per tal de controlar MXI aïllades, MXI interconnectades entre elles, o hibridacions d'aquestes. Això és possible utilitzant els models dels elements més representatius d'aquests sistemes com són un camp fotovoltaic, bateries, generadors, càrregues...; un mòdul de captació de paràmetres dels diferents elements de les MXI; uns fulls de càlcul amb dades externes per cada MXI a simular i finalment amb un "script" que permet dur a terme la simulació de la llargada i precisió temporal escollida per l'usuari.

S'il·lustra el correcte funcionament del simulador amb la implementació d'uns algoritmes de gestió d'energia. En aquest cas d'estudi també es pretén demostrar la maniobrabilitat del simulador permetent la implementació de dos algoritmes diferents per estudiar com afecten en un mateix habitatge i comparant-ne els resultats.

El programa és ampliable per afegir-hi altres elements interessants com podrien ser els generadors eòlics, càrregues desplaçables... I també es podria ampliar per tal de realitzar l'estudi d'energia reactiva. No es considera interessant augmentar-ne la complexitat dels models ja que això esdevindria en uns temps de simulació molt més elevats.

Resumen

El Trabajo presente pretende aportar una herramienta para el análisis de las Micro Redes Inteligentes a nivel de políticas energéticas y gestión de flujos de potencia. Se presenta la herramienta como un simulador desarrollado en Matlab que permite implementar una gran variedad de algoritmos de gestión teniendo en cuenta un amplio abanico de variables. El nivel de flexibilidad es elevadísimo pudiéndose integrar en el algoritmo diferentes niveles con tal de controlar MRI aisladas, MRI interconectadas o hibridaciones de éstas. Esto es posible utilizando modelos de los elementos más representativos de estos sistemas como son los campos fotovoltaicos, las baterías, generadores, cargas…; un módulo de captación de parámetros de las diferentes MRI; unas hojas de cálculo con datos externos mara cada MRI a simular y finalmente con un "script" que permite llevar a cabo la simulación de la duración y precisión temporal escogida por el usuario.

Se ilustra el correcto funcionamiento del simulador con la implementación de unos algoritmos de gestión de la energía. En este caso de estudio se pretende también demostrar la maniobrabilidad del simulador permitiendo la implementación de dos algoritmos diferentes para estudiar cómo afectan a una misma vivienda y comparar los resultados finalmente.

El programa es ampliable para añadir otros elementos interesantes como podrían ser los generadores eólicos, las cargas desplazables… Y también se podría ampliar con tal de permitir estudios de energía reactiva. No se considera interesante aumentar la complejidad de los modelos ya que esto devendría en unos tiempos de simulación muy superiores.

Abstract

The present paper aims to provide a tool for the analysis of Smart Micro Grids at the level of energy policies and management of power fluxes. The tool is presented as a simulator developed in Matlab that allows implementing a wide variety of management algorithms taking into account a wide range of variables. The level of flexibility is high, being able to integrate different levels in the algorithm to control isolated SMG, SMG interconnected between them, or hybridization of them. This is possible using the models of the most representative elements of these systems such as a photovoltaic field, batteries, generators, loads... A module for capturing parameters of the different elements of the SMG. Spreadsheets with external data for each SMG to simulate and finally with a script that allows to carry out the simulation of the length and timing chosen by the user.

It illustrates the correct operation of the simulator with the implementation of some energy management algorithms. In this study case, it is also intended to demonstrate the maneuverability of the simulator, allowing the implementation of two different algorithms to study how they affect the same house and comparing the results.

The program is expandable to add other interesting elements such as wind generators, movable loads... And it could also be expanded to carry out the reactive energy study. It is not considered interesting to increase the complexity of the models, as this would become in a much higher simulation times.

Agraïments

Vull donar les gràcies als meus tutors.

Al Guillermo per haver-me donat una dosis tant clara de coneixements sobre el funcionament dels diferents elements reals que conformen les xarxes, tant les intel·ligents com les que no. Van resultar unes hores molt enriquidores i aclaridores de molts dubtes que havien anat sorgint a mesura que avançava el projecte.

A l'Herminio per haver primer de tot escoltat la meva proposta de TFG, acceptar fer-me de tutor tot i la tardança de la meva petició i finalment proposar-me un projecte molt semblant a la meva idea principal però amb un enfoc que a la llarga s'ha donat a conèixer com molt més interesant des del punt de vista global i transversal.

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1. Preface

1.1. Origin of the project

This paper pretends to be the continuation of a previous project developed in the subject “Control de Sistemes Energètics”. This was maybe the most interesting project developed during the bachelor because it had everything one Energetic Engineering Student searches when chooses to study this degree. It had renewable generation, domestic applications and intention of home automation.

The initial idea for the project was to develop a software to design efficient SMGs automatically. At that time I was underestimating the power of the EMS in the final results and overestimating the power of the hardware in the final results. And starting the project made me realize the high impact of the energetic policies, and the results of this project made me understand that more than what do you have is how do you use it.

1.2. Motivation

I was truly to do a final thesis about computing and energy. The objective was to have reliable results without have to get them using real components and the time it takes to get them. There was also a lot of interest on having good models for different elements such PV panels and batteries, to realize which the real potential of those elements is. Advancing more in to the project this motivations were satisfied and ended in the background. The new motivational points were to make the program really flexible, able to study the most complex and outlandish situations, and everything in a not complex way.

2. Introduction

2.1. Objectives of the paper

The project pretend to ease the way we study and test the energetic policies of the SMG. When a new algorithm is being developed it is for sure not going to work exactly as expected. It is necessary to find a way to test this algorithm easily and to get reliable results. And process this interesting results to finally detect in which points the algorithm is not doing well and modify the algorithm to have a good and accurate EMS.

This objectives can be accomplished in different stages. They are discussed in the next section.

2.2. Scope of the paper

The first stage is to conceive how can this system be implemented to allow the study of SMG. This first stage was completed, the first ideas were to implement a type of program in Simulink because it allowed very interesting features that would make the program very attractive. This features are masks, the use of blocks, the possibility to create libraries with blocks… All this features are very visual, but this option was finally discarded because the working nature of Simulink is time dependent and did not fit with the nature of the simulator. So this system was going to be implemented in Matlab (high versatility) and a global idea of how to implement the system was found.

The second stage is to put the idea into practice to get a functional tool, the system was completely coded in Matlab, it has very important elements to work such the main console, the data spreadsheets, the parameters' catcher function and the SMG elements functions. When all this elements were done the second stage was reached, the program was in a functional level.

The third stage is to make the tool more user friendly, this stage is done at the same time when the second stage is developed. Consists in coding the program in order to make it more easy to use. This stage is reached but not finished there is always path to improve on it.

The next stages consist in making the program more complete such adding more elements to create more variety on the simulations, to add the component of reactive power which means a huge modification in quite a lot of elements. To sum up make the simulator more transversal.

3. Introduction to the Smart Micro Grids

Robert H. Lasseter used concept Micro Grid for the first time in 1998. A Micro Grid is an electric system with three characteristics, it has:

- Distributed generation, this could be typically photovoltaic arrays, wind turbines, diesel generators…
- Power flow control, the power electronics take this role, they are capable to modify the amount of power injected or absorbed to actuate differently as in natural conditions. Charging a battery at maximum power, half of the power…
- Energy storage systems, this elements introduce the flexibility needed on the MG to make the pertinent time affectations. The energy is not necessary to be consumed at the same time is generated.

A MG also needs a control, this control is implemented on the static converters and is called Droop control, this type of controls is based on frequency variations in order to send signals between the different elements which form the MG. Then there are two more levels of control, the second level is used to correct the errors on stationary state introduced in the primary control (Droop control). The third level of control is based on high-level decisions such the import or export of energy from/to other grids.

The last two levels of control compose another level on the functionality of the MG, they are the Smart Micro Grids. By definition the concept Smart is added when the MG include some SCADA system (Supervisory Control and Data Acquisition System) and is structured in a hierarchical model such CIM (Computer-Integrated Manufacturing).

In the present document the concept SMG is used referring to any kind of consumption point with its generation. On section 6.3 the so called SMG 5 is not by definition a SMG but the program processes it as it was, but without having any extra element. So the use of SMG in the document is wider.

Another interesting aspect for the MG is that they are scalable. A MG will be a MG independently of the power managed, the conditions are the same listed above. But is possible to talk about modular scalability, this means changing the size or the number of one element to affect on the final results.

4. Explaining the different elements of the simulator

The simulator is a computer environment developed with Matlab language and allows testing active energy management algorithms. To do this it has several elements that can be classified in:

- SMG elements' models
- External data
- Functions of external data
- The main script console

In the following sections they are further explained.

4.1. SMG elements' models

The elements of the SMG have been modelled in different grades of complexity to allow the simulation of the algorithm in the active power spectrum.

4.1.1. Photovoltaic array

The photovoltaic array function is a quite complete model; there are single-diode models and two-diode models.

To simplify the model understanding a single diode model is used, but there are also some levels of complexity in it. They are showed in Figure 4.1.

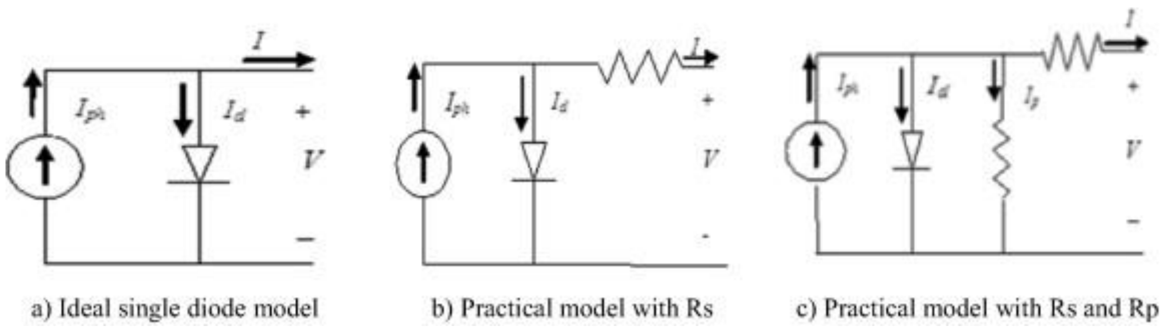


Figure 4.1. Different single-diode models for PV cells (1)

The practical model with Rs and Rp is adopted. This model is the most realistic but has some difficulties such determining the values of the resistances, because they are cyclically dependent on the other variables. In (2) some approximate equations are given to calculate these parameters. There are different ways to express the equations of this model, the final used equations are a combination of different bibliography. Also they are slightly modified to allow flexibility and usability, most of the equations are conceived to model one single panel, but the needs of the simulator are to easily choose and model full arrays. (1) (2)

In Table 4.1. it is showed the parameter list, its information and an example value, and in Table 4.2. the inputs.

Parameter name	Definition	Example
$\boldsymbol{N_{s_i}}$	Number of series-connected panels of the array.	4 panels
$\boldsymbol{n_{s_i}}$	Number of series-connected cells of the panel	72 cells
$\boldsymbol{N_p}$	Number of parallel-connected panels of the array.	4 panels
$\boldsymbol{NOCT}$	Nominal Operating Cell Temperature	47 °C
$\boldsymbol{A}$	Ideality factor	1,2 (Si-mono)
$\boldsymbol{K_i}$	Current temperature coefficient	0,0006 K^{-1}
$\boldsymbol{K_v}$	Voltage temperature coefficient	-0,0032 K^{-1}
$\boldsymbol{I_{sc}}$	Short-circuit current of the panel	9 A
$\boldsymbol{V_{oc_i}}$	Open-circuit voltage of the panel	30 V
$\boldsymbol{V_{mpp}}$	MPP voltage of the panel	25 V
$\boldsymbol{I_{mpp}}$	MPP current of the panel	8,5 V
$\boldsymbol{n_s}$	Number of series-connected cells of the array, resulting of multiplying $n_{s_i} * N_s$	288 cells
$\boldsymbol{E_g}$	Energy gap	1,12 eV
$\boldsymbol{k}$	Boltzmann constant	1.38065e-23 $J \cdot K^{-1}$
$\boldsymbol{q}$	Electron charge	1.602e-19 J
$\boldsymbol{G_{stc}}$	Irradiance at standard conditions	1000 W/m^2
$\boldsymbol{T_{ref}}$	Temperature in standard conditions	298 K
$\boldsymbol{V_{oc}}$	Open-circuit voltage of the array.	120 V

Table 4.1. PV model parameters' information

Input name	Definition
$\boldsymbol{T_a}$	It's the external temperature where the PV array is placed, it's given in °C by the temperature function (see 4.3.5)
$\boldsymbol{G}$	The irradiance in W/m2 given by the irradiance function (see 4.3.3)

Table 4.2. PV model inputs' information

The model is divided in several equations that are quite large and listed below. That is done in order to calculate the variables of the model, these variables are listed and explained in the Table 4.3.

Variable	Explanation
$\boldsymbol{T_c}$	Temperature of the cell.

V_{tn}	Reference thermal voltage.
I_{on}	Reference leakage current of the diode.
I_o	Leakage current of the diode.
I_{pv}	Photoelectric current.
R_s	Series resistance.
R_p	Parallel resistance.
V_t	The voltage imposed on the diode, called thermal voltage, “because of its exclusive dependence of temperature” (1).

Table 4.3. PV model variables’ information

$$T_c = \left(\mathrm{T_a} + \frac{\mathrm{NOCT} - 20}{800} * \mathrm{G}\right) + 273$$ **Eq. 4.1**

$$V_{tn} = n_s * \left(k * \frac{T_{ref}}{q}\right)$$ **Eq. 4.2**

$$I_{on} = \frac{I_{sc}}{\left(e^{\left(\frac{V_{oc}}{A*V_{tn}}\right)}\right) - 1}$$ **Eq. 4.3**

$$I_o = I_{on} * \left(\frac{T_c}{T_{ref}}\right)^3 * e^{\left(q*\frac{E_g}{A*k}\right)*\left(\frac{1}{T_{ref}} - \frac{1}{T_c}\right)}$$ **Eq. 4.4**

$$I_{pv} = \left(I_{sc} + K_i * \left(T_c - T_{ref}\right)\right) * \left(\frac{G}{G_{stc}}\right)$$ **Eq. 4.5**

$$R_s = \frac{A * V_{tn} * ln\left(1 - I_{mpp} * \frac{N_p}{I_{sc} * N_p}\right) + V_{oc} - V_{mpp} * N_{s_i}}{I_{mpp} * N_p}$$ **Eq. 4.6**

$$R_p = \frac{V_{mpp} * N_{s_i} + I_{mpp} * N_p * R_s}{I_{pv} * N_p - I_{mpp} * N_p - I_{on} * N_p * e^{\frac{V_{mpp}*N_{s_i} + I_{mpp}*N_p*R_s}{A*V_{tn}}} - 1} * n_s * N_{s_i}$$ **Eq. 4.7**

$$V_t = n_s * \left(k * \frac{T_c}{q}\right) \qquad \textbf{Eq. 4.8}$$

Once these variables are found they will be used to find the other variables and outputs that are dependent on voltage, these are listed in the Table 4.4. All these variables have to be evaluated in a range of values for the voltage.

Variable	Explanation
I_{part}	It is the sum of the diode current and the leakage current through the parallel resistance. It's an auxiliary variable.
I	The resulting current of the array.
V	The voltage of the array.
P	The product of the voltage and the current.

Table 4.4. PV model outputs' information

The equations are listed below.

$$I_{part} = N_p * I_o * \left(e^{\frac{\left(V_i + \left(I_i * \frac{R_S}{N_p}\right)\right)}{V_t * A}} - 1 \right) + \left(\frac{V_i * N_p + R_s * I_i}{R_p} \right) \qquad \textbf{Eq. 4.9}$$

$$I_{i+1} = N_p * I_{pv} - I_{part} \qquad \textbf{Eq. 4.10}$$

$$P_i = V_i * I_i \qquad \textbf{Eq. 4.11}$$

Note in the equations (**Eq. 4.9**, **Eq. 4.10**, **Eq. 4.11**) the presence of the sub index "i" that's because the values are vectors and they are evaluated in a loop. The current variable is initialized with the short-circuit current multiplied by the number of panels connected in parallel.

The function is easily accessible running the simulator, it gives big matrix of values because the outputs are the vectors of I, V and P per instant. The results of one day are shown in Figure 4.3. and Figure 4.4.

The parameters of the PV array are in Figure 4.2.

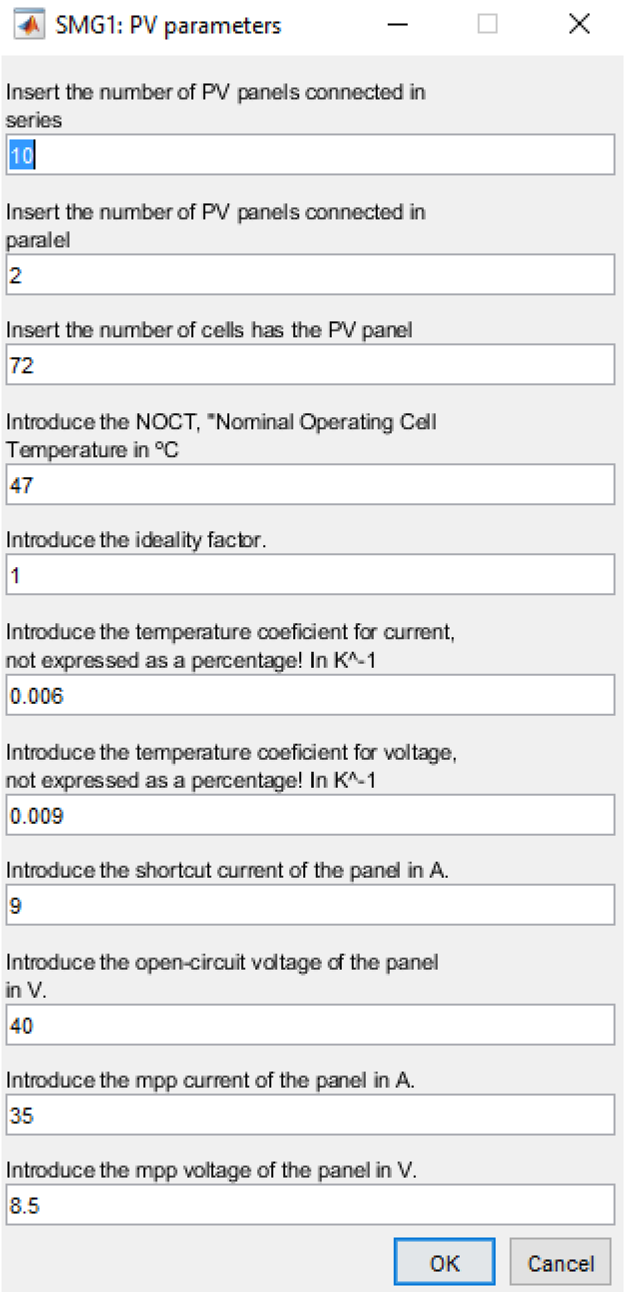


Figure 4.2. PV array parameters

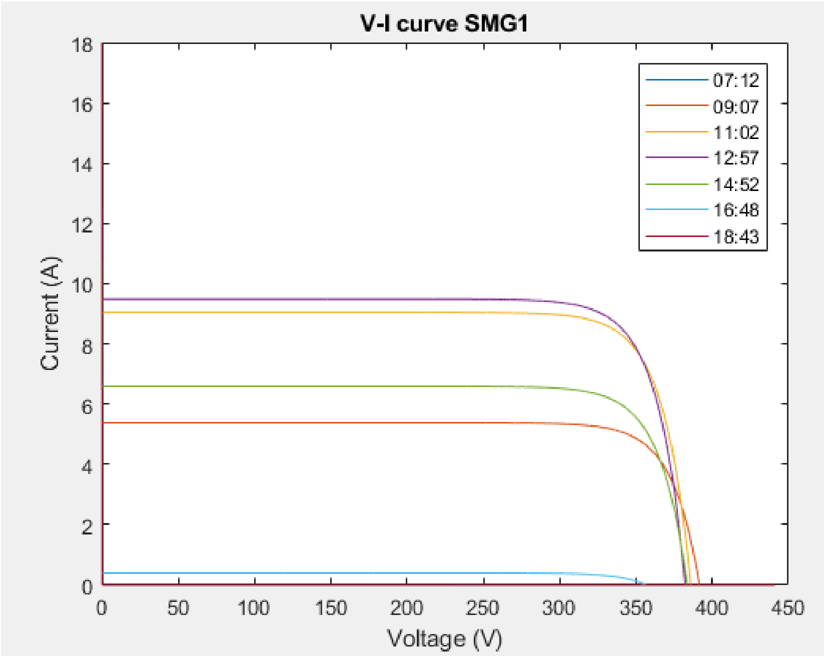


Figure 4.3. PV array V-I curve at different instants

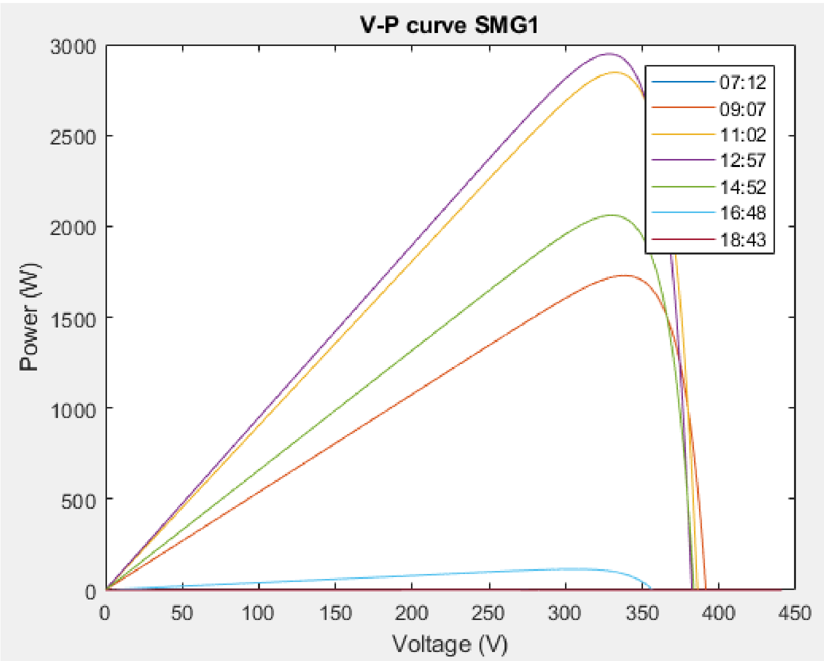


Figure 4.4. PV array V-P curve at different instants

4.1.2. Photovoltaic inverter

The photovoltaic inverter is a simple function that treats the power curve of the PV array at every instant. It's necessary to size the inverter to calculate the efficiency of the inverter, this can be seen in Figure 4.5.

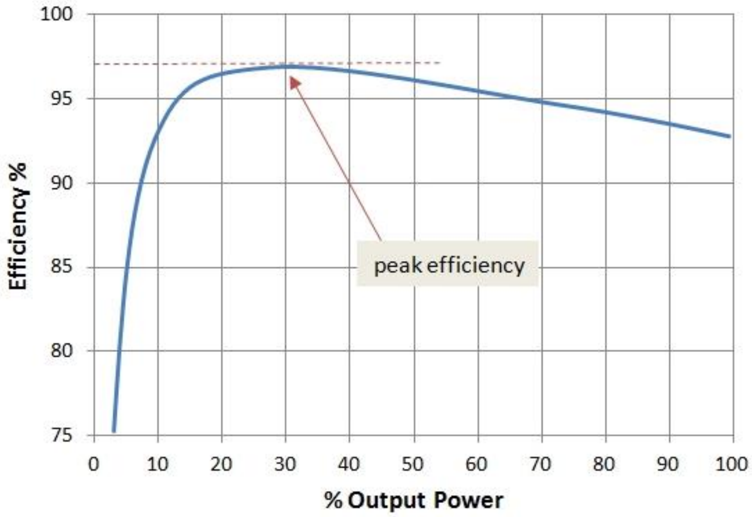


Figure 4.5. PV inverter efficiency curve

This shows how important is to size properly the inverter, because the efficiency can be seriously affected.

In Figure 4.6. the result of the simulation can be seen, for the SMG1 the inverter has a peak power of 2 kW, and the SMG2's inverter has a peak power of 20 kW. As can be observed the different results the inverters give are interesting, and the first inverter is shut down when the income power overpass its capacity. Another simulation result is seen in Figure 4.7. the peak PV array power in the day of study is 3 kW and it matches perfectly with the inverter of 3 kW. It's interesting to compare it with the 20 kW inverter. And finally in Figure 4.8. the efficiency curves of the inverters can be seen. It's important to say that the curve is completely shapeable.

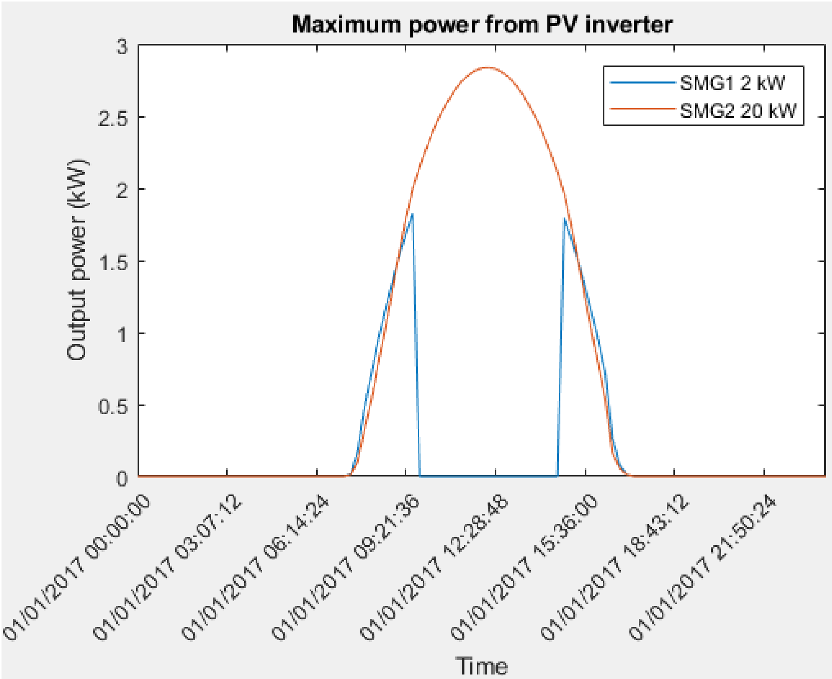


Figure 4.6. PV inverters' output

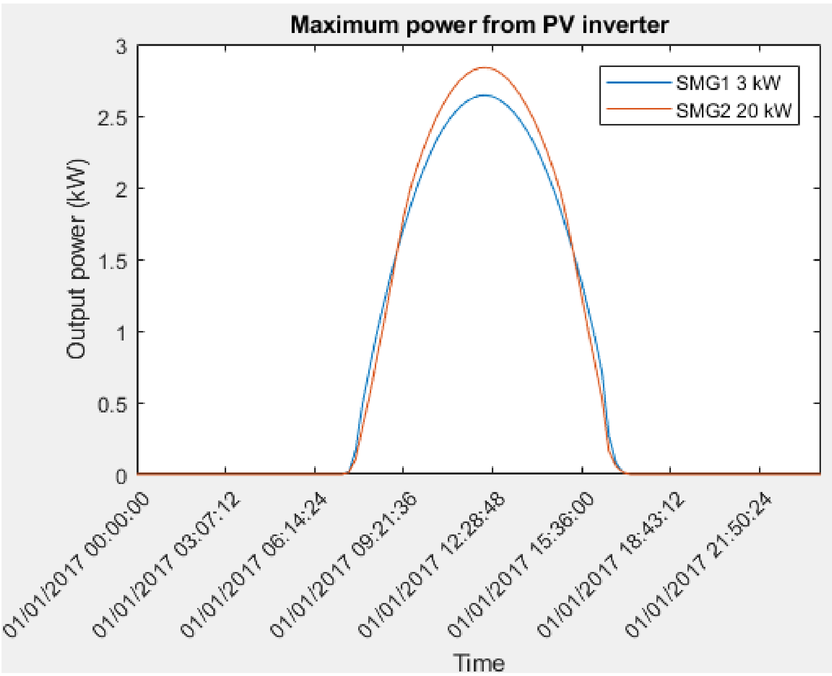


Figure 4.7. PV inverters' output

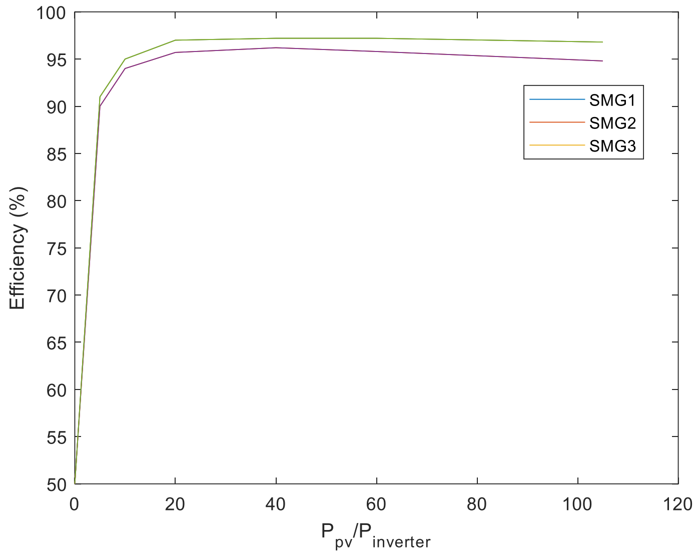


Figure 4.8. PV inverters efficiency curves

4.1.3. Batteries

The batteries model is quite simple; it acts as an energy container with a constant efficiency value of 95% when discharging and a temperature and SoC dependent value of efficiency when charging.

The parameters demanded by the program to configure the batteries are showed in Figure 4.10. , the efficiency vectors can be better understood regarding Figure 4.9. the program does an interpolation of this three variables.

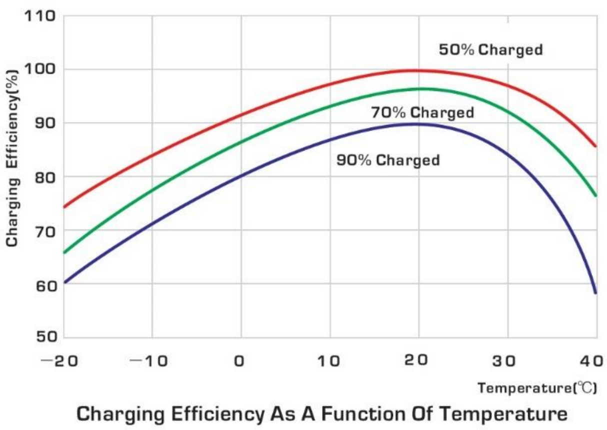


Figure 4.9. Battery charging efficiency curves.
Source: Wikimedia

The efficiency of the battery when charging variates because of gassing, and this depends on the temperature and the SoC. “In practice charge efficiency will range in between 80 % and 95 %.” (3)

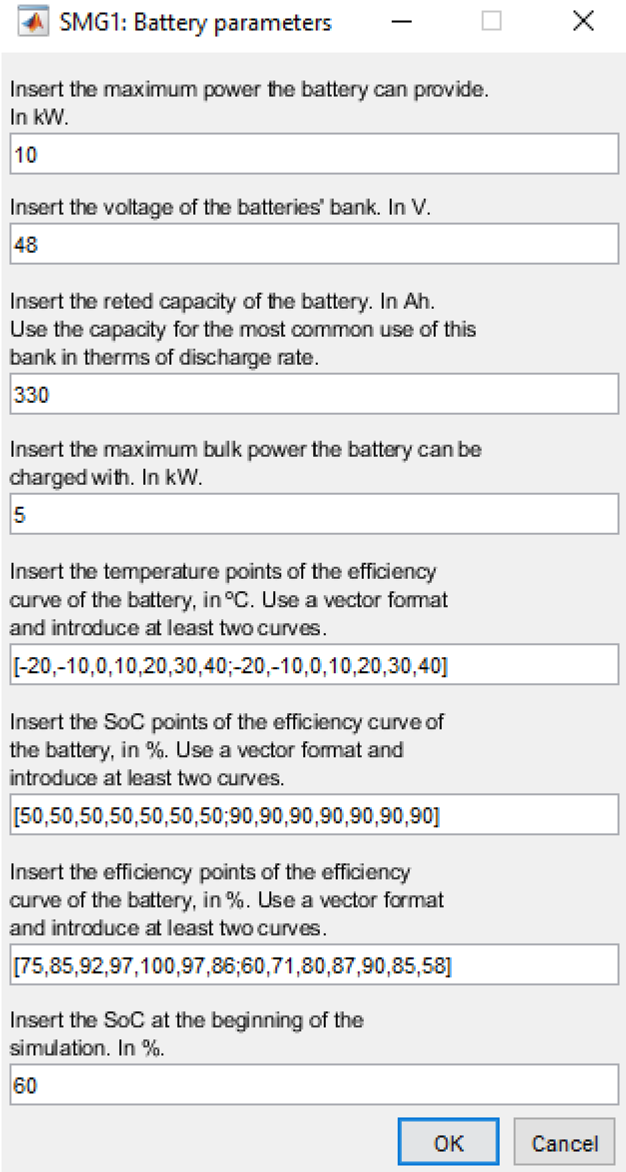


Figure 4.10. Battery parameters.

The model is split in two steps the first one is only informative for the EMS to take decisions and the second is binding and produces changes on the state of charge of the battery.

Implementing a very basic algorithm in the simulator that says “discharge the battery until 40% and in that point start to charge it until 98% and so on”, the power command is a random value between the maximum the battery can charge or discharge and zero. The results of this are shown in Figure 4.11. and Figure 4.12.

The simulation takes thirty seconds for 10 days, and it is interesting to notice how the charging power is reduced once the SoC is over 80 %.

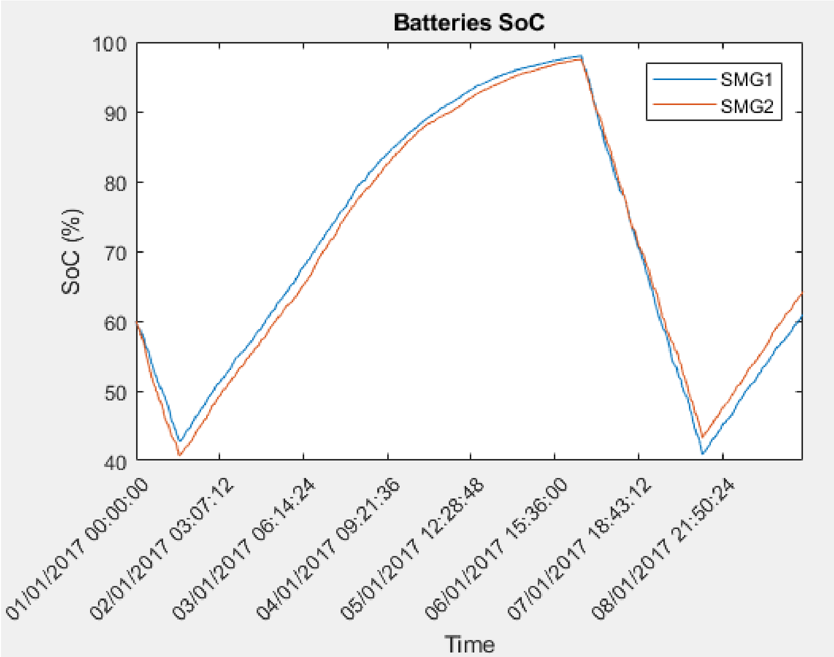


Figure 4.11. Batteries' SoC.

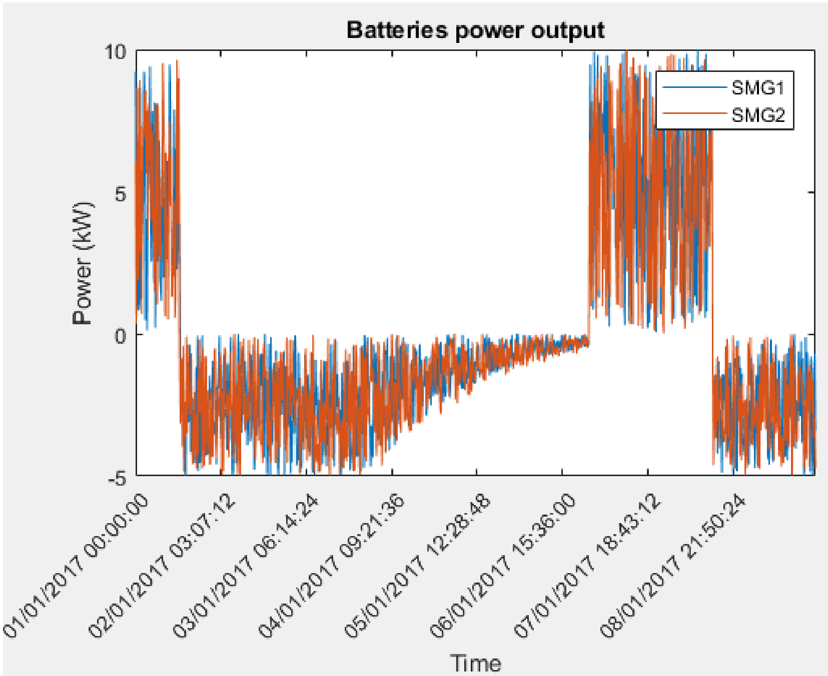


Figure 4.12. Batteries' output power.

4.1.4. Generator

The generator is conceived as a substitute for the grid because it works as a voltage source (the simulator allows the combination but).

The generator has some particularities, it needs some time to warm up until can be connected to the internal grid and it needs some time to warm down. It affects on when the generator can give the needed power or when can be turned on.

The function has four steps explained below:

1. Informational, just for the EMS to take decisions. It gives outputs, they are:
    a. The power vector, is a vector of three values containing the maximum power it can provide, the medium and the lowest power. For efficiency reasons the gensets are limited to the 10 % of it's nominal power, below this level the generator should be disconnected. In kW.
    b. Emission vector, is the quantity of CO_2 the generator will emit in each power along the time step. In kg.
    c. Cost vector, is the variable cost at every time step for each power, it takes into account the amount of fuel used. In €.
    d. Autonomy vector, the time the generator will be able to provide energy at an specific power. In hours.
    e. State, says the current state. Not suitable to use in the algorithms in specific cases when the time step is longer than the start and stop times of the generator.
    f. Fuel level, the level of fuel in the tank. In %.
2. Binding, to tell to the generator how much power will have to provide in that instant, this will make the respective changes on the tank's level and the possible output power for the next instant.
    a. The power is the value that the EMS tells it to give.
    b. Emission is the specific amount of CO_2 emitted in the current time step.
    c. Cost is the specific amount of € burned in the current time step.
    d. Autonomy is the number of hours it will last at the current power.
    e. State, indicates the current state.
    f. Fuel level, indicates the fuel level at the beginning of the instant, it will be actualized in the next time step.
3. State, the generator has four states explained below, in this step is possible to change the state of the generator, this means to turn it on or down. Does not give any output.

4. Refilling, this step is like a command that says, “Refill the tank” and after the specified time in the parameters it will be refilled. In reality, this is turning on an alarm. Does not give any output.

The states of the generator are:

0. When the generator is stopped and disconnected.
1. When the generator is warming up (running) but not connected. After the specified time it will be automatically connected to the grid, this means will change to state 2.
2. When the generator is connected to the grid and therefore giving energy.
3. When the generator is warming down. After the specified time it will change to state 0.

The only states that can be manually set are states 1 and 3. The others are automatically changed after the specified time.

The parameters needed for modelling the generator appear in Figure 4.13.

Note that there are two parameters called power ramping, they are the capability of the generator to change the power given, in batteries it’s supposed to be whatever but the generators have some physical restrictions. Then these values are taken into account when in step 2 the function tells to the algorithm the range of power it can give.

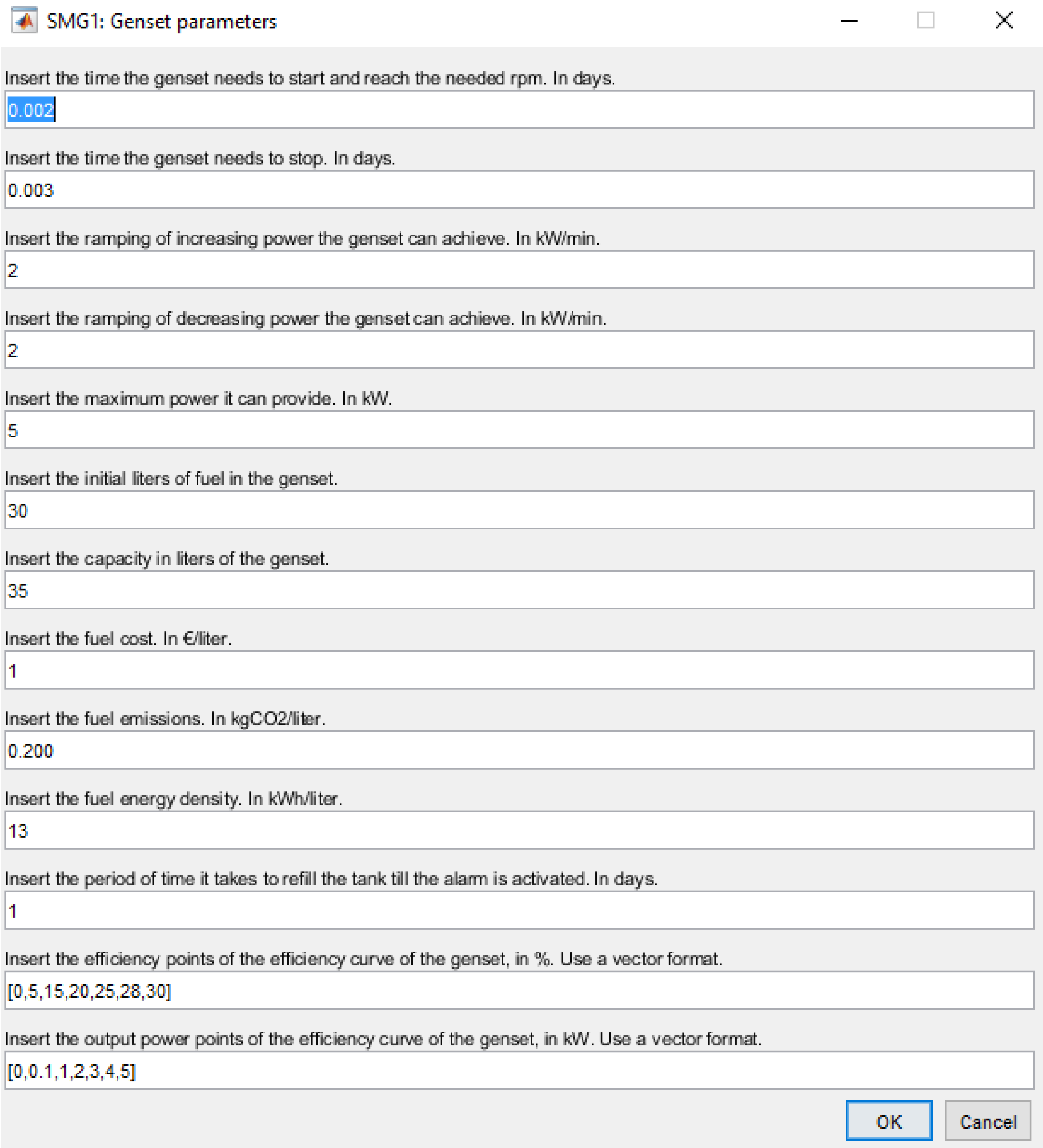


Figure 4.13. Genset parameters.

To show how the model behaves a simple algorithm is implemented, this algorithm starts the gensets at 6 am each day and turns it down at 3:30 am and a random power is demanded taking into account its possibilities. When the fuel level is below 20 % an alarm is set and one day later the tank is refilled. If the level arrives to 10 % the genset is disconnected. The following graphs show its performance.

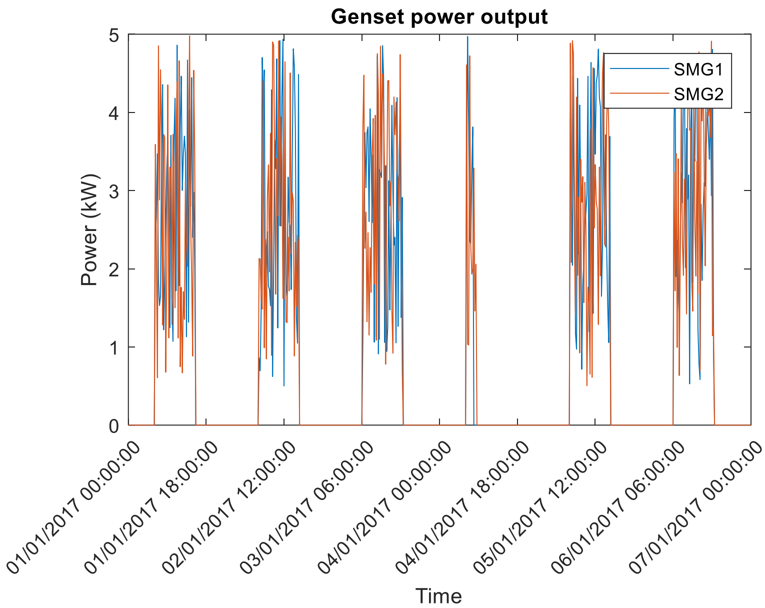


Figure 4.14. Gensets' power.

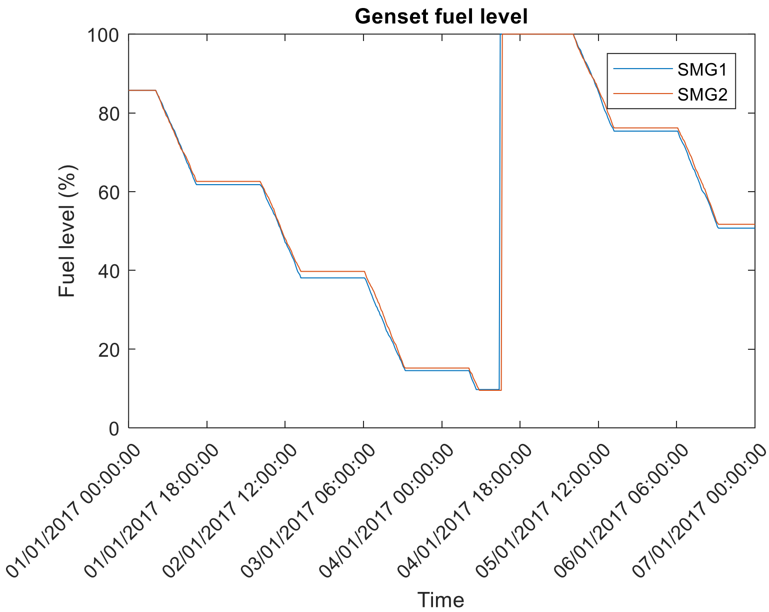


Figure 4.15. Gensets' fuel levels.

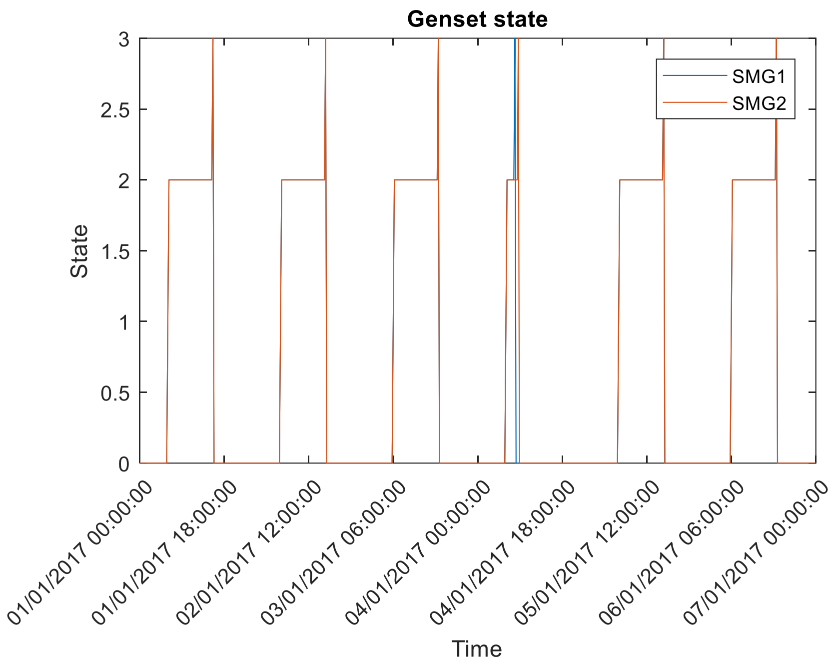


Figure 4.16. Gensets' states.

It's interesting to see how the model accomplishes the algorithm, the algorithm has to be robust to not have bugs, it's quite easy to do mistakes in it but just requires more dedication.

4.1.5. Grid

The grid is a function that has three outputs, they are:

1. The maximum power, is the available power of the grid the system can use.
2. The purchasing price, this function implements the function explained in 4.3.1
3. The selling price, this function implements the function explained in 4.3.2

When starting the simulation it is possible to indicate if there is any fall in the supply and the function will take it into account. In figures 4.17. , 4.18. and 4.19. it's possible to see how the program demands the information and the results.

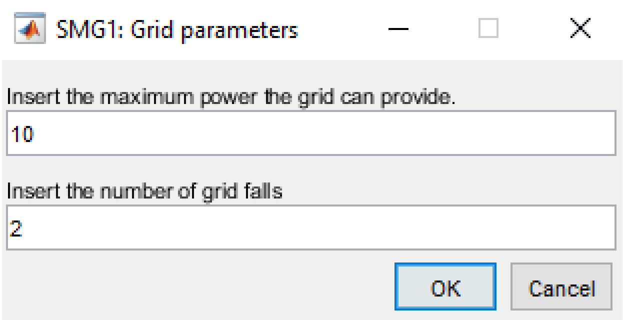


Figure 4.17. Grid parameter window.

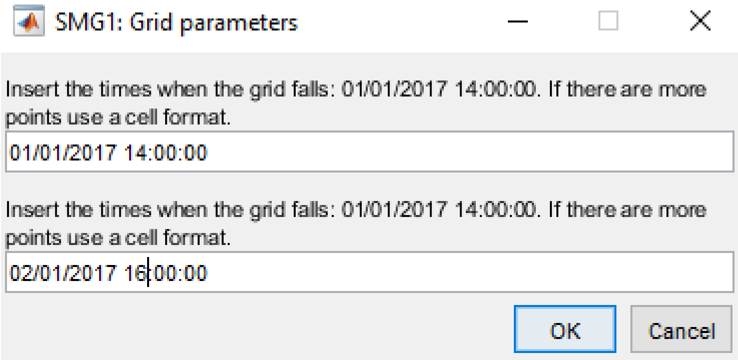


Figure 4.18. Grid parameter window the falls.

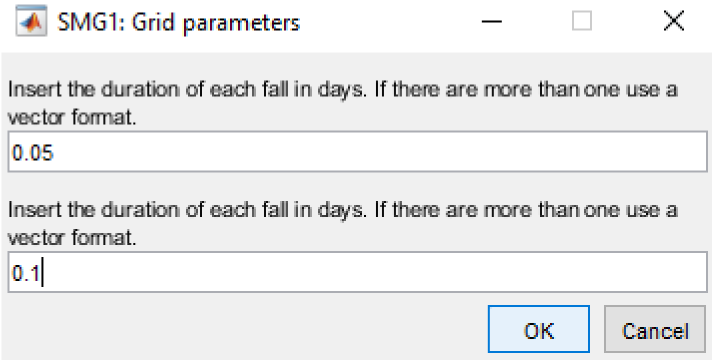


Figure 4.19. Grid parameter window the falls duration.

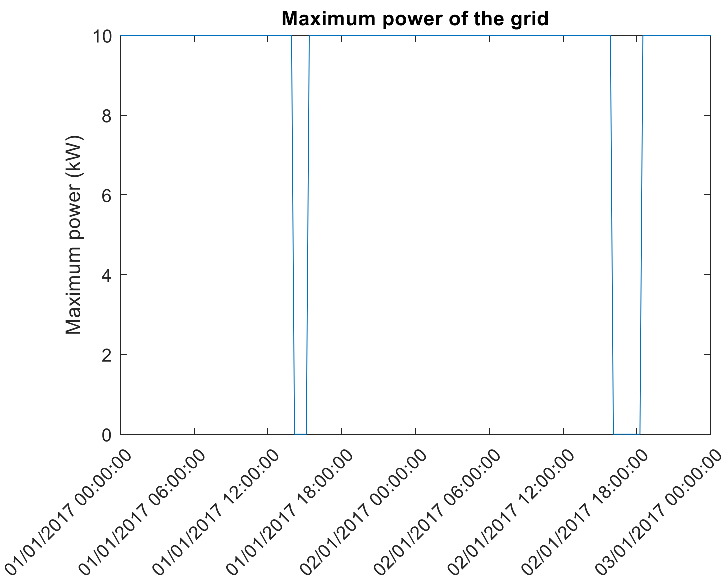


Figure 4.20. Grid function output.

This output is just informative; the algorithm can modify it according to the specifications of the case.

4.1.6. Loads

The loads function processes the data given in the Excel and gives an output that is a vector as long as the number of loads there are. The size of this vector is different per each SMG. The result of it can be seen in Figure 4.21. for the nominal power and in Figure 4.22. for the minimum power.

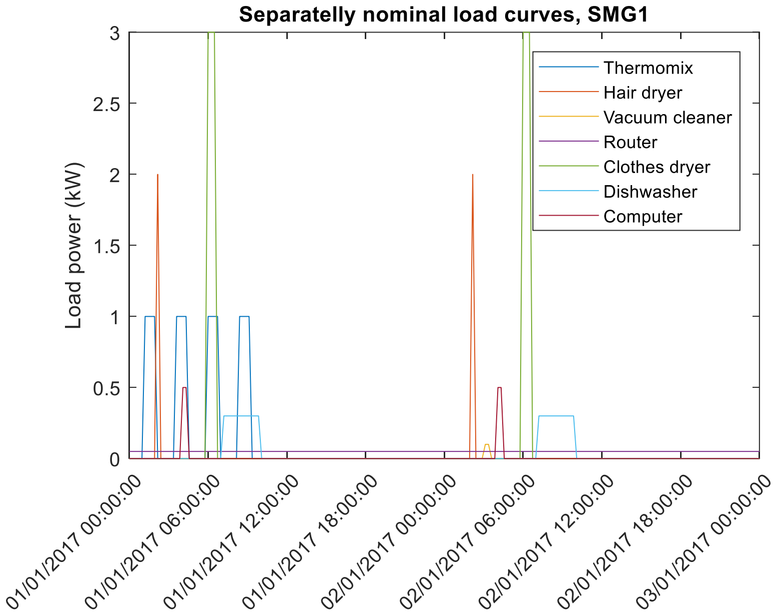


Figure 4.21. Loads' nominal curves.

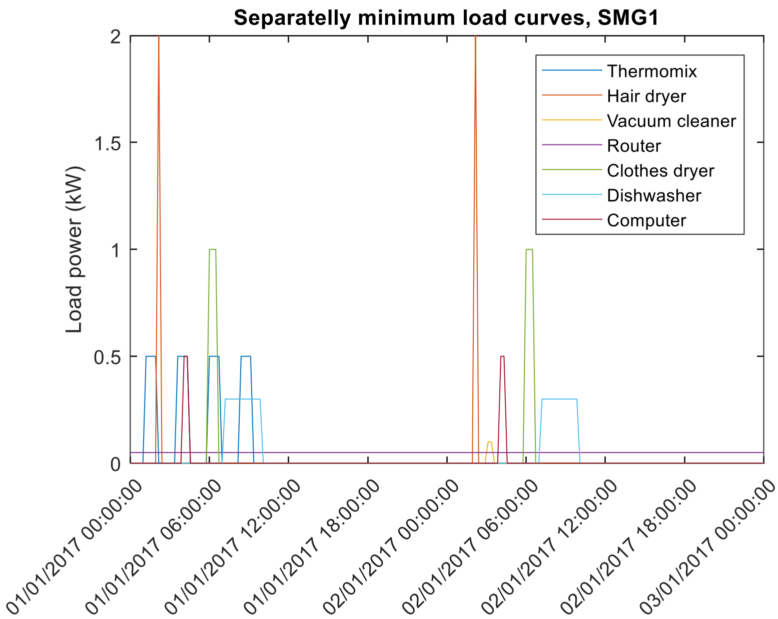


Figure 4.22. Loads' minimum curves.

Note that the loads' curves are separated this makes possible for the EMS to disconnect them or regulate them with a quite good precision.

The function has different interesting outputs that will let the algorithm have a lot of flexibility:

1. Nominal power, it is a vector of the instantaneous power of each load.
2. Minimum power, it is a vector of the instantaneous power of each load, it is the same of the nominal power but when the load is dimmable it's a lower value.
3. Priority value, is a value assigned at each use of each load the criteria is not fixed, the algorithm maker can play with it.
4. Load name
5. Load identifier, it's thought to distinguish each load of the SMG numerically if needed. Usually is better than using strings.

4.2. External data

The elements composing this section are .xlsx files. All the information has to be written in them in a specific way to allow the Matlab functions read them and understand the data that is inside.

4.2.1. Environmental data

The environmental data contains the data of the irradiance received by the photovoltaic arrays and the environmental temperature. This data can be easily taken from PVGIS (4).

The aspect of it is showed on Figure 4.23.

	A	B	C	D
1	Time	*Irradiance*	*Temperature*	*Month*
2	5:07	0	3,9	1
3	5:22	0	3,9	
4	5:37	0	3,9	
5	5:52	0	4	
6	6:07	0	4,1	
7	6:22	0	4,1	

1 2

Figure 4.23. View of the file environmental_data.xlsx

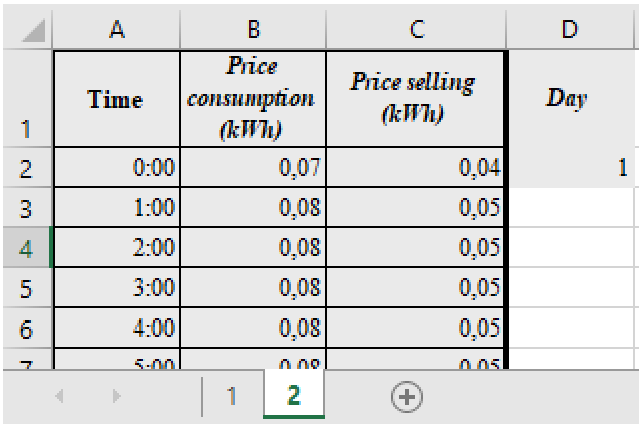
As can be seen the Excel allows creating more pages in the same file, they are used to distinguish the data between different SMGs. Note that with it each SMG will be characteristic and the fidelity of the program is quiet high.

Important, the data has to be written with comma "," to separate the decimals not with dot ".", if not the matlab function won't get the values properly.

4.2.2. Grid data

The grid data contains the data of the prices of the energy for each hour (can be more precise if needed, how to use it will be explained on the user manual) both the buying prices and the selling ones.

The aspect of it is showed on Figure 4.24.



	A	B	C	D
1	Time	Price consumption (kWh)	Price selling (kWh)	Day
2	0:00	0,07	0,04	1
3	1:00	0,08	0,05	
4	2:00	0,08	0,05	
5	3:00	0,08	0,05	
6	4:00	0,08	0,05	

Figure 4.24. View of the file grid_data.xlsx

As can be seen the Excel allows creating more pages in the same file, they are used to distinguish the data between different SMGs. Note that with it each SMG will be characteristic and increases the flexibility.

Important, the data has to be written with comma "," to separate the decimals not with dot ".", if not the matlab function won't get the values properly.

4.2.3. Loads data

The load data is the most complex file of external data, because it has to contain all the loads of each SMG and its information. See Figure 4.25. for easier understanding.

	A	B	C	D
1	**Name**	**Load identifier**	**Nominal power (kW)**	**Minimum power (kW)**
2	*Thermomix*	1	1	0,5
3	*Hair dryer*	2	2	2
4	*Vacuum cleaner*	3	0,1	0,1
5	*Computer*	8	0,5	0,5
6	*Router*	5	0,05	0,05
7	*Clothes dryer*	6	3	1
8	*Dishwasher*	7	0,3	0,3
9	*Thermomix*	1	1	0,5
10	*Hair dryer*	2	2	2
11	*Vacuum cleaner*	3	0,1	0,1
12				

Figure 4.25. Detail of the file grid_data.xlsx

It will incorporate a specific list of all the loads for every single one of the micro grid, there are no maximum entries.

The following columns are the necessary information for the function to understand it, all the columns are listed below and explained:

- Name
- Load identifier
- Nominal power
- Minimum power
- Starting hour
- Starting minute
- Starting second
- Starting day
- Starting month
- Starting year
- Duration
- Repetition frequency
- Repetition times
- Priority

With all this information it is possible to create very complete load curves, and with some interesting functionalities.

- ✓ The loads can be dimmable, so them will let the EMS in certain occasions to reduce their power consumption and adjust it to the power availability.
- ✓ Differentiate the use of each load between certain periods of time, how? It is possible to create more lines for the same load (see Figure 4.25. the thermomix, hair dryer and vacuum cleaner), so they can start in a different moments of the year (filling properly the columns of starting day, hour, minute, second, month and year). From this specific time point it's use can be repeated as many times as it's desired and with the desired frequency (filling the columns repetition frequency and times).
- ✓ Assigns a specific identifier to the loads to work easier on the algorithm if needed.
- ✓ Assigns also a priority value to each use of the loads. This is very useful when talking about decisions of the algorithm.

4.3. Functions of external data

All this functions have a similar data process explained in Figure 4.26.

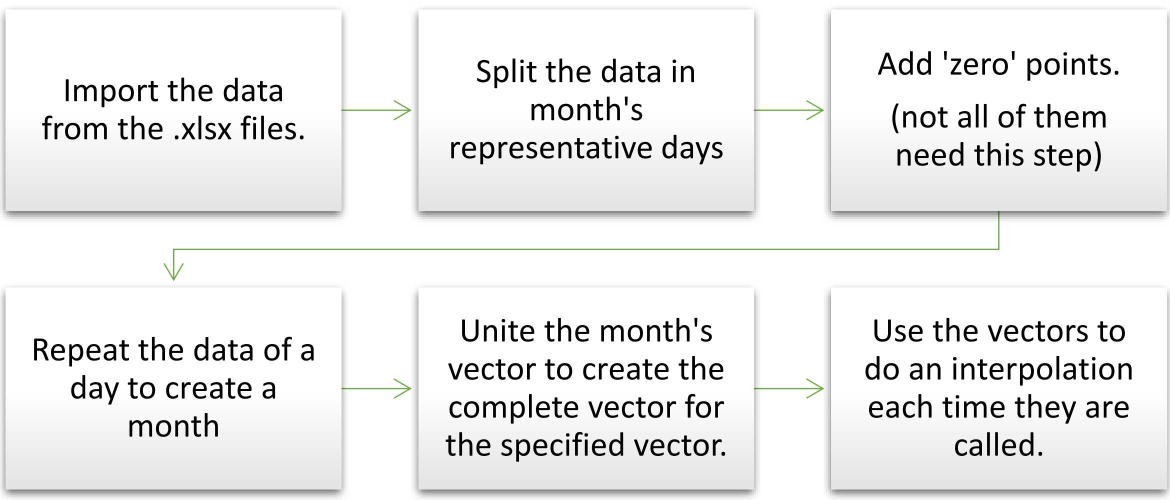


Figure 4.26. Steps in data processing functions

4.3.1. Grid purchasing price function

This function reads the Grid data file (explained in 4.2.2) and processes this information to give finally the price of purchasing a kWh in any demanded time. In the Figure 4.27. the price for a specific day can be observed.

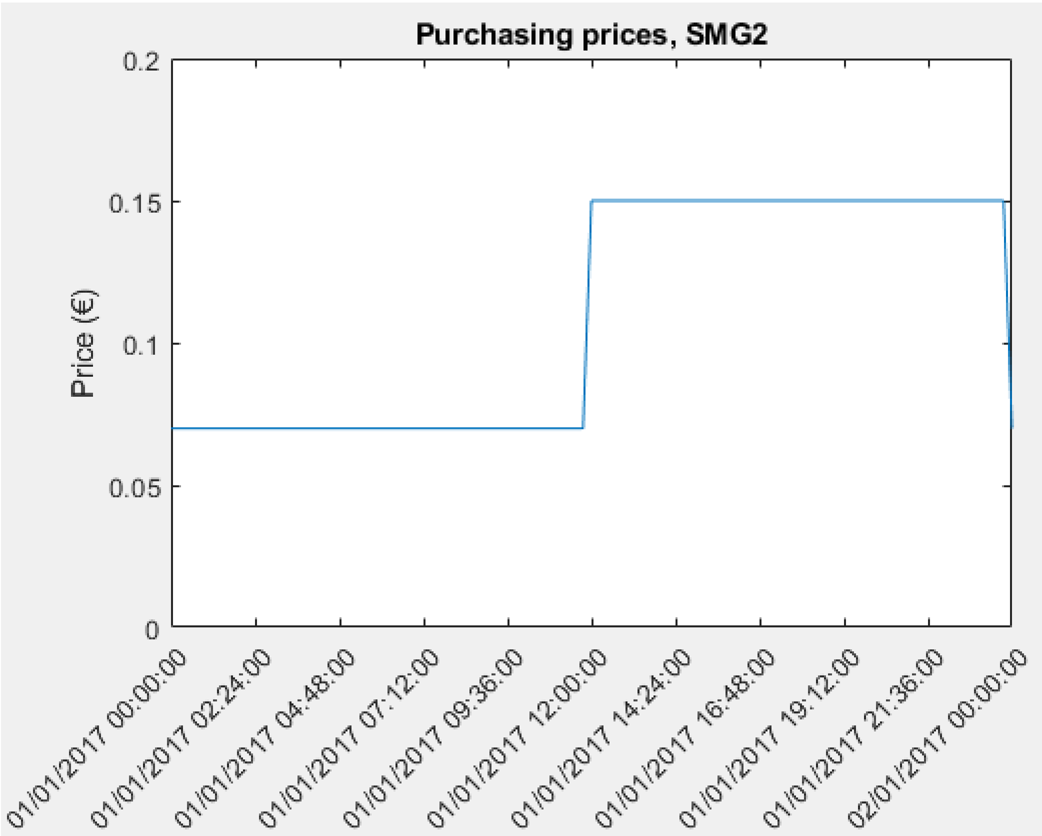


Figure 4.27. Plot of energy prices in one day

4.3.2. Grid selling price function

This function reads the Grid data file (explained in 4.2.2) and processes this information to give finally the price of selling a kWh in any demanded time. In the Figure 4.28. the price for an specific day can be observed.

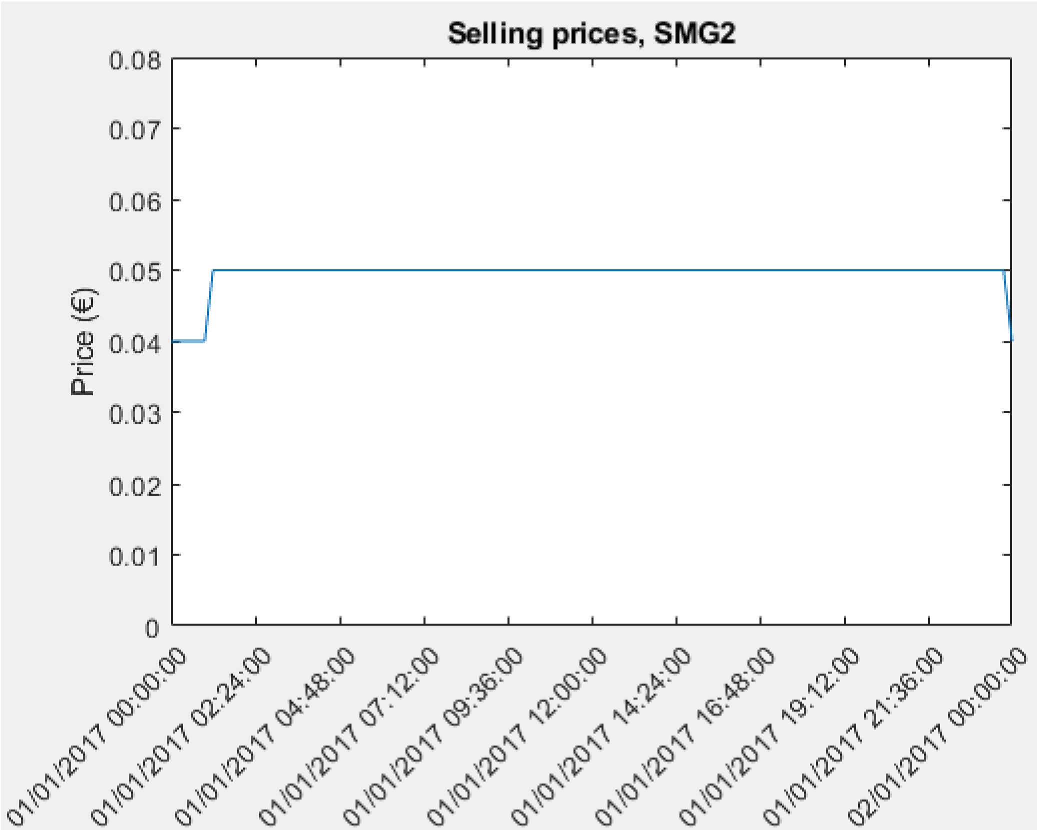


Figure 4.28. Plot of energy prices in one day

4.3.3. Irradiance function

The irradiance function has a similar data process but in the 4th step showed in Figure 4.26. . one random variable is introduced. The aim of it is to reproduce that the reality has many unknown variables that cannot be taken into account.

The equation used is shown below (**Eq. 4.12**).

$$random_{value} = k_{mean} + k_{variance} * rand(1{,}30) \qquad \textbf{Eq. 4.12}$$

Where k_{mean} is a constant to set the mean of all the randomized values, $k_{variance}$ is the variance of the random values and rand(1,30) is a matlab function that returns an M-by-N matrix containing pseudorandom values drawn from the standard uniform distribution on the open interval (0,1).

This random value is used directly multiplying the whole irradiance daily vector and as a result, we have a smaller or bigger irradiance curve. On the Figure 4.29. the results are showed.

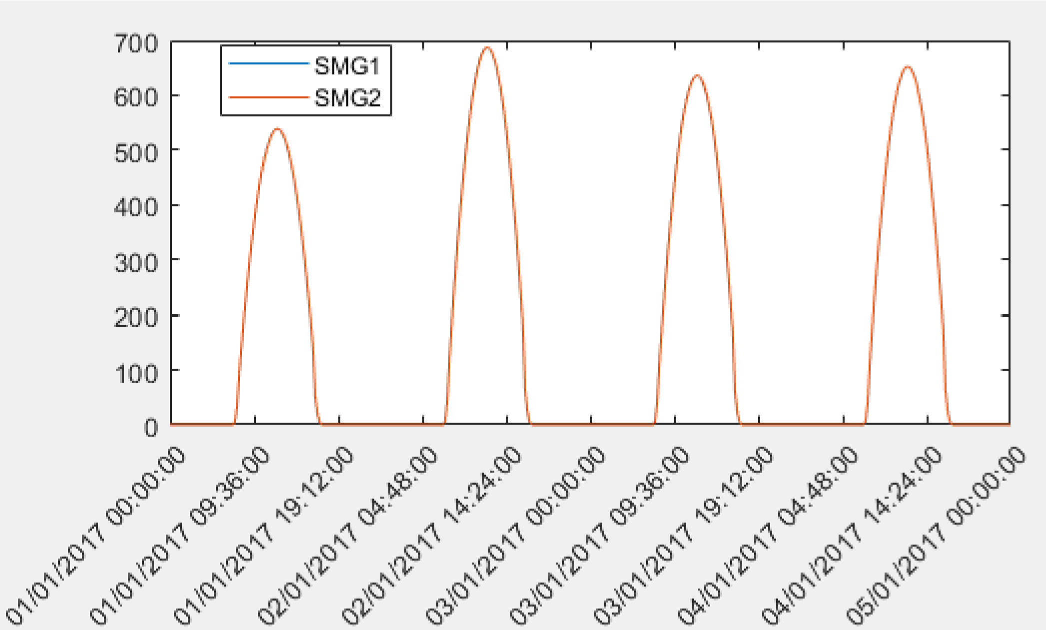


Figure 4.29. Plot of irradiances for two different SMG

Note that the irradiance curves are the same for both SMG. That's because the irradiance data is exactly the same, they are geographically near and the PV arrays have the same orientation and inclination.

4.3.4. Irradiance forecast function

This function works the same as the irradiance function except that it does not make any random treatment to the data. This aim function is just to use it as a forecast for the EMS algorithm.

In Figure 4.30. it is possible to compare the results between the "expected" ones and the "real" ones.

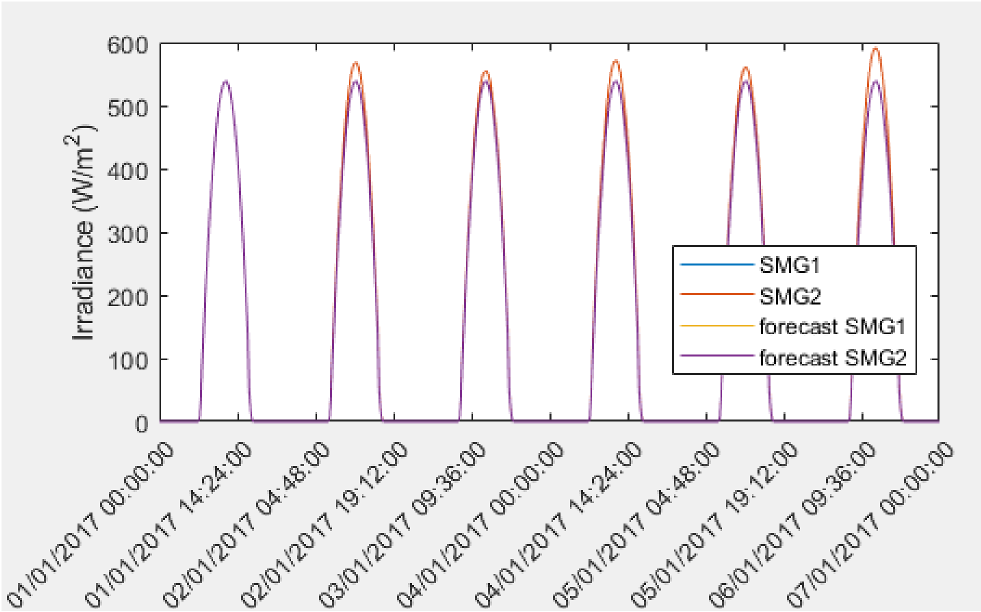


Figure 4.30. Plot of real and forecasted irradiances for two different SMG

Note again that as in 4.3.3. only two curves appear because the two PV arrays are identically placed.

4.3.5. Temperature function

The temperature function works similar to the irradiance function, but the random values are different for every SMG even if they are near. That is because the temperature is really influenced by other factors as the exposition or not to the wind of the PV array, the place the batteries are kept and all this stuff. In Figure 4.31. the temperature curves for the SMG are shown.

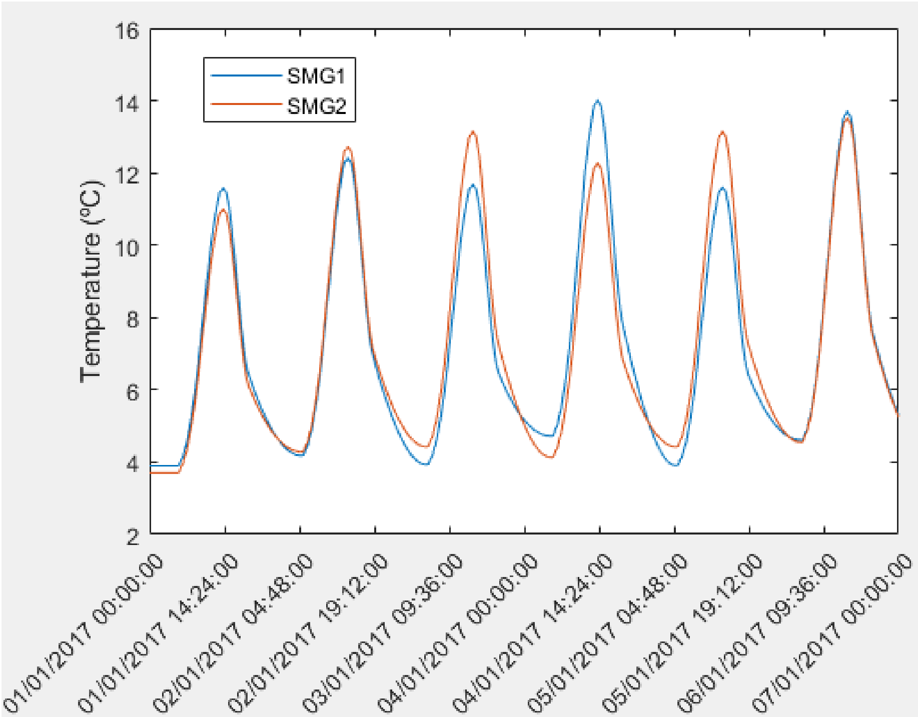


Figure 4.31. Plot of "real" temperatures for two different SMG

4.3.6. Temperature forecast function

As the irradiance forecasts the daily temperature curve is the same during all the month period. In Figure 4.32. it is possible to appreciate this and compare the forecasted with the real temperature.

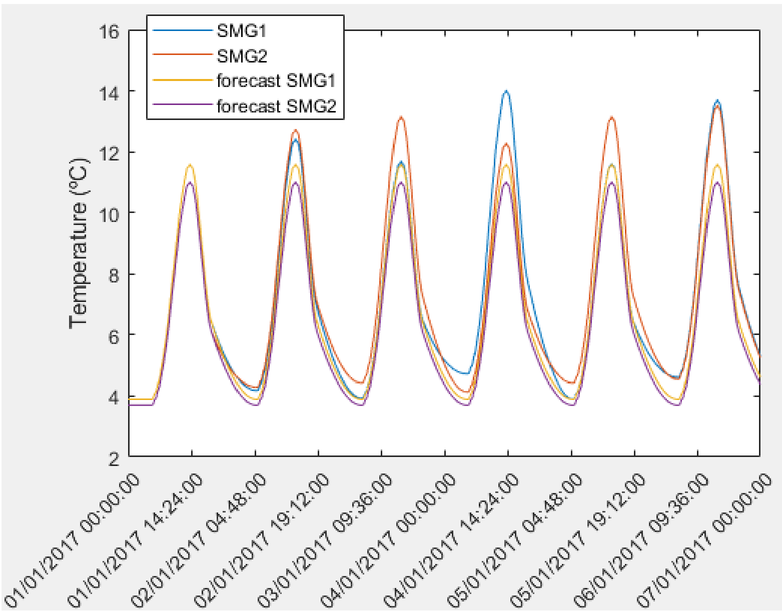


Figure 4.32. Plot of real and forecasted temperatures for two different SMG

4.4. The main script console

Not all the main script is in one file, the main script has a starter function to improve the user experience with the simulator.

4.4.1. Simulator starter

The simulator starter is a big function which gets all the information needed to configure the system, this information is all the parameters of the elements contained in the SMG. It does so using quite user-friendly functions.

It will ask the parameters of the data provided in the excels, the PV array parameters, the PV inverter parameters, the ones of the grid and its falls, the batteries' parameters and the generator parameters. The aspect of this function can be seen in Figure 4.2. Figure 4.10. Figure 4.13. for example. It is important to be very careful when entering the data that everything is in the correct units and there are no mistakes in the vectors introduced. This can lead to mistakes difficult to detect.

A thing that has to be warned is that the efficiency vectors are treated with an interpolation, if any value goes out of the vector points will produce a NaN value, this means that the simulation will have some mistakes and not always will appear as an error.

The function also allows to save the data in a file so you can directly load the parameters previously saved and go faster. In figures 4.33. 4.34. and 3.35. this can be seen.

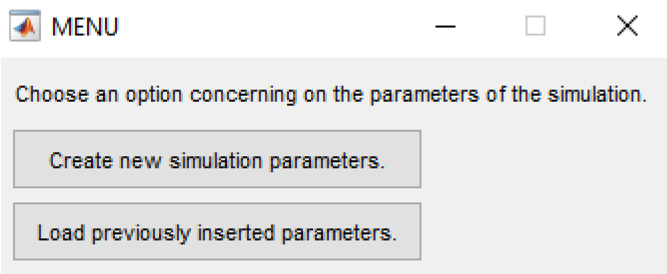


Figure 4.33. Option parameter window

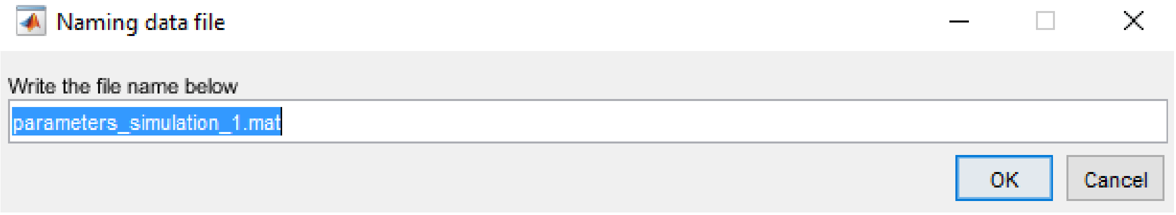


Figure 4.34. File name window

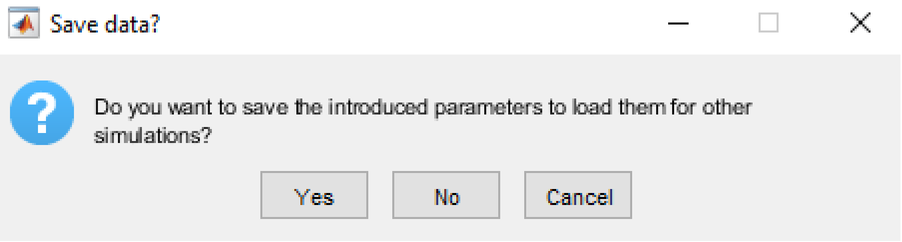


Figure 3.35. Saving parameters' window

The idea behind this is to ease the use of the simulator in what is possible. The windows to insert the parameters have some default values to go faster.

Once all the parameters are inserted the built-in function "setappdata" is used, this function allows the functions get this parameters using the built-in function "getappdata". This makes simpler the function calling of the different models of the SMG.

Finally the final window is always demanded by the program and sets the parameters of the simulation. See Figure 4.36. These parameters are usually expected to be easily modifiable.

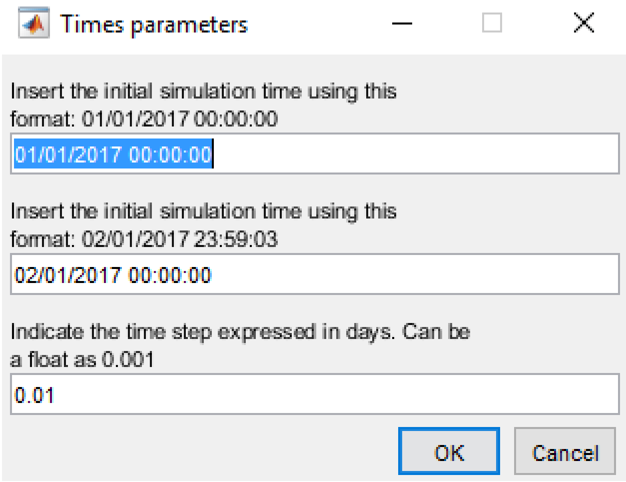


Figure 4.36. Simulation parameters' window

4.4.2. Simulator principal script

The principal script has several parts such:

1. The starter, where appear the functions "clear all" and "clc" to reset everything and don't lead to confusing errors. There is also the "simulator_starter" function.
2. The initialization space, where all the variables needed by the algorithm can be initialized.
3. The time loop, is a for-loop from the starting time to the ending time in time periods specified in the parameter "time_steps", all of them set in the simulator parameters' window (see Figure 4.36.) all the algorithm that has to be evaluated at every instant must go into this loop. Inside the time loop there can be one or more SMG loops. Each SMG loop will apply the same algorithm to every SMG, if the different SMG have different policies there will be more loops. How has to be structured the code in this part is completely flexible but in section 5.1 there is one proposal.
4. Plots sections, in this part the script is split in sections that can be ran separately, each one of them makes a plot of the variables we are interested in.

5. How to use the simulator?

5.1. Why procedure steps in the simulator?

The simulation tool will be step dependent. This means that all the executions will advance by steps; they will not be time dependent.

The explanation for this is that in a real system the actuation times of most of the elements are very little, usually expressed in milliseconds, then the elements can detect voltage and frequency variations on the grid and by a control solve the power unbalances. On a simulation, the model has bigger actuation times because the selected time steps constitute the smallest period, so the model is discrete. This does not allow the elements act in function of the voltage and frequency variations.

This translated to MATLAB code means there would be a time counter that will not advance until the system's algorithm has made all the decisions.

The necessary steps to be done in the system before advance in time are listed below and explained in the next sections.

1. The elements of the microgrid send the information to the local EMS.
2. The local EMS with all the information determines its current state.
3. The local EMS give their information to the central EMS.
4. The central EMS takes decisions.
5. The central EMS sends the commands to the local EMS.
6. The local EMS take decisions.
7. The local EMS send the commands to the components of the microgrid.
8. The components act.
9. The local EMS register and save the instant data.

For the same instant all these steps will be done, when they will be finished the system will advance to the next instant.

5.1.1. The elements of the micro-grid send the information to the local EMS

All the functions, which model the several components of the microgrid, will send their possibility of producing or absorbing power in that instant.

The solar inverter for example will check the irradiance and temperature in that precise instant and after doing all the calculations explained in 4.1.1 and 4.1.2 will send to the local EMS the maximum power that is able to give. Another interesting example, the battery charger will inform to the local EMS how much power can give, receive and other interesting parameters such the time it will be able to maintain this power, also give the SoC (state of Charge). The loads will send to the EMS the amount of power they will need, and like this for the rest of the components.

5.1.2. The local EMS with all the information determines its current state

Once the local EMS has all this interesting information to take locally the decisions (this decisions are taken according to the policies implemented on the algorithm) it could send the commands back to the components. If the modeled system is compounded only by one SMG (Smart Micro Grid) the next step would be 5.1.6. Else, if the system is compounded by more than one SMG it can report the relevant information to the central EMS. However, is also possible not to have a central EMS, then all the SMG actuate over themselves without interact between them.

This relevant information is called the current state of the SMG, where it says in general terms the possibility of receiving or giving power from or to the other SMG. The code is completely flexible and this information can be simple or complex. It depends on the policy of the EMS, examples for this possibility could be a price for each energy unit given or stored, the origin of the energy (renewable or not), etc…

5.1.3. The local EMS gives their information to the central EMS

This step is clear when physically talking but programmatically talking is not that significant, maybe it's a renaming of the variables sent by the local EMS to the central EMS and then apply the algorithm (see 5.1.4).

5.1.4. The central EMS takes decisions

The central EMS could be represented as a MATLAB function to ease the understanding of the code. But it's not necessary. This part of the code will be an algorithm that will have the function to understand the information sent by the local EMS and decide which transfers of power will take place between the SMGs.

5.1.5. The central EMS sends the commands to the local EMS

Again this step exists physically but programmatically it's just a renaming of the power setpoints in to a variable in the memory of the program.

5.1.6. The local EMS take decisions

Once the local EMS knows the new power balances to arrange it takes the decisions of who will give the power or who will receive it, or maybe which load must be disconnected. In this step, it can also store in memory some information such the economic counts of this power transaction or many other things.

5.1.7. The local EMS send the commands to the components of the micro grid

Now the local EMS calls again the different functions, which model the elements of the SMG, and give them the power setpoints.

5.1.8. The components act

Because of the previous step the functions release some outputs such as power in the simplest case, or the SoC, these outputs are better explained in the user manual.

5.1.9. The local EMS register and save the instant data

The outputs obtained could be stored in the memory to plot them, and analyze de dynamics of the systems, the solvency, the efficiency, etc. This data can be used to compare between algorithms and find the better one or the best parameters, etc.

6. Study case

The simulated SMG can have PV arrays, batteries, genset and control on loads. The simulated case will try to demonstrate whether yes or no the use of this expensive elements make the energy consumption cheaper, cleaner or/and trustable.

So three "different" homes will be considered, they will not be interconnected between them because they will be the same home with the same loads but with different elements in them and legislative differences too. Their differences are detailed on the following sections. As said the consumption point will be a familiar home with common loads.

6.1. SMG1

This SMG will have all the elements and an EMS control which features will be in the preference order shown below:

1. Peak shaving (5)
2. Renewable usage
3. Low price energy usage

And will also have some functionalities such control of loads (diminish the demand or even disconnect them), supply during a grid outage and control of energy produced by the PV array.

The aim will be if with this policies the investment on the batteries, genset and PV array is justified.

The first step will be to choose the characteristics of the elements. Taking a look at the load curves of the house (Figure 6.1. and Figure 6.2.) for winter, when the demand is higher, it's seen that:

- The maximum peak demand is less than 4,5 kW.
- The amount of energy demanded below the 1,75 kW (normalized power in Spain (6)) represents the 75 % of the day, taking into account a margin till 2 kW the 88% of the energy can be supplied with only 1,75 kW.
- In a normal day the home demand 17,6 kWh and almost 20 kWh the worst day.

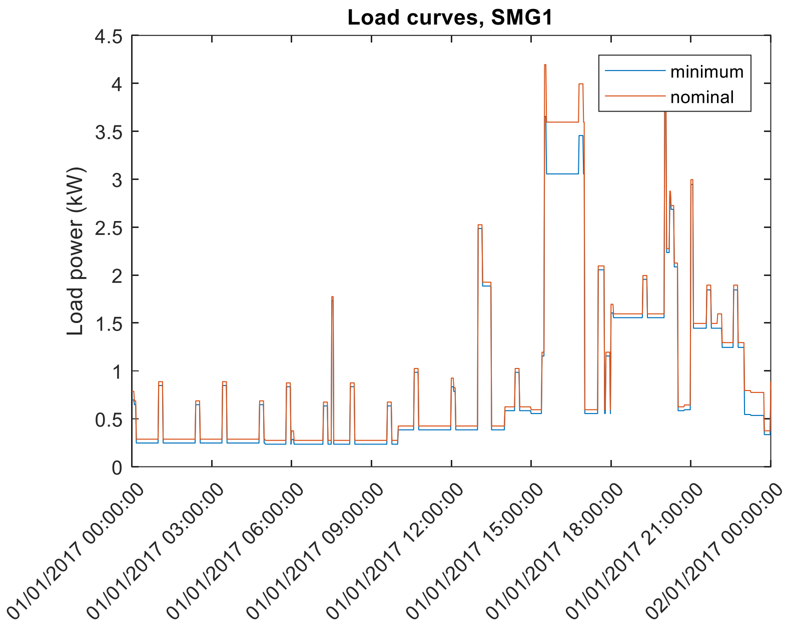


Figure 6.1. Load curve in a winter Sunday

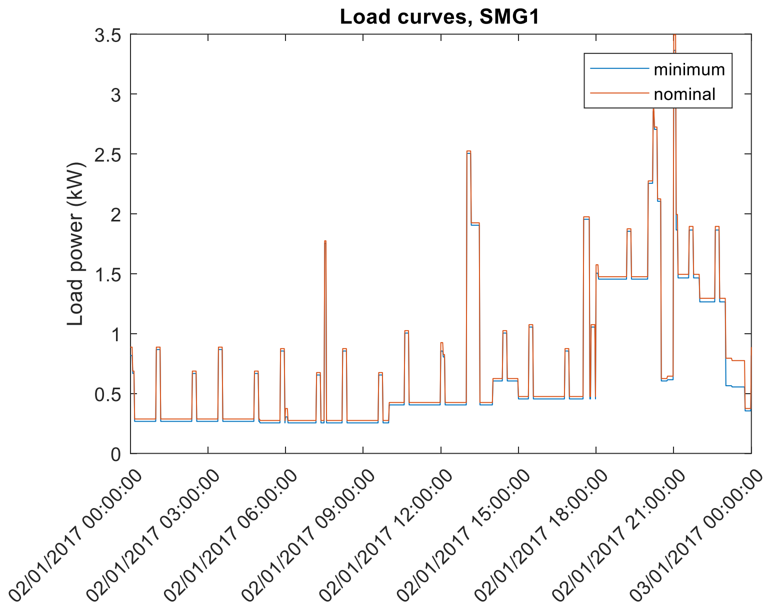


Figure 6.2. Load curve in a winter Monday

Secondly it is necessary to define where the SMG is located to get its external data. It will be located on the village of Puigpelat for example in latitude 41,276 and longitude 1,297. The irradiance values are for a PV array oriented to the south and with an inclination of 45° because the winter demand is higher than the summer demand.

6.1.1. Elements

6.1.1.1. The battery

So the battery will have to be able to supply a power of 2,5 kW and has a capacity of 10 kWh approximately. According to (3) a battery technology to perform this can be the tubular-plate traction batteries. They have a quite good price per kWh (190€/kWh (3)) a good rate of power and good durability. A bad thing is they have a high self-discharge ratio of 12 % per month at 20 ºC, the simulator doesn't take this into account. But can be simulated giving a worse performance in the efficiency curve.

So the battery pack chosen will be 12 batteries of OPzS 5 350Ah (7) of 2 Volts and 303 Ah at C / 3 it will be able to provide a power of 2,4 kW during 3 hours. But the capacity at C / 5 will be considered. So 345 Ah, or 8,3 kWh (for this use). The bulk charging power is considered the one able to charge the 15 % of the capacity per hour then 1,25 kW. The cost is of approximately 2.400 € (8).

The DoD assumed is calculated below.

$$\frac{17.6 * (1 - 0.88)}{8.3} * 100 = 25\%$$

With this DoD a life of 6.500 cycles is expected (see Figure 6.3.). This means a life of approximately 18 years.

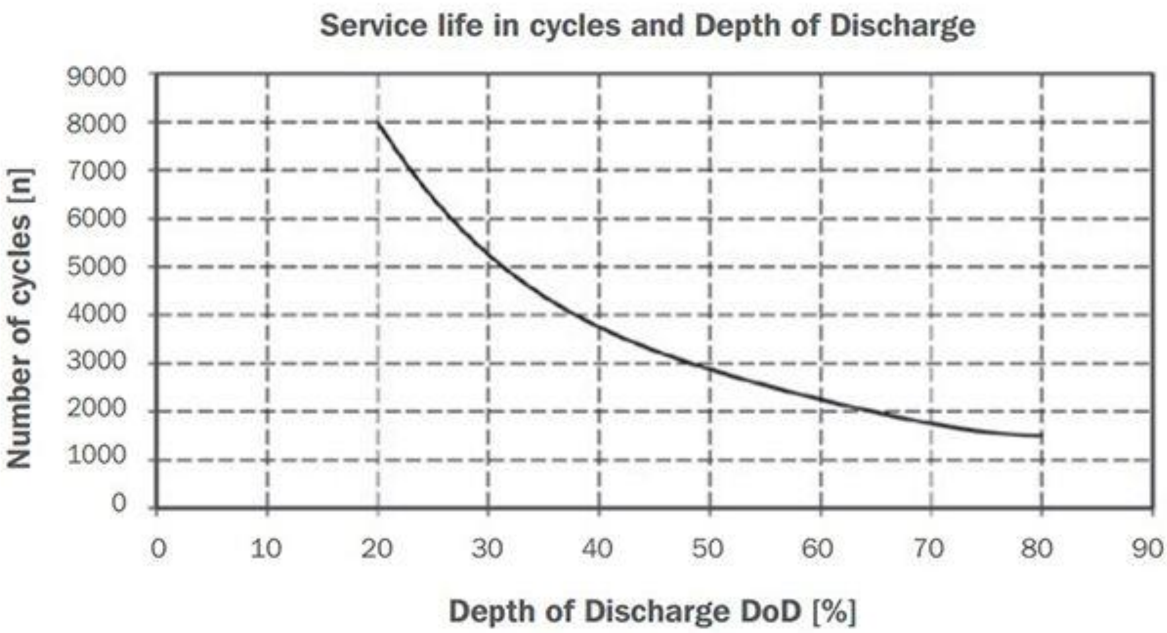


Figure 6.3. Number of cycles depending on DoD (8)

In Table 6.1. there is a summary of all the information:

Aspect	Value
Product name	OPzS 5 350Ah
Units	12
Discharge ratio	C / 5
Capacity at specified discharge ratio	345 Ah
Volts per unit	2 V
Battery pack volts	24 V
Maximum output power	2,4 kW
Considered energy storage	8.3 kWh
Bulk power	1,25 kW
DoD	25 %
Expected cycles	6.500
Expected life	18 years
Cost	2.400 €

Table 6.1. Battery information (8)

There is no battery charger function on the simulator because it is "integrated" in the battery function. But the price of it has to be considered. The model choosen is Victron Energy MultiPlus 24/3000/70 (9), the expected price is 1.500 € (10). This model has a nominal power of 3 kW and an input voltage of 24 V. And has a lot of functionalities. The efficiency of it is estimated of 95 % when charging and discharging, this efficiency is integrated in the battery function and can be set easily at when defining the parameters (see section 4.4.1).

Also an efficiency of 95 % due to joule loses is applied to the power provided by the battery.

6.1.1.2. PV array

The PV array has to be designed no not give very much extra energy because the amount that can be stored daily is about 2 kWh. The rest should be used directly or given to the grid. According to 6.1 maximize the usage of renewable energy is the second priority. Another way to achieve this is implementing certain control on movable loads, the simulator doesn't have this feature available yet but can be reproduced just changing the data in the Excel sheets.

In Figure 6.1. and Figure 6.2. the loads curves have the dishwasher displaced, usually was started at 23h to use the cheap energy hours and now is placed in at 15:30h to use the solar energy. Since is the only displaced load is done manually. This doesn't change very much the battery information we had but allow to give more direct use for the PV energy.

A PV array of 1,5 kW of peak power is considered to supply energy. In the Table 6.2. and the Table 6.3. the information is specified. The model does not take into account more loses than the ones of the inverter, the other loses (connection and joule effect) have to be considered in to the same algorithm. So an efficiency factor of 0.81 is considered for the power of the PV array.

Aspect	Value
Product name	SunPrimo PM060PWI
Series connected panels	6
Parallel connected panels	1
Peak power	265 W
Number of cells	60
Technology	Polycrystalline
$\boldsymbol{V_{oc}}$	37,9 V
$\boldsymbol{I_{sc}}$	8,89 A
$\boldsymbol{V_{mpp}}$	31,7 V
$\boldsymbol{I_{mpp}}$	8,36 A
NOCT	46
$\boldsymbol{K_v}$	-0,003 K^{-1}
$\boldsymbol{K_i}$	0,0007 K^{-1}
Expected life	30 years

Table 6.2. PV panels information (11)

Aspect	Value
Product name	Sunny Boy 1.5
Nominal power	1,6 kW
Input voltage range	160 V – 500 V
Expected life	30 years

Table 6.3. PV inverter information (12)

The expected price for the total equipment and installation is 4.750 € (13). In Figure 6.4. the power curve and the demand curve can be seen.

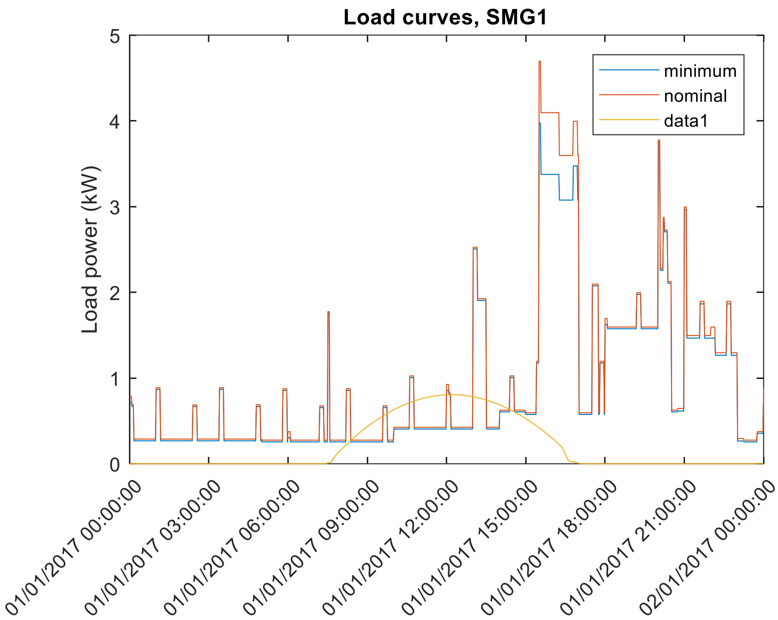


Figure 6.4. Power curves SMG1

These are the curves for a winter day, the solar production is very low, but the capacity of the batteries for storing PV energy is also very low, then the PV array don't have to be over dimensioned.

Notice that the PV inverter used cannot control the active power injection see **¡Error! No se encuentra el origen de la referencia.**. Then all the energy that cannot be stored will be given to the grid.

6.1.1.3. Generator

Because of the reliance of the grid where it is placed the SMG and that the application is not crucial in case of fall in supply it is considered not necessary to have a generator. It will not be economical, efficient and eco-friendly at all.

6.1.1.4. The grid

The maximum allowed power will be 2 kW, in order to reduce the electricity bill. The contractual information is showed in Table 6.4.

Concept	Value
Contracted power	1,75 kW
Access fee	2.0 A
Power price	38 €/year
Energy purchasing price peak period	0,152 €/kWh
Energy purchasing price valley period	0,078 €/kWh
Energy selling price	0 €/kWh
Electric tax	5,0113 %
IVA	21 %

Table 6.4. Grid prices

This constitutes the information related with the electricity bill. The CO_2 emissions per kWh considered will be 0,245 kg/kWh. Loses of 5 % due to joule effect are considered.

6.1.2. The algorithm

The principles of the algorithm will be:

- Priority of providing energy
    1. PV array
    2. Grid
    3. Battery
- Priority to charge the battery
    1. PV array
    2. Grid valley hours
    3. Grid peak hours
- Lowest allowed SoC for the batteries 50%
- The nominal demand curve is the demand to satisfy.
- In case of outage the energy will be provided by the batteries and PV array until 50 % of SoC.

The algorithm is explained step by step following a similar structure as in 5.

1. Step 1

According to first step the elements will give to the EMS the values of the variables to determine the state.

2. Step 2

Solving the following equations it's possible to determine the state at that instant.

There are five possibilities that constitute two states:

- Emergency stop of PV supply
  - i. $P_{max,pv}$ - $P_{nom,load}$ - (-$P_{max,charge,bat}$) > $P_{max,grid}$
- Excess energy
  - ii. $P_{max,pv}$ > $P_{nom,load}$ + (-$P_{max,charge,bat}$)
- Energy available:
  - iii. $P_{nom,load}$ < $P_{max,pv}$
  - iv. $P_{nom,load}$ < $P_{max,grid}$ + $P_{max,pv}$
  - v. ($P_{nom,load}$ < $P_{max,grid}$ + $P_{max,pv}$ + $P_{max,discharge,bat}$) & SoC > 50%
- No energy
  - vi. $P_{nom,load}$ > ($P_{max,grid}$ + $P_{max,pv}$ + $P_{max,discharge,bat}$) OR ($P_{nom,load}$ > ($P_{max,grid}$ + $P_{max,pv}$) & SoC <= 50%)
- Zero energy
  - vii. ($P_{max,grid}$ + $P_{max,pv}$ = 0) & SoC <= 50%

Notice that the order of coding this logical equations is essential to simplify the code. Notice too that the battery function says that the $P_{max,charge,bat}$ is 0 when SoC = 100 % and this simplifies even more the logical statements.

Once determined in which situation is the system is necessary to calculate the rest of variables:

i. Emergency stop of PV supply

This is an extreme situation where the energy of the PV array does not have anywhere to put its energy. In this case the optimum would be to reduce the power provided by it but the inverter chosen cannot control this. Then before the house protections open the circuit the EMS will disconnect completely the inverter and provide the energy for the loads using the grid and the batteries.

So:

$$P_{load} = P_{nom,load}$$

$$P_{PV} = 0$$

$$P_{grid} = \begin{cases} P_{max,grid}, & P_{load} > P_{max,grid} \\ P_{load}, & P_{load} \leq P_{max,grid} \end{cases}$$

$$P_{bat} = \begin{cases} P_{load} - P_{grid}, & P_{load} > P_{max,grid} \\ 0, & P_{load} \leq P_{max,grid} \end{cases}$$

ii. Excess of energy in the system but not on the grid

$$P_{load} = P_{nom,load}$$

$$P_{PV} = P_{max,PV}$$

$$P_{bat} = P_{max,charge,bat}$$

$$P_{grid} = -P_{PV} + (-P_{bat}) + P_{load}$$

Notice when the grid has negative power means that is receiving energy of the SMG.

iii. Energy available, PV alone.

$$P_{load} = P_{nom,load}$$

$$P_{PV} = P_{max,PV}$$

$$P_{grid} = 0$$

$$P_{bat} = P_{load} - P_{grid} - P_{PV}$$

iv. Energy available, photovoltaic supply with grid support.

$$P_{load} = P_{nom,load}$$

$$P_{PV} = P_{max,PV}$$

$$P_{grid} = P_{load} - P_{PV}$$

$$P_{bat} = \begin{cases} \dfrac{P_{max,charge,bat}}{2}, & SoC < SoC_{grid}\ AND\ P_{max,PV} > 0\ AND\ grid_{purch,price} \leq price \\ P_{max,charge,bat}, & SoC < SoC_{grid}\ AND\ P_{max,PV} = 0\ AND\ grid_{purch,price} \leq price \\ 0, & SoC > SoC_{grid} \end{cases}$$

$$P_{grid} = P_{grid} + (-P_{bat})$$

Where SoC_{grid} is a parameter that can take a value of 85 for example and means the maximum SoC that the battery can be charged by the grid. The term $P_{max,charge,bat}$ is substituted by

$-(P_{max,grid} - P_{grid})$ when $\left(P_{grid} - P_{grid}\right) < -P_{max,charge,bat}$.

The aim of adding the $grid_{purch,price} \leq price$ and $P_{max,PV} > 0$ restrictions is to charge the battery only when the price of the energy of the grid is below an accepted value for the first restriction and to charge at a low power when there is PV power. Notice that normally the lower prices are at night and there is no PV production at night, but this makes the algorithm more robust in case that in a future the low prices are located in a different period of time.

Notice that P_{grid} is calculated twice this is because it charges the battery if it still has enough power.

v. Energy available, with photovoltaic supply and support from the grid and from the batteries (Peak Shaving).

$$P_{load} = P_{nom,load}$$

$$P_{PV} = P_{max,PV}$$

$$P_{grid} = P_{max,grid}$$

$$P_{bat} = P_{load} - P_{PV} - P_{grid}$$

vi. No energy available.

It will be necessary to actuate in order to reduce the demand so the first step is to try if the $P_{min,load}$ can be supported by the generators, if not the EMS will proceed to disconnect the loads that are less critical using the values of priority previously assigned.

When finally the loads demand accomplishes one of the enough energy situations it just actuates as if it was in those situations.

vii. Zero energy

It happens when there is an outage when there is no sun and the batteries are at 50 %.

All the power variables are zero.

$$P_{load} = 0$$

$$P_{PV} = 0$$

$$P_{grid} = 0$$

$$P_{bat} = 0$$

3. Step 7

The power commands are sent by the EMS to the elements that have to do some internal changes (in this case only the batteries).

4. Step 8

The elements act, they give or receive the power previously accorded. In this case the battery function gives an output with the information of its current state.

5. Step 9

The interesting values are stored in variables if they are not stored yet.

6.1.3. Simulation analysis

In this section all the aspects seen during the application of the algorithm for the SMG1 are presented in graphics and commented. There are different objectives behind this analysis as checking if the dimensioning could be improved, if the forecasted life of the battery is correct, and wonder in which external conditions the system could be better.

Once the simulation of the whole year is done after 431 seconds the results are analyzed and plotted.

The simulation is done from the 01/01/2017 until 01/01/2018 at 0h. Then 365 days in total. The precision is of 0.01 days per step in minutes is 14,4 minutes, the precision is though enough for the aim of the study.

6.1.3.1. Battery released power

This part of the code creates a histogram of all the power points of the battery, excluding the ones that are 0. See Figure 6.5.

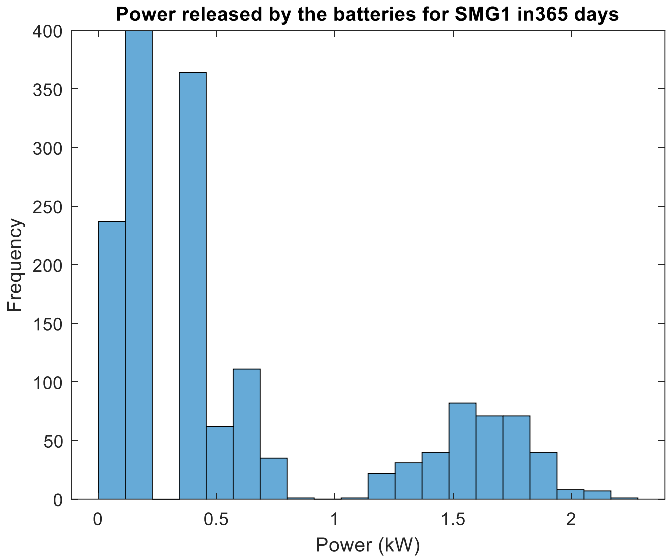


Figure 6.5. Power released by the battery during the whole year

It is seen that the maximum power the battery can provide is mostly lower than the needed. This leads to think that the initial supposes for the dimensioning of the battery were not enough accurate. The mean demanded power (in the points that is demanded) is of 610 W.

6.1.3.2. Deep of Discharge of the battery

This result is also presented on a histogram (see Figure 6.6.), as can be observed the expected daily DoD was far bigger than the final obtained. During the complete year there has been 544 cycles.

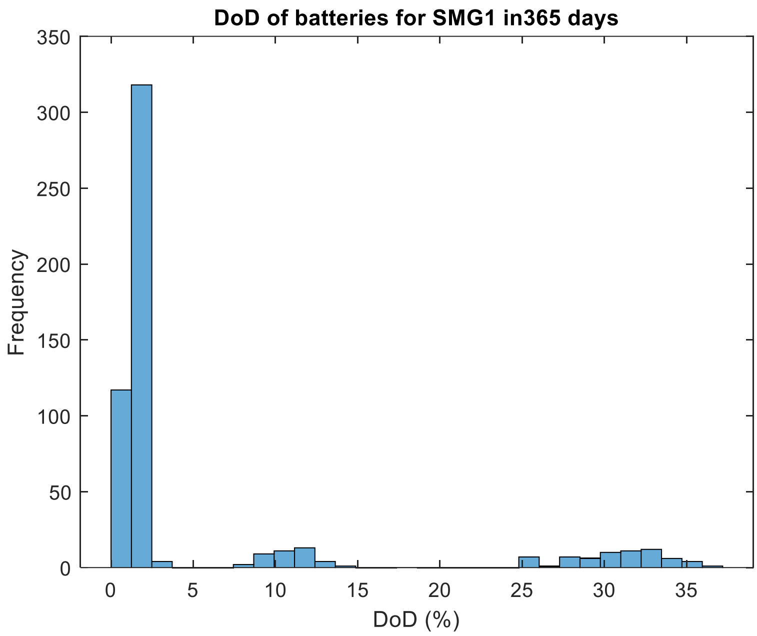


Figure 6.6. DoD of the battery during the whole year

It is clear that the battery is nearly full all the day. The mean DoD is of 5,7%.

6.1.3.3. Energetic mix analysis

To continue the diagnosis of the system is necessary to know how much energy was provided by the PV array, how much by the grid and how much coming from the PV array was injected to the grid. See Figure 6.7. Notice that the PV could provide almost the half of the energy needed by the system (5500 kWh), but nearly 650 kWh are just given away.

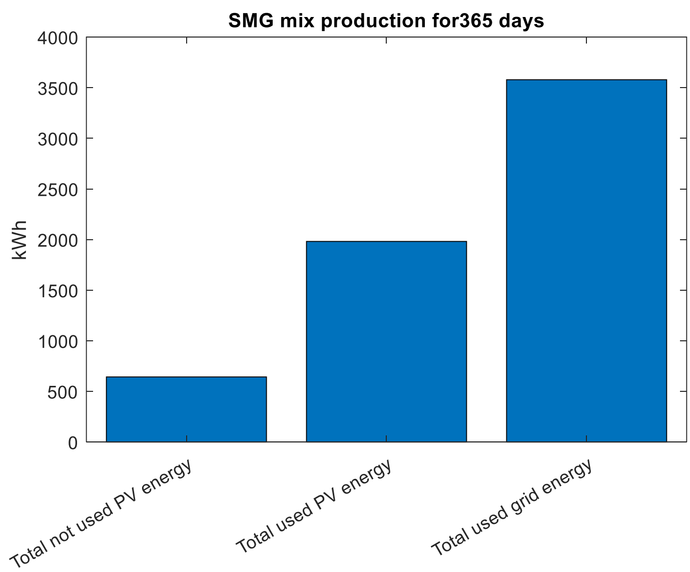


Figure 6.7. Energetic mix

This presents a problem, from the sections 6.1.3.1 and 6.1.3.2 we know that the battery is bigger than needed, so it can be reduced and with it the costs. Now a lot of energy during the year is not well used, the first thoughts can be… We need a bigger battery! But that is not true, first will be necessary to know from where comes the energy used to fulfill the battery. This is explained in the next section.

6.1.3.4. Origin of the energy of the battery

The energy used to charge the batteries is mostly coming from the PV array this shows that the algorithm with its restrictions works quite well (see Figure 6.8.). These restrictions are the ones of not charge the battery more than the 80 % with the grid and only do it at night when the price is lower.

Notice too that the energy that the battery manages is low compared with the total, because the algorithm is mostly developed around the “Peak Shaving” strategy.

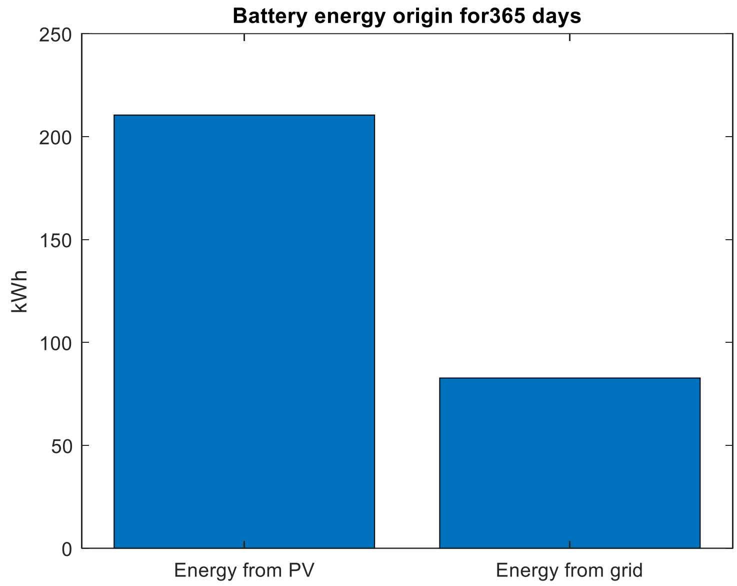


Figure 6.8. Battery’s energy origin

6.1.3.5. Reliance

Another usual question related to this systems is if they are capable to provide the total energy to the system without any gap.

Using an histogram again can be seen in which states do the system usually stays (see Figure 6.9.).

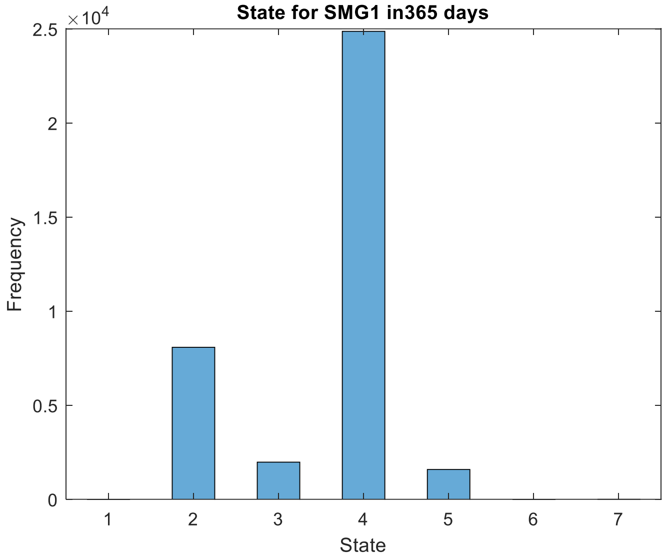


Figure 6.9. System states

The explanation of each state can be seen in 6.1.2. The histogram shows that the most common state is the number 4, in which the energy is provided by the grid and the PV array (or the grid alone), and the second most common is number 2 where there is too much PV energy.

This clearly shows that there are some inefficiencies on the system because in the case of study the energy injected to the grid has no payback. It is just given for free.

During the simulation one grid fall in energy supply took place, concretely on 05/08/2017 during a little bit more than one hour, luckily there was not very much demand in that moment and no loads needed to be disconnected, in Figure 6.10. the moment can be seen, and in Figure 6.11. how the SoC was affected by it.

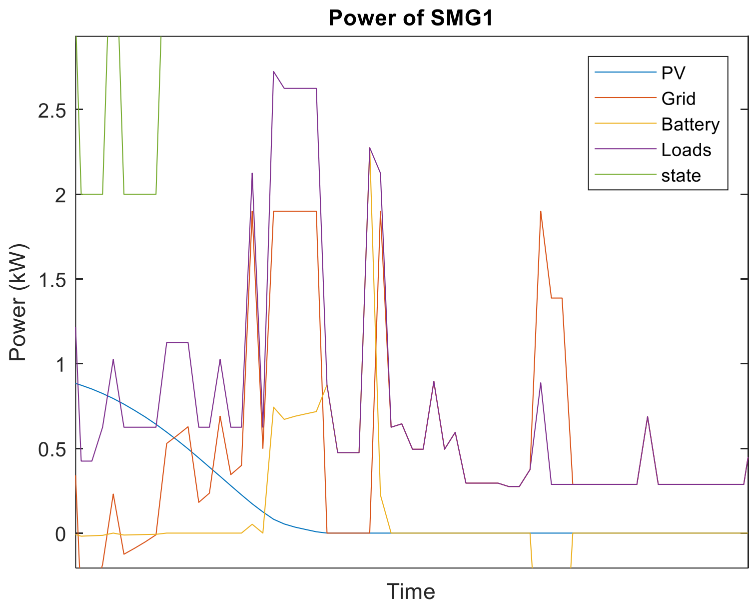


Figure 6.10. Power plots during the outage

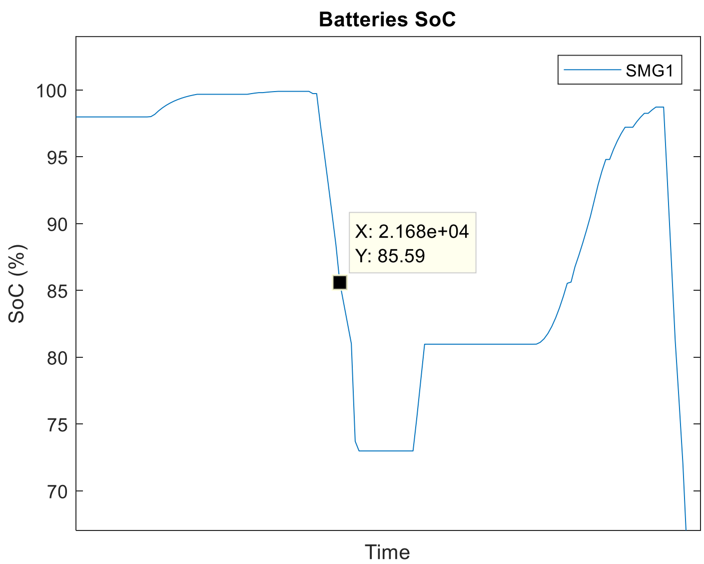


Figure 6.11. SoC during the outage

6.1.3.6. Power's flux behave

Finally it is really interesting to see how do the power of every element of the grid behave, the Figure 6.12. and Figure 6.13. show the system's behave for two days the first on summer and the second on winter.

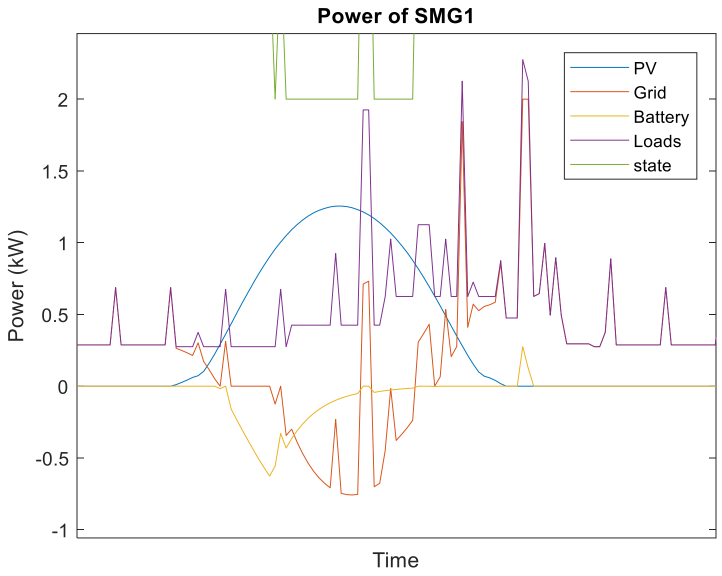


Figure 6.12. Powers' fluxes behaves in a summer day

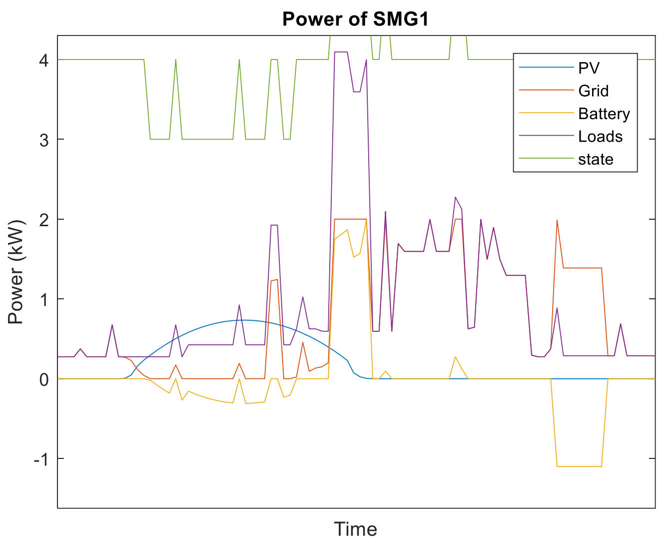


Figure 6.13. Powers' fluxes behaves in a winter day

It is noticeable that when the battery is almost charged a lot of PV energy is unused. An improved SMG can be seen in SMG2

6.1.4. The economic study

The economic study is showed on section Results' analysis7. Where all the economic results are analyzed together.

6.2. SMG2

This SMG is dimensioned in order to improve the previous design (SMG1) and have better use of the energy and lower costs.

6.2.1. Elements

6.2.1.1. The battery

Taking a look at the results of the first simulation, the power of 2,4 kW is never used, and to consider a power of 1,6 kW would be enough for the simulation, it doesn't means that in reality for certain occasions the battery will give more power, but to size the battery this will be a good approximation.

So the battery pack chosen will be 12 batteries of OPzS 5 350Ah (7) of 2 Volts and 345 Ah at C / 5 it will be able to provide a power of 1,6 kW during 5 hours. So 345 Ah, or 8,3 kWh exactly as spected in SMG1. The bulk charging power is considered the one able to charge the 15 % of the capacity per hour then 1,25 kW. The cost is of approximately 2.400 € (8).

The DoD assumed in SMG1 was of 25 % each day. The reality is more complex a lot of cycles are of DoD of 10 % or less, approximately 450 cycles out of 544. The others are split around the value of 30 % then 90 cycles at 30 % of DoD per year can be considered. With it can be said that the battery is too big for the use that is giving. In years this gives a life longer than 50 years. So for the new SMG the battery will be allowed to be discharged until a DoD of 70 % and will be only allowed to be charged with PV power.

In Table 6.5. there is a summary of all the information:

Aspect	Value
Product name	OPzS 5 350Ah
Units	12
Discharge ratio	C / 5

Capacity at specified discharge ratio	345 Ah
Volts per unit	2 V
Battery pack volts	24 V
Maximum output power	2,4 kW
Considered energy storage	8.3 kWh
Bulk power	1,25 kW
DoD	?
Expected cycles	?
Expected life	?
Cost	2.400 €

Table 6.5. Battery information (8)

The battery charger chosen will be the same.

6.2.1.2. PV array

A bigger installation could be considered because the use of PV energy will be considerably increased. The installation could be of 2,8 kW. This installation is based on the price presented on (14), the estimated cost is of 6.100 €. There's not very much information but the aim of the project is not to dimension too realistically the SMG if not to test the improvements on the algorithm. So similar aspects with the SMG1 PV array but with more power and cheaper. See Table 6.6. for more information.

Aspect	Value
Product name	Amerisolar AS-6P30
Series connected panels	10
Parallel connected panels	1
Peak power	280 W
Number of cells	60
Technology	Polycrystalline
V_{oc}	38,6 V
I_{sc}	9,42 A
V_{mpp}	31,5 V
I_{mpp}	8,89 A
NOCT	45
K_v	-0,0031 K^{-1}

K_i	0,0005 K^{-1}
Expected life	30 years

Table 6.6. PV panels information (15)

Aspect	Value
Product name	Fronius GALVO 3.0-1
Nominal power	3 kW
Input voltage range	185 V – 550 V
Expected life	30 years

Table 6.7. PV inverter information (16)

6.2.1.3. The grid

The grid will have the same properties than in SMG1

6.2.1.4. The loads

With the improvement on the algorithm (see section 6.2.2) it is possible to put more loads on the noon even if they use more power than the power the PV array can provide without wondering if the price of the energy will be higher. So some loads are displaced to the noon, with it more PV energy will be used.

The changes are slight but it is remarkable the change on the use of the washing machine. It was intensively used on Saturdays on the morning (when the price was low), now is distributed on the noon in the middle of the week indistinctly. It is easier and more comfortable and this helps a lot to reduce long power peaks (on weekends) and give better use to the PV energy in the middle of the week.

6.2.2. Algorithm

Forbidding the grid to charge the battery will not be possible to use all the PV energy given to the grid, for this another state is introduced in the algorithm to try to improve the system efficiency giving more use to the battery.

This state will go between state 3 and 4 but will be called state 8.

viii. $P_{nom,load} > P_{max,pv}$ & $P_{nom,load} < (P_{max,pv} + P_{max,discharge,bat})$ & $P_{max,pv} > 0$ & $SoC > 30\ \%$ & $(P_{max,pv} - P_{nom,load}) <= (-P_{max,charge,bat})$

In the previous SMG the PV power was supported with the grid, in this algorithm will be supported by the battery itself, then more energy of the PV will be used and the batteries will have more cycles and therefore a higher use. This state has more logical complexity. When this conditions are found:

$$P_{load} = P_{nom,load}$$

$$P_{PV} = P_{max,PV}$$

$$P_{grid} = 0$$

$$P_{bat} = P_{load} - P_{PV}$$

The simulator allow to write more than one algorithms, so both will be compared at the end of the simulation.

6.2.3. Simulation analysis

Once the simulation of the whole year is done after 1.039 seconds the results are analyzed and plotted.

The simulation is done from the 01/01/2017 until 01/01/2018 at 0h. Then 365 days in total. The precision is of 0.01 days per step in minutes is 14,4 minutes, the precision is though enough for the aim of the study.

6.2.3.1. Battery released power

This part of the code creates a histogram of all the power points of the battery, excluding the ones that are 0. See Figure 6.14.

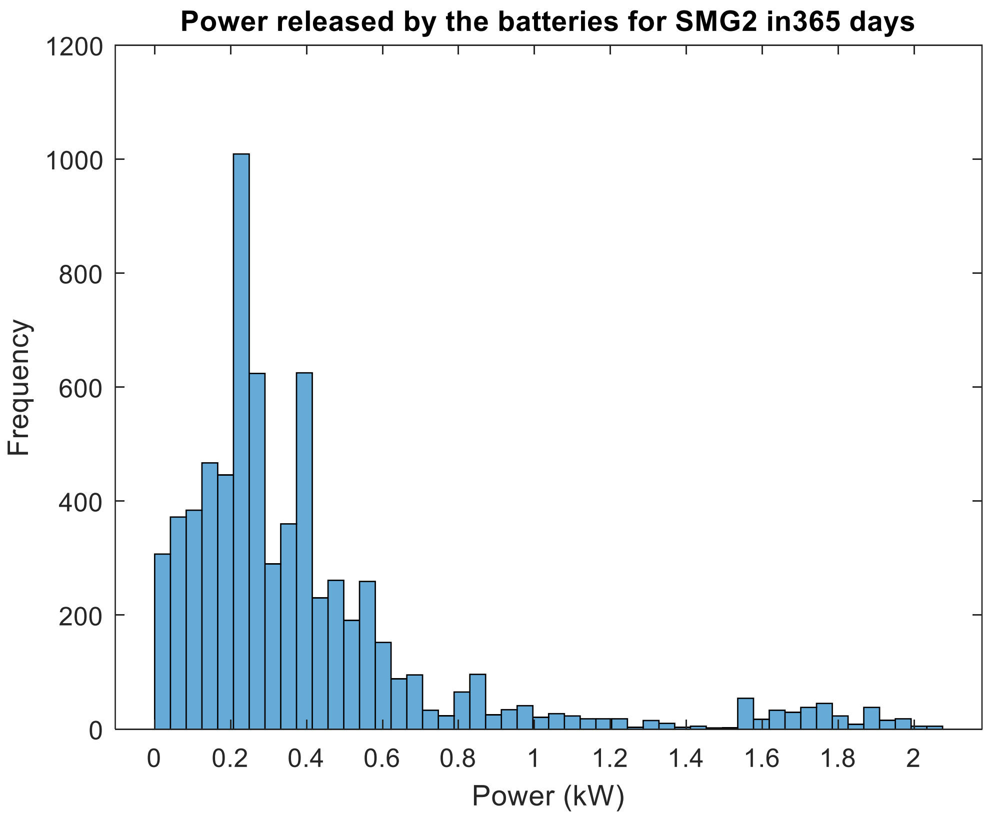


Figure 6.14. Power released by the battery during the whole year

The usage of the battery us much more intense than in SMG1. In SMG1 exist 1.576 power points and in SMG2 6.970, almost 5 times more usage. The mean demanded power (in the points that is demanded) is of 400 W. Seeing the power used can be said that is a good approximation use the capacity of 450 Ah.

6.2.3.2. Deep of Discharge of the battery

This result is also presented on a histogram (see Figure 6.15.), as can be observed the expected daily DoD is bigger than in SMG1. During the complete year there has been 1728 cycles, three times more.

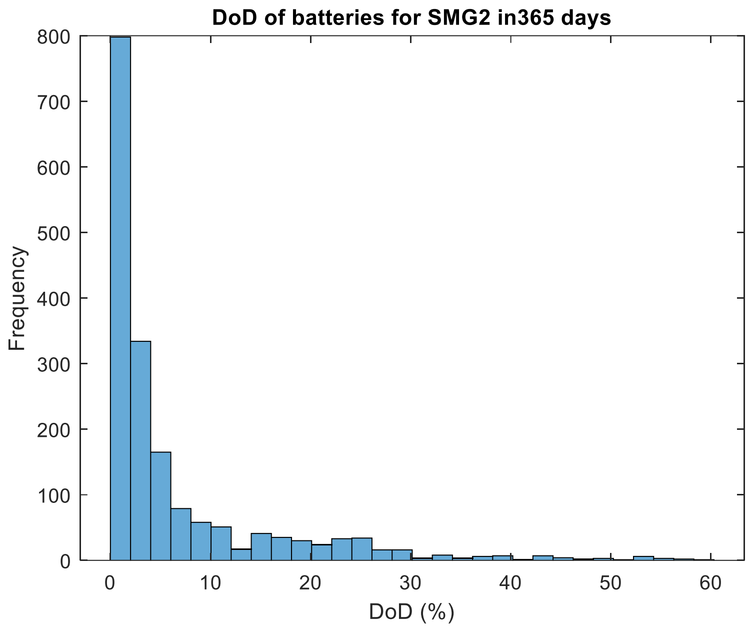


Figure 6.15. DoD of the battery during the whole year

It is clear that the usage is more intense. The mean DoD is of 6,4%. But this type of mean is not a good approximation because doesn't take into account the amount of cycles in each DoD and how this DoD affects.

To solve this a modified version of a weighted arithmetic mean is done, the usual equation for this mean is showed in **Eq. 6.1**

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i * w_i}{\sum_{i=1}^{n} w_i} \qquad \textbf{Eq. 6.1}$$

Where x are the data points we want to know the arithmetic mean, and w is the weight of each of this points. For this situation x will be the DoD and w the number of cycles.

The modification is done because according to Figure 6.3. the weight of one cycle is not the same of another cycle in a different DoD, so w will be multiplied by a value which revalorizes the weight of that cycle (see **Eq. 6.2**).

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i * w_i * k_i}{\sum_{i=1}^{n} w_i * k_i} \qquad \textbf{Eq. 6.2}$$

This k will be 1 divided by the number of cycles each DoD can afford. With this value will be easy and exact to determine the life of the batteries. The results are plotted in Figure 6.16.

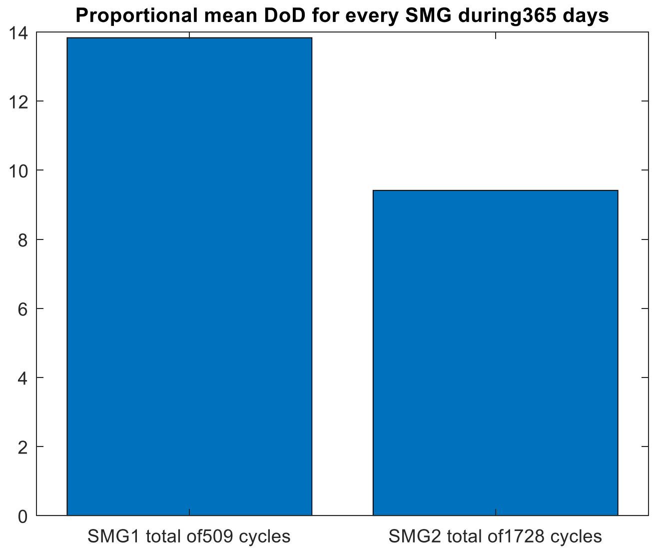


Figure 6.16. Weighted mean of DoD of the battery during the whole year

The life in cycles for the SMG1 is about 12.300 cycles and for SMG2 15.600 cycles. But the number of cycles per year is really different, so the expected life in years for SMG1 is 24 years and for SMG2 is 9 years. This will make more expensive the value of the batteries per year on SMG2.

6.2.3.3. Energetic mix analysis

The amount of PV energy in SMG2 is considerably increased, in Figure 6.17. it is possible to see it and compare it with SMG1.

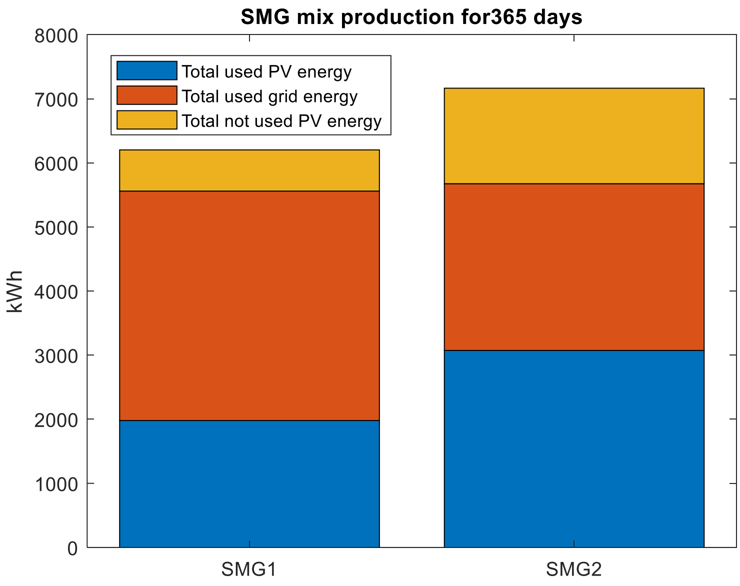


Figure 6.17. Energetic mix

The change on the algorithm gives more possibility to use PV energy, but the PV energy was not enough to maintain the batteries well charged, so more PV was installed. The result as can be seen is that the not used PV energy is higher than before. The good thing is that the PV energy supplies more than the half of all the energy demanded.

6.2.3.4. Origin of the energy of the battery

In this simulation the algorithm is not only based on Peak Shaving, it gives a lot of importance to use the PV energy as much as possible, so there is a very strong restriction that is that the grid will only charge the battery until 60 %, the rest is for the PV. The results can be seen on Figure 6.18. The results are very visual, the amount of energy managed by the batteries has increased a lot. Even though the life of the batteries is lower, at the end of its life will have managed 7.600 kWh of PV energy while in SMG1 significantly less, 5.090 kWh. So this is a good economically saving point.

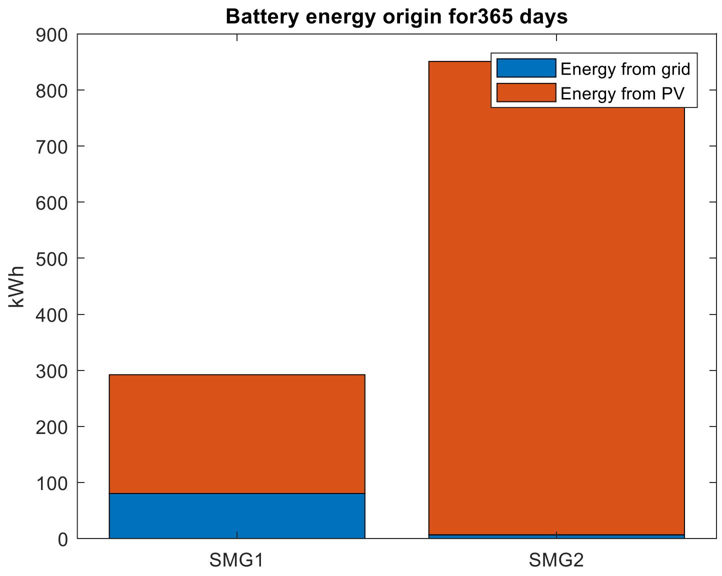


Figure 6.18. Battery's energy origin

6.2.3.5. Reliance

Taking a look to the states of the system we will be able to know if there were some kind of lack of energy at some point (see Figure 6.19.).

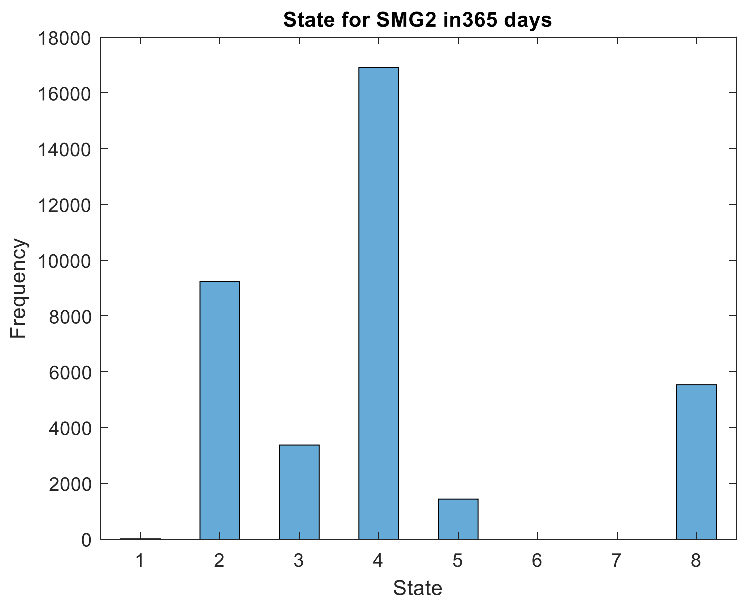


Figure 6.19. System states

The explanation of each state can be seen in 6.1.2. The histogram shows that the most common state is the number 4, in which the energy is provided by the grid and the PV array (or the grid alone), and the second most common is number 2 where there is too much PV energy. And now the state 8 where the battery and the PV array are actuating together is also a common state.

In the histogram cannot be seen clearly but there were 6 points were the system was in state 1, this means too much PV energy on the system, if Figure 6.20. this moment can be observed.

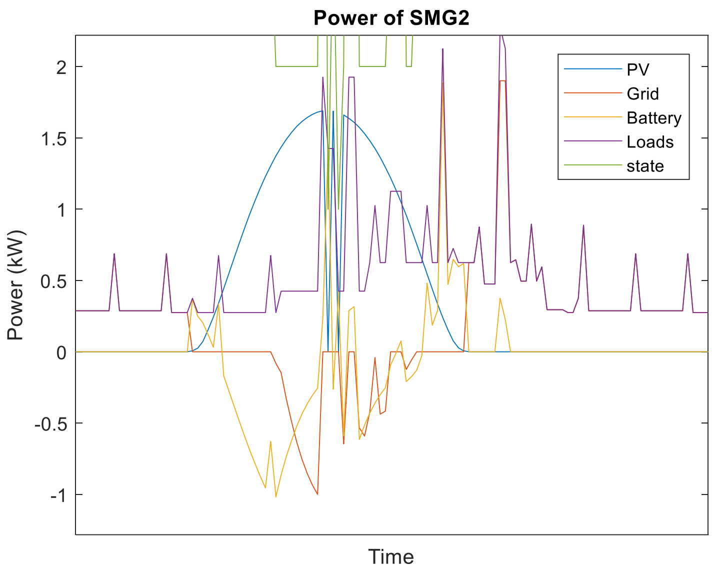


Figure 6.20. Power plot during state 1

During the simulation two grid fall in energy supply took place, concretely on 05/09/2017 during almost two hours and the next day during almost one hour. In Figure 6.21. the moments can be seen, and in Figure 6.22. how the SoC was affected by it. It is the same day the system had an excess of energy, because when the grid falls it cannot receive energy and the batteries where almost full. Then the system was working without PV and without grid only with the batteries. As can be seen was not a big deal.

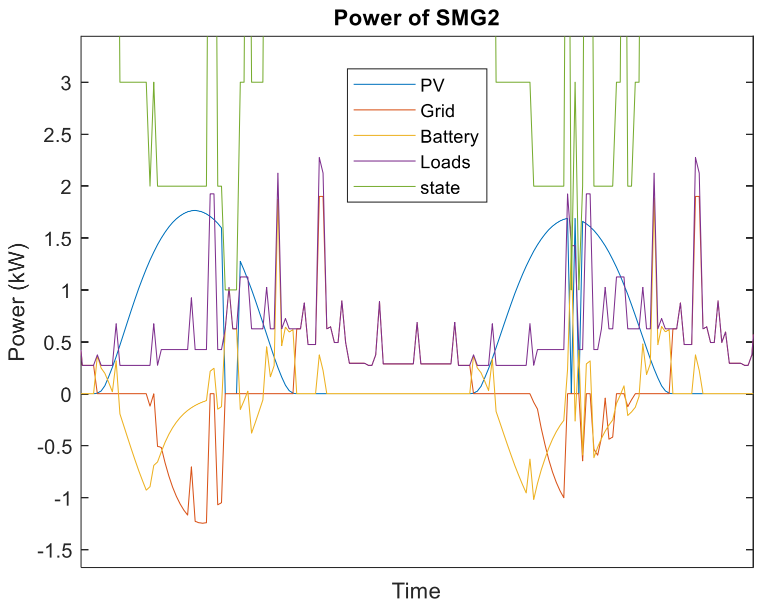


Figure 6.21. Power plots during the outage

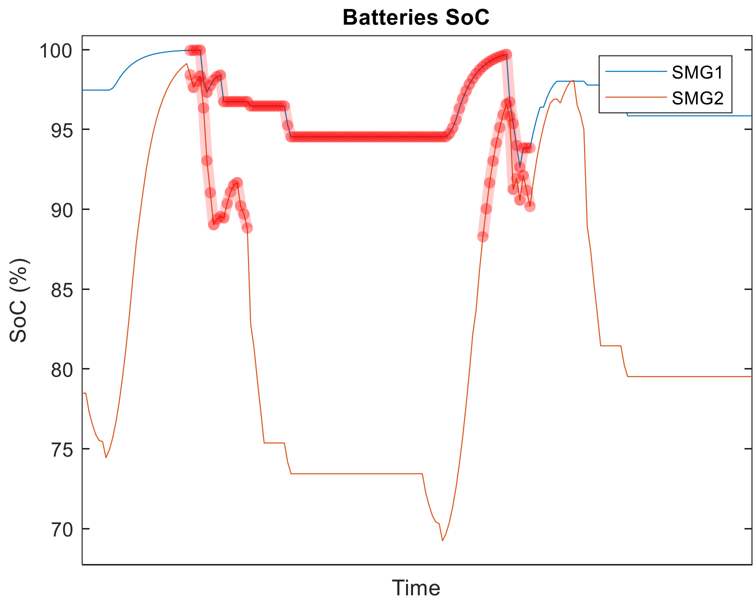


Figure 6.22. SoC during the outage

6.2.3.6. Power's flux behave

Finally it is really interesting to see how do the power of every element of the grid behave, on Figure 6.23. can be seen how the system actuates with the new algorithm. And can also be observed that increasing the PV power doesn't allow the batteries actuate very much and a lot of energy is not used.

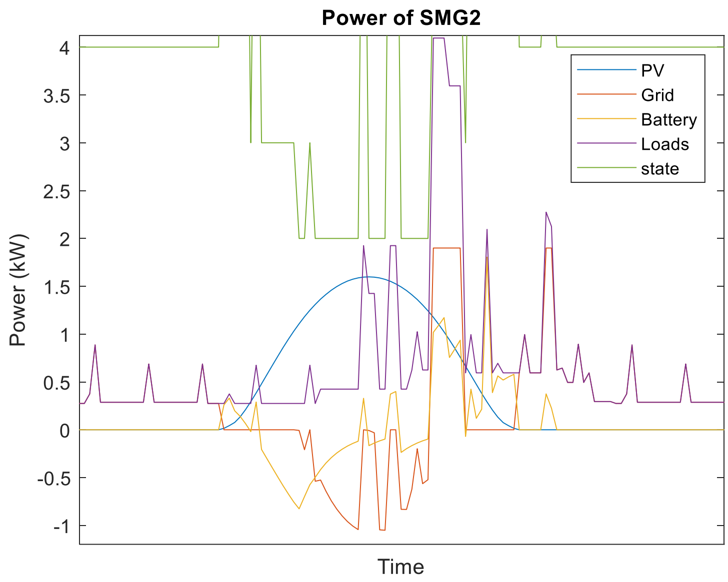


Figure 6.23. Powers' fluxes behaves in a summer day

6.2.4. The economic study

The economic study is showed on section 7. Where all the economic results are analyzed together.

6.3. SMG3 and SMG4 and SMG5

The first two SMG will be the SMG1 and 2 but with better external conditions such payment for the given PV energy. The rest is exactly the same. The payment is thought to be 0,04 € per kWh given to the grid.

SMG5 will be a normal home without any element, only paying the electricity bill. The contracted power of SMG5 will be 4,6 kW but the maximum it can use is 5 kW. After a simulation of 3.493 seconds the results obtained are similar to the previous ones but without grid outages, they are discussed together on section 7.

7. Results' analysis

There are some interesting aspects to mention and discuss about the results. They are:

1. The energetic mix

When the power of the grid can be supplied by more than one type of production technology it is interesting after the studied period what is the penetration of each technology. In the studied case there is only one additional energy source, but a differentiation in the PV production is done (see Figure 7.1.). There is the amount of PV energy used in the system and the amount injected to the grid.

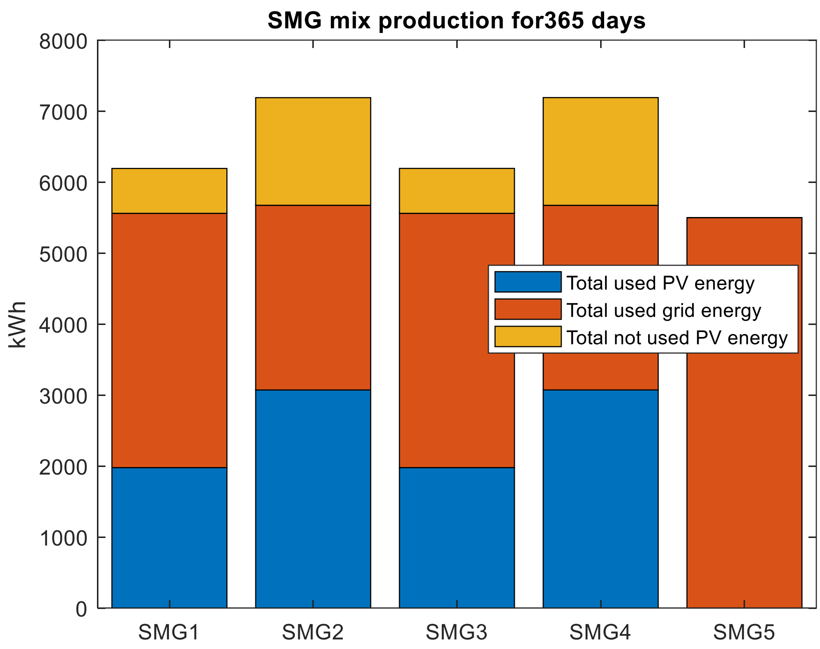


Figure 7.1. Energetic mix

In SMG2 and SMG4 there is an interesting increase on the penetration of the PV energy about a 55 % more than in SMG1 and 3, and representing the 54 % of the mix, while in 1 and 3 it represents the 35 %. This is due to the increase of the PV array and the algorithm modification.

Analyzing the not used energy in the SMGs 1 and 3 it represented the 24 % of the PV production and in SMGs 2 and 4 the 33 %. But this not used energy is increased by 140 %. This last values can be used as an indicator of the efficient use of the energy by the algorithm. The second algorithm provides more penetration but for doing this needs more PV production or the batteries will be most of the time discharged. Then the perfect equilibrium point has to be found adding more restrictions to the algorithm in order to make the most efficient use of the energy possible. The correct policies of the algorithm and the algorithm itself is not redundant and can make a big difference with the same hardware.

Notice that the sum of used PV energy and used grid energy is different in each SMG, that's because if the use of the battery is higher more loses occur and more energy is needed.

2. The grid congestion

The grid congestion is an aspect that could be considered while developing the algorithm because in some countries the amount of energy injected on the grids by particulars is not controlled. This leads to an overcharging of the grid, in form of an increase of the frequency. This can result on a fall in of the supply. Then the algorithm should take this into account, because the released energy by the PV array can be important if there are more. Normally the state regulation would reflect it "in a logic way" penalizing when injecting energy at some hours and subsidizing the injection on other hours, or in other words the correct use of batteries determined by the EMS.

3. The costs

The most interesting aspect usually is if is worth it economically talking only. So the investments are annualized taking into account the expected life in years of each element. In Table 7.1. and Table 7.2. the detailed information can be seen.

Initial investment	**PV array + inverter + all derived costs**	**Battery**	**Inverter/Charger**	**EMS + study**	**Annualized cost**
SMG1	4.750 €	2.400 €	1.500 €	2.000 €	400 €
SMG2	6.100 €	2.400 €	1.500 €	2.000 €	611,7 €
SMG3	4.750 €	2.400 €	1.500 €	2.000 €	400 €
SMG4	6.100 €	2.400 €	1.500 €	2.000 €	611,7 €
SMG5	0 €	0 €	0 €	0 €	0 €

Table 7.1. Costs

Initial investment	PV array + inverter + all derived costs	Battery	Inverter/Charger	EMS
SMG1	30 years	24 years	20 years	30 years
SMG2	30 years	9 years	20 years	30 years
SMG3	30 years	24 years	20 years	30 years
SMG4	30 years	9 years	20 years	30 years
SMG5	0 years	0 years	0 years	0 years

Table 7.2. Expected life of the elements

The grid costs can be seen in Table 6.4. .

Evaluating all the costs along the year of simulation the findings are showed in Figure 7.2.

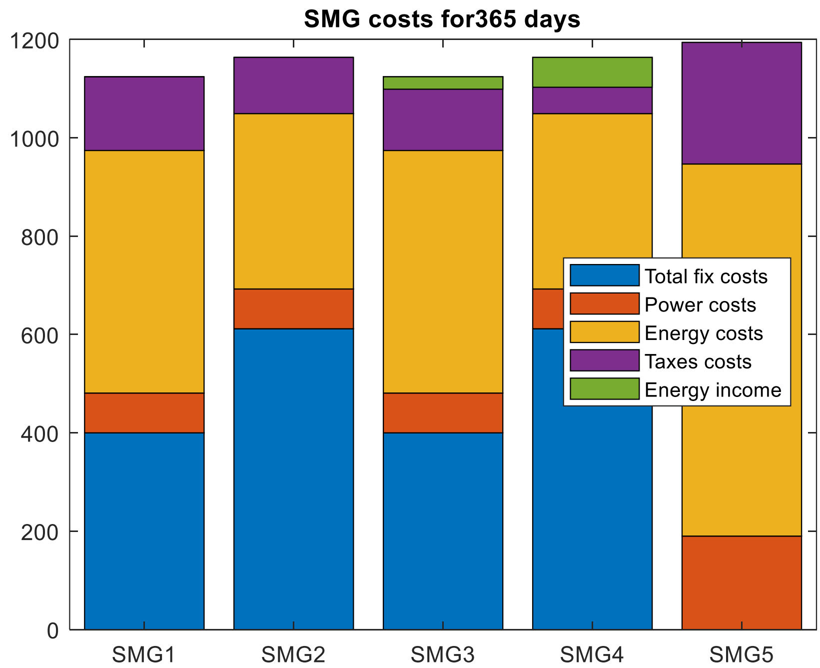


Figure 7.2. Annual costs

As can be seen, the savings in energy, power and taxes are really high, 469,7 € for SMGs 1 and 3 and 642 € for SMGs 2 and 4. The objective is this savings being bigger than the annualized cost of the investment (in blue).

The results show that the use of this elements to transform the home into a SMG is cheaper annually talking. But it could be better, note that the earnings for the extra energy sold are really small in comparison with the percentage they represent in the energy mix. The value of these kWh hours is reduced by a 4,8 factor when saving energy in peak hours and 2,3 in valley hours. This means that potentially with a good algorithm the money payed by selling energy could be increased 3 times annually (more or less) and this without depending on the regulations. Increasing the savings until 150 € for SMGs 1 and 3 and until 200 € for SMGs 2 and 4 compared with SMG 5 (which is not actually an SMG). In the actual situations this economical earnings are represented in green and are negative, subtracting instead of adding, so the annual costs are lower in SMGs 3 and 4 than in 1 and 2.

4. The environmental impact

The aspect that should be most remarked and often the most omitted one even for the engineers is the positive impact this renewable integration has on the environment. This impact is counted with the amount of emissions supposed per each kWh consumed from the grid. The results are showed in Figure 7.3.

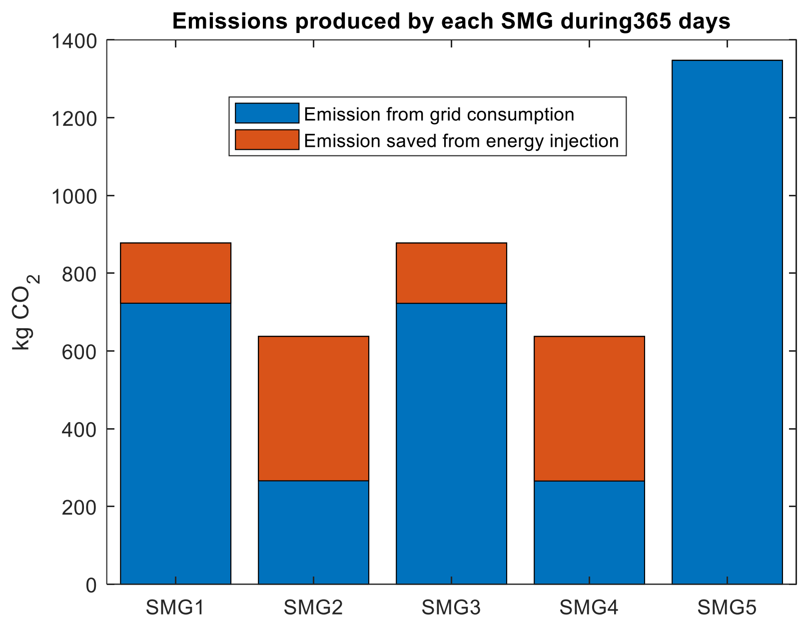


Figure 7.3. Annual emissions

In red are the emissions saved by the energy injected to the grid, note that it is negative it is actually subtracting again. Therefore, a normal home would emit 1350 Kg per year and our SMGs 720 Kg or 270 Kg. These reductions are of 47 % and 80 % respectively. A huge reduction for a similar annual cost. This reduction is minor when talking of global emissions but has to be taken into account that such systems can be applied to any building even if they are not domestic. The potential savings are very big.

Conclusions

The present project started with the aim of simulating a real Smart Micro Grid. After some reflection can be said that the aim of simulating an SMG is to know how it behaves. Depending on the elements and its size, properties and technology, also depending on each particular demand and finally depending on the policies of control applied the results can be very different between them. To know how the system behaves along the year, the simulator needed to be provided by easy usable functions of these elements with a quite faithful representation. But an increase of the complexity would end with a really complicated compilation and long times of execution often to find just little differences on the results.

The simulator can be improved yes, but in order to add more elements and do more interesting studies. Can be improved also to represent the reactive power and have also simulation results on this field. But adding more complexity such the real parameters used by the real elements (explained in **¡Error! No se encuentra el origen de la referencia.**) will not give much more interest on control policies testing. But for sure it will increase the simulation times that are already quite long.

A usual problem of projects which have really differentiated and completely autonomous elements is that is difficult make them fit together inside an integrated system. Therefore has to be said that coding it and following a similar structure for all of them give rise to a logical method quite easy and learnable to use. Once all the elements were finished and debugged an integration of them into an algorithm was tricky but really logical. All the parts of the program did their job and allowed a very flexible coding of algorithms where all types of ornamental rules can take place.

To conclude after using the program itself it is rewarding to see how just calling a function in one line everything is modelled, reducing incredibly the complexity of the use and letting focus only on how to apply the policies.

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