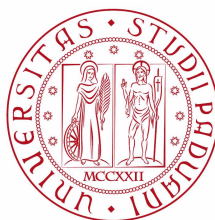


UNIVERSITÀ DEGLI STUDI DI PADOVA

Corso di Laurea in Ingegneria Energetica

Tesi di Laurea Magistrale

**PV and Storage systems Management.  
Analysis of Self-Consumption strategies  
for Italian and Spanish Householders.**



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# Summary

This master thesis is a research on the combination of photovoltaic systems and BES for LV end-users like householders. Different models of commercial BES on the market are presented. Eventually, several charge/discharge power battery curves are performed in relation with the energy market prices, in order to investigate which one of them may lead to a higher saving for the householder, who follows the modelled profile.

This is a simplified study on an aspect of the new upcoming energy market trend, in which the renewable energies have to face the difficulties in the interaction with the existing networks system. From this point of view the storage assumes an important role in the energy management.

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# Chapter 1

## Introduction

In the past few years an improvement of renewable energy production came out, both in MV and LV network. In particular the installation of rooftop PV systems revealed to be preferred by many countries for its simplicity of installation, modularity and pollution free, [12]. Even the promotion throughout the FIT tariffs helped the diffusion of this technology. The purpose of this work is to analyse the effects of combination of photovoltaic systems with energy storage systems in the LV network, in particular pointing out what are regulations policy which regulate the market of photovoltaic end-users systems in relation with the upcoming of the energy storage phenomena.

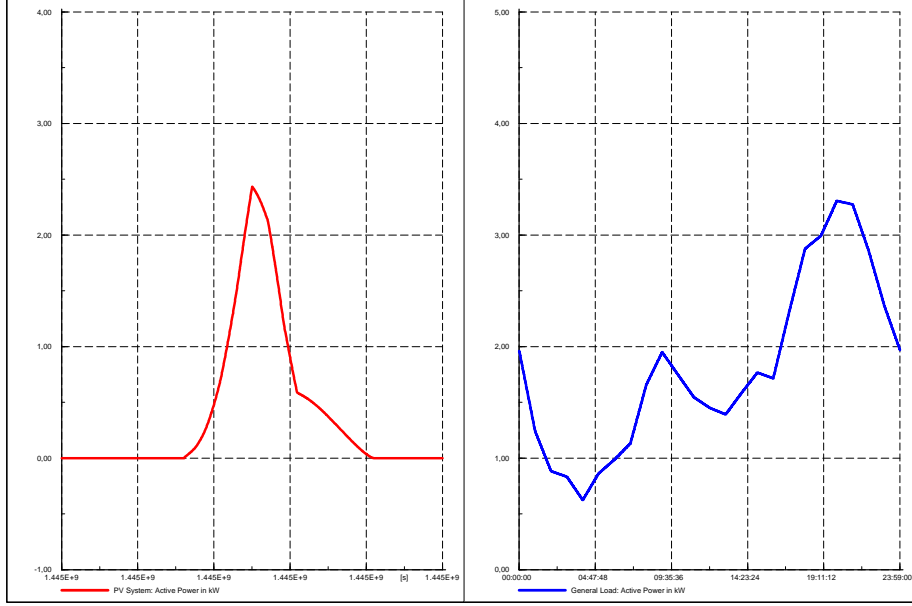
### 1.1 State of the Art

Since '90s Europe chose RES for their safety in supply and minor impact on the environment; countries which buy energy from abroad see in RES a new opportunity for energy production independence, but the economic structure adopted in the past years cannot match the new market, thus a new economic model must be developed in order to give advantages both suppliers and consumers who support renewable production. In the recent few years the installed photovoltaic capacity in the world has rapidly increased; in the 2013 the total installed capacity around the world was about 37 GW. The growth of PV market has led to a significant price drop of new installations, with an average PV system price decline of 6–7% per year since 1998, [5] [18]. In distributed generation, new renewable energy production systems, such as small scale PV and micro-turbines for end-users, are often located closer to the consumers, resulting a number of potential benefits such as reduced peak power consumption and increased power quality. There are however challenges needed to be solved to achieve a high penetration of intermittent electricity production in the electric power system, such as frequency regulation, the ability to rapidly start and ramp the remaining electric power generation and better match the consumption with the intermittent generation to avoid exceeding voltage limit, [14]. The latter case can partly be achieved with increased *self-consumption* of the distributed generation, [3]. For self-consumption it means the idea of the PV production consumed directly by the producer, which is often (and in particular in this case) the owner of the PV system [3].

Still, it cannot be said that in the near future all householders can separate themselves from the network, influence to the electric system should be taken in consideration; as a matter of fact energy production at the customers level brings problems to the distribution grid. A high penetration, for example, of rooftop solar PV units can worsen the classical neutral current of the low voltage grid because of the uncontrolled injection of power in the grid [15]. In fact the power peak production



of the solar photovoltaic systems, beyond being unpredictable and intermittent, it can also do not match the peak demand of the users. As can be seen on the fig. 1.1 peaks in consumption occur during the morning and the evening hours, instead peaks of renewable generation occur in the noon. This unbalance between energy demand and production needs to be fixed. Certainly, a photovoltaic



**Figure 1.1:** Example of a PV generation profile and demand profile for a typical end-user [kW] during the 24 hours.

system cannot satisfy a users on a 24 hours basis. Often the variation of solar energy generation do not match the time distribution of the demand. Therefore, power distribution systems dictates the association of storage system to dampen the time distribution of the demand, [15]. Energy storage results as a solution for the mismatch, so when the production is higher than the demand peak electricity can be stored in storage devices and after the same device can provide energy during the demand peak.

There exist different technologies to increase PV self-consumption, where the two major ones are energy storage, mainly using batteries, and active load shifting, which is an important part of the concept demand side management (DSM), [15] [6]. In particular it means to analyse the advantages for the users who adopt the storage technologies. Yet, while studies on the storage integration in PV systems have strongly advanced our knowledge about the role that can play for residential PV, two main shortcomings remain. First, existing studies examine the economic viability of storage under the assumption of policy support in the form of feed-in tariffs for solar photovoltaic power and/or additional premiums for self-consumed electricity. However, feed-in tariffs in many countries have significantly decreased over the last years and are expected to be phased out in the foreseeable future. From this point of view it seems important to investigate the profitability of storage in an environment without demand-side subsidies for PV and storage technologies, [6].

## 1.2 Profitability of PV-Storage integration studies

As previously said, there is a decreasing of incentives, thus profitability of storage in an environment without subsidies for it or PV installations should be studied. In this case wholesale electricity market price developments will strongly affect storage profitability. Moreover the existing forward-looking studies that investigate the profitability of storage for residential PV have usually investigated a limited number of sizes for both the PV system and the battery storage. However, especially under the assumption of no additional policy incentives, the chosen size of the PV system and battery storage strongly affects the economic viability of the integrated PV-battery system, [6]. This is due to the fact that the size of the storage device depends basically to the degree of PV power is self-consumed. Thus, at the present time it is impossible to define if storage investments will be convenient for the householders or not for both the sizing of the PV system and the purchasing. The table 1.1 shows all recent researches on the profitability of the storage integration with PV production, especially for the distributed generation. Most of these studies are focused on a lead-acid technology because it is one of the cheapest battery storage on the market. To economically assess the inclusion of storage in distributed PV systems, the majority of studies calculate the cost of electricity that results when installing storage of a particular size. In these studies, storage is often used as a means to reach a predefined level of energy autonomy or self-consumption. So far, only few studies, namely Bost et al., Braun et al., Clastres et al. and Colmenar-Santos et al., explicitly compute economic revenues from storage investments. Clastres et al. investigate the possibility of a household providing ancillary services and find that, even considering forecasting errors of electricity production, a household could profitably supply active power. In contrast, similar to the focus of this study, Bost et al., Braun et al. and Colmenar-Santos et al. see the main financial incentive for investments in storage in influencing the gap between retail and wholesale prices. They assume that, by using storage, a household may raise the self-consumption ratio. Since this reduces both the amount of electricity to be fed into the grid at wholesale prices and the electricity to be purchased at retail prices, investing in storage may increase the households' return from the PV plant [6].

**Table 1.1:** Summary about the recent studies centred on the cost of storage devices integration on distributed PV generation, [6]. \*FIT:Feed-in-Tariffs. \*\*SC:Self-Consumption

Author	PV Technology	Battery Technology	Varied Input Parameters	Econ. Output Parameter	FIT*/ SC** premium	Time of investment
Arun et al. (2009)	Not specified	Not specified	PV system and storage size	Cost of electricity	No/No	Not spec., one year
Askari and Ameri (2009)	Not specified	Lead-acid	PV system and storage size	Cost of electricity	No/No	Not spec., one year
Avril et al. (2010)	Crystalline silicon (poly)	Lead-acid, Nickel Cadmium Lead-acid, lithium-ion, sodium-sulfur, vanadium redox flow	Technology cost	Cost of electricity	No/No	2011-2020
Battke et al. (2014)	Not specified		Storage cost, storage roundtrip efficiency, life time and cycle life	Cost of electricity	No/No	2013
Best et al. (2011)	Crystalline silicon (mono)	Lithium-Ion	PV system and storage size, technology cost, consumption pattern	Cost of electricity, Grid Parity	Yes/Yes	2010-2020
Braun et al. (2009)	Crystalline silicon (mono)	Lithium-Ion	Storage size, electricity price, FIT depression rate	IRR, payback period	Yes/Yes	2010,2014
Celik et al. (2008)	Crystalline silicon (mono)	Lead-acid	PV system size, location	Cost of electricity	No/No	Not spec., one year
Clastrès et al. (2010)	Crystalline silicon (poly)	Not specified	Consumption pattern	Profit	No/No	Not spec., one year
Colmenar-Santos et al. (2012)	Not specified	Lead-acid	PV system and storage size	IRR, payback period	Yes/No	2011
Denholm and Margolis (2007)	Not specified	Not specified	PV system and storage size	Cost of electricity	No/No	Not spec., one year
Jaliloli and Krichen (2012)	Not specified	Lead-acid	Storage size, PV system size, energy autonomy, solar irradiation, discount rate, investment subsidy, electricity price	Cost of electricity	No/No	Not spec., one year
Kaldellis et al. (2009)	Not specified	Lead-acid, sodium-sulfur		Cost of electricity	No/No	Not spec., one year
Kolhe (2009)	Not specified	Not specified	PV system and storage size, technology cost	Cost of electricity	No/No	Not spec., one year
Kolhe et al. (2002)	Not specified	Lead-acid	Discount rate, solar irradiation, technology cost, O&M costs	Cost of electricity	No/No	Not spec., one year
Lazou and Papatsoris (2000)	Crystalline silicon (mono)	Lead-acid	Technology cost, location	Cost of electricity	No/No	1998,2005
Li et al. (2009)	Crystalline silicon (poly)	Lead-acid	PV system size, technology cost, component efficiency	Cost of electricity	No/No	Not spec., one year
Liu et al. (2012)	Thin-film	Lead-acid	PV system and storage size, PV panel slope, technology cost and life-time, electricity price	Cost of electricity, net present cost	Yes/No	Not spec., one year
Wisseem et al. (2012)	Crystalline silicon (mono & poly)	Lead-acid	PV system and storage size, PV panel slope	Cost of electricity	No/No	Not spec., one year

From these studies two main questions come out: first it is assumed that the households receive premium paid on top of electricity market prices for PV generated electricity that is self-consumed or fed it into the grid. In any case, both feed-in premiums and self-consumption paid have been subjected to several changes in the last years, i.e. the feed-in tariff decreased about 43% between 2009 and 2011, [6]. What is new is that PV now has to compete in a market with other many energy resources without being supported by incentives like in the past.

The second question investigates another aspect: a part of the works in 1.1 deals with the optimization of the size of PV and storage system for a given electricity consumption in order to have the maximum saving. To analyse a wider range of PV-storage combinations is important since the self-consumption ratio, and hence the financial return of the storage investment, is highly sensitive to the assumed PV and storage size, [6]. So it appears interesting to investigate whether and when economic optimization of PV system and storage size allow operating storage profitably in an environment without policy support.

Therefore, the study is divided in two main parts: the first one starts describing the adopted model, what are the models and options of BES in the energy market, goes through a detailed description of strategies for improving self-consumption of householders; and it develops the actual situation in terms of electricity market in Italy and Spain and which policies rule the scene of self-consumption.

Eventually, the study focuses on a brief presentation of what effects the assumption of aforementioned strategies, the most remunerative bring to the simplified distribution grid.



## Chapter 2

# Modelling of components

The electric system can be distinguished in four voltages levels as depicted in the following table:

Denomination	Voltage
Extra High Voltage EHV	>230 kV
High Voltage HV	<230 kV and >35 kV
Medium Voltage MV	<35 kV and >1 kV
Low Voltage LV	<1 kV

**Table 2.1:** Voltage levels.

Extra high and high voltage are part of the transmission system, while medium and low voltage form the distribution grid. The power is delivered through alternate mode. The electrical quantities considered follow sinusoidal law, so they can be written in two different ways:

- Temporal representation  $X(t) = \hat{X} \cos(\omega t + \phi)$
- Complex phasors  $\bar{X} = \frac{\hat{X}}{\sqrt{2}} e^{i\phi}$

More than the transmission system, which deals with high voltage and power, it is important to describe the distribution grid; substantially there are two different types, the radial type and the meshed network. Meshed network can have several connections to the medium voltage grid, and are mainly found in city centre. In rural or suburban areas, most of the grids are radial. These grids have a tree-shape, with a central feeder, the connection to the medium voltage network, from which branches lead to the households. Usually low voltage networks are built as open ring networks, which are opened under normal conditions, but can be closed in case of a fault to satisfy the  $N - 1$ -criteria. As described in table ?? the last step in the network is the low voltage (LV) network. The LV network is responsible for delivering the energy from the substation to the end-user. Since more and more end-users are also producers, the LV network is also responsible for distributing the local generated energy through the network, [17],[15].

Seeing the topic from a wider point of view, the effect of using photovoltaic rooftop structures with BES has to be also analyse . Thus to start study the problem, it can be used as example a simple MV/LV grid composed of a MV substation connected to the distribution grid, a transformer Dyn11, a low voltage station, a line which connect a LV load to the structure. The load is modelled like a users load with the addition of PV panel and a storage battery.

For starting the analysis a simple low voltage load, a typical householder, is taken in consideration;

in addition a photovoltaic system with a storage device is sided to the load. For all the representation of power curves in *PowerFactory* it adopted the convention of the load side for load, and storage, while for the connection line and the PV system the convention of generator.

## 2.1 Photovoltaic System

For the household a PV panel rooftop is modelled with *PowerFactory*. It is denominated *ElmPvsys* in the category of the Static Generator; it is an array of photovoltaic modules, connected to the grid through a single inverter.

Differently to a static generator, the PV system provides an option to estimate the active power set-point, given location, date and time. The active power input can be calculated with data of solar panel type, the arrangement of the solar array and the irradiance data with the option **Solar Calculation**, [8].

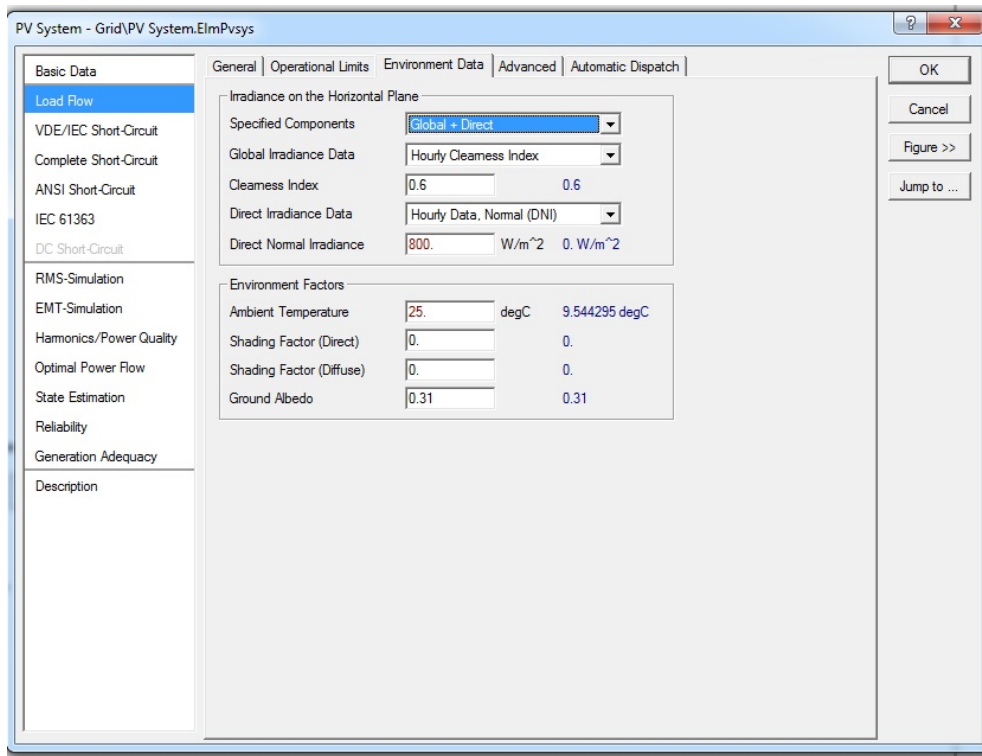


Figure 2.1: Window where can be set data for Solar Calculation.

### 2.1.1 Solar Radiation

Solar energy has its own pros and cons, as advantages it is free, diffused all over the earth surface, and it is unlimited, on the other hand it is aleatory, with a low power density, and its power production is shifted respect to the load demand. In order to better understand the PV production some concept must be recalled.

In PV system design it is essential to know the amount of sunlight available at a particular location at a given time. The two common methods which characterise solar radiation are the solar radiance

(or radiation) and solar insolation. The solar radiance is an instantaneous power density in units of  $kW/m^2$ . The solar radiance varies throughout the day from  $0kW/m^2$  at night to a maximum of about  $1kW/m^2$ . The solar radiance is strongly dependant on location and local weather. Solar radiance measurements consist of global and/or direct radiation measurements taken periodically throughout the day. The measurement were taken by *Pyranometer* for the global radiation and by *Pyrheliometer*, which measures the direct radiation.

While solar irradiance is most commonly measured, a more common form of radiation data used in system design is the solar insolation. The solar insolation is the total amount of solar energy received at a particular location during a specified time period, often in units of  $kWh/(m^2 day)$ . While the units of solar insolation and solar irradiance are both a power density (for solar insolation the "hours" in the numerator are a time measurement as is the "day" in the denominator), solar insolation is quite different than the solar irradiance as the solar insolation is the instantaneous solar irradiance averaged over a given time period. Solar insolation data is commonly used for simple PV system design while solar radiance is used in more complicated PV system performance which calculates the system performance at each point in the day [24]. The active power output follows some main equations respectively for the single panel and the system:

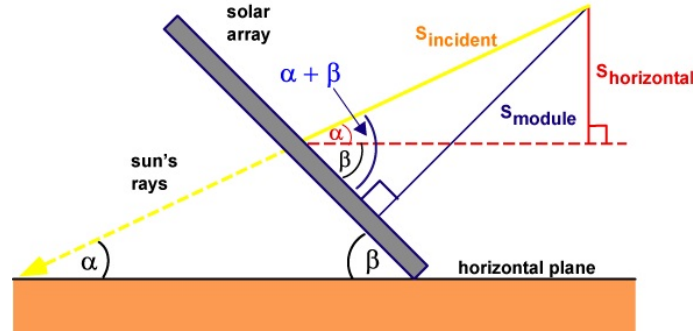
$$P_{panel} = \frac{E_{g,pv} \cdot P_{pk,panel} \cdot \eta_{rel} \cdot \eta_{inv}}{E_{STD}} \quad (2.1)$$

$$P_{sys} = P_{panel} \cdot num_{panels} \quad (2.2)$$

Where  $E_{g,pv}$  is the global irradiance on the plane of the array measured in  $W/m^2$ . The common denominator is  $E_{STD}$  or the standard irradiance value  $1000W/m^2$ ; the power  $P_{pk,panel}$  is the total rated peak power for the solar panels,  $\eta_{rel}$  is the relative efficiency of the panel imposed at 15.2% using a poly-crystalline Si panel<sup>1</sup>.  $\eta_{inv}$  is the efficiency factor for the inverter set at 95%.

The solar constant  $I_0$  is the incident power flow on a horizontal surface unit that resides at the limit of the atmosphere on the mean distance earth-sun<sup>2</sup>, its value is  $1360W/m^2$ , and all data of the sun radiation derive from this constant, [24].

To perform the analysis of the system it was important to derive the sun position and collect all the data useful for modelling the rooftop panels. To calculate the irradiance on the surface of the



**Figure 2.2:** Solar coordinates on a tilted surface.  $\alpha$  and  $\beta$  are respectively the incidence angle and the tilt angle.

<sup>1</sup>The model will be explained in 2.1.2.

<sup>2</sup>**Mean distance earth-sun:**  $r = 1 + 0.033 \cos(360n/365)$  with  $n$  the number of the day of the year.



PV panel  $E_{<g,pv}$  it is necessary to calculate the angle of incidence of the solar irradiance <sup>3</sup>, [8].

$$\nu(\beta, \alpha) = \cos^{-1}(\cos \gamma_s \cdot \cos \alpha_F \cdot \sin \beta + \sin \gamma_s \cdot \cos \beta) \quad (2.3)$$

where  $\alpha_F$  is the Julian day number (1 to 366),  $\gamma_s$  is the solar altitude angle in degrees,  $\alpha$  is the azimuth angle and  $\beta$  the surface tilt angle from the horizontal plane in degrees. The global irradiance is the sum of two components: direct and diffuse  $E_{g,hor} = E_{b,hor} + E_{d,hor}$ , so those values can be in the form of historical or forecasted data, or can be estimated through simple or complex models. For the estimation of diffuse irradiance on the horizontal plane *PowerFactory* used the **Liu-Jordan Model**

$$E_{d,hor} = \frac{E_{g,hor}}{KT} \cdot (0.384 - 0.416 \cdot KT) \quad (2.4)$$

where KT is the clearness index, with value around 0.6-0.72 (set at 0.6 for the analysis). The DNI data or the Hourly Data, Normal were added as a characteristic. The **Normal direct irradiance** calculates the direct horizontal irradiance

$$E_{b,hor} = E_{b,norm} \cdot \sin \gamma_s \quad (2.5)$$

with  $E_{b,norm}$  in  $W/m^2$ . Eventually, the global irradiance on an inclined surface like the rooftop panels  $E_{g,pv}$  is derived, counting also the shadowing factors  $S_{dir}$  for the direct irradiance,  $S_{diff}$  for the diffuse on, the slope ground reflected component  $E_{r,pv}$  and the slope sky diffuse component  $E_{d,pv}$

$$E_{g,pv} = E_{b,pv} \cdot (1 - S_{dir}) + E_{d,pv} \cdot (1 - S_{diff}) + E_{r,pv} \quad (2.6)$$

Thanks to PVGIS software it was possible to collect all data of solar radiation for a determinate location; for this work Padova in Italy and Gijón in Spain were chosen as locations for measurements. A 3 kW<sub>p</sub> photovoltaic panels rooftop integrated is the model component, the technology used for the panel is a poly-crystalline silicon. The chosen tilt angle is  $\beta = 30^\circ$  to simplify the calculations for the two cities. As previously explained to derive the power output of the system the DNI<sup>4</sup> and the Liu-Jordan model were implemented. Henceforth in the following table are represented all the DNI for the two cities over the four samples months of the year. To simplify calculations mean value for each month studied were taken, and the time resolution was in hours. In addition an average day-time temperature was set, taking in consideration its variability over the year. The Solar Radiation data through the months are shown in tables 2.2 and 2.3.

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<sup>3</sup>The angle between the solar rays and the perpendicular to the surface of the panel.

<sup>4</sup>**DNI**:Direct normal irradiance.

**Table 2.2:** Gijòn DNI mean day value for each month.

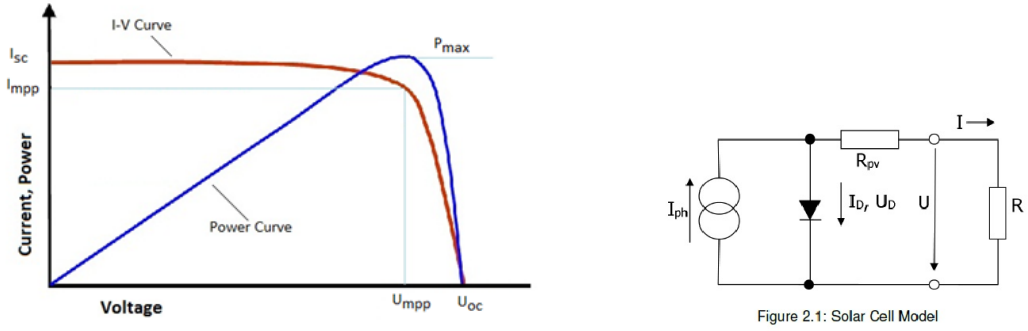
Hour of day	January [W/m <sup>2</sup> ]	April [W/m <sup>2</sup> ]	July [W/m <sup>2</sup> ]	October[W/m <sup>2</sup> ]
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	0	0	45,75	0
6:00	0	105,5	248,25	0
7:00	0	281,75	325,5	58,5
8:00	45,6	344,75	376,5	301
9:00	268,5	384	410	372,75
10:00	307,75	406,75	430	412,75
11:00	324,5	417,25	439,25	430,75
12:00	324,5	417,25	439,25	430,75
13:00	307,75	406,75	430	412,75
14:00	268,5	384	410	372,75
15:00	189,25	344,75	376,5	301
16:00	54,5	281,75	325,5	176
17:00	0	159,8	248,25	33,5
18:00	0	28,66	45,75	0
19:00	0	0	0	0
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0
00:00	0	0	0	0

**Table 2.3:** DNI mean values in Padova for each month along the year.

Hour of day	January [W/m <sup>2</sup> ]	April [W/m <sup>2</sup> ]	July [W/m <sup>2</sup> ]	October[W/m <sup>2</sup> ]
1:00	0	0	0	0
2:00	0	0	0	0
3:00	0	0	0	0
4:00	0	0	0	0
5:00	0	58	149,25	0
6:00	0	217	404,5	0
7:00	0	327	501,25	154
8:00	138	392,75	563,25	261
9:00	210,25	457,5	603,5	321,5
10:00	238,75	468,25	627,75	354,5
11:00	251	457,5	639	369,5
12:00	251	433,5	639	369,5
13:00	238,75	392,75	627,75	354,5
14:00	210,25	327	603,5	321,5
15:00	150,5	217	563,25	261
16:00	44	38,67	501,25	154
17:00	0	0	404,5	30
18:00	0	0	149,25	0
19:00	0	0	0	0
20:00	0	0	0	0
21:00	0	0	0	0
22:00	0	0	0	0
23:00	0	0	0	0
00:00	0	0	0	0

### 2.1.2 Photovoltaic Modules

Therefore, the photovoltaic modules presents the same features but due to the different position of the sun in the two cities, the solar radiation is different and consequently the power output of the modules. Clearly the maximum power output trend of the PV modules is given by the figure2.3, thanks to the MPPT function it is possible to work at the maximum power obtainable. For the simulations a single inverter was chosen because it is an expensive component of the system. The



**Figure 2.3:** PV module characteristic current-voltage with the power pattern, and circuit representation of photovoltaic cell.

PV electricity production in kWh per  $kW_p$  is a function of the available global radiation and the tilt angle. It was used a real photovoltaic module sold in the market: **SHARP ND-R250A5** with the technical data show in tables 2.4 and 2.5.

**Table 2.4:** Characteristic of the photovoltaic module ND-R250A5 at Standard Test Conditions.

Electric Data at STC	Value	Unit
Power peak $P_{max}$	250	W
Voltage open-circuit $V_{oc}$	37.6	V
Current short-circuit $I_{sc}$	8.68	A
Voltage at Maximum Power $V_{mpp}$	30.9	V
Current at Maximum Power $I_{mpp}$	8.1	A
Module Efficiency $\eta$	15.2	%

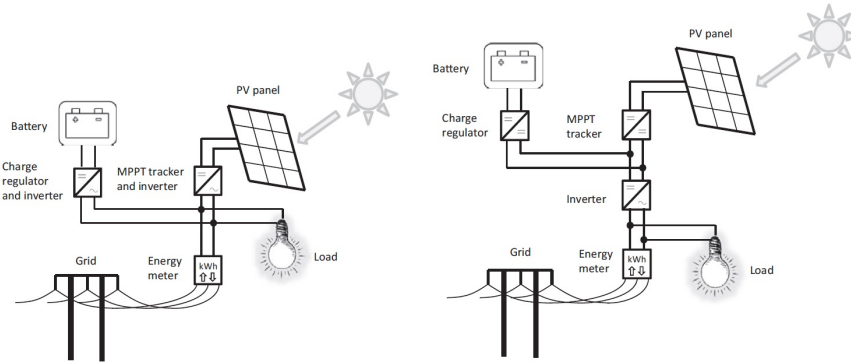
**Table 2.5:** Values at Nominal Operating Cell Temperature.

Electric Data at NOCT	Value	Unit
Power peak $P_{max}$	180.2	W
Open-circuit Voltage $V_{oc}$	36.7	V
Short-circuit Current $I_{sc}$	7.0	A
Voltage at Maximum Power $V_{mpp}$	27.7	V
Nominal Operating Cell Temperature NOCT	47.5	°C

## 2.2 Residential Storage

Energy storage devices are being integrated with the PV systems to mitigate solar PV impacts. They are charged over the day with the surplus power coming from the PV peak production, thus they reduce the reverse power flow and mitigate the voltage rise. The stored energy can be used to supply the load peak that comes during the night, [18].

Residential battery storage refers to a stationary storage (BES or Battery Energy Storage) system used only together with the PV system. There can be two main layouts for PV systems with battery storage, either AC coupled where the battery is connected via an inverter and a charge regulator to the AC link of the PV device, or DC coupled where batteries are connected to the DC link through an inverter, [3]. On fig. 2.4 a MPPT<sup>5</sup> is added in order to maximize the output from the panels.



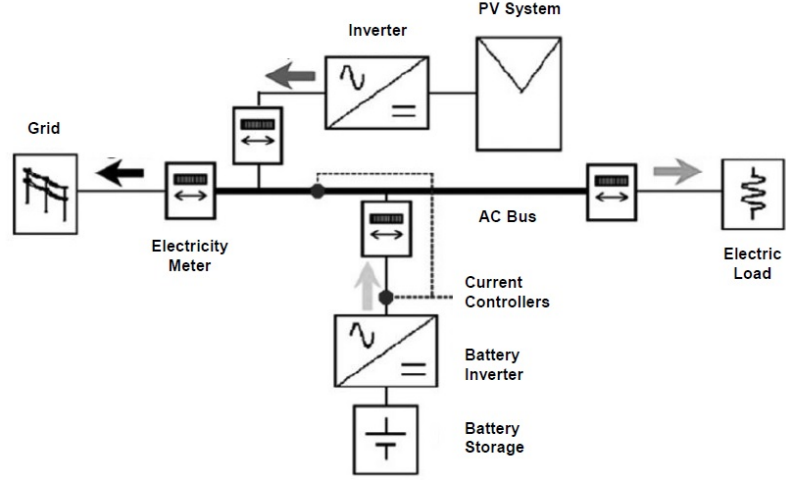
**Figure 2.4:** Simplified system layouts of AC coupled (on left) and DC coupled (on right) residential PV battery storage systems, [3].

If PV system and battery storage are connected to only one phase on AC side of the electric system, the self-consumption will be lower compared to a connection to all three phases, depending on how the power flows are measured. The single-phase connection allows that the electric power flows in only one phase, and supplies only the connected load. Otherwise the power, with a three-phase connection, flows into each phase, with an increment of self-consumption. An example of the system can be seen in figure 2.5 in which the electricity generated by the PV system is inverted and transmitted to an AC bus where it can either directly assigned to the loads of the household, stored in the storage device or transmitted to the grid. To store electricity, the amount fed into the storage is tapped from the AC bus and inverted to DC in order to be stored. When the household needs to access electricity from the storage, the DC power in the storage unit is re-inverted to AC and fed into the household through the AC bus, [3].

### 2.2.1 Modelling of the Storage Profile

To give a first analysis of the problems that this work deals with, in *PowerFactory* the battery-storage unit is used, without taking in consideration voltage droop, but using only a curve of power charge-discharge which follows the load power demand under imposed conditions. It should be noted that the leaded performance neglects the dependence of the efficiency on several factors

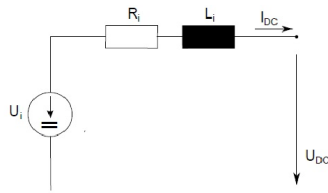
<sup>5</sup>**MPPT:** maximum power point tracker.



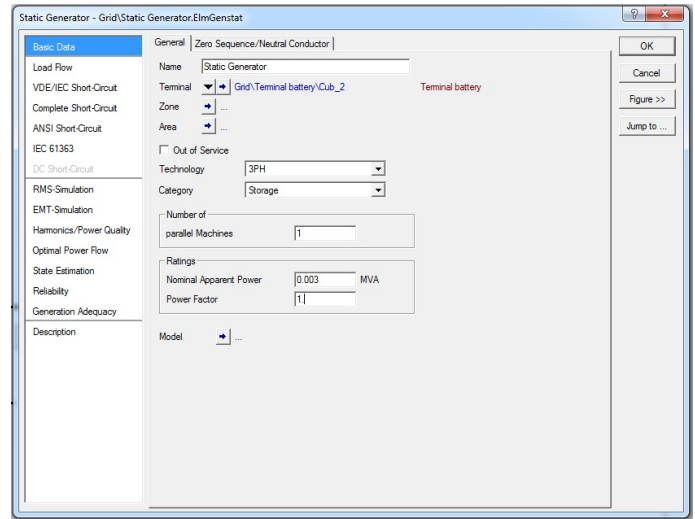
**Figure 2.5:** Layout of integrated PV-storage systems

of influence like the discharging power, the temperature and the battery age (the number of cycles that battery can perform are limited and decrease with the passing of the time). Thus, the model implemented is based on a theoretical and idealized configuration composed by lithium ion technology. The state of charge of the battery is restricted to a range between 20% and 80% of the nominal battery capacity, [3].

Clearly the storage device cannot provide all the load demand, so at the beginning the performed curve is built on the differences between load demand and solar power production. In figure 2.6(a)



(a) DigSILENT battery model.



(b) Set condition for the storage unit.

**Figure 2.6:** In 2.6(a) there is the simplified scheme circuit of the storage, while in 2.6(b) there is the technical data for the device.

there is the representation of the model used by *PowerFactory* and basically it is a DC voltage

source element, saved as *ElmDcu*. For the AC balanced load flow analysis the internal inductance  $L_i$  was ignored, so the internal voltage follows the equation

$$U_i = U_{nom} \cdot u_{set} U_{DC} = U_i - I_{DC} \cdot R_i \quad (2.7)$$

with  $U_{nom}$  is the nominal voltage of the battery and  $U_i$  the internal resistance, [8]. As later will be explained the storage trends is calculated by different simulations in MATLAB, which have the purpose to optimize the customers' purchase or the utilization of the storage device, [8].

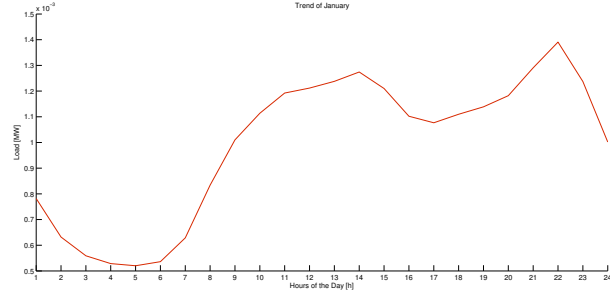
The model of storage is based on Tesla's powerwall, even though the storage's operation mode is idealized because storing energy creates, like every process that involves conservation of energy, losses which sometimes do not promote an energy-saving. The traditional charging strategies do not consider the dynamic variations which occur during the PV production while the storage device is charging. Similarly, the traditional discharging strategies do not consider the instantaneous variations of the evening load peak demand. Moreover it would be necessary a discharging strategy during the day while there is the cloud passing. If that short-term discharge period is applied, it necessary to adjust charging rates for the post-discharge periods, in order to let the storage capacity be effectively used. Hence, instead of traditional or prefixed discharging/charging patterns, with the addition of dynamic adjustments new control strategies to match the load and PV pattern have to be developed, [22], [12].

## 2.3 Load Profile

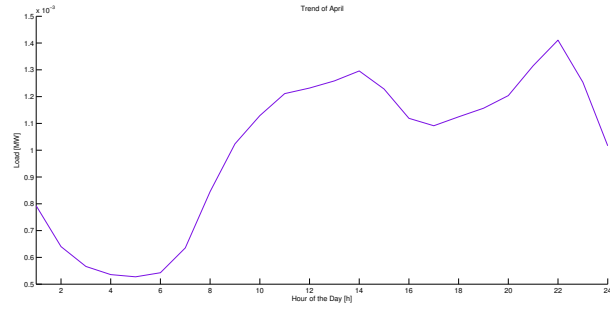
Here comes the modelling of the load curves. First of all it has to be clear that every end-user has his own load profile, and the power demanded is not constant and varies in unpredictable ways; so far, it can be seen a main trend of the curves due to the routine of householders. Ulterior simplifications are done because of both the time resolution (better explained in chapter ??) and the type of user chosen. The latter means that the samples of user chosen might not be representative for all the users. As a matter of fact a household with an installed power of 3 kW was chosen both for Italy and Spain, because it seems to be a usual value of power for end-users in both countries; even though householders may have contracts for higher power use (i.e. in Italy there are tariffs for households costumers who adopt 3 kW and who use power with more than 3 kW).

Problems in the collection of the profiles were found even for Spain and Italy. Spain provides value of power consumption for a typical household through application of indices and data collected from national database; thus, it was possible to collect trends for each sample month. On the other hand, Italy has data collected from 2013 of the total power demand during the year [25]. Therefore, at least for Italy, there exists a missing in the update of database; because of this depletion of data for all the seasonal simulations a single trend was used.

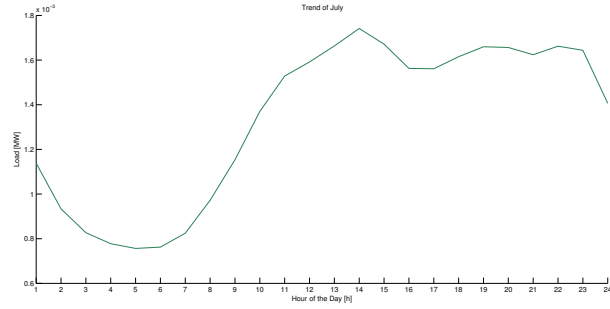
As following, the load profile are presented; what can be discussed for the Spain is that the profile among the seasons varies due to the different types of load used. Same assertions may be done for the Italian load profile, even though that there are no available data to show that.



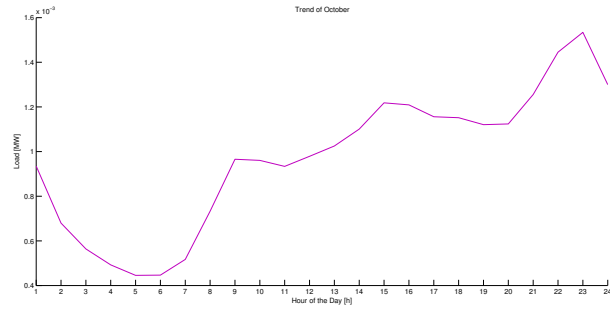
(a) Spanish load champion January 2015



(b) Spanish load champion April 2015



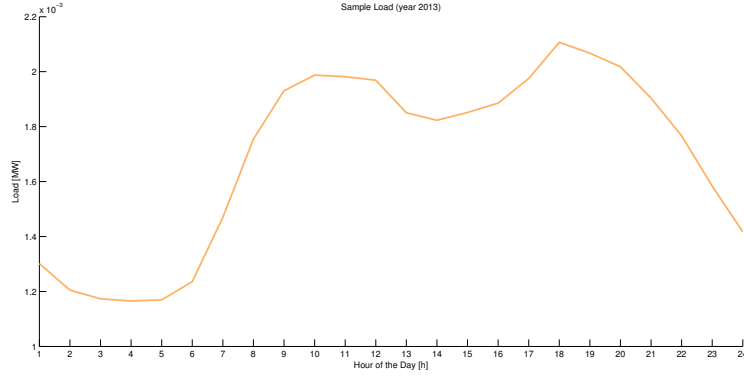
(c) Spanish load champion July 2015



(d) Spanish load champion October 2015

**Figure 2.7:** Load trends for Spain.





**Figure 2.8:** Italian load champion used for the study (2013 mean value).

For example during the winter season illumination is more used than in summer period because of the poor natural light lasting, on the other hand in summer air-conditioning is activated rather than the heating, which is preferred in winter. So far, for every month there is a different utilization of loads.

As can be seen all the profiles contain two peaks which occur during the day and during the night; this happens because there are periods which the users consume more than the usual, in order to satisfy their basic necessities. All the values used to perform the two curves can be seen in the Appendix 8.

## Chapter 3

# Storage solutions for households

It is important to be able to tell apart the terms power and energy to understand the application attributes of storage technology. Energy can be defined as a quantity or volume whereas power is the rate of which the amount of energy changes. Energy in storage applications is measured as Wh and power is measured in W. Energy and power are prioritized differently for different storage applications. As a matter of fact Load shifting during longer periods requires a large energy volume of storage, whereas applications which treat power quality, i.e. voltage stability, require power to be absorbed or injected fast, so in short periods of time. Thus, it becomes important to distinguish between cost of **Power Capacity** €/kW and **Energy Capacity** €/kWh, [22].

Another term to be familiar with is **Pulse power** which, opposed to constant discharging, is the ability to discharge a volume of energy quickly. Pulse power is needed for mainly power quality applications and is found in batteries and capacitors allowing energy to be stored and quickly discharged at high power and voltage as a pulse. Besides the **Response time**, or how quickly the device discharges, is a crucial factor for the choice of the storage technology as different applications require different time response.

**Depth of discharge** (DoD) indicates the percentage of energy discharged relative to the full storage capacity before the storage is recharged. Some battery technologies are sensitive to how deep the discharging goes and can reduce the life time expectancy. Meanwhile the **Frequency of discharge** refers to how often a storage unit will be discharged during its operation. Also here the application dictates the frequency, where some storage units are almost never completely discharged and some are cycled continuously.

The **Efficiency** defines the ratio between storage cycle input and output. An amount of energy is lost during the discharging processes due to the conversion process AC to DC and conversely, while other type of losses occurs when energy is stored for a long period, [22].

As said in the introduction chapter a high renewable penetration can lead to upcoming disturbance in the distribution network. The few studies that investigate profitability of storage for PV typically examine its potential to raise the share of electricity generated by the residential PV system that is consumed by the household. Thus the use of storage is necessary to smooth the disturbance created; it can be the bridging technology between RES and the network. By investing in storage technologies households can leverage the existing spread between wholesale and retail electricity prices by reducing both the volume of electricity that is bought at retail prices and the one to be sold at wholesale prices, [14].

Energy storage devices are charged over the day with surplus power from the solar panels, this use results in reducing the reverse power flow and mitigate the voltage rise. Storage benefits regards also the shifting of peak production of RES respect the peak of load demand; for instance photovoltaic system have a peak of production during midday, and do not produce during the night,

this peak is higher than the demand of the user so the excess of energy can be stored in storage units in the household. Furthermore the unpredictable production, i.e. when the weather is cloudy PV panels do not work at their fullest possibilities, is the reason for use storage devices which use energy stored in a previously moment. All these benefits allow the owner of PV+Storage unit to manage and utilize the energy to its fullest, and lead to the self-sufficiency of the users. It is useful to extend life time of components as its upper limit. Moreover the implementation of this system will surely bring more reliability for the users, thanks to the independence from the network. As a matter of fact the number of breakdowns in the distribution grid can affect less the users, [18]. Certainly talking about the advantages for end-users does not mean the same for grid operators; with the self-sufficiency of users there will be no need to buy electricity from the network, thus apparently there will be no economical profits for companies involved in electricity market. In this perspective the idea of *arbitrage* comes to mind. This term describes the simultaneous purchase of a product when its price is low and then selling the same product when the price rises. Electrical companies which sell energy to the costumers take advantages with this principle. On the other hand, with the advent of the storage the arbitrage for the users becomes truth. As a matter of fact with an optimized BES it is possible deciding when buying or selling energy to the grid. Grid owners design the peak demand charges to cover their expenses of the grid. Lower peak demand would mean less income possibly making it less attractive to support for utilizes. However, as the grid infrastructure is designed for maximum peak demand a reduction would mean lower requirements for future investments and possibly deferring infrastructure investments in existing grids, [14].

The technical maturity is a measurement of how much of the potential technical improvements have been realized. New technologies generally have a greater potential for improved performance and costs but they also come with a greater uncertainty for estimations of cost. Eventually, the scalability of a storage technology indicates how the unit cost is affected by the unit size where some technologies show a decreased cost for larger units. For PV systems, bigger installations have no cost advantage leading to a more small installations as the cost  $W/m^2$  is almost the same, [7].

### 3.1 Available Solutions

In response to the electricity role in the European Union, the International Electrotechnical Commission - Market Strategy Board (IEC-MSB) established a project team in October 2010 to investigate the current situation and the future orientation upon the electrical energy storage (EES) technologies, roles, markets, and perspectives. Storage technologies can be classified according to energy form of the storage systems, such as: mechanical, electrochemical, chemical energy, electrical, and thermal. Key-factors of a storage device are the physical facilities, interactions with existing uses of gas, optimal chemical processes, safety, reliability and efficiency. By using the storage unit to provide power during the households peak demand it can save money and at the same time lower the overall load on the grid during periods of peak demand. The energy charge depends on the amount of energy the customer consumes over a month and is expressed in a fee per kWh. The peak demand charge is calculated differently depending on the utility's tariffs but it often takes one or the average of several peak power measurements during one month and charges thereafter, expressed in a fee per kW [16]. On the market there exist several storage technologies:

- Mechanical: flywheel, CAES<sup>1</sup>, hydro-storage

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<sup>1</sup>**CAES:** Compressed Air Energy Storage.

- Electrical: super-capacitor, SMES<sup>2</sup>
- Electrochemical: batteries which involve many different chemical reactions and configurations (Na-S, ZEBRA, Lead-acid, Lithium-ion).

Relating to the type of user and power utilization it is possible to do a classification of requirement and characteristic that a storage system should have. From table 3.1 it can be assumed that

**Table 3.1:** Application for storage system in relation with the type of user, [16].

Area	Size	Application
Household	0.5-10 kW	Optimization of self-consumption, warranty power supply during network outages
Small industry	5-500 kW	Peak-shaving, power supply integration, power sale
Industry	0.5 -5 MW	Tariffs organization, Co-generation, auto-production
Utility	0.5-5 MW	Distribution assets
Big size	5-50 MW	Energy trade

households' applications prefer electrochemical storage as battery systems, due to their versatility, assured technology, fast time-response (less than seconds), and because of possibility to work as hybrid applications. Battery storage for PV systems grid-connected work with continuity, even when networks failures occur; electronic central control unit monitors the battery charge/discharge rates, and it is modelled in order to manage to let the device absorb or deliver energy (both to the grid and the household). The control unit consists in circuital microprocessor hardware which throughout a software tries to increase the self-consumption of the household. Moreover it manages the power rate charge of the batteries in order to guarantee longest life-time of the device.

Among all EES electrochemical storage, batteries are considered more efficient compared to other EES in terms of scalability, efficiency, lifetime, discharge time, weight and mobility of the system. Among batteries devices the re-chargeable lithium-ion batteries (LiBs) are the most successful electricity storage devices, but their applicability is limited to small electronic equipment, in table 3.2 their benefit are pointed out. However, the LiB is not appropriate to stationary applications due to decreased performance and to high cost, [22]. Table 3.2 presents all the feature for the storage systems available for the residential applications. Lead acid and Li-ion are the most preferred types for residential storage; the formers are advantageous for their cheapness, for the great efficiency charge/discharge and they have a good rate price/quality; instead the latter is on the centre of the innovation (this means that it is a technology that can improve), also its life is longer than the lead-acid's one. For what may concern the cons: lead-acid batteries are heavy and bulky, on the contrary Li-ion technology is really expensive, since Lithium is a rare metal. Other types in table 3.2 are Nickel electrode technology that presents high value of auto-discharge or the memory effect.

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<sup>2</sup>**SMES:** Superconducting Magnets Energy Storage.

Table 3.2: Comparison between common solid state battery technologies, [22].

Specifications	Lead acid	Nickel electrode		NaS	Flow batteries		Cobalt	Li ion	
		NiCd	NiMH		VRB	ZnBr		Manganese	Phosphate
WH/kg	30-50	45-80	60-120	80-140	20-30	30-45	150-190	100-135	90-120
Cycle life (80% DoD)	200-300	1000	300-500	5000-6000	6000-8000	1500-2500	3500-8000	3500-8000	3500-8000
Typical lifetime(years)	3-15	15-20		12-20	10-20	5-10		8-15	
Recharge time (hours)	8-16	1	2-4	9	<= 1	4	2-4	<= 1	<= 1
Self-discharge/month (room temp.)	5,00%	20,00%	30,00%	62-70%	58-68%	62-70%	<10%	<10%	<10%
Nominal cell voltage	2 V	1,2 V	1,2 V	2 V	1,41 V	1,85 V	3,6 V	3,8 V	3,3 V
Operating temperature (°C)	-20 to 50	-20 to 65		300-360	-5 to 55			20-60	
Round trip efficiency (%)	70-80	70 to 80		70-90	60-65			85-92	
Maintenance	Topping charge every 3-6 months	Discharge every 30-60 days	Discharge every 60-90 days	Not required	Leakage control		Not required	Not required	
Safety requirements	Thermally stable	Thermally stable, fuse protection		Avoid contact with water	Special care during decommissioning,			Protection circuit mandatory	
Toxicity	Very high	Very high	Low	High	High			Low	

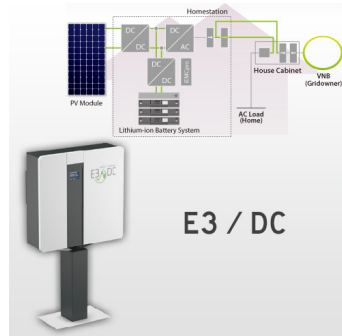
In the following paragraphs examples of storage unit for the residential battery storage are shown, the majority are based on Li-ion technology, but exceptions like FIAMM's device present interesting features, which yield the designed device competitive in the market.

### 3.1.1 Panasonic 1.35 kWh lithium-ion battery and Sharp BMZ ESS 3.0

The lithium-ion battery system consists of the Panasonic battery module with nominal capacity of 1.35kWh and a battery management system designed to control charge and discharge of the battery in accordance with customer needs. The battery system stores excess energy generated from the photovoltaic (PV) power system during peak hours of PV generation and discharges the energy as needed, providing an ideal solution as a household battery storage system that helps self-consumption of solar-generated power. It will also enable households to reduce the dependence on grid power, [34]. The main feature of the model are:

- Life-time of 5000 cycle<sup>3</sup>, as realizes for long-term operations.
- The high-performance battery management provides battery status information to the controller of home energy storage system, which allows users to remotely monitor the status of the system and battery.
- A high-capacity and high-voltage lithium-ion battery system employs a lithium-ion cell that is specifically developed for an energy storage application.

Quite similar features can be found in BMZ ESS 3.0, a lithium-ion battery device of 5 kWh sold by Sharp. As main points of strength it has an high efficiency of 97%, 7 years warranty to covering the system's current value and possibility to perform a parallel installation, [35]. It has a capacity of 5 kWh, it is based on a li-ion technology. Aside from the battery device, the inverter and management system are sold.



(a) Panasonic E3/DC



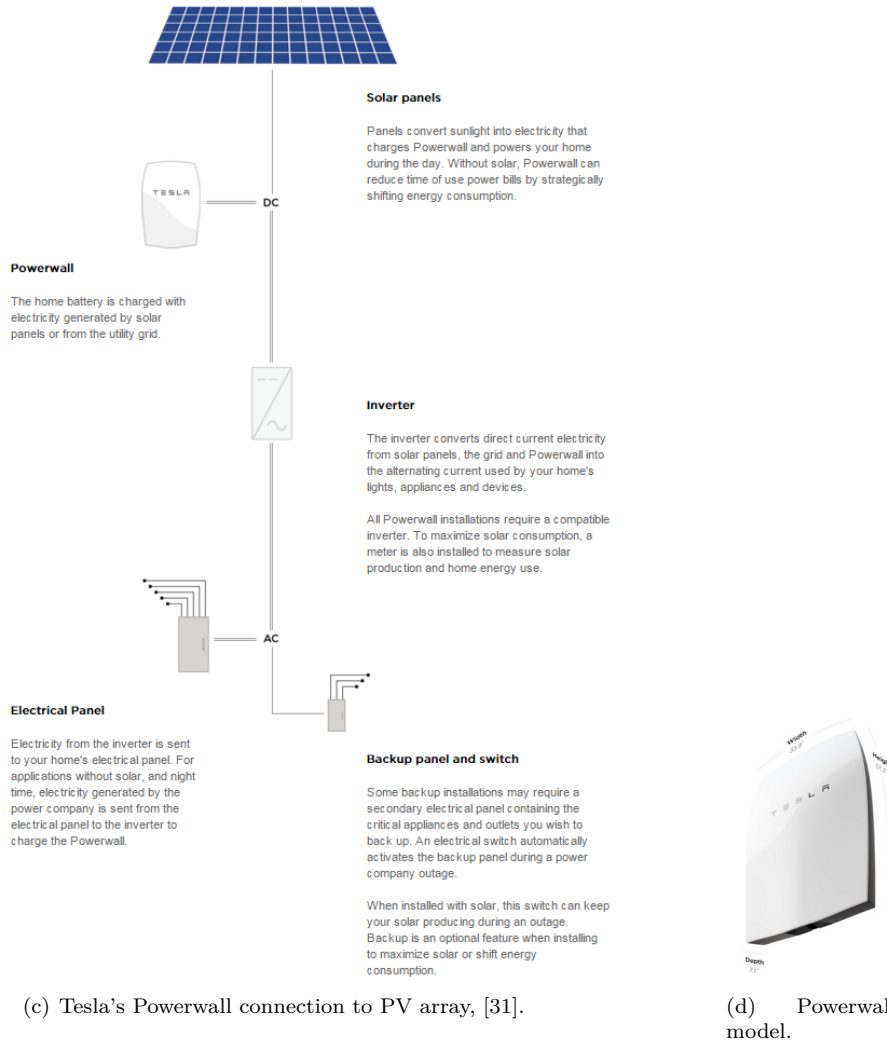
(b) Sharp BMZ ESS 3.0

### 3.1.2 Tesla Powerwall

Tesla offers a 7 kWh energy storage capacity, sufficient to power most homes during the evening using electricity generated by solar panels during the day.

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<sup>3</sup>at 80% depth of discharge.



**Table 3.3:** Basic features of Tesla's Powerwall 7 kWh, [31].

<b>Technology</b>	Wall mounted, rechargeable lithium ion battery with liquid thermal control.
<b>Compatibility</b>	Single phase and three phase utility grid compatible.
<b>Operating Temperature</b>	-4°F to 122°F / -20°C to 50°C
<b>Enclosure</b>	Rated for indoor and outdoor installation.
<b>Installation</b>	Requires installation by a trained electrician. DC-AC inverter not included.
<b>Weight</b>	220 lbs / 100 kg
<b>Voltage</b>	350-450 V
<b>Dimensions</b>	1300 mm x 860 mm x 180 mm
<b>Current</b>	9.5 A
<b>Certification</b>	NRTL listed to UL standards

Multiple batteries may be installed together for homes with greater energy needs. A 10 kWh

weekly cycle version is available for backup. The technology is based on a wall mounted, rechargeable lithium ion battery with liquid thermal control, [31].

- Round-trip DC efficiency of 92%
- Power 3.3 kW
- Price for 7 kWh unit \$ 3000

In table 3.3 other basic features of the 7 kWh model can be seen. Meanwhile in figure ?? a simple connection scheme is shown.

### 3.1.3 FIAMM RES-S

Italian company FIAMM also provides battery for residential storage. An example of it can be found in the model RES-S (Residential Energy Storage System); it is composed by a catalogue of 6 models (with voltage level of 24 V or 48 V) and a capacity up to 12.5 kWh, it can performs a backup solution that guarantees to the costumer power supply continuously. Technological features

TECHNICAL FEATURES
SMG 12V model FIAMM batteries with Built-In Flame Arrestor
Short recharge time
<2% self-discharge per month at 20°C
Maintenance free
2500 cycles, 50% max DoD
Battery containers constructed with ABS IEC 707 FV0 - UL 94 V0 flame retardant plastics
1.3 mm thick metal casing to the EN 10130:2007 standard
4 sides accessible for inspection with safety locks and ventilation grilles
Safety components and wiring included

(e) Technical references for SMG12V



(f) RES-S model

**Figure 3.1:** FIAMM RES-S model, [32].

are:

- VRLA or Valve Regulated Lead Acid battery;
- SMG maintenance free-gel, thus battery with immobilized electrolyte in gel structure;
- TPB: tubular plate battery

These kind of design and technology assure reliable maintenance and high cyclic performance. The importance of RES-S resides in the 6 hours backup function and the 100% possibility of recycling, [32].

### 3.1.4 JuiceBox Energy 8.6 kWh

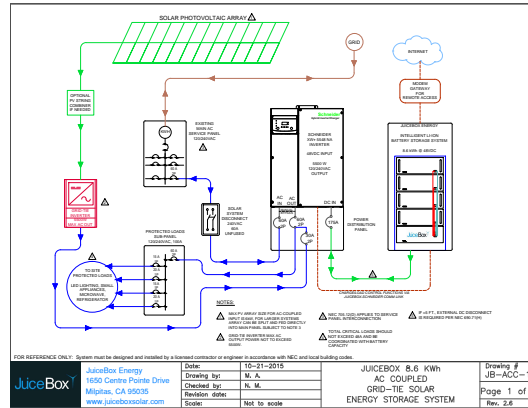
The following storage system is an 8.6 kWh lithium-ion battery for residential and small scale commercial buildings. The presence of system controller permits JuiceBox's integration with a full-featured commercially available inverter/charger and can be deployed in parallel for higher power and energy needs. Basically the strong point of this device stands in the controller, as it manages a control of charge and has redundant protection mechanisms to prevent over voltage,



<b>PHYSICAL</b>	Dimensions	43"x22"x17"
	Module weight (qty 4)	50 lbs
	Enclosure weight	80 lbs
	Total installed weight	280 lbs
	Color	White or Black
	Enclosure material	Aluminum
	Enclosure rating	NEMA 3R
	Maintenance	None
	Operating temperature	-10°C to 50°C
	Installation	Wall-mounted
	Modular assembly - no special equipment	
	LED State of Charge gauge	
	LCD for battery and system metrics	
<b>ELECTRICAL</b>	Nominal voltage	50V
	Capacity	172Ah
	Rated energy / continuous power	8.6kWh / 5.5kW
	Rated power at 2 hour discharge (per CA SGIP)	4.0kW
	Battery life	10 year, 4000 cycles
	Max discharge rate	140A
	Max charge rate	80A
	Round trip efficiency of battery charge/discharge cycle Internal cell balancing	98%
<b>CONNECTIVITY</b>	Web-enabled customer interface via cellular modem	
	Remote firmware updates	
	Cloud-based monitor and control	
	Designed to support smart grid and home energy management systems	
<b>CERTIFICATIONS</b>	Cell safety	UL1642
	Main contactor	UL508
	Automotive grade current sensor	IEC60068
	Stainless steel 3/8" main terminals	UL1059
	Battery module transportation certified	UN38.3
<b>SAFETY PROTECTIONS</b>	Over voltage shutdown	
	Over temperature shutdown	
	Under voltage shutdown	
	8 independent temperature measurements:	
	Reverse polarity protection	
	3-level redundancy on over voltage control	
	Autonomous operation with no gap in safety coverage if connectivity is lost	
	On board diagnostics	

**Figure 3.2:** Technical references for JuiceBox storage system 8.6 kWh.

over current, under voltage and over temperature conditions. It is interesting the call gateway cloud-based enables remote monitoring, updates and control. The battery chemistry selected is a lithium-ion Nickel Manganese Cobalt (NMC). The JuiceBox system delivers a minimum of 4000 cycles and 10-years of operation with this cell. The possibility of recycling makes this storage system be a competitive technology in the market. In fig 3.2 technical features are presented, while in fig3.3 a simple electrical circuit of the device connected to a PV array is shown. The data is securely managed and used to provide the home-owner with a mobile status, reporting and control app. The connectivity allows JuiceBox to roll out firmware updates and provide monitoring services for customers, [33].



**Figure 3.3:** JuiceBox AC-coupled scheme connected to a PV array, [33].

### 3.1.5 Samsung SDI battery storage

Samsung offers a storage systems with 3 functions in one enclosure. Samsung SDI's All-in-One solution enhances energy efficiency through a simple DC system and provides feasibility through a compact design of the device. The DC system only has to convert electricity once from PV panels on the rooftop before its use for home appliances, thereby increasing energy efficiency. The battery bases on a lithium-ion technology, is provided with inverter, with life-cycle 6000 cycle<sup>4</sup>. The device can be monitored through its own mobile app, [30].

Data	unit	Single Phase		Three Phase
Model		AIO series 3	AIO series 5	AIO series 8
Capacity	kWh	3.6	5.5	8.0
Power	kVA	4.6	4.6	8.0
Dimension	mm	1,000x267x680	1,000x267x680	1,070x260x880
Weight	kg	95	100	154



(a) Samsung storage types SDI's All-in-One.

(b) Technical references for Samsung storage devices.

**Figure 3.4:** Samsung storage, [30].

### 3.1.6 ZEN urban PowerBank

The ZEN Urban PowerBank offers customers a flexible energy storage solution, it can be installed at a property with an existing solar system or at a household where ZEN is installing a new solar system. Components of the systems are, [29]:

- Grid connected battery backup Control Module.
- Maintenance free batteries

<sup>4</sup>Proof tested at 25°C.

- Battery enclosure
- Battery fuse
- AC panel

In figure 3.5 technical data about 10 kWh and 20 kWh systems are reported; households applications require the 10 kWh model, because of the increasing costs of the device with its capacity.

ZEN URBAN POWERBANK COMPONENT DETAILS	10kWh MODEL	20kWh MODEL
Operating System	ZEN Battery Control System	ZEN Battery Control System
Control Module	CM-3/24V Single Phase	CM-5/48V Single Phase
Max Continuous Backup Power	3.0 kW	5.0 kW
Energy at 100% Depth of Discharge	10 kWh	20 kWh
Energy at 70% Depth of Discharge Min Battery Life 3000 Cycles, Standard Factory Setting	7 kWh	14 kWh
Voltage	230V <sub>AC</sub> / 50Hz	230V <sub>AC</sub> / 50Hz
Inverter	Australian made AS4777 approved	Australian made AS4777 approved
Battery type	8 x Lithium Iron Phosphate 400 Ah	16 x Lithium Iron Phosphate 400 Ah
Rated Cell Voltage	3.2V	3.2V
Battery Discharge Rate (at maximum power)	0.3C	0.3C
Battery warranty	3 years	3 years
Control System warranty	5 years	5 years
Dimensions	1800H x 800W x 580D mm	1800H x 800W x 580D mm

**Figure 3.5:** ZEN battery storage systems features.

So far, the aforementioned technologies basically offer similar products, i.e. most of them are lithium-ion battery, except the FIAMM's device that is lead-acid technology. The choice of the chemical composition is due to economical and technological reason: for example the lithium-ion technology provides higher performance than the lead-acid one, but on the other hand lead-acid is an assured technology, and in term of costs is less expensive than lithium-ion. So the producer needs to find a compromise between offering a cheaper technology or a more performed one. What is, indeed, new among all the product is the presence of the control app. The presence of a software part usually sited on the inverter permits to monitor both battery's and grid's conditions, and to manage operations of charge and discharge of the device. This tool gives to the customers the possibility to check the performance of his own PV-storage system. Thus, more than improving the electrical/mechanical side, providers choose to improve the software interface in order to strength the sensitivity of the device towards loads' fluctuations, and the interactions with the grid. However it has to be remarked that not all the presented devices offers the inverter part; that means an additional expense to take in consideration in the profitability analysis. A simple profitability analysis will be done in the following chapters, but the performed results do not how the profitability will change in the future; in other words the decreasing efficiency and the maintenance costs which affects all the EES are not considered due to the unpredictability both of technology improvements and the energy market development. Thus, all the results should be used as a guide-line for more detailed studies on the topic.

## Chapter 4

# Analysis of different strategies

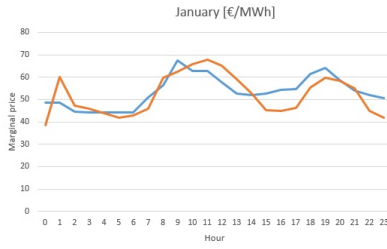
The main purpose of the study is to show how different strategies based on storage technologies can improve the costumers' saving. First of all it is obvious the data collected are based on simple models and no transient effect are considered; furthermore the characteristics of load demand and photovoltaic production are fixed, basing the measurement of the data on a time-resolution of 1 hour. For the analysis a month which represent a season was considered, since the photovoltaic panels' production changes because of the changing of solar radiation and weather's conditions. On the economic aspect also the prices curves [c€/kWh] change through the months, eventually the storage device's curve will not be the same through seasons.

Months chosen are January for the winter season, April for spring, July for summer and October for autumn; of course during these months also the load patterns may vary due to changing of habits through the seasons.

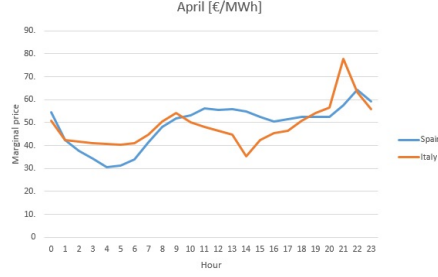
### 4.1 Energy price variations

As already said for each month a different prices curve trend is set; electricity prices in Europe are set on a daily basis (every day of the year) at 12 noon, for the twenty-four hours of the following day, in what we refer to as the *Daily Market*. The price and volume of energy over a specific hour are determined by the point at which the supply and demand curves meet, according to the marginal pricing model adopted by the EU, based on the algorithm approved for all European markets (EUPHEMIA), [26]. Clearly Italy and Spain have distinguished prices' trends because of different choices in energy supply and policies. What is similar in both two countries' curves is the presence of two peaks (with different amplitudes) that follow the load peaks' demand. The following graphics put in confrontation the two different trend of the two countries for each month chosen as samples. Therefore 4 different cases are analysed. As can be seen from fig ?? for each month prices are different, because of various types of loads and consumes that occur in the network. For the winter season household loads consist most in heaters and illumination, the last one due to the minor amount of solar radiation during the day; while in the summer there is a more prevalent presence of cooling systems. Common to all the trends is the presence of two peaks, which occur at the same time with the peaks of load demand, these peaks will be fundamental for the analysis.

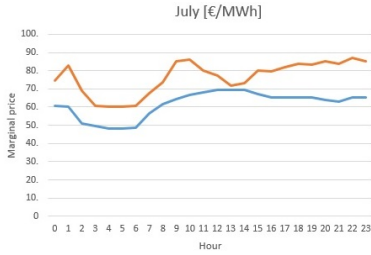
Therefore, 4 different cases are analysed. We already pointed out that each month has its own prices trends, because of various types of loads and consumes that occur in the network. For the winter season household loads consist most in heaters and illumination, the last one due to the less



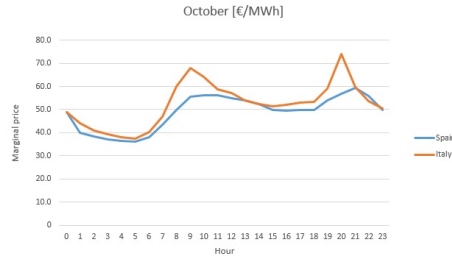
(a) Variations in January



(b) Variations in April



(c) Variations in July



(d) Variations in October

hour of light during the day; while in the summer there is a more prevalent presence of cooling systems. Common to all the trends is the presence of two peaks, which occur at the same time with the peaks of load demand.

The chosen end-users are typical Spanish and Italian families with photovoltaic rooftop integrated panels of about 3 kW<sub>p</sub> and a BES device which absorbs and provides power in a range of  $\pm 2$  kW. For the analysis a representative day of the month was selected, the third Wednesday of each month of 2015. So as samples days were chosen among year 2015:

- 21<sup>th</sup> January;
- 15<sup>th</sup> April;
- 15<sup>th</sup> July;
- 21<sup>th</sup> October;

This choice is due to the fact the peak of monthly demand occurs usually the third Wednesday of the month. All calculations were based on MATLAB (script are in the APPENDIX); their purpose is to model the storage power supplying/absorbing during the 24 hours/day respecting determined conditions imposed by loads, photovoltaic production and grid power limits. So far as to be said that all calculated scenarios are ideal, and many factor were avoided during the analysis. Thus, medium and/or typical values to perform the calculations were chosen.

## 4.2 Simulations

### 4.2.1 First scenario

At the beginning the analysis starts with the option of not following the prices of the electric market. In this way the storage device is exploited at its maximum limit. The applied algorithm

for calculating the battery curve consists in following determinate conditions:

$$\begin{cases} P_{load} > P_{panels} \\ P_{storage} = 0.7P_{load} - P_{panels} \end{cases} \quad (4.1)$$

$$\begin{cases} P_{load} < P_{panels} \\ P_{storage} = P_{load} - P_{panels} \end{cases} \quad (4.2)$$

Maintaining the condition that  $-2kW < P_{storage} < 2kW$ . Thus the total power which flows in the line<sup>1</sup> is given by

$$P_{tot} = P_{load} + P_{storage} - P_{panels}. \quad (4.3)$$

In addition, an ulterior restriction was imposed, that the line does not overcome the total power  $P = 3kW$ . Thus, basically the total purchase per hour for the end-user is calculated by multiplying the hourly price of the electric energy per the total power flowing in the grid. As can be seen by the following results, if the user has a load demand higher than the photovoltaic production the storage device supplies the household's demand with energy absorbed both by the grid and the surplus of PV electricity. During the PV peak production instead, the surplus energy is all collected to charge the storage unit; if this amount exceeds the capacity of the unit, the surplus is delivered in the grid. Hence, there exists an exchange of power between LV network and household.

### Spanish and Italian Storage's curve trends

The application of this strategy leads to the following storage's trends. It can be seen from fig 4.1 and fig 4.2 that with the foregoing conditions the storage device supplies power when the household needs it. According to the imposed conditions, the unit absorbs power when there is the peak of PV production, which occurs prevalently during midday; on the contrary the device does not charge, but discharges when PV production is equal to load demand or even lower. A more accurate comparison among the results in relation with the LV line is shown in chapter 6.

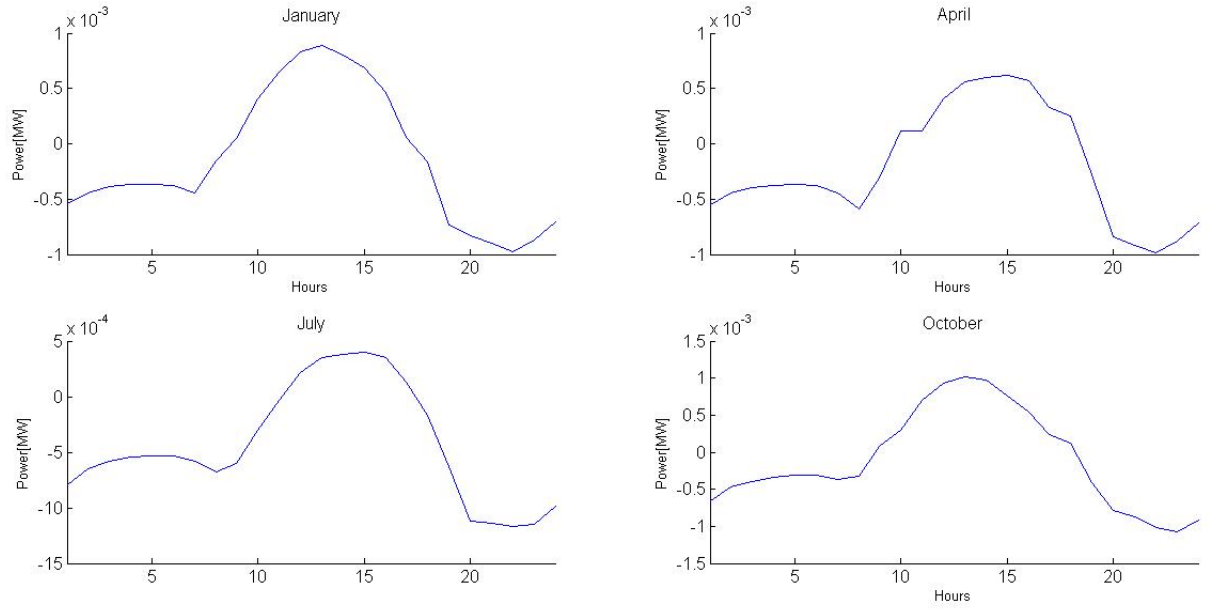
### Spanish and Italian Householder's Purchase

Here, there are the trends of customer's daily expense. From the figures 4.3 and 4.4 can be seen that storage is following the load, in particular during the peak of photovoltaic production, there is no purchase as the load is almost fully supplied by it. Even though the difference between the two countries' trends due to different load demands, there is a time-slot in which both Spanish and Italian users do not purchase from the network, but supply their demand with the photovoltaic system. This phenomena occurs especially during the PV power generation peak.

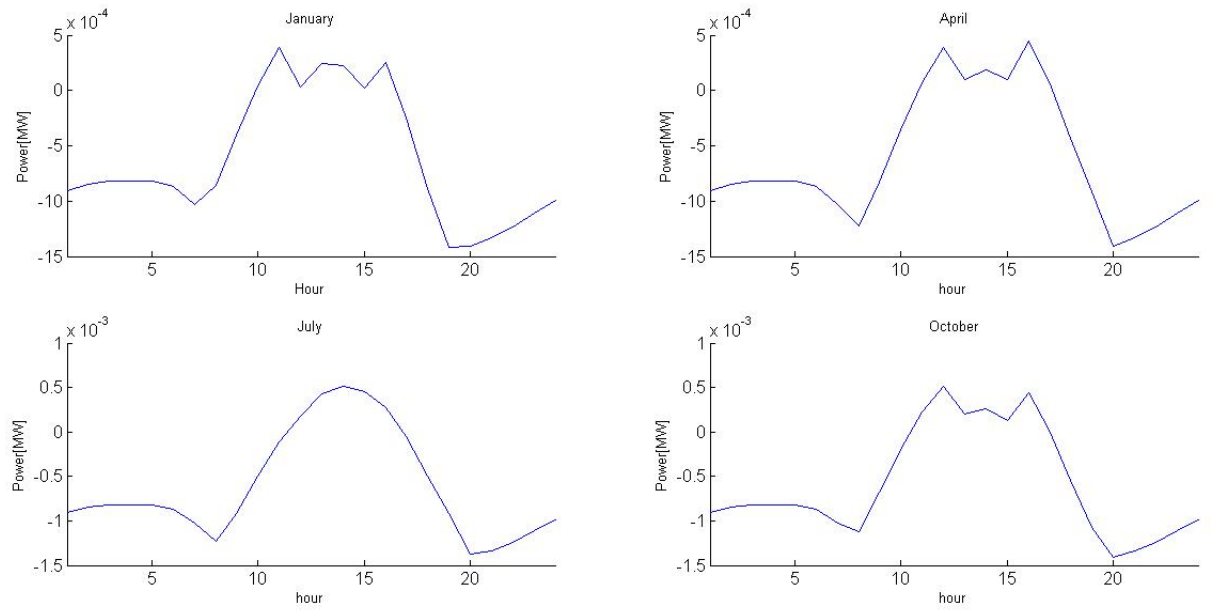
A more evident peak in the expense trend occurs during evening hours; that happens because of the high load demand. The storage system cannot supply the entire user power demand because of the imposed conditions; thus power from the distribution network must be injected.

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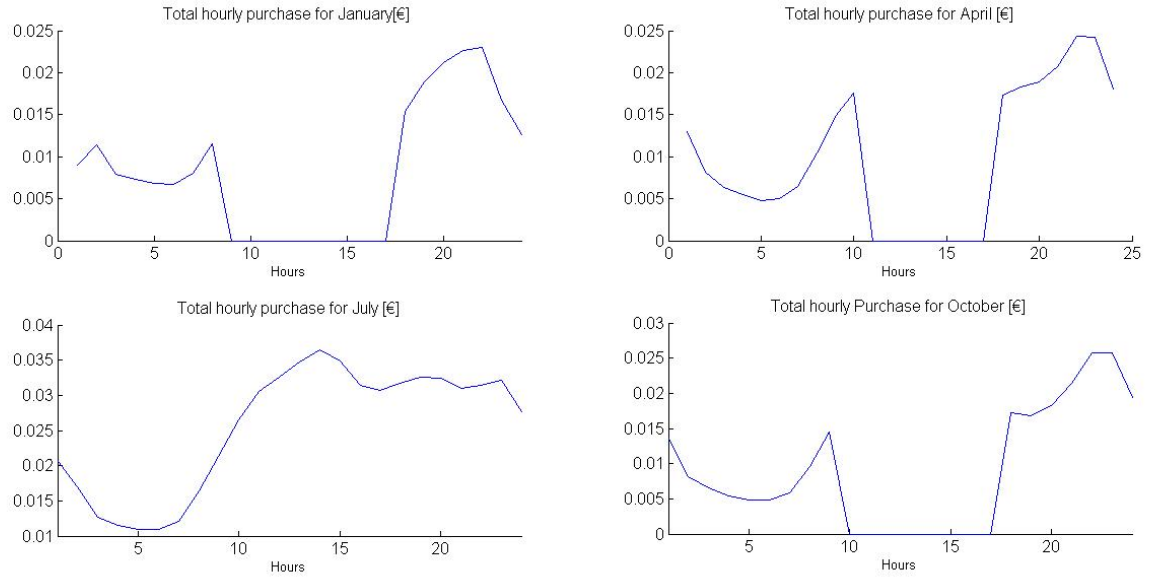
<sup>1</sup>Line which connect the end-user to the distribution network.



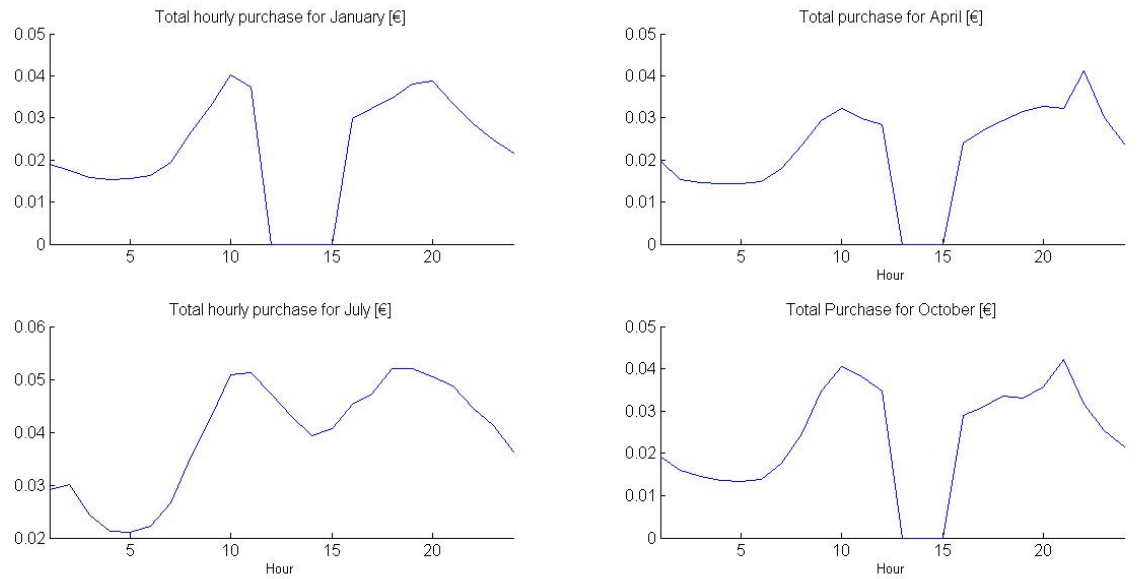
**Figure 4.1:** Spanish storage curves for the chosen months.



**Figure 4.2:** Italian storage curves for the chosen months.



**Figure 4.3:** Representation of total energy purchase and sale for Spanish householder during 24 hours/day.



**Figure 4.4:** Representation of total energy purchase and sale for Italian householder during 24 hours/day.

## 4.2.2 Second scenario

With the second simulation it means to point out a storage charge/discharge trend which permits to the user to save money following the hourly price of electrical energy (this can be done practically



thanks to the net-metering<sup>2</sup>). From this point of view the costumer's saving is granted by a storage device which discharges if the price of electric energy surpass a fixed threshold value. The conditions to follow are the same like in equation 4.2 if the PV production overcomes the load demand. Otherwise if the PV hourly power is less than the load demand  $P_{photovoltaic} < P_{load}$ , the storage unit must follow other conditions which deal with the prices of electrical market:

$$\begin{cases} Pr > Pr_{max} \\ P_{storage} + P_{load} - P_{photovoltaic} = 0.002 \end{cases} \quad (4.4)$$

$Pr_{max}$  is a new mean value calculated by the average calculation between mean price value  $Pr_m = \frac{\sum_{i=1}^n Pr}{n}$  and the maximum value reached by price trend  $Pr_{max} = \max\{Pr_1, Pr_2, \dots, Pr_n\}$ . In this way the storage provides power when the price per hour surpass the imposed value, meaning that the householder is consuming his own power or he is selling power to the network; otherwise if the price is included between  $Pr_{max}$  and  $Pr_{min}$ , the storage behaves in two different ways as the  $P_{load}$  is higher or less than the  $P_{photovoltaic}$ . For  $Pr_{min}$  it means the calculation of mean value between the least price value  $P_{min} = \min\{Pr_1, Pr_2, \dots, Pr_n\}$  and the mean value of all the prices. If the load demand is lower, the storage follows 4.2; for this scenario and the following ones,

**Table 4.1:** Threshold prices.

	$Pr_{max}$ [€/MWh]		$Pr_{min}$ [€/MWh]	
	Italy	Spain	Italy	Spain
<b>January</b>	53,48	59,93	48,78	45,30
<b>April</b>	63,05	56,67	41,92	39,70
<b>July</b>	81,68	65,64	68,19	54,78
<b>October</b>	63,15	54,18	44,94	42,43

there is no limit of power flowing throughout the line, in order to see later how much the line can be loaded.

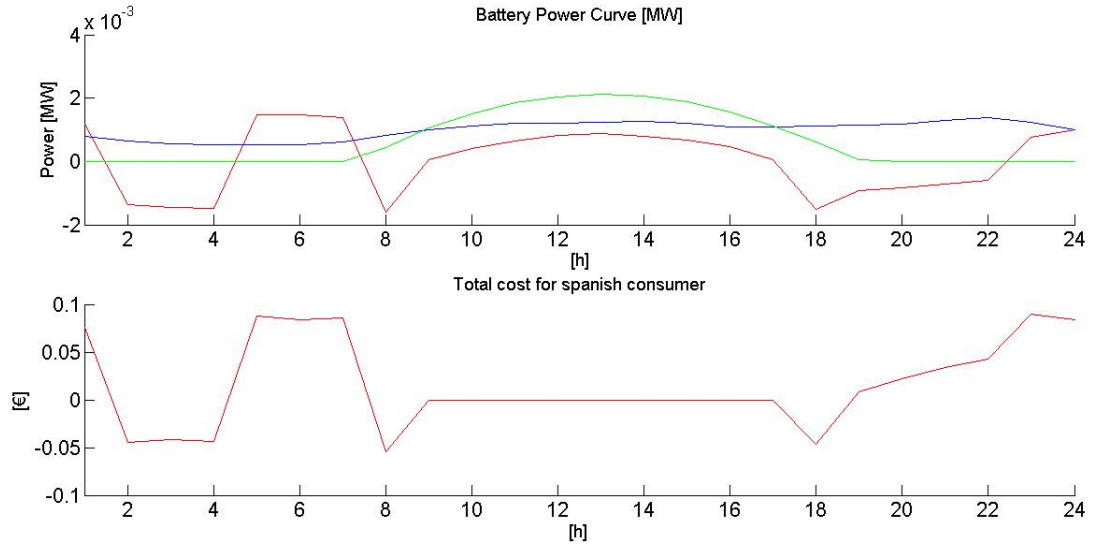
It can be seen that occurs always the same formulas but in different time of the day because of the conditions of price imposed. In table 4.1 there are the threshold values price used for the simulation. According to the settled values and the used algorithm three slots divide the price curve: an upper area which comprehends the maximum reached peaks, a medium area in which the hourly price floats between the upper and the lower mean values; and a lower area which divides the lowest price peaks from the other values.

### Spanish and Italian curve trends

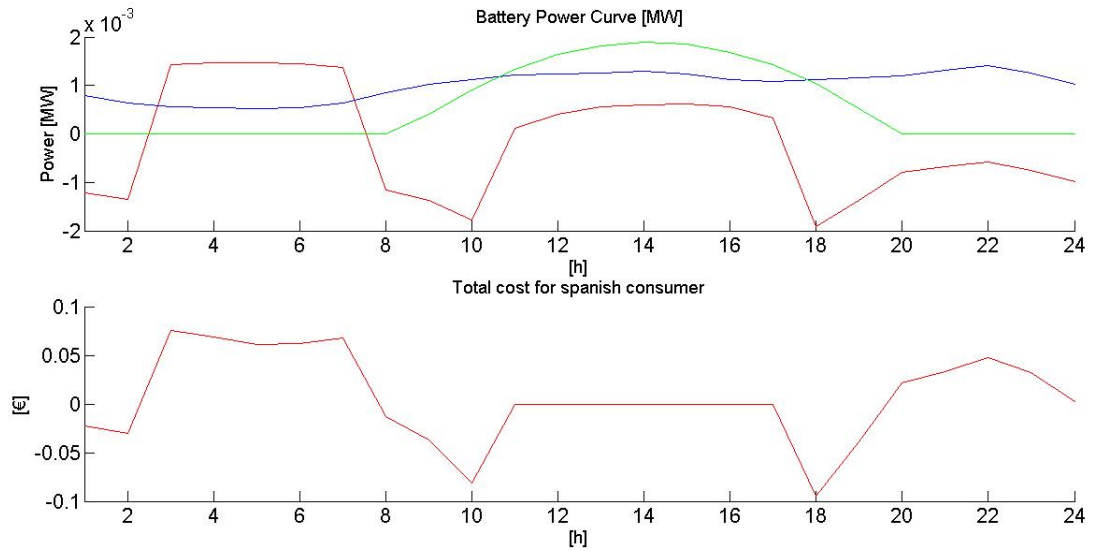
Figures 4.5 and 4.6 present consequently power curves of the storage's system through the season, this time it is also shown the relationship with load and PV power flow during 24 hours/day. This time the imposition of following the hourly price has brought a discharging/charging trends quite different from the ones presented in the first scenario.

Even though that with the PV power generation peak the storage charges, this time the storage device for the Spanish user absorbs power during the overnight hours, though the PV panels are not producing; the explanation of the phenomena has to be searched in the price of electricity during that hour. It is more convenient for storage system charging with power flowing from the grid, since the hourly price of sale is low. A quite different situation appears in the Italian trends:

<sup>2</sup>Concept well explained in the following chapter.

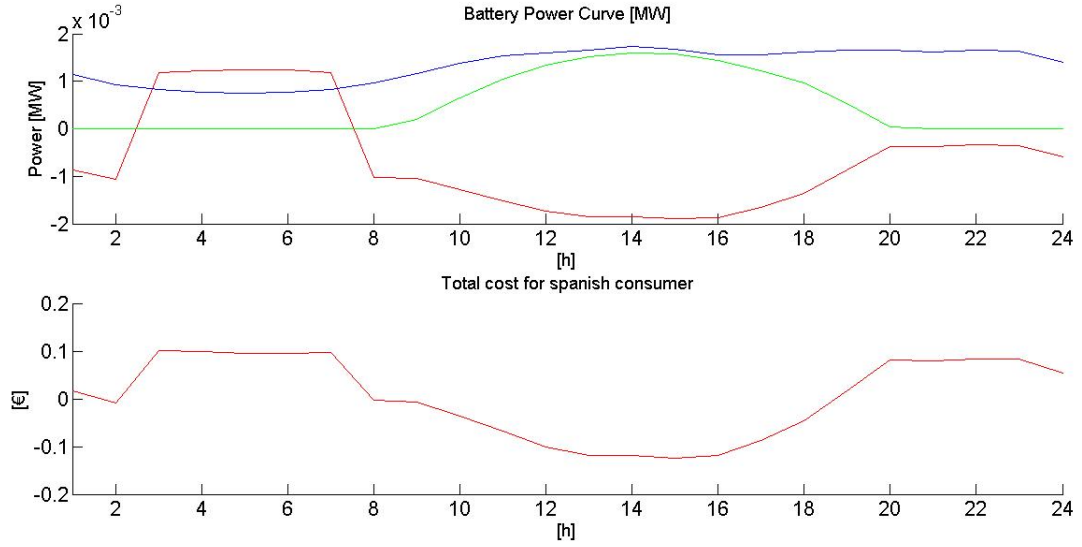


(a) January

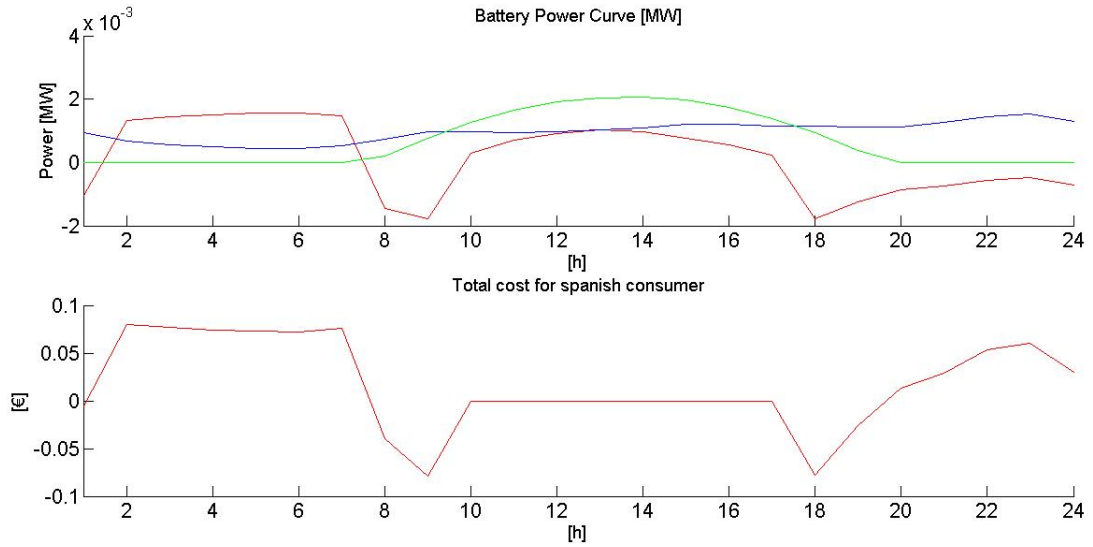


(b) April

due to the higher price, the storage device has to provide power even during overnight hours. Another sort of values appears in the simulation of July, because of a load demand higher than the PV production; for the set values the storage device is delivering continuously power for all the day, bringing up unreal storage curve trends.

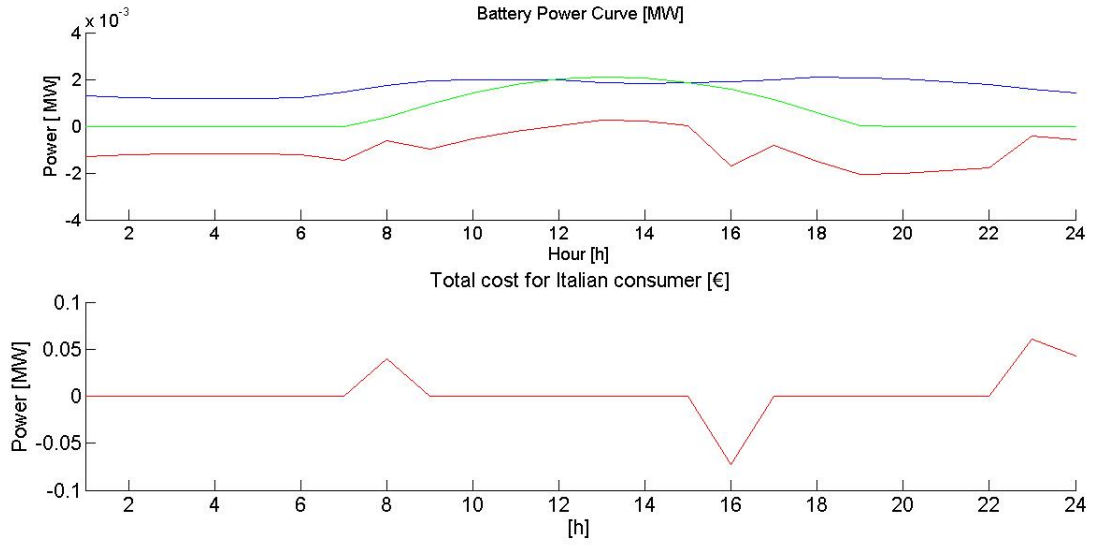


(c) July

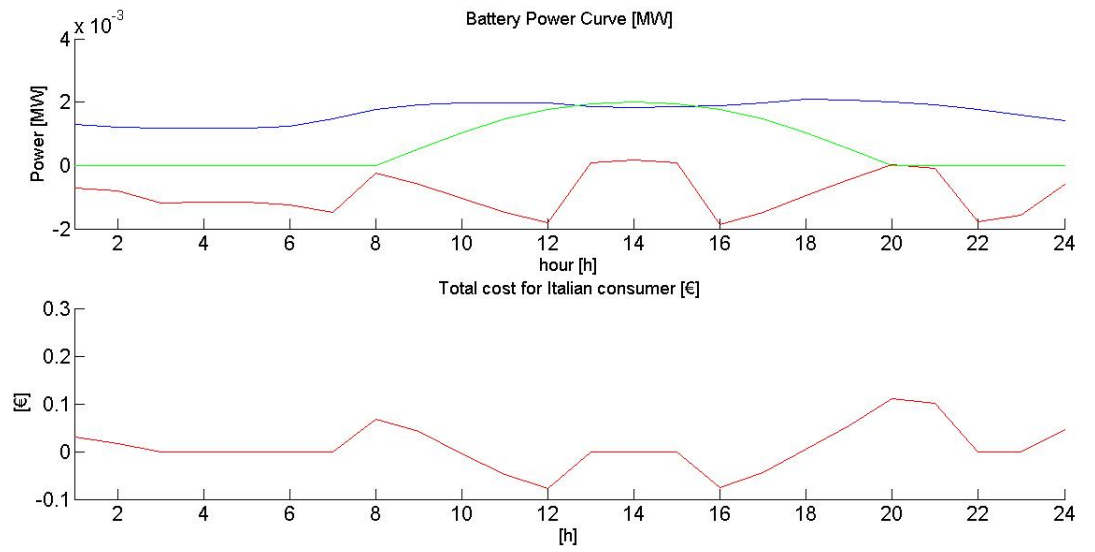


(d) October

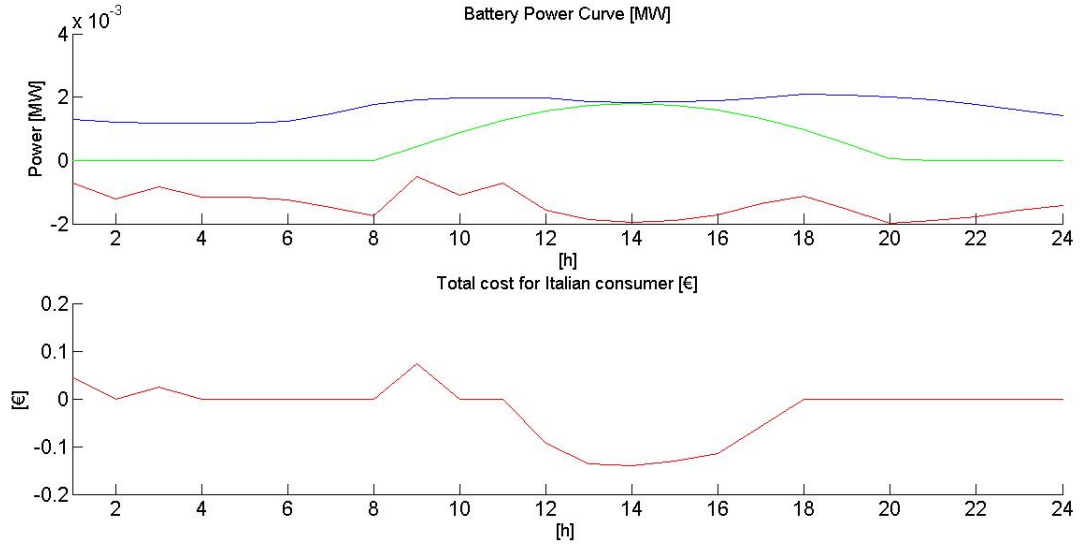
**Figure 4.5: Second scenario:** Spanish trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total expense-sale of the user.



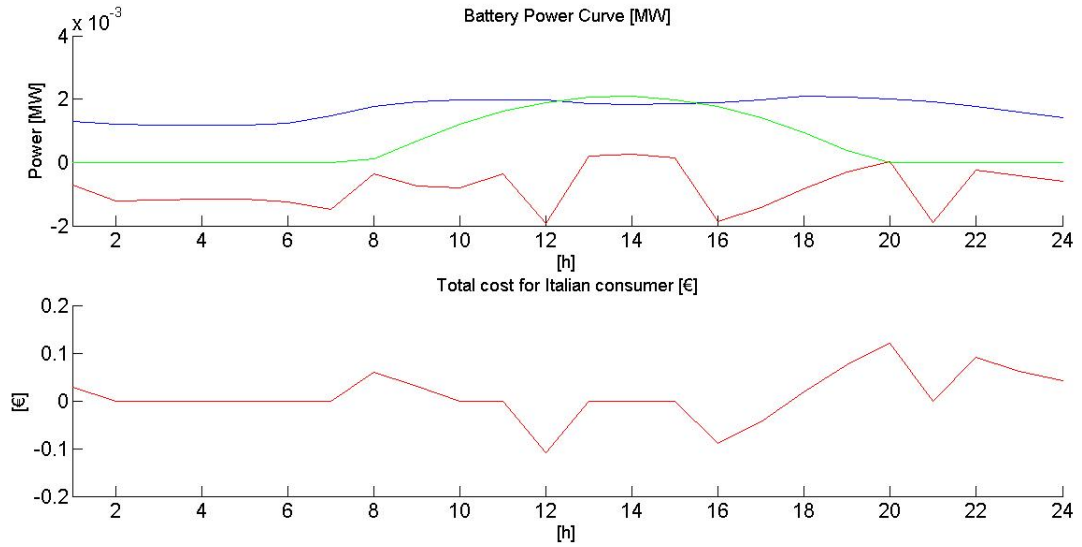
(a) January



(b) April



(c) July



(d) October

**Figure 4.6: Second scenario:** Italian trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total expense-sale of the user.

### 4.2.3 Third Scenario

For this kind of scenario it was chosen as threshold price the mean value price.

$$\frac{\sum_{i=1}^n Pr_i}{n} \quad (4.5)$$

Same conditions imposed in the section 4.2.2 still last in this scenario. Basically, the main difference is in the choice of the threshold price; thus, the storage device supplies power or charges whether the hourly price is higher than the threshold value or not. In this way the price curve is divided in two different areas. As for the previous scenarios it was taken in consideration the PV production. When it is sufficient to supply the user, surplus in power can be delivered to the grid when hourly price overcomes the mean price. On the other hand, when the hourly price is lower, but still the PV production is in surplus, the storage unit stores the energy. Clearly, it charges also when PV system does not produce, but it is convenient to buy power from the grid.

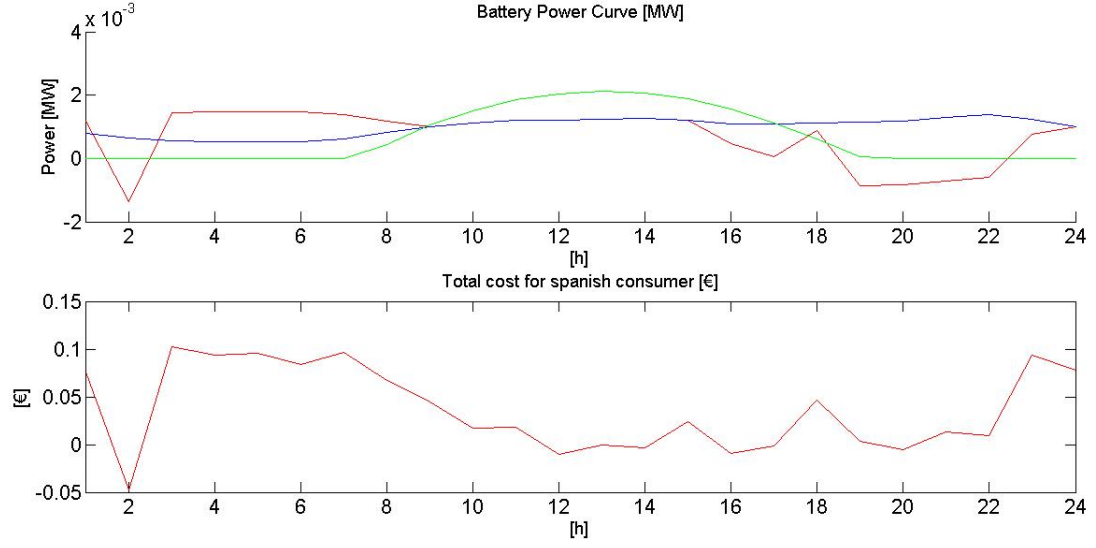
In table 4.2 the values of the medium prices are presented. As can be seen Italy has higher prices values due to the higher value of the considered hourly prices.

**Table 4.2:** Medium prices for Italy and Spain

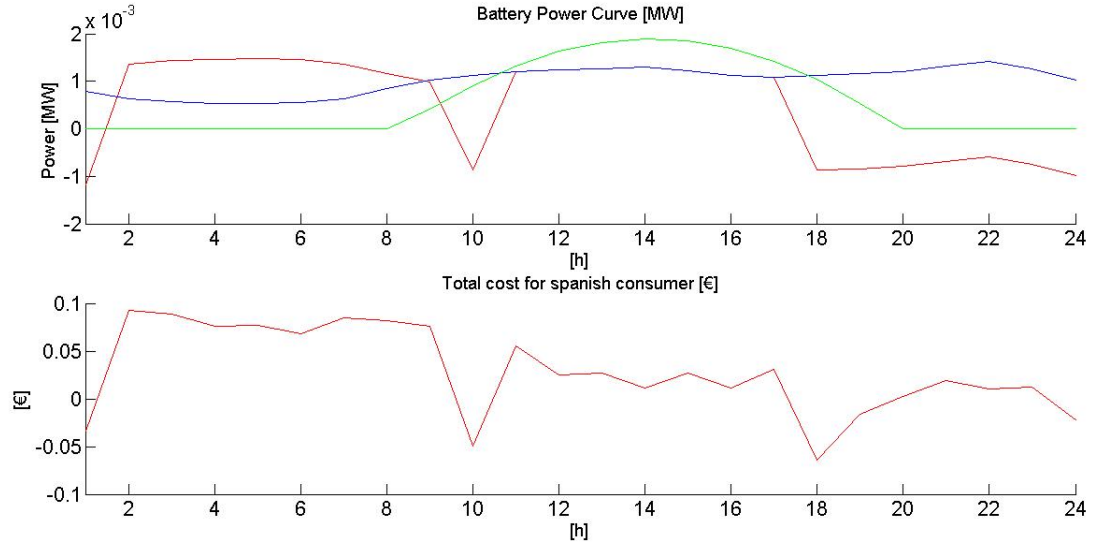
	Italy [€/MWh]	Spain [€/MWh]
<b>January</b>	53,48	52,11
<b>April</b>	48,51	48,95
<b>July</b>	76,36	61,59
<b>October</b>	52,36	48,87

### Spanish and Italian curve trends

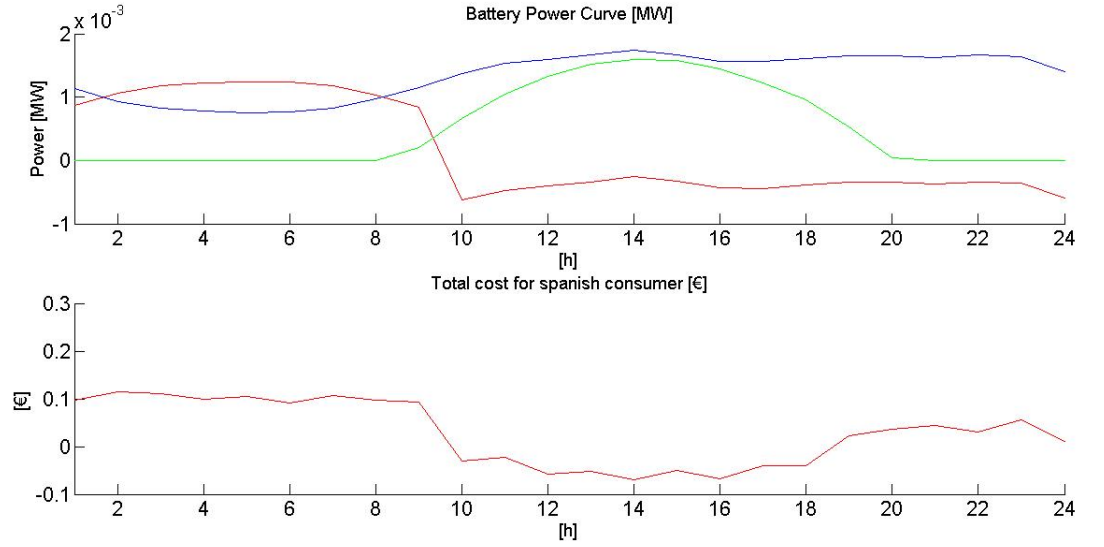
Henceforth, we can analyse the trends provided by this strategy in the following figures. From fig 4.7 and 4.8 can be seen that there is a segmentation of the purchase-sale energy curves due to the variability of the hourly price towards the mean price value. Aside from July's storage trends, due to a photovoltaic curve lower than the load demand (probably because of the prevalent using of cooling systems in the house), the storage curves present values higher even than the load, which means that the device is injecting power in the grid. This happens because the mean price value is higher than the hourly price, so the user can inject power into the grid.



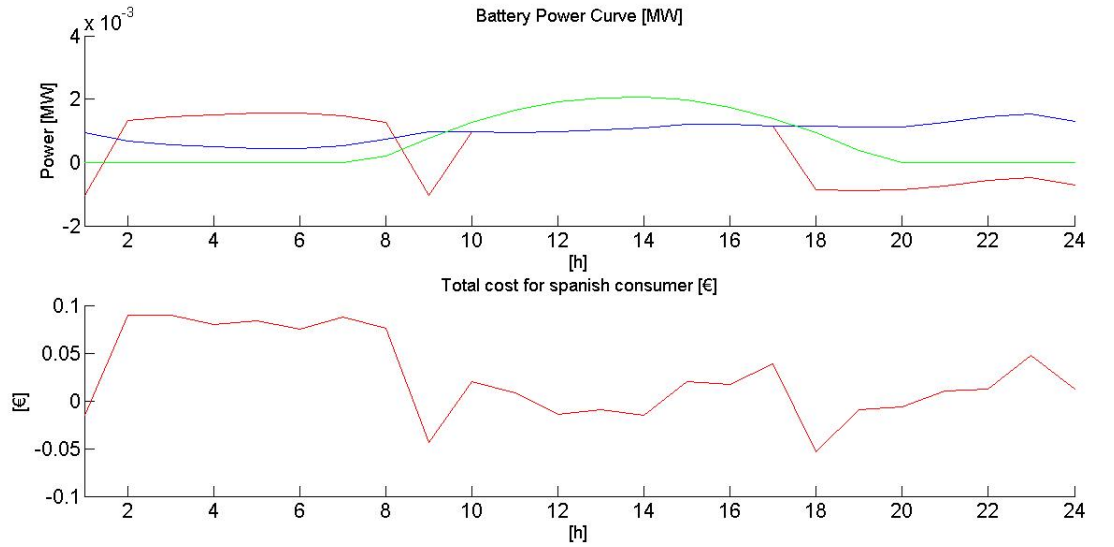
(a) January



(b) April



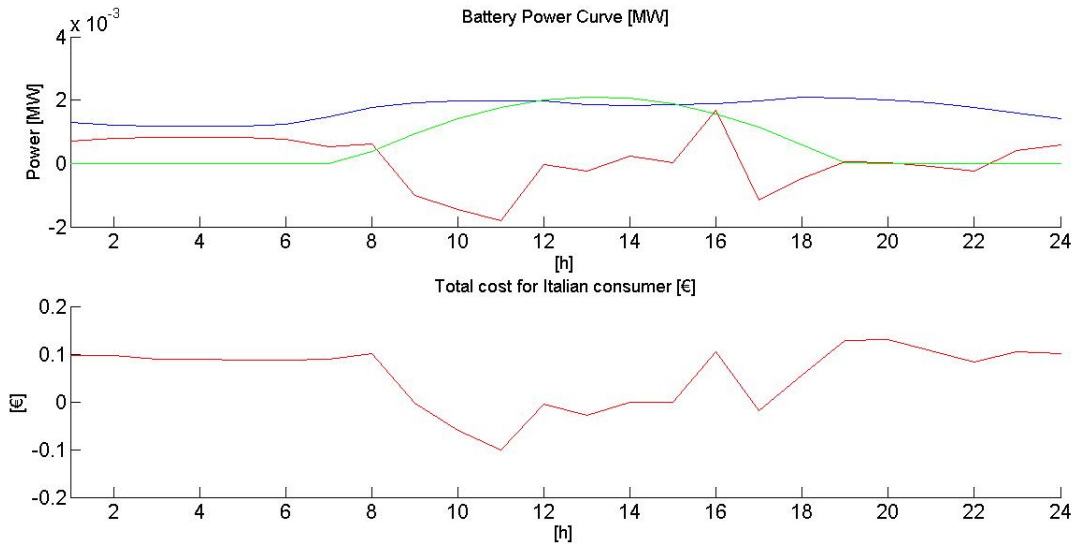
(c) July



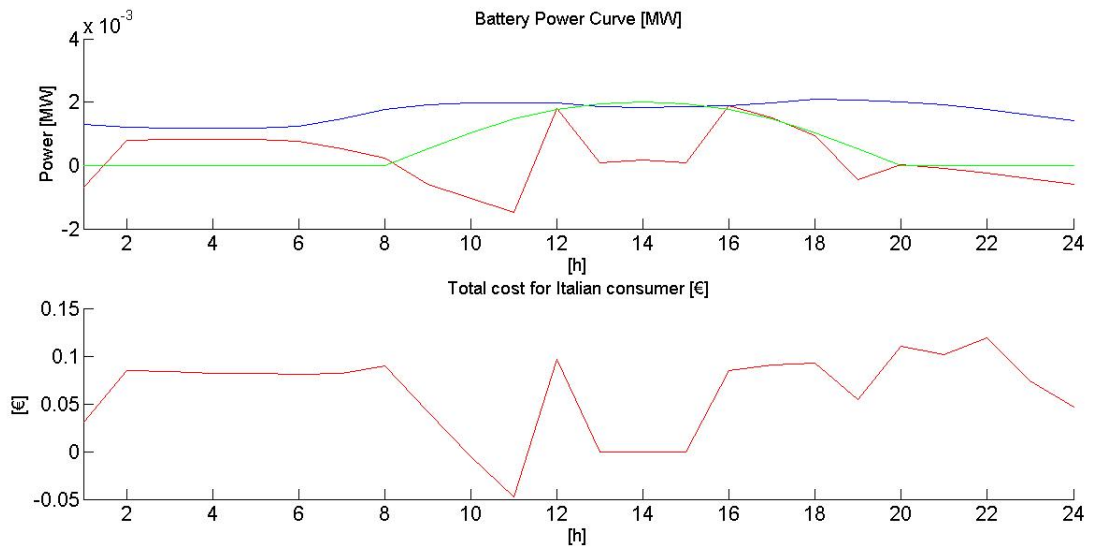
(d) October

**Figure 4.7: Third scenario:** Spanish trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total purchase-sale of the user.

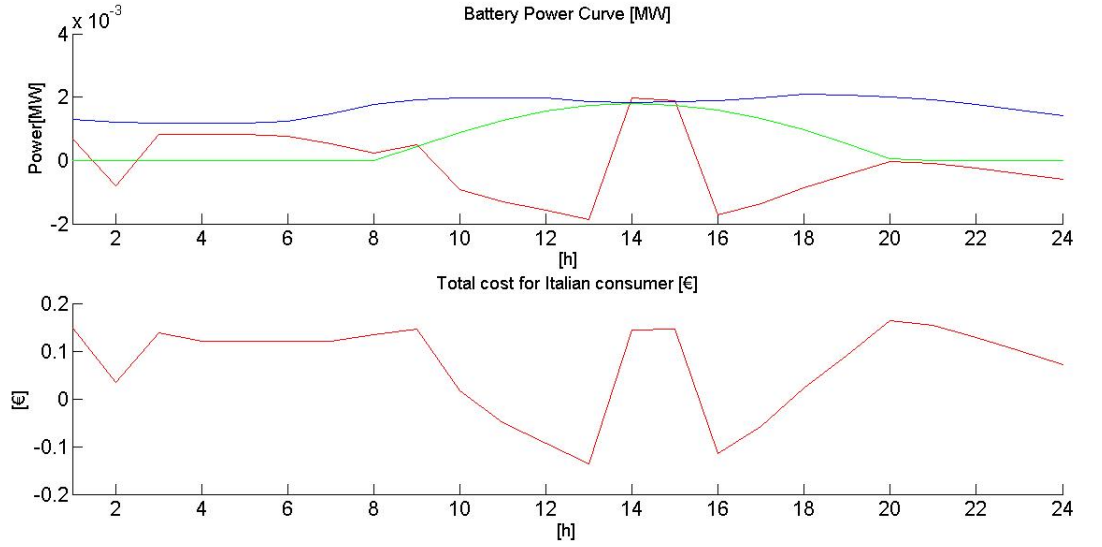




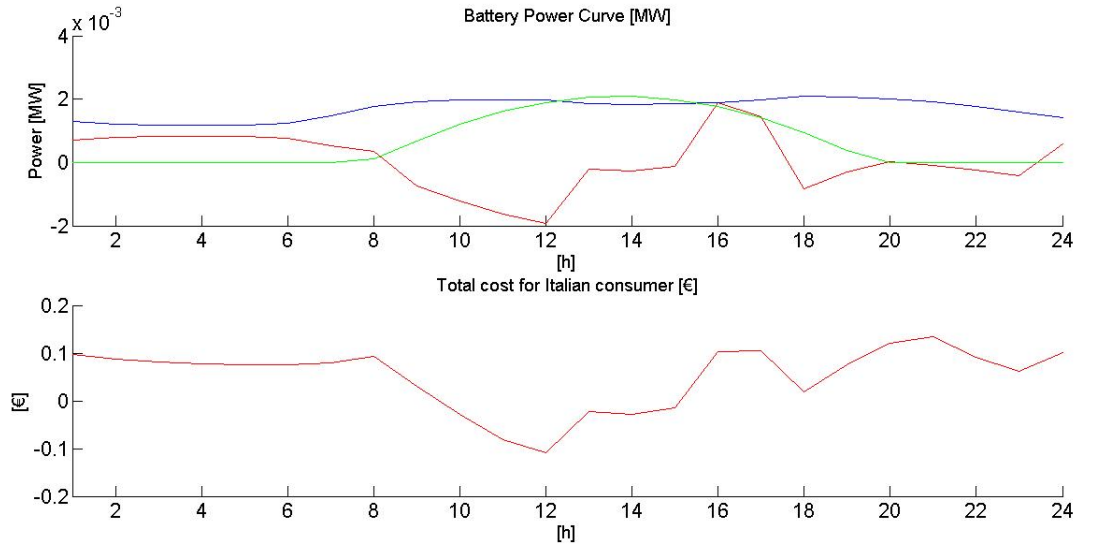
(a) January



(b) April



(c) July



(d) October

**Figure 4.8: Third scenario:** Italian trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total purchase-sale of the user.

#### 4.2.4 Fourth Scenario

For the last simulation 24 hours' prices were divided in three time-slots of about 8 hours range. Each slot has its own medium price, which means that there are three different mean value prices. So in MATLAB the following formulas were used:

$$\begin{cases} \frac{\sum_{j=1}^n Pr_j}{n} & n = 8 \\ \frac{\sum_{k=9}^n Pr_k}{n} & n = 16 \\ \frac{\sum_{h=17}^n Pr_h}{n} & n = 24 \end{cases} \quad (4.6)$$

In other words, there are three zone of absorbing/generating power. The power trends can be divided through the day in 3 areas: from 00:00 am to 7:59 am, 8:00 am to 3:59 pm and from 4:00 pm to 23:59. Values of threshold prices for each time slot are presented in table 4.3. Each time-slot is indicated by  $\delta_i$ , where the index  $i$  indicates the slot. The division in time-slots imposes to the BES' control unit to be more sensitive and reactive to the price changing; in fact reducing the number or elements in the average price calculations means to respond to several price variation, a wider range of possibilities.

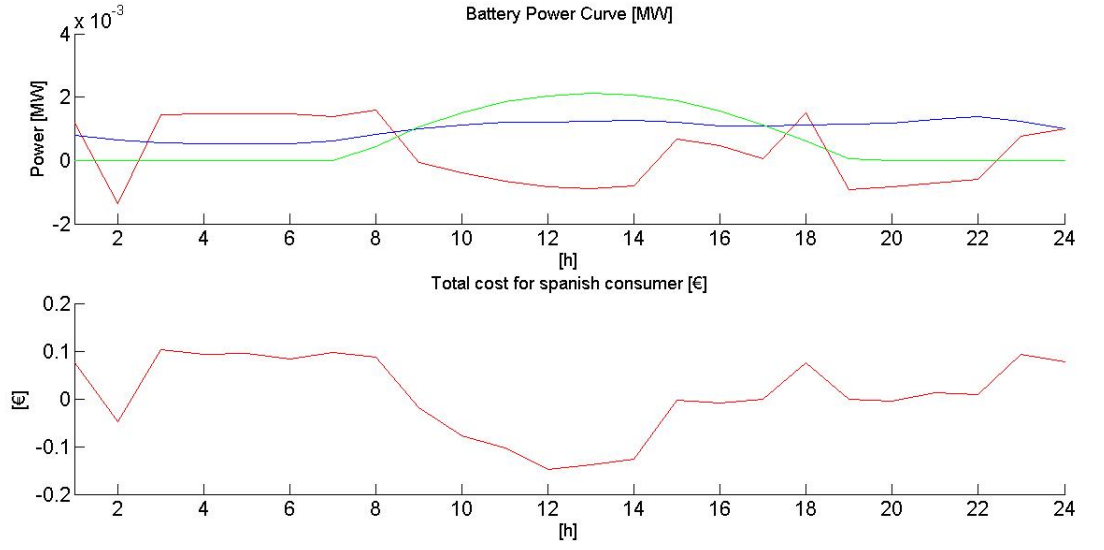
**Table 4.3:** Prices for the different time-slots in Italy and in Spain.

	Spain			Italy		
	$\delta_1$ [€/MWh]	$\delta_2$ [€/MWh]	$\delta_3$ [€/MWh]	$\delta_1$ [€/MWh]	$\delta_2$ [€/MWh]	$\delta_3$ [€/MWh]
<b>January</b>	48,48	57,80	50,05	47,17	57,75	55,53
<b>April</b>	37,44	53,82	55,59	42,81	45,85	56,87
<b>July</b>	52,94	67,54	64,28	66,75	79,18	83,15
<b>October</b>	39,90	53,62	53,11	43,36	57,21	56,52

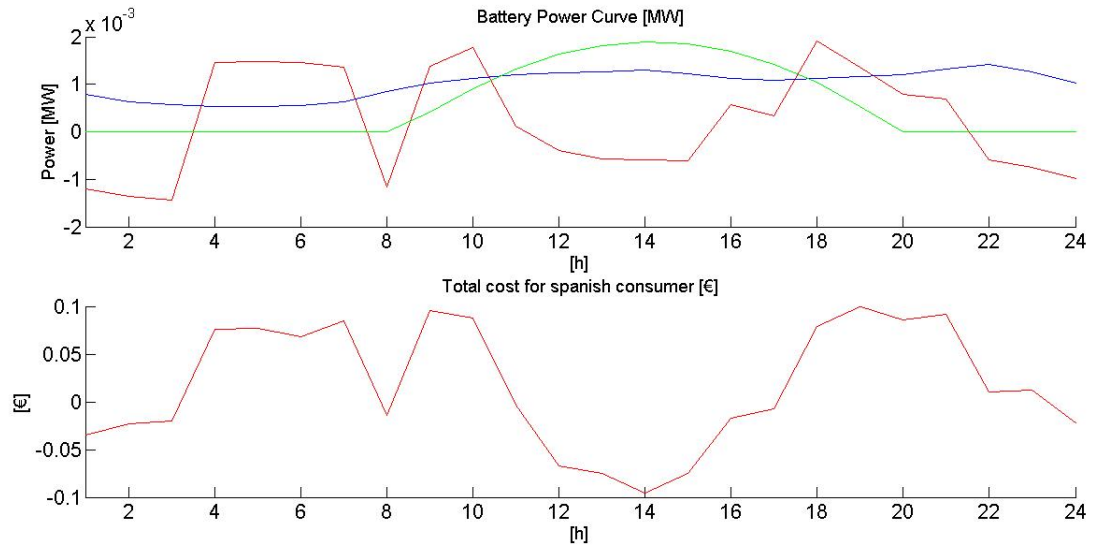
#### Spanish and Italian curve trends

Here, there are the results of the simulation. As presented previously each figure contains on the top household's load, PV generation and storage curve trends, while on the bottom there is the purchase/sale for the user measured in € per hour.

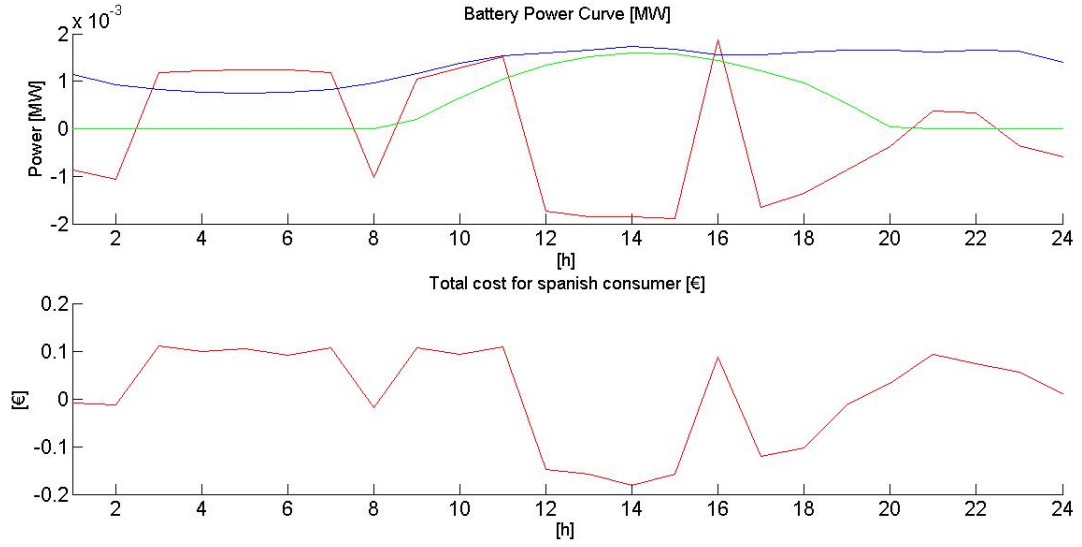
As the third scenario during the PV production peak the storage system absorbs the surplus of power between  $P_{load}$  and  $P_{photovoltaic}$  only if the price allows it. It has to be noticed that both for Italian and Spanish users, the storage system absorbs power during the night, because of the lower price value. Contrary to what can be expected, during the PV peak the storage system is generating too (during the morning energy price peak), so the load is fully fed by PV and storage, and the surplus power is injected in the network. Thus, this strategy does not helps the household self-consumption, rather it is oriented to idealistic idea of free exchange with the network, that it is not applicable to the nowadays energy trade market.



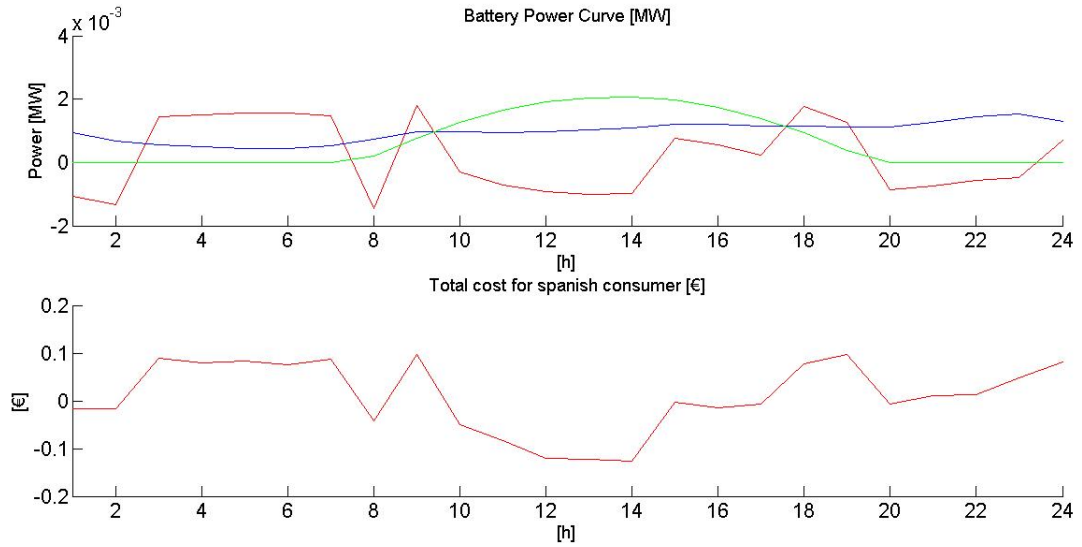
(a) January



(b) April

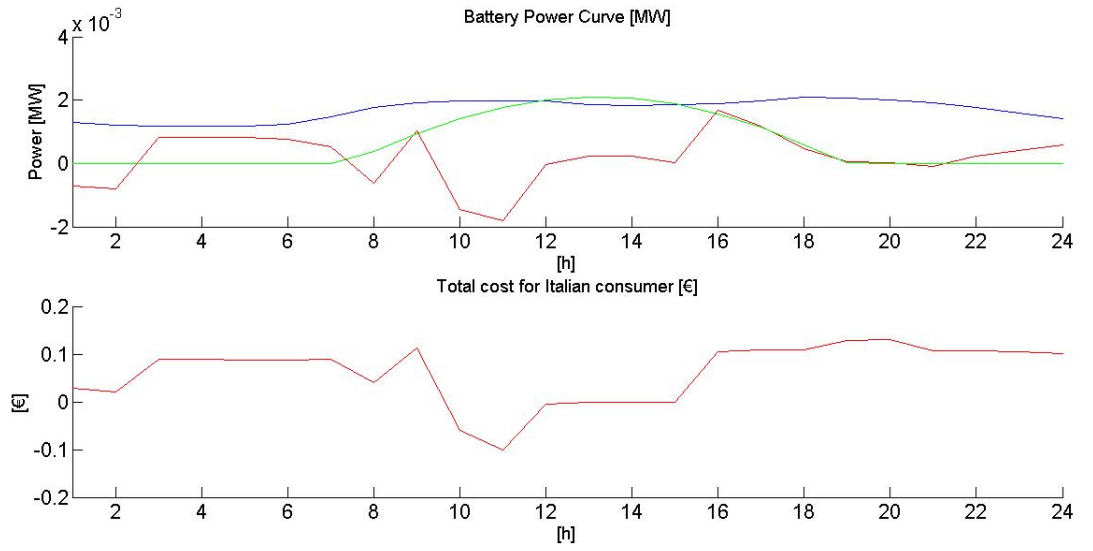


(c) July

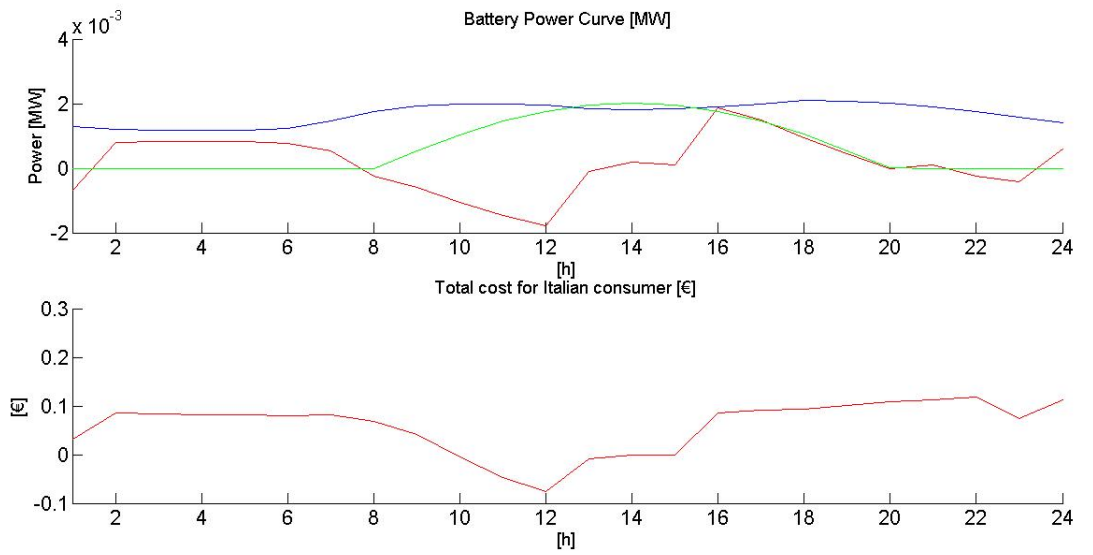


(d) October

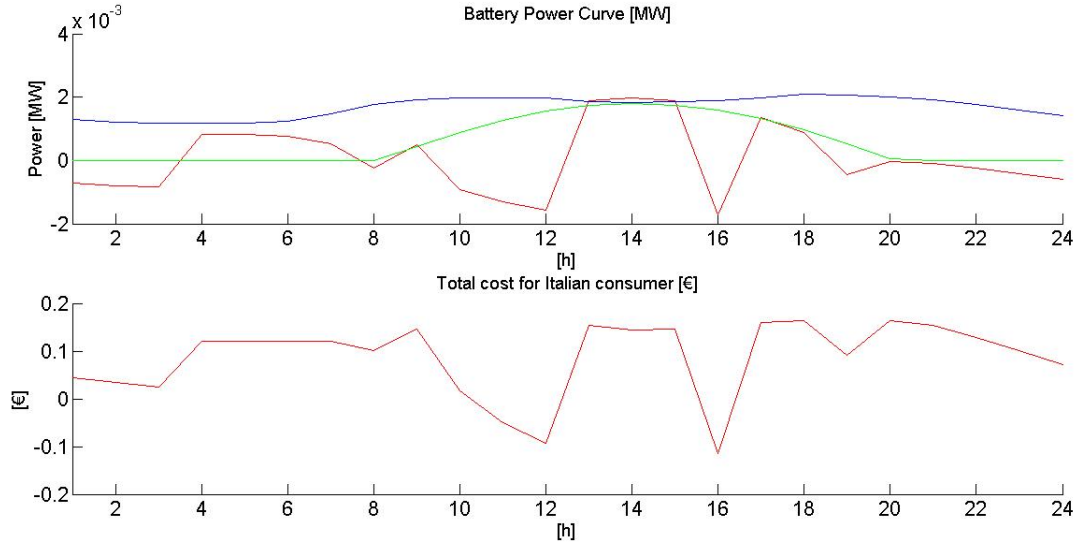
**Figure 4.9: Fourth scenario:** Spanish trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total purchase-sale of the user.



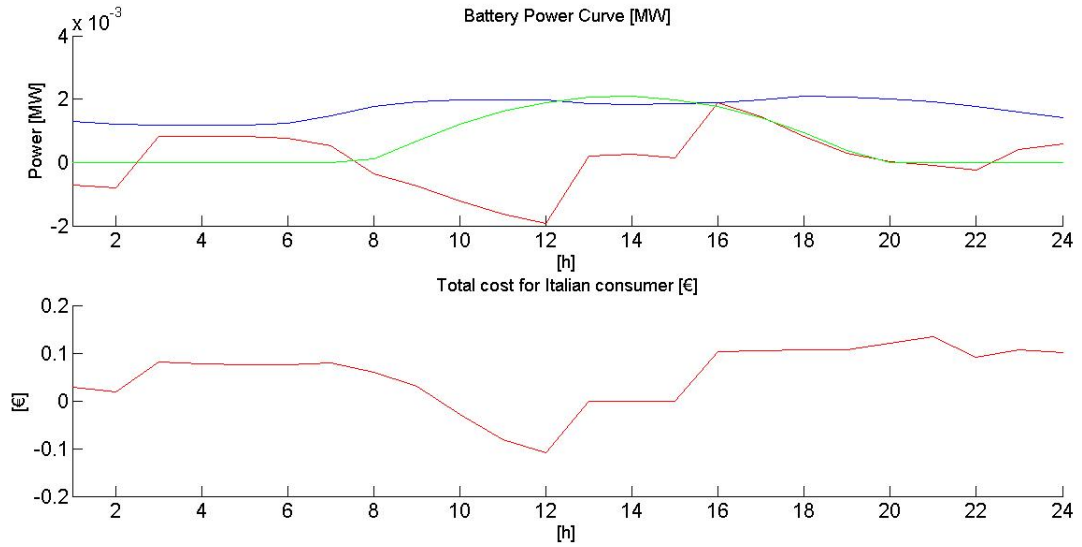
(a) January



(b) April



(c) July



(d) October

**Figure 4.10: Fourth scenario:** Italian trends, on the top part storage curve is put in contrast with PV power generation and load demand; while in the bottom there is the total purchase-sale of the user.

## 4.3 Conclusions

The solar electricity produced is self-consumed to the maximum extent possible, which depends on the load profile. Generally speaking, the share of self-consumed electricity is higher the lower the installed capacity of the PV system, which is intuitive (if production is lower than the actual consumption, all solar electricity can be self-consumed). With higher sizes of the PV plant, the share of self-consumption decreases rapidly. The higher the self-consumption, the less grid electricity needs to be purchased, reducing the annual electricity costs, [10].

Now we can focus on the hourly trend of the costumer's purchase-sale of electricity. Positive and negative values are plotted in the graphics; the meaning of this depends on the fact that positive value corresponds to what the costumer owns to the grid's operator, meanwhile the negative values mean that the user, feeding power to the grid, receives a payment from the network's operator. Regarding the calculations, the plot follows the formula  $C_t = P_{line} \cdot Pr$  where  $C_t$  is what the householder has to pay or receive to/from the network operator,  $P_{line}$ <sup>3</sup> is the total power that the connection line to the grid let flowing,

$$P_{line} = P_{storage} + P_{load} - P_{photovoltaic} \quad (4.7)$$

and  $Pr$  is the hourly price of energy.

In the first scenario it can be seen that there are time-slots in which the user does not pay, but on the other hand he is never paid from the grid operator, the storage never supplies power to the grid; this trend can be seen in fig 4.3 and 4.4. As a matter of fact the storage is modelled in order to supply the load when the PV system cannot, and charges when there is a surplus of power production; however it does not mean to create remuneration for the user. From this point of view, the BES is a useful tool to improve self-consumption and it becomes a device to manage the power exchanging in the network during the PV power peak production. The second scenario shown in figures 4.5 and 4.6 may be interpreted in another way: the Spanish model sees a zero cash flow (except for July) during the PV production peak, meaning that the householder is independent from the grid along that period, while he pays on the night hours when the price of the electrical energy is low. The Italian model present a more segmented expense curve due to the fact of a more aleatory price, and as can be seen in January simulation the daily expense is almost zero. In the month of July in which the storage is supposed to generate constantly energy (it is impossible perform only a discharge, but because of avoiding many factors in the BES model, the result came out). However, because of taking only a sample day, if we suppose that the following day the device charges, it can be accepted as simulation results. As far as concerned the third scenario in fig 4.7 and 4.8, the Italian model presents for January and April a retribution for the injected power only during the PV peak, so between 10 am and 2 pm hours. July presents a storage absorption peak among the central hours of the day due to the convenient hourly price to absorb power for charging. In the October simulation there is a trend similar for January and April results. For the Spanish householder, instead, we see a high expense during the night hours, while during the day there is yet a purchase but less lasting and with a lower value. The trend occurs in each month used for simulation. Regarding the fourth scenario, the purchasing trends results are presented in figures 4.9 and 4.10. the Italian model presents peaks of purchasing energy from the grid during the night, while the users receives the payment during the PV peak; the trend similarly occurs in all months, except for July in which there exists a peak of expense in correspondence of midday (thus when the PV system produce the most). Spanish trends are quite similar to the Italian ones,

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<sup>3</sup>It was adopted the convention of the load for the signs, so  $P_{photovoltaic}$  needs to have the minus in the formula, while the power of the storage can be positive or negative, depending on charging or discharging period.



even thought that the sale peak is shifted to first hour of the afternoon (i.e. 2 pm). As already said the fact of discharging the storage during the PV power peak production means that, from the point of view of exchanging power with the network, it is more convenient to injecting power to the grid than to consume it on-site, even though that it means to overloading the grid. It happens that during the evening peak of hourly prices trends the storage provides power as well.

Therefore, after analysing in detail all the trends for given simulations, it is now possible to suggest which strategy leads to an improvement for self-consumption management and saving. So far, the first scenario leads to an improvement of self-consumption and it is the most feasible strategy due to the electrical market regulations. Clearly, current policies do not permit to the end-users like householders to inject power in order to be paid by grid's operators, but the storage system can be installed only has a backup solution; thus nowadays it is only possible to improving the self-sufficiency. Nevertheless, if a new regulation will be set in the future, it will be possible to adopt one of the other three strategies. The one that create the better compromise between self-sufficiency and saving is the second scenario. As a matter of fact it provides storage's charging during the PV power peak production, which means to help the energy management; and permits to the device discharging when the price of the electricity is high, meaning the rising of benefits for the householder, who can "decide" when exchanging power with the grid.

## Chapter 5

# Self-Cosumption

Basically systems with high power produce a high percentage of self-sufficiency and high storage increases the auto-consumption; so self-sufficiency and auto-consumption assume two different meanings: the former implies a state of not requiring any aid, support, or interaction, for survival; it is therefore a type of autonomy, while the latter means the possibility of consuming the energy produced by own self.

The figure 5.1 represents an example of daily profiles during the 24 hours and also put in confrontation two different options to manage the self-consumption the *Load Shifting* and the *Energy Storage*. The letters A and B correspond respectively to power profiles of total net electricity demand and PV generation. The overlapping area C is the PV production consumed by the household. Thus self-consumption is the percentage of self-consumed part of energy relative to the total production

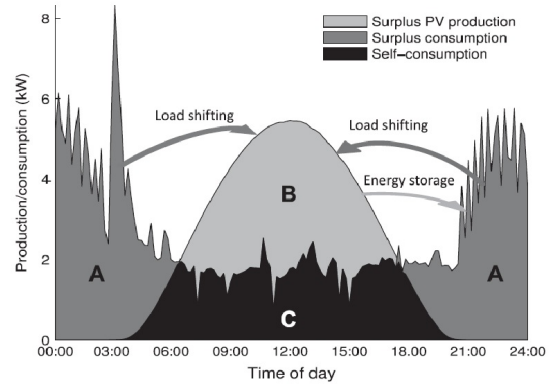
$$SC = \frac{C}{B + C} \quad (5.1)$$

Meanwhile for self-sufficiency shows the degree to which the on-site generation is sufficient to fill the energy needs of the building

$$SS = \frac{C}{A + C} \quad (5.2)$$

To formally define the two terms, they can be analysed in the time domain. The instantaneous building power consumption is  $L(t)$  and the instantaneous on-site PV power generation  $P(t)$ . The power generation utilized on-site is obviously limited by which of the load or PV profile is the smallest. So  $M(t) = \min(L(t), P(t))$  denominate the overlapping zone in fig.5.1; with the storage unit  $M(t)$  can be rewritten as

$$M(t) = \min(L(t), [P(t) + S(t)]) \quad (5.3)$$



**Figure 5.1:** Schematic outline of daily net load (A + C), net generation (B + C) and absolute self-consumption (C) in a building with on-site PV, [3].

with  $S(t)$  the power coming from the storage, that can be  $< 0$  or  $> 0$  if it is charging or discharging. Therefore self-consumption and self-sufficiency can now be written

$$\phi_{sc} = \frac{\int_{t=t_1}^{t_2} M(t) dt}{\int_{t=t_1}^{t_2} P(t) dt} \quad (5.4)$$

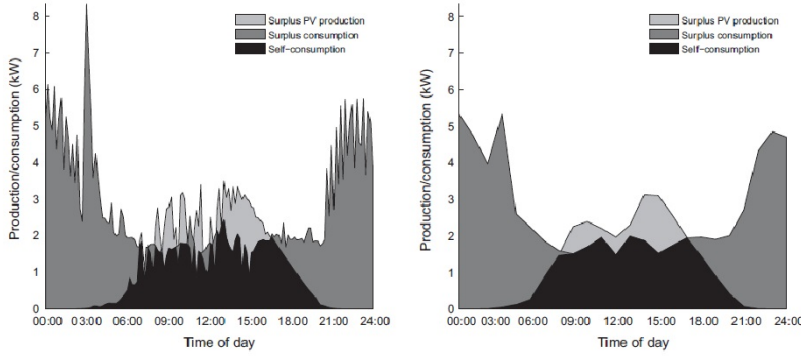
$$\phi_{ss} = \frac{\int_{t=t_1}^{t_2} M(t) dt}{\int_{t=t_1}^{t_2} L(t) dt} \quad (5.5)$$

Thus the relationship between the two terms is in equation 5.6, which provides a possible conversion between them, with load and PV production fixed or given, [3].

$$\frac{\phi_{sc}}{\phi_{ss}} = \frac{\int_{t=t_1}^{t_2} L(t) dt}{\int_{t=t_1}^{t_2} P(t) dt} \quad (5.6)$$

By the way, self-consumption results can be affected by a few factors that have to be taken in consideration:

- *Relative size of PV power generation and power demand* that means increasing PV generation in relation to the load demand will decrease the self-consumption and on the other side increase the self-sufficiency.
- *Time resolution*, that is very important because the data series are collected typically with hourly width<sup>1</sup>.



**Figure 5.2:** Two profile with different time resolution.

- *Number of buildings.* Since load demand depends also from random loads with fluctuations, a large number of buildings will change the power profiles of the network. Here in the study a single household was used, thus the collected results may diverge from the obtained results with more buildings.

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<sup>1</sup>A lower resolution will lead to an overestimation of the self-consumption since fluctuation causing mismatch between generation and load profile.

After pointing out these definitions, it is important as well to note another major difference between two terms such as *load matching* and *grid interaction*. The former is mainly important for determining the value of on-site generation, and quantify the energy over longer periods of time; while the latter is mainly relevant for the capacity of distribution grid or the operation of a building in response to time-of-use (TOU) tariffs, in addition it is based on the instantaneous power imported from or exported to the grid. These two concepts are used with electricity prices to evaluate the on-site matching and with power system data to value the system impact of grid interaction [5].

An important question regarding self-consumption of PV electricity is the potential impacts that a PV installation has on the energy behaviour in households, i.e. how many households with this kind of configuration interact with the electric power grid. It may be hypothesized that a PV installation in itself, or in combination with electricity production and consumption monitoring and visualization, could spark an interest in the households' energy use and lead to efforts to further reduce it, or to match it to the PV power generation, causing both the total electricity use and the daily load patterns to be different before and after installation. Households' electricity consumption can only be understood as parts of daily habits and routines that families, [5].

As previously outlined the storage technology can increase the self-consumption in the residential PV systems, and on the market there are several solutions different in prices, technology applied and size. Since management of energy storage, i.e. charging, storing energy and discharging, always leads to losses, it is more efficient to use the generated PV electricity instantly. This aspect is important to take into consideration, since energy storage is likely to be used as method of increasing the self-consumption.

However it is also true that the costs for a battery storage system is high, from a few hundred up to thousands € per kWh of capacity. In fact the installation costs is an important decision factor for users who want to add the BES in their own PV system. Besides, only a few type of storage are available on the market and suitable for residential electricity storage, as described in the Chapter 3. Thus self-consumption through PV and storage is still rather scarce both in the market and in the households, [3].

## 5.1 System Costs

Different PV support measures were introduced in the last decade: capital subsidies, VAT<sup>2</sup> reduction, taxes credits, quota obligation, net-metering, feed-in tariffs (FiTs), and so on. Each support mechanism offers both strengths and weaknesses for the producers and the collectivity, depending on the ways of implementing each national policy.

### Feed-in-Tariffs

Taking a look to the most common tariffs provided by the market, the *Feed-in-Tariff* mechanism involves the obligation on the part of an Utility to purchase the electricity generated by RES, paying a tariff determined by Public Authorities and guaranteed for a specific time period, [14]. A FiT's value represents the full price received by an independent RES producer for any kWh of electric energy produced, including a premium above or additional to the market price, but excluding tax rebates or other production subsidies paid by the Government. The FiT's value is determined by each country Government, based on the construction and management costs of a specific RES technology, [5].

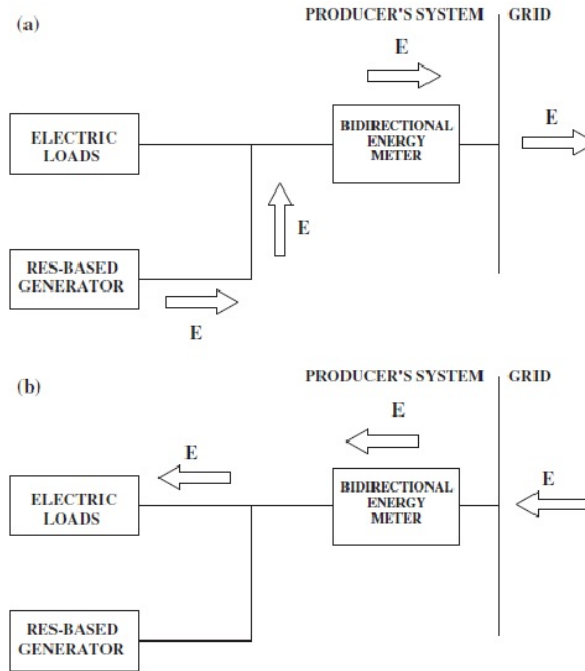
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<sup>2</sup>VAT: Valued Added Tax.

This tariff was created in order to support the RES development in Europe and U.S., and today it is present in 20 EU member countries.

### Net-Metering

Net-metering is a simple standardized protocol for the exchange of the electric energy produced by active residential customers (equipped with RES-based generators). When net-metering is active, the energy produced and injected into the grid has the same economic value of the energy consumed by the customers. The electricity consumption can thus be offset over an entire billing period by using the RES plant, regardless of when the energy is consumed or generated. The excess energy is temporarily stored in the storage device of the householder. To this aim a bi-directional energy meter is generally used, able to measure the energy flow in both directions. In this situation the grid acts like a virtually infinite energy storage system and the customer's electricity bill is not influenced by the double exchange of energy; this concept is well explained in fig. 5.3. With net-metering there is no restriction about the use of storage systems, and eventually, the surplus of injected power to the grid is remunerated at the 90% of the market price, [5], [18].



**Figure 5.3:** Example of Net-Metering, the energy is measured by a bi-directional meter at two different times. At  $t = t_0$  (a) the energy is injected into the grid and at  $t = t_1$  is absorbed by the grid(b).

However, a description of the two electrical markets regulations must be done, in order better explain how wholesale markets work; for example the net-metering in Italy is permitted, on the contrary in Spain is avoided. Even though for Italy and Spain the system regulation can be quite different, both in tariffs and costs' components, the following paragraphs do not give a deep detailed vision of the actual electricity markets; rather they sum up what is going on for householders in terms of tariffs and regulations.

### 5.1.1 Italian Electricity Market Regulations for RES

Electrical energy cost for Italian householders is defined summing 3 components:

- *Corrispettivo fisso* measured in c€/year
- *Corrispettivo di potenza* proportional to the value of used power [c€/kW year]
- *Corrispettivo variabile* related to effective consumes of household [c€/kWh]

FiTs for PV in Italy were first established with the Ministerial Decree of the 28th of July 2005 (*Ministerial Decree 28/07/2005*), through the introduction of the “*Primo Conto Energia*”. From 2005 to 2012 the FiT mechanism was changed five times, and the current framework for PV support in Italy is the Ministerial Decree of the 5th of July 2012 (*Ministerial Decree 05/07/2012*). The decree simplified the procedure to obtain the incentive and introduced a support system composed by two terms: a FiT for the electricity produced and injected into the grid and a premium for the electricity produced and used for personal consumption. Both the FiT and the premium are reduced every quarter, assuming new values reported in the *Ministerial Decree 05/07/2012*. Hence, for PV installations below 200 kW, the producers can choose between FiT or net-metering. FiTs are granted for a period of 20 years, with constant remuneration. At the end of the eligibility period, the producer benefits only of net-metering or can sell the energy directly to the grid. FiTs are paid by GSE, the Italian Institution for the Management of Energetic Systems. In addition FiTs distinguish the different types of PV systems, thus, depending on the type the tariff provides different options, [5].

As an alternative to net-metering and FiT mechanism, PV producers like householders can opt to sell PV energy on the free market, within the so-called “*ritiro dedicato*” regulatory system. In this case, RES owner is entitled to choose between a minimum tariff and the market price, if the yearly energy produced by the RES plant does not exceed 2000 MWh. The amount of energy exceeding 2000 MWh need to be sold at the current market prices, [16].

In Italy the available tariffs for electricity are divided per voltage levels, type of user and power required. For end-users, like householders, three tariffs’ options are provided: D1, D2 and D3. The first one is the newest introduced in the 2014, while D2 regards contracts which deal with power of 3 kW. At the end of 2015 and beginning of 2016 a new policy regarding tariffs for end-users was introduced. In this new decree, AEEG<sup>3</sup> puts an end to D2 and D3 regulations and focuses on the D1 one. The D1 tariff is applied to the householders who utilize electrical heat pumps for heating. It presents a constant price component for consumed kWh (it is independent from the annual consumption); it is a tariff created in order to improve the energetic efficiency and the RES development [4].

Regarding the *net-metering*, there exists the exchange contribute (“contributo di scambio”) provided by GSE<sup>4</sup> that follows the formula:

$$CS = \min(O_E; C_{Ei}) + CU_{Sf} \cdot E_s \quad (5.7)$$

where  $O_E$  is the part paid by the user during the exchange for buying taken electric energy;  $C_{Ei}$  is the value of energy injected in the grid, based on hourly zone prices of MGP.  $CU_{Sf}$  is the part for fixed share<sup>5</sup> on annual base; eventually  $E_s$  is the amount of exchanged energy, [28],[27].

<sup>3</sup>AEEG: Autorità Energia Elettrica e del Gas.

<sup>4</sup>GSE: Gestore Servizi Energetici.

<sup>5</sup>Quota Forfettaria

### 5.1.2 Spain Electricity Market Regulations for RES

The Iberian Electricity Market or MIBEL, is organised as a sequence of several markets, namely the day-ahead market, six intra-day markets and the ancillary services market. Each market contributes to the market component of the electricity price, although the day-ahead market accounts for about 80-90% of this component. The day-ahead market is executed once a day. This market allows participants to set their positions on an hourly basis for the following day. This is done by means of bids, which relate prices to amounts of energy that each participant is willing to produce/purchase for a certain hour. It needs to be clear that this market is uniform-price auction, meaning that the price at which producers are paid and retailers purchase electricity is the same for all the participants and equal to the final market-clearing price, [2].

In Spain, the legal framework for RES support is the *Royal Decree n.661/2007*. In 2008, the *Royal Decree n.1578/2008* was published, setting new regulations for PV systems commissioned after September 29th 2008, introducing a strong reduction for PV FiTs. The support mechanism for PV systems in Spain is based on the possibility for the producer to choose whether to sell the electricity produced under a FiT mechanism or whether to sell it in the free market, taking advantage of a premium above the market price. FiTs are supplied for an undefined number of years with a reduction after 25 years [5], [2].

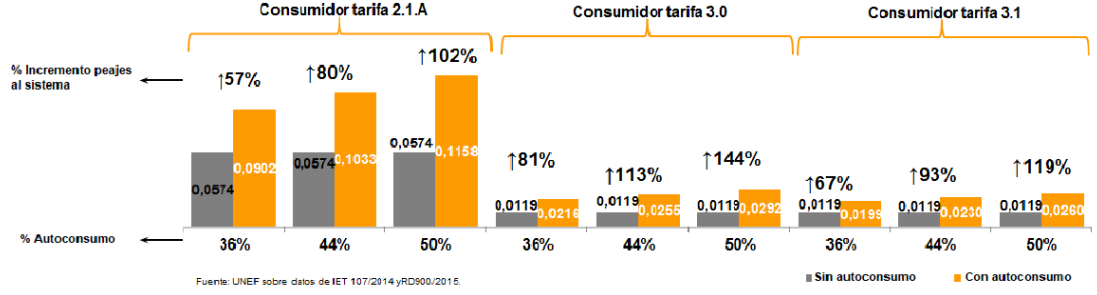
PV support policies in Spain were suspended by the *Royal Legislative Decree n.1/2012* and no other support scheme was active until 2015. Eventually, *Royal Decree-Law 9/2013* culminated this process by lowering the level of FiTs retroactively for the whole of the renewable generators. In Burgos-Paya'n et al. (2013) a detailed analysis of the costs and benefits of the electricity production from RES in Spain is reported, including the situation of the PV market. At present, the Spanish Government is working in a partial net-metering support scheme (for PV systems below 100 kW) where the compensation of electricity flows will be calculated on a yearly basis, [2].

Recently another policy on self-consumption was introduced with the *Royal Decree 900/2015*. Basically, it distinguishes two types of end-user.

- *Type 1*: it refers to small end-users, such as householders, with an installed power <100 kW. This type has the right to inject the surplus of generation power in the grid, but they do not receive any sort of payment for that.
- *Type 2*: users associated to production facilities rightfully signed in "*Registro administrativo de instalaciones de Produccion de Energia*". Their feeding power is over 100 kW. Only this kind of costumers receives retribution for injecting power in the grid.

Therefore it can be seen that the real economical scenario is far from being the ones hypothesised in the previous chapters. As a matter of fact with the new decree the costumer pays even for the surplus of energy which is fed to the network ("*Cargo de respaldo*"), while users that belong to type 2 only receive remuneration for the amount of electricity fed to the grid. Moreover, from 2016 it is introduced a type of fee for users who intend to adopt PV system with battery device. This new fee is known as "*Impuesto al sol*", and it means that if the user is grid-connected, he is obliged to pay for his own self-consumption [19].

On the other hand there exists an exception for householders who basically inject the power surplus to the grid without receiving remuneration. Thus, new Spanish policies are performing regulations which obstacle the spreading of self-consumption rather than improve it.



**Figure 5.4:** Costs comparison for system management for consumed energy (self-consumption configuration vs no self-consumption)

## 5.2 Brief discussion on the possible benefits of some strategies

In the light of the fact that first and second strategies yield interesting results, it is now possible to make a simple calculation in order to analyse what can bring more benefits for the householder who decides to install the performed PV+BES system. It is hypothesised that the photovoltaic modules are already on the building (it is not so far away from the truth if we think that in the past years, thanks to FIT tariffs, many end-users adopted a PV system integrated on their rooftops). For what concerns the battery storage, in the previous chapters it was mentioned that the model is based on Tesla Powerwall's characteristic, though it is idealized, so the price of the device can be used. Powerwall's price for the base model (7 kWh) is about 2700 € without the inverter<sup>6</sup>. Thus the inverter's price is about 1300 €, [11]. The total expense for the installation is about:

$$I_0 = 1300 + 2700 = 4000\text{€} \quad (5.8)$$

known now as investment. Thus, with the results of first and second simulations it is possible to calculate the profitability of the system beginning with NPV. Supposing a bid rate  $i$  about 5 %, it is possible to derive the discount rate  $d = \frac{i}{(1+i)} = 0.047$ .

$$NPV = \sum_{j=1}^n \frac{D_j}{(1+d)^j} - I_0 \quad (5.9)$$

where  $D_j$  is the saving that the user gains for the  $j$  year. Imposing a life of the battery and inverter of 10 years (which is a reasonable hypothesis) and without keeping in consideration the costs for maintenance of storage and inverters. Similarly, it is calculated the time of return of the investment basing on NPV calculations. In fact it is calculated the number of years  $n$  which bring the NPV to 0, that is a tool to decide the profitability of the investment.

For Spanish first scenario comes out a NPV of about -2733 €, which points out the economical inconvenience of the investment. The NPV reaches the 0 in more than 10 years. So without subsidies and having already a PV system in the house, the investment reveals to be inconvenient for the users, because the time of the return surpass the duration of the system itself. Similarly

<sup>6</sup>The costumer cannot use the inverter of the PV system, since the new inverter has to monitor loads, to regulate the charge and discharge rate and to communicate with electrical system of the house.



calculations were done for the second strategy and it comes out a NPV=-2526.93 €, a result better than the first strategy, however yet negative (payback time is always more than 20 years).

For what concerns Italian scenarios, even if same imposed conditions last here, the NPV assumes very different values from Spanish results. For the first scenario upgrading the PV system with the storage unit brings to NPV= -1562 €, a more convenient result in contrast with the obtained ones for the Spanish calculations; the user might obtain a saving after about 20 years, achievement difficult to obtain due to the level of the actual technology. A more interesting data emerges from the calculations in the second scenario; here the upgrading from PV system to PV+BES reveal a NPV of about 242 €, with a possible benefit after 9,2 years.

Talking about Italian regulation policy, thanks to *art. 1, comma 88 Legge n. 208/2015* for energetic qualification it let end-users benefit from financial deduction up to 50% of the initial investment in distributed payments along 10 years. The user can benefit from it when he intends to install a PV+Storage system in a household without solar plant. Imposing that the cost of the photovoltaic part is about 2500 €/kW<sub>p</sub>, [11].

In this new optic the NPV of the first scenario upgrades to -25.4 €, also achieves the remuneration of the investment after 11 years. The second scenario NPV results 1779 € for ten years of duration of the plant, and the complete remuneration after 7 years. Tables 5.1 and 5.2 resume all the results for NPV and time of return, and put in comparison the two models results. It is clear that with the financial deduction there is a major profitability for the user.

**Table 5.1:** First Scenario Results

	<b>Spain</b>	<b>Italy</b>	
	PV → PV+BES	PV → PV+BES	Traditional → PV+BES
<b>NPV</b>	-2733 €	-1562 €	-25.4 €
<b>PB</b>	>20	20 years	11 years

**Table 5.2:** Second Scenario Results

	<b>Spain</b>	<b>Italy</b>	
	PV → PV+BES	PV → PV+BES	Traditional → PV+BES
<b>NPV</b>	-2526.93 €	242 €	1779 €
<b>PB</b>	>20 years	9,2 years	7 years

## Chapter 6

# Effects on the Distribution Grid

### 6.1 DigSILENT Software

The calculation program *PowerFactory*, as written by DigSILENT, is a computer aided engineering tool for the analysis of transmission, distribution, and industrial electrical power systems. It has been designed as an advanced integrated and interactive software package dedicated to an acronym for “**DIG**ital **SI**muLation of **E**lectrical **NeT**works”, [8]. *PowerFactory* was designed and developed by qualified engineers and programmers with many years of experience in both electrical power system analysis and programming fields. The accuracy and validity of results obtained with *PowerFactory* has been confirmed in a large number of implementations, by organizations involved in planning and operation of power systems throughout the world. The key features include:

- Core functions: definition, modification and organization of cases; output and documentation function.
- Integrated interactive single line graphic and data case handling.
- Power system element and base case database.
- Integrated calculation functions.
- Power system network configuration with interactive or on-line SCADA access.
- Generic interface for computer-based mapping systems.

In the *PowerFactory*, electrical network information is stored in "Grid" folders. A power system can be divided in many grids as defined by the users. These grids may or not may be interconnected. As long as they are active, considered by the calculations. Data can also be assorted according to logical, organisational or geographical areas, [8].

The simulation methods applied are "*Load-flow analysis*" and "*Quasi-static simulation*".

#### 6.1.1 Load Flow Analysis

Load flow calculations are used to analyse power systems under steady-state non-faulted conditions. The steady-state is a condition in which all the variables and parameters are assumed to be constant during the period of observation. It reflects a certain condition in a precise point in the time. A feature of *PowerFactory* is that active and reactive power of the loads can be set with a *characteristic*, in order to follow a defined profile; in this way active/reactive power will change

automatically according to the date and the time specified for the analysis. The calculation will determine both active and reactive power flows for branches<sup>1</sup>, and voltages magnitude and phase for all nodes<sup>2</sup>. The nodes can be classified as:

- **PV nodes:** active power and voltage magnitude are specified. The reactive power limits for the corresponding network components are used as input information.
- **PQ nodes:** where active and reactive power are specified. They are used to represents loads and machines with fixed values. Loads can be set to change as a function of the voltage of the node to which the load itself is connected.
- **Slack node:** voltage magnitude and angle are fixed. It is associated to the external grid component, this option carries out the balancing of power in the system.

### AC Load Flow Method

Two different formulations of *Newton-Raphson method* lead the analysis: Current Equations, and Power Equations. In both of them the iterative method solves non-linear equation systems. The selection of the method used to formulate the nodal equations is user-define, and should be selected based on the type of network in analysis; for example distribution systems, especially unbalanced ones, usually converge better using the Current Equations formulation, [8].

In addition the software applies an outer loop when the control characteristic of automatic transformer tap changers and/or switchable shunts is considered. Once the method converges to the solution within a defined tolerance, the outer loop is applied in order to reach the target values, [8].

In the classical load flow calculation approach, the unbalance between phases are neglected. For the analysis of distribution networks, the assumption may be inappropriate depending on the characteristics of the network. Thus *PowerFactory* admits both balanced and unbalanced load flows for the proper situation.

### Result Analysis

Once a load flow is successfully performed, the results appear in the single-line diagram. The values shown in the result boxes depend on the element which they are associated to. During the calculations the single-line diagram shows different colours as a quick overview of the results; for example if elements are overloaded above 90% or the busbars' voltages exceed specified limits, they will be coloured in red. The diagram colouring has three priority levels according to the criteria:

- **Energising status:** if check box is enabled "De-energised" or "Out of calculation" elements are coloured according to the settings in "Project colour".
- **Alarm:** if check box is enabled a drop down list containing alarm modes will be available. Thus elements exceeding their corresponding limits will be coloured.
- **Normal:** when all the calculations finish and the elements respect their defined limits.

---

<sup>1</sup>**Branches:** grouping of elements, they include two/three-connection elements such as transmission lines, transformers, AC/DC converters with two DC terminals etc etc.

<sup>2</sup>**Node:**structure to connect lines, generators, loads to the network. It is grouped under the name of *Busbars* of different types.

There is also available a sign convention for different elements:

- **Branches:** power flow going out of the Busbar is positive, otherwise is negative.
- **Loads:** power flow going out of the Busbar is positive.
- **Generation:** if the power flow is going out of the Busbar, then it is negative.

### 6.1.2 Quasi-Dynamic Simulation

This tool completes a series of load flow simulations spaced in time, with the user given the flexibility to select the simulation period and the step-size. To achieve this, the Quasi-Dynamic Simulation makes use of time based parameter characteristics and variations, [8]. To be executed it requires a few steps:

1. The set-up of parameter characteristics on time varying components of the network.
2. Defining the variables to be monitored during the simulation.
3. Running the simulation.
4. Analysing the results.

The type of variables that has to be monitored should match the type of load flow calculation that it is used in the simulation. Moreover the step size time unit can be chosen among seconds, minutes, hours, days, weeks, months years. After starting the simulation, *PowerFactory* determines the number of load flows required based on the entered step settings.

#### Results Analysis

The results can be presented in a tabular form using the build-in reports, and graphical form using the *plot tool*. *PowerFactory* also stores summary statistics for every analysed variable. The simulation tool provides a mean summarise and examine system conditions over the simulated time period. The reports available are:

- **Loading ranges** that shows the maximum and the minimum loading of each monitored branch element and also the time that each of these occurred.
- **Voltages ranges** which presents the maximum and the minimum values of voltage for each terminal and the relative times that each of these happened.
- **Non-convergent cases** shows a list of all the cases that did not converge and the time that these occur.

Of course the results can be exported in several formats (such as *excel,HTML*).

Hence to lead a Quasi-Dynamic simulation it is necessary defining time characteristics.

#### Parameter Characteristics

An important feature of this software is the possibility of defining characteristics, load states, and load distributions. In *PowerFactory* any parameter may be assigned a range of values that is then selectable by date and time or by a user-defined trigger. Thus a load state, implemented in the study, may be based on the minute, hour, day, season or year of the study. The value of the characteristic is defined by the value of the scale. When a scale is created, a means to set the scale and consequently to set the parameter for the corresponding value, is required. Some types of characteristic are, [8]:

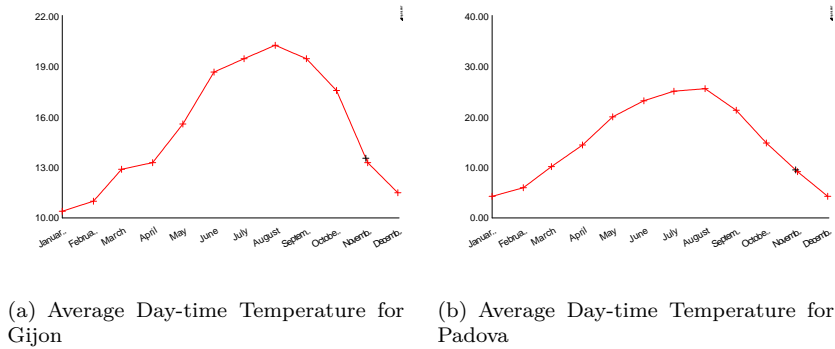
- Time Characteristics
- Profile Characteristics
- Scalar Characteristics
- Vector Characteristics with Discrete Scales
- Matrix Parameter Characteristics
- Parameter Characteristics from files
- Characteristic References

### Time Characteristic

The most used for the analysis was the Time Characteristic. It determines values of the parameter according to the *Study Time*. The *ChatTime* uses an internally defined Recurrence period that is convenient to define a periodically recurring characteristic. It can be

- Daily
- Weekly
- Monthly
- Yearly

In particular for defining the load, irradiation and storage trends it was selected an hourly recurrence of a typical day, while for setting the Average Daytime Temperature<sup>3</sup> a yearly scale was used, an example of that can be seen in figure 6.1.



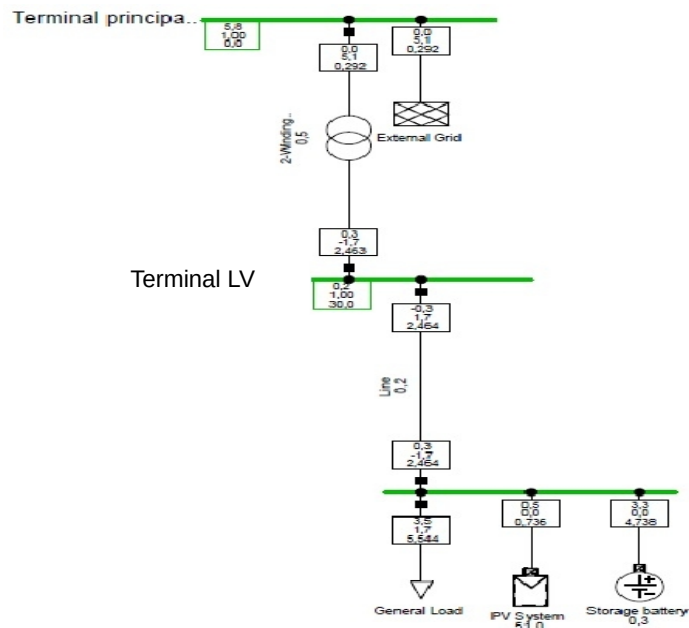
**Figure 6.1:** Example of yearly-based scale used for solar calculation, [20].

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<sup>3</sup>Necessary to define along the year the temperature for environmental parameters for solar irradiation calculations.

## 6.2 Overview of Effects on the connection line with the LV Network

A power system is structured upon the connectivity of power grids with generators and consumers. Electricity production and consumption has to be always balanced, since any imbalance between supply and demand will cause power flow congestion on the power lines, instability of power supply, quality fluctuation – in terms of voltage and frequency – electrical interruption, as well as seasonal variations in the cost of electricity generation, [15]. Therefore, in this chapter curve trends



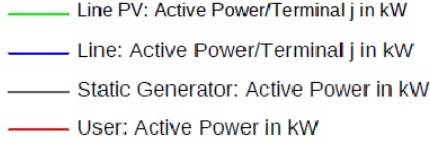
**Figure 6.2:** PowerFactory network and household scheme.

collected during the aforementioned simulations are analysed in detail, this time also focusing on the interaction with the line connection to the distribution network. In other words, once conditions for storage system are settled, consequences brought up by these strategies need to be discussed,

basing on a simplified grid. The software DigSILENT helped to perform the quasi-static simulations of 24 hours power flow exchange between household and grid. In fig 6.2 there is the scheme used for simulations in DigSILENT *PowerFactory*. The simplified network presents an external grid of infinite power, a MV/LV substation and an LV line connected to a LV busbar that idealize the household with the photovoltaic system, the storage unit and the load. The results are plotted in graphics thanks to a quasi-dynamic simulation along 24 hours. In all the graphics the following legend counts:

- PV power generation: green curve
- Load household power demand: red curve
- Storage power absorption/supply: grey curve
- Line power: blue curve

The different power flow conventions envisage a different meaning for each element: for example the line has negative values it means that power flow is oriented from the grid versus the load, instead of storage's and PV's trends

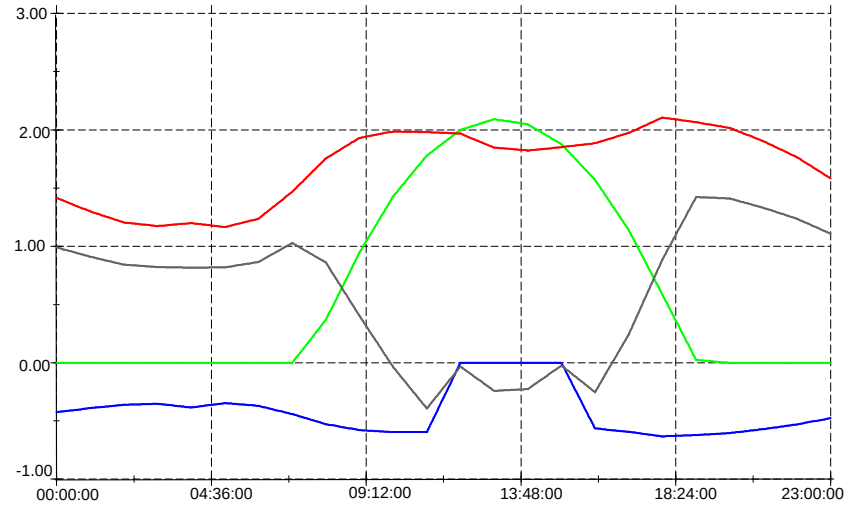


which positives values mean respectively a power output and power generation. Yet, load demand curve is always positive, which means constant power absorption. Since only simulations 1 and 2 return the higher benefits, there will be discussed only their results.

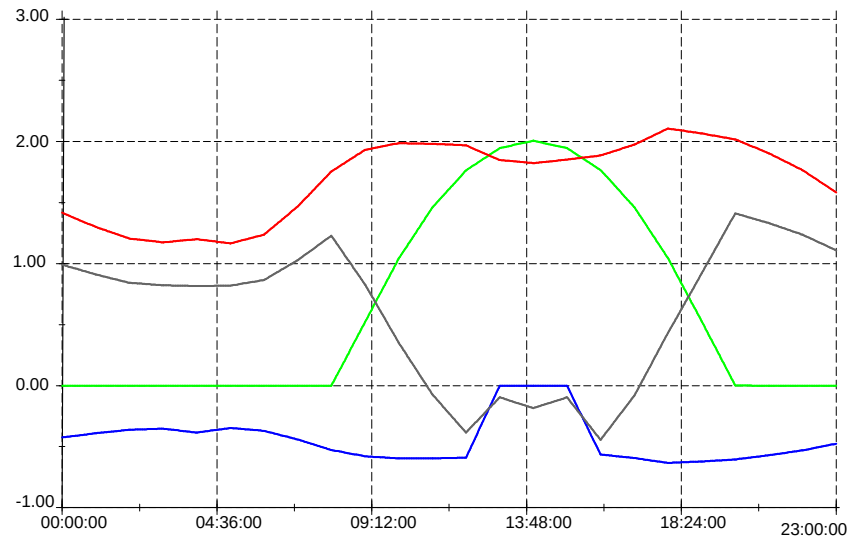
### 6.2.1 Italy

From the following graphics can be seen how the line reacts to the using of PV-storage system. It is obvious that depending on the type of charging/discharging strategy applied the line will presents different trends. As can be seen from figures 6.3, the line is not over-loaded, yet it is kept for most of the time under 1 kW of power delivered. This is due to the optimization of the storage curve; as a matter of fact it was imposed to follow the load demand and the PV power generation, without taking in consideration prices trends.

Clearly, it can be noticed that this kind of optimization leads an evaluation of self-consumption, and to increase the independence from the network. It does not provide remuneration for the user (or better, the grid operator does not have to pay the costumer), but on the contrary it leads to a better integration with the network. Another line curves come out from the second scenario in figure 6.4. In these simulations the line power flow is compensated by the storage. In fact most of the time the storage device supplies power in place of the distribution grid. It is interesting that in July, even though the load demand is always higher than the PV power output, there are a few time-slots, between midnight and 4 am, 8 am and 9,30 am, in which the line gives power, since the hourly price is advantageous. Yet in this scenario there is a strong independence from the grid.

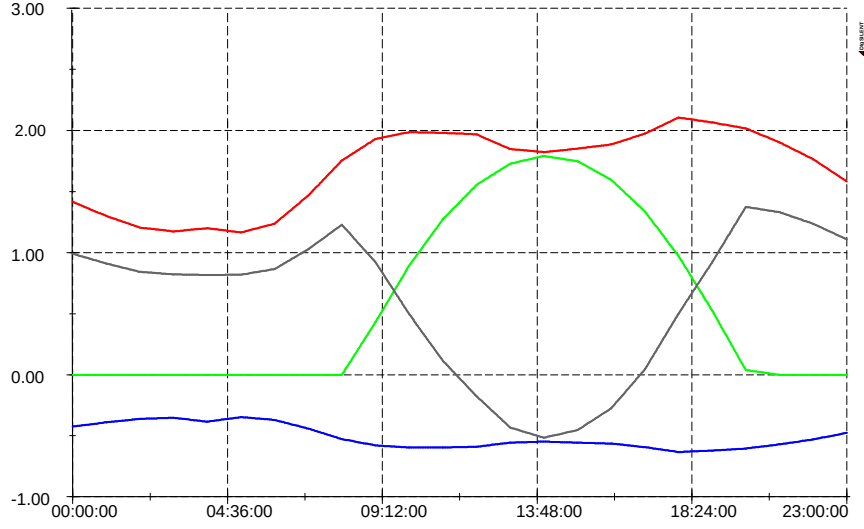


(a) January 2015

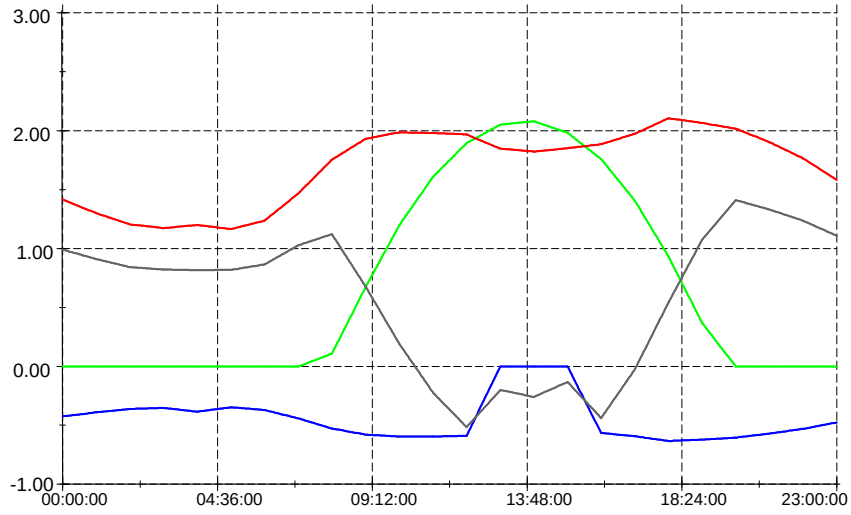


(b) April 2015



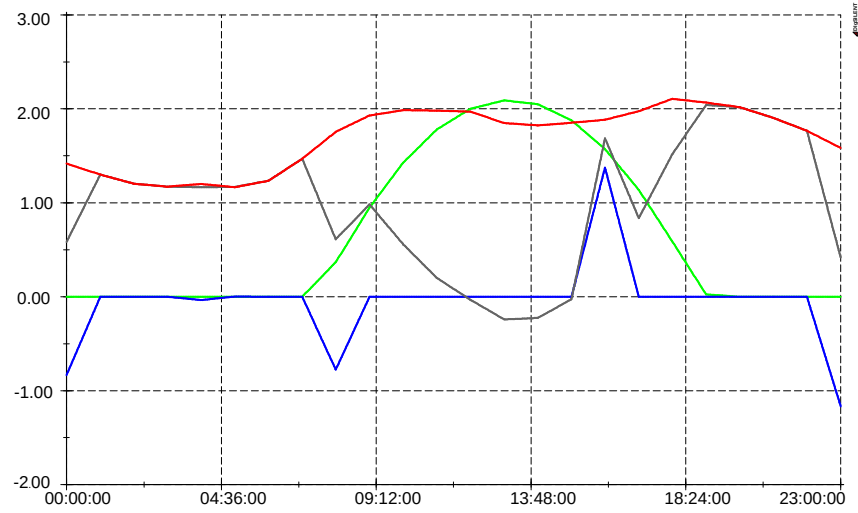


(c) July 2015

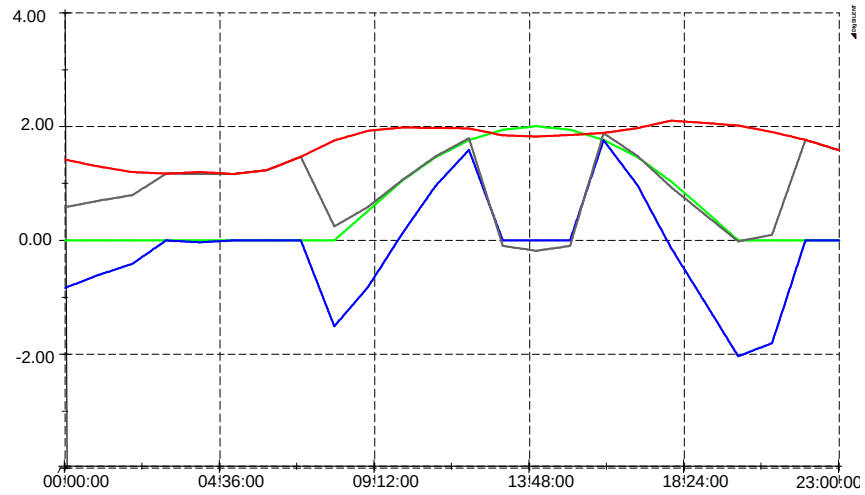


(d) October 2015

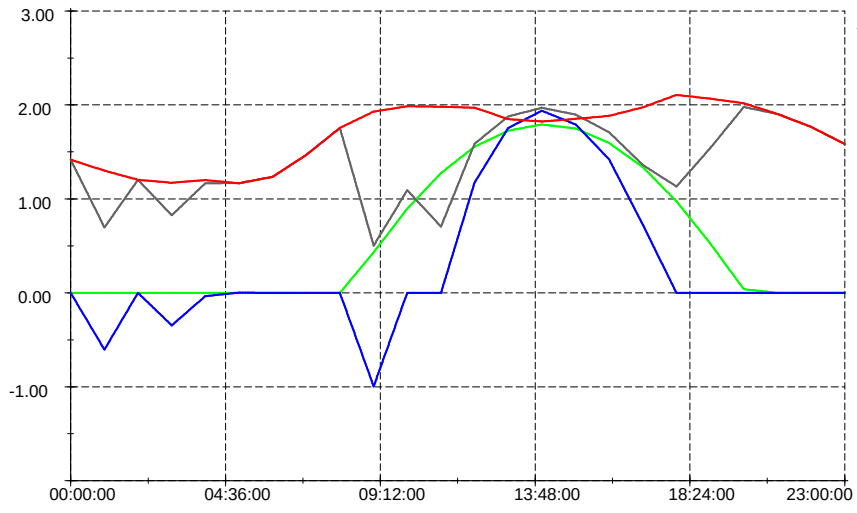
**Figure 6.3:** First Italian scenario line output. In the y-axis the Power is in kW.



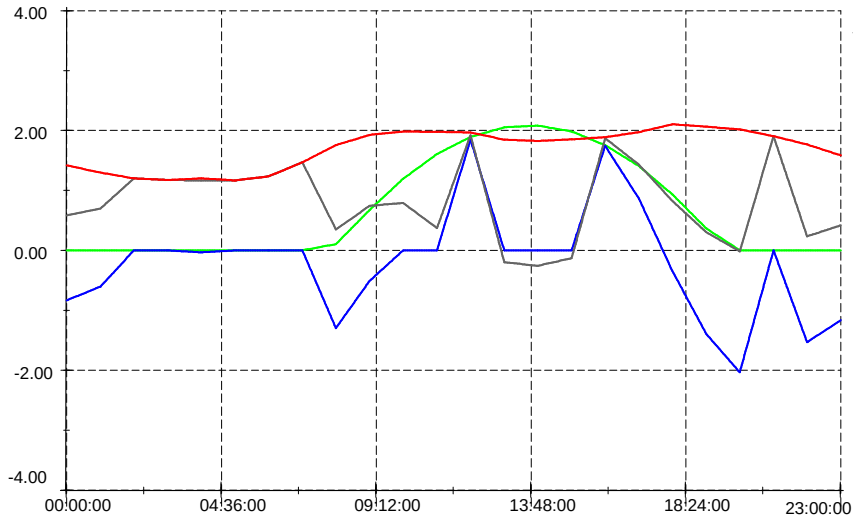
(a) January 2015



(b) April 2015



(c) July 2015



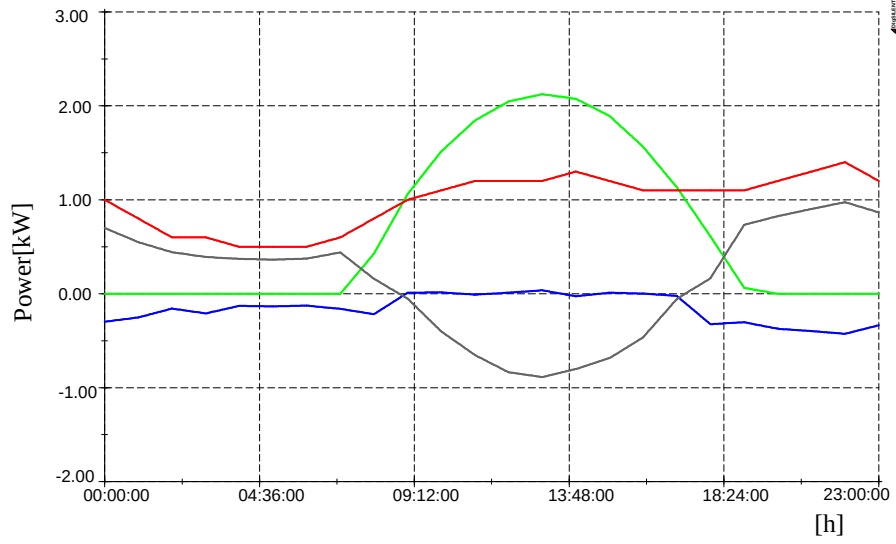
(d) October 2015

**Figure 6.4:** Second Italian scenario line's output. The power on the y-axis is in kW.

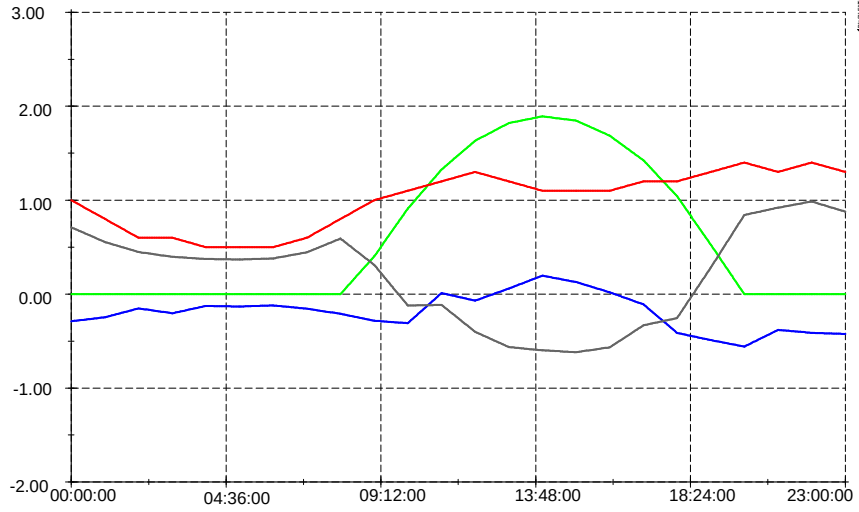
### 6.2.2 Spain

Now Spanish model is analysed, and the comparison of the trends with the LV line is provided. Figures 6.5 present the first strategy for the champion months. Here the storage compensate the grid supply when the PV is not working. Thus, the line is always loaded with a power flowing less than 1 kW; furthermore during the PV peak's production the power end up to about 0 kW, meaning that the storage is absorbing all the self-generated power.

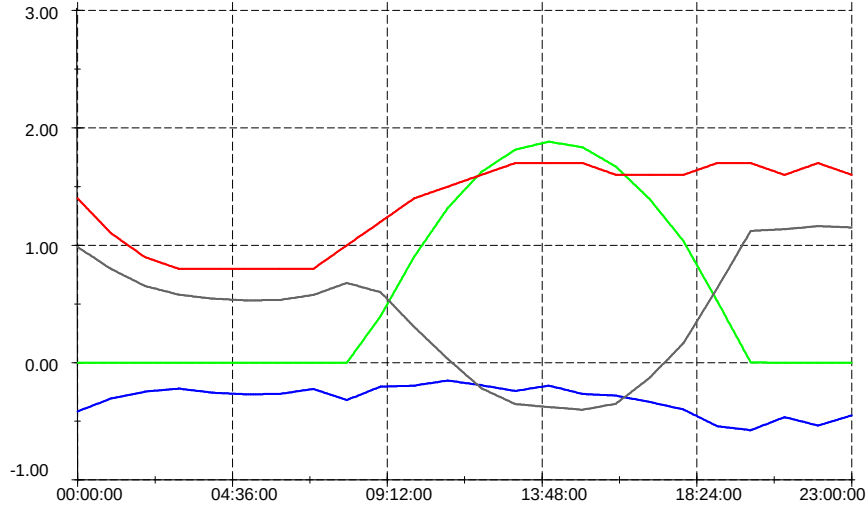
In figures 6.6 we can see the application of the second scenario to the Spanish model. The line receives power from the storage during overnight hours, and, at least for January, April and October, it happens to not absorb power or feed the household. On the contrary in July during the midday PV peak the storage supplies power into the grid, since the hourly price is convenient. As already said the results for July present anomalies, since the load curve is higher than PV production. With these values it means to over-load the LV network during the PV peak, which it would be a important issue for the future grid. Because of the price variation, even if the storage continues to provide power to the household, it can be seen a decreasing of that power; this is due to price variation which leads to a usage of the power from the grid rather than the storage's one.



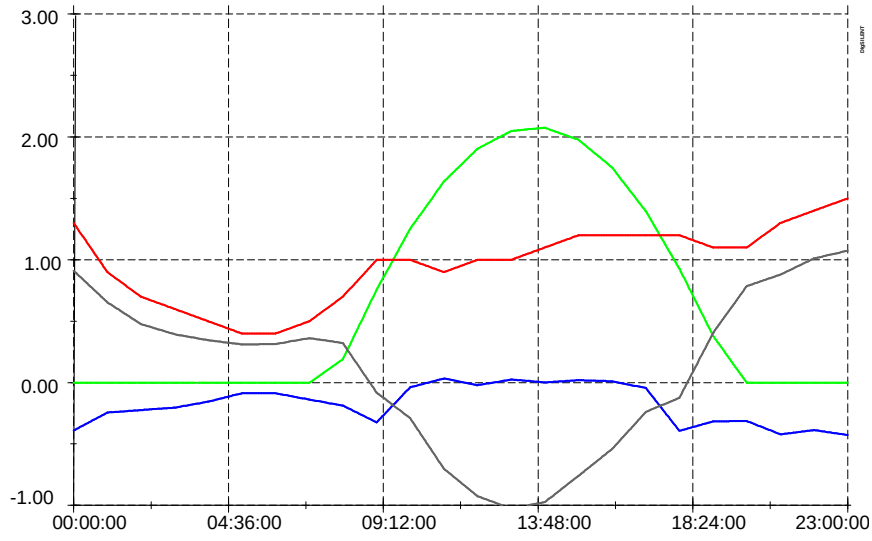
(a) January 2015



(b) April 2015

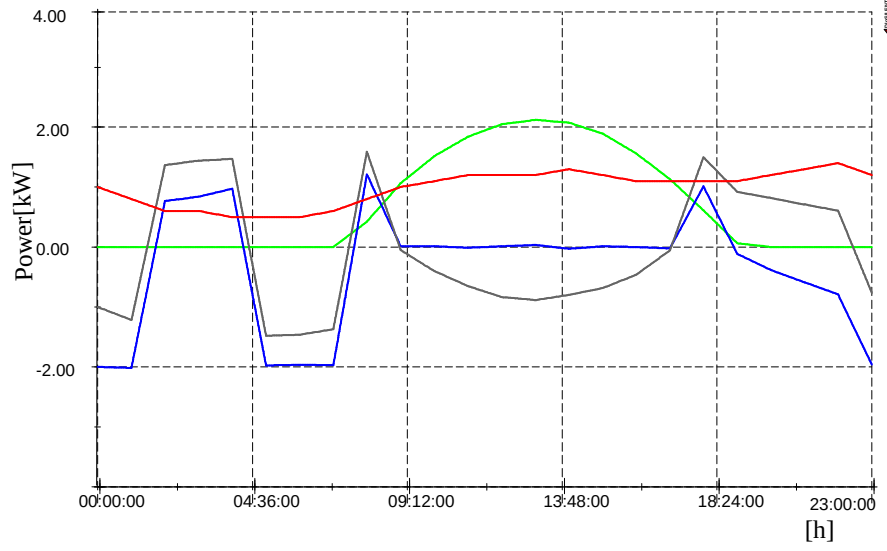


(c) July 2015

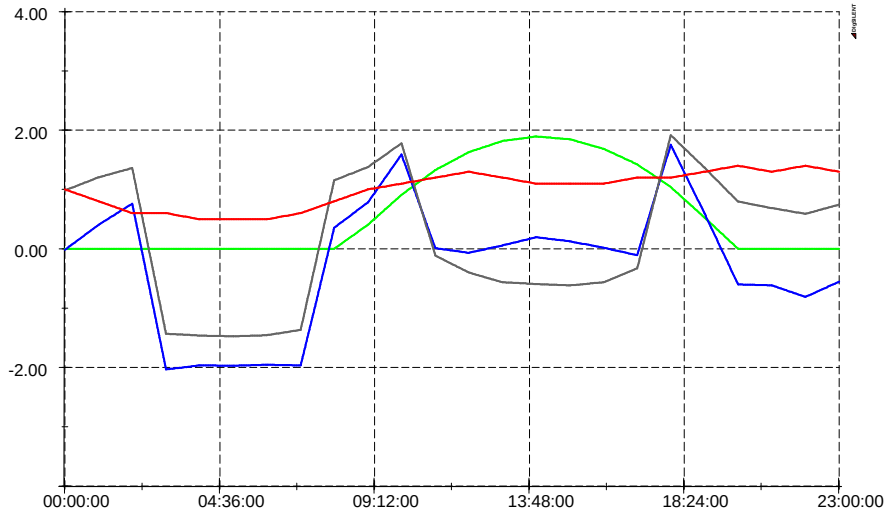


(d) October 2015

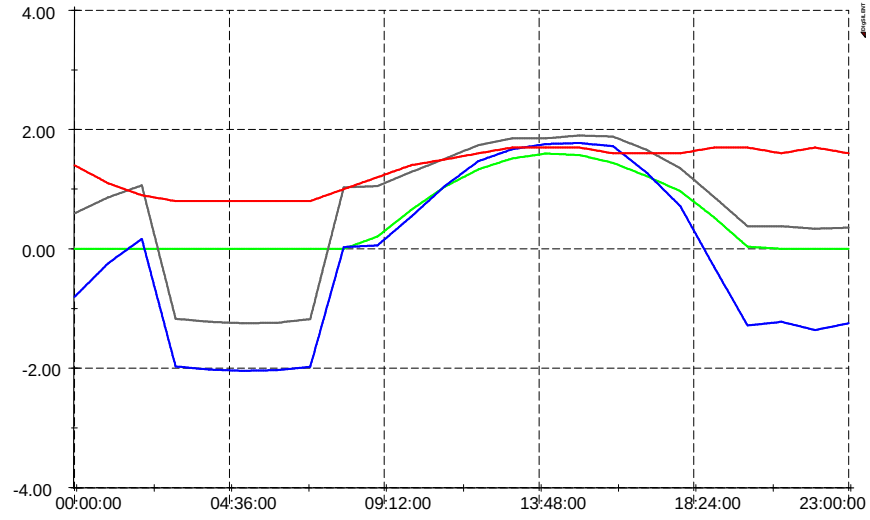
**Figure 6.5:** First Spanish scenario line output. Power in kW on the y-axis.



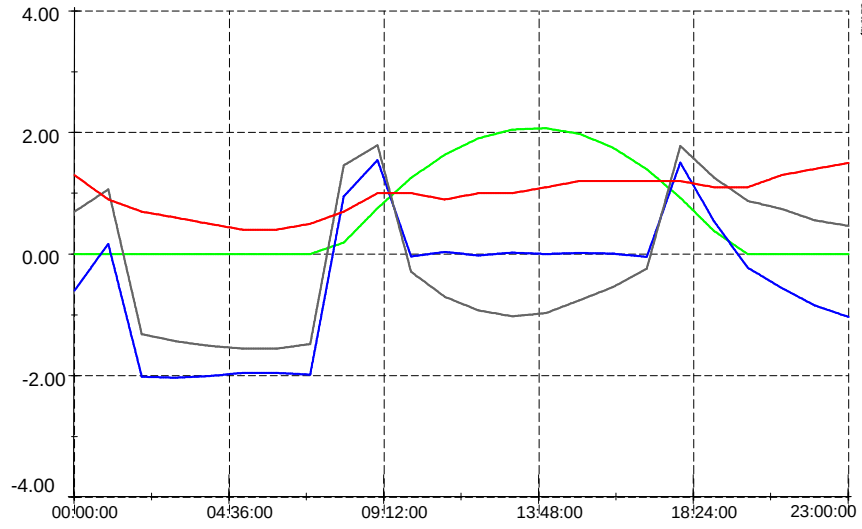
(a) January 2015



(b) April 2015



(c) July 2015



(d) October 2015

**Figure 6.6:** Second Spanish scenario line output. Power on y-axis in kW.



It can be seen from these presentation how an efficient use of BES and PV system unburdens the LV line, and consequently it helps to manage the shifting load caused by the PV power production. Eventually, the combination of the photovoltaic with the storage can face problems with for example overloading or power quality, [15]. The results of this study are obtained under the assumption of ideal batteries, and lines. Since this is not the case in a real-life situation, then the models may be improved in terms of reality with a more detailed analysis of the LV network behaviour.

## Chapter 7

# Conclusions

In the end a brief resume of what it was analysed so far can be made. Even a little conclusion on it can be opened.

It must be taken in consideration that hourly prices fluctuate continuously during the day and even along the days of the month, so it is difficult to perform a curve that follows efficiently the medium price, also because it would be just a forecast value for the day. In addition the used values for the power output of the PV system are not accurate, since average monthly values for the chosen areas and data of clear-sky irradiation were adopted; obviously during the day clouds pass and obstruct right radiation on the panels, and the phenomena is unpredictable; thus the central control unit of the battery must be prepare to face all the variation in the power output of the PV unit.

Moreover households' load patterns deviate from the given data, so each control unit management of the storage must respond to variations of each household's pattern. An optimization of the PV/storage assessment that perfectly follows load deviations is really hard to perform, which means to put high effort in the innovation technology. The attention of the research has to focus on the inverter of the storage, since it is the device which interconnects battery, PV circuit, household and network and contains the electronic part of the system. The strategies so far developed underline the feasibility of the PV+storage combination in the optic of a free exchange with the network in terms of absorbing and supplying energy and power. Nowadays the energy market regulations prevent the idealized strategies to be actuated, thus they underline that the saving is possible (strategy 1 it is the one that respects the regulations policy) in an ideal market regulation, in which the householders can exchange in a net-metering optic the power with the network. Thus the study demonstrates that BES can be used to allow high shares of renewable distributed generation in the distribution grid. However, the investment costs of today for such applications are too high due to the high battery prices, [22]. Hopefully, the forecast price development might enable the use of battery storage within the next 5-10 years, [22]. An investment in battery energy storage might then be a feasible alternative solution regarding the integration of distributed intermittent generation.

For the future scenario the adoption of storage devices in the households depends strongly on the environmental and social factors. In fact households investments are driven by the knowledge of the investments opportunities. From the economical analysis made in the previous chapters, it comes out that for users who already have a PV system in their house, have to face an ulterior expense for the storage installation. Moreover the technologies on the market provide battery devices which last for 10 years, thus they need to be changed every ten year, meaning a surplus in costs, [7]. A saving (in particular for the Spanish user) may come out after 20 years of usage of the two systems without replacement of storage or inverter device, that is actually an optimistic

prevision. So far, the results return values that storage effectively improves self-consumption and savings during the year, but analysing also the cost of the investment and in the light of the lack of a subsidies' policy for storage integration in households, the combination does not bring benefits in the brief time. In fact Spanish scenarios, even if provides savings for the householder along the year the investment it will not be remunerated. On the contrary in Italy, the possibility to benefit of financial deductions helps the adoption of PV+storage for the users who only have a traditional contract with the network's operator. It has to be remarked that financial deductions do not count when the user upgrades from PV to PV+storage, and the incentives that count for the PV system stop with the installation of the storage system. In the end, the utilization of the storage with the PV system should be diffused among the LV users in order to increase the cycle-virtuosity of renewable energy technologies. The ES enhances the utilization of RES and helps the management of the distributed energy in the network.

# APPENDIX



## Chapter 8

# MATLAB Script and Data

In this chapter an overview of the used model script for the simulations is presented. There are Spanish scripts, since the Italian model is the same, changing the used parameter .

### 8.1 First Scenario model script

```
%Without following the prices
BATTERY=size(PV_s);
B=size(BATTERY);

for i=1:24
    for n=1:4
        if LOAD_s(n,i)>PV_s(n,i);
            %Decided to follow an algorithm in which the storage device discharges for
            %0.9%of the total load demand minus the fotovoltaic production
            BATTERY(n,i)=0.7*LOAD_s(n,i)-PV_s(n,i);
        elseif LOAD_s(n,i)<PV_s(n,i);
            %while here the battery charges the exact amount of the difference
            %beteween the two values
            BATTERY(n,i)=-LOAD_s(n,i)+PV_s(n,i);
        end
        B(n,i)=BATTERY(n,i);
        if B(n,i)<-0.002 %MW
            B(n,i)=-0.002;
        elseif B(n,i)>0.002
            B(n,i)=0.002;
        end
    end
end

P_tot=size(PV_s);
P=size(PV_s);
COST_SPAIN=size(PV_s);
COST_SPAIN1=size(PV_s);
```

```

for k=1:24
for n=1:4
    %Imposing a limit for the line up to 3 kW
P_tot(n,k)= LOAD_s(n,k)-PV_s(n,k)+B(n,k);
if P_tot(n,k)>0.003; %[MW]
    P(n,k)=0.003;
else
    P(n,k)=P_tot(n,k);
end
COST_SPAIN(n,k)=P(n,k)*Prices_s(n,k);
B(n,k)=P(n,k)-LOAD_s(n,k)+PV_s(n,k);
%COST_SPAIN1(n,k)=B(n,k)*Prices_s(n,k)+LOAD_s(n,k)*Prices_s(n,k)
-PV_s(n,k)*Prices_s(n,k);
end

end

```

## 8.2 Second Scenario model script

```

%TOTAL COST= Sum of all vectors[MW]*Prices
%Building a matrix 24X2 that resembles the storage unit,
%X1 contains the generation components, thus is <0
%X2 is the store component, when it behaves like a load >0

none=ones(24,1);
X1=size(none);
X2=size(none);

prompt='Prices of which month are we using?
(1) January, (2) April, (3) July, (4) October'\n';
n=input(prompt);
%Idealized values for 24 hours in vectors of 24 components
for j=1:24

    %This if declares if the component of the PV is bigger than load and
    %the prices is higher than the imposed value the battery won't store
    %but generate energy. On the contrary if the price is lower than the
    %settled minimum value the device will store
    if PV_s(n,j)>=LOAD_s(n,j)
        %the generation component is 0, but the load component absorb the
        %difference between the photovoltaic production and the load demand
        X1(j)=0;
        X2(j)=-LOAD_s(n,j)+PV_s(n,j);

        %On the contrary if PV is lower than load's component the conditions
        %are the same
    elseif PV_s(n,j)<LOAD_s(n,j)

```

---

```

        if Prices_s(n,j)>MEDIOMAX_s(n)
            X2(j)=0;
            X1(j)=0.002-LOAD_s(n,j)+PV_s(n,j);
            X1(j)=X1(j)*-1;
        elseif Prices_s(n,j)<MEDIOMin_s(n)
            X1(j)=0;
            X2(j)=0.002-LOAD_s(n,j)+PV_s(n,j);
            end
        %Here is taken in consideration the condition in which the Price is compreh
        if Prices_s(n,j)<MEDIOMAX_s(n) && Prices_s(n,j)>MEDIOMin_s(n)
            if PV_s(n,j)<LOAD_s(n,j)
                X1(j)=0.002-LOAD_s(n,j)+PV_s(n,j);
                X1(j)=X1(j)*-1;
                X2(j)=0;
            else
                X2(j)=-LOAD_s(n,j)+PV_s(n,j);
                X1(j)=0;
            end
        end
    end
end
x=[X1' X2'];
%Now Battery will be the single vector which contain all the values assumed
%by the storage unit during the 24 hours
BATTERY=size(none);
COST=size(none);

%When the cost for the costumer is negative it means that he is paid.
for h=1:24
    if X1(h)==0
        BATTERY(h)=X2(h);
    elseif X2(h)==0
        BATTERY(h)=X1(h);
    end
    COST(h)=X1(h)*Prices_s(n,h)+X2(h)*Prices_s(n,h)+LOAD_s(n,h)
    *Prices_s(n,h)-PV_s(n,h)*Prices_s(n,h);
end

```

### 8.3 Third Scenario model script

```

        if PV_s(n,j)>LOAD_s(n,j)
            if Prices_s(n,j)>Pmedium_s(n)
                X2(j)=0;
            X1(j)=-LOAD_s(n,j)+PV_s(j);
            X1(j)=X1(j)*-1;
            elseif Prices_s(n,j)<Pmedium_s(n)
                X2(j)=PV_s(n,j)-LOAD_s(n,j);
                X1(j)=0;
            end
        elseif PV_s(n,j)<LOAD_s(n,j)

```



```
        if Prices_s(n,j)>Pmedium_s(n)
            X2(j)=0;
X1(j)=0.002-LOAD_s(n,j)+PV_s(j);
X1(j)=X1(j)*-1;
        elseif Prices_s(n,j)<Pmedium_s(n)
            X2(j)=0.002-LOAD_s(n,j)+PV_s(j);
            X1(j)=0;
        end
    end
end

BATTERY=size(none);
COST=size(none);
P_tot=size(none);

for h=1:24
    if X1(h)==0
        BATTERY(h)=X2(h);
    else
        BATTERY(h)=X1(h);
    end
    COST(h)=X1(h)*Prices_s(n,h)+X2(h)
    *Prices_s(n,h)+LOAD_s(n,h)*Prices_s(h)-PV_s(n,h)*Prices_s(n,h);
    P_tot(h)=BATTERY(h)+LOAD_s(n,h)-PV_s(n,h);
end
```

## 8.4 Fourth Scenario model script

```
(1) January, (2) April, (3) July, (4) October''\n';
n=input(prompt);
%From 1:00 to 8:00 am
for j=1:8
    if PV_s(n,j)>LOAD_s(n,j)
        if Prices_s(n,j)>Delta_P_m(1,n)
            X2(j)=0;
X1(j)=-LOAD_s(n,j)+PV_s(n,j);
X1(j)=X1(j)*-1;
        elseif Prices_s(n,j)<Delta_P_m(1,n)
            X2(j)=PV_s(n,j)-LOAD_s(n,j);
            X1(j)=0;
        end
    elseif PV_s(n,j)<LOAD_s(n,j)
        if Prices_s(n,j)>Delta_P_m(1,n)
            X2(j)=0;
X1(j)=0.002-LOAD_s(n,j)+PV_s(n,j);
X1(j)=X1(j)*-1;
        elseif Prices_s(n,j)<Delta_P_m(1,n)
            X2(j)=0.002-LOAD_s(n,j)+PV_s(n,j);
            X1(j)=0;
        end
    end
end
```

```

        end
    end
end
%9:00am to 4:00pm
for k=9:16
    if PV_s(n,k)>LOAD_s(n,k)
        if Prices_s(n,k)>Delta_P_m(2,n)
            X2(k)=0;
        X1(k)=-LOAD_s(n,k)+PV_s(n,k);
        X1(k)=X1(k)*-1;
        elseif Prices_s(n,k)<Delta_P_m(2,n)
            X2(k)=PV_s(n,k)-LOAD_s(n,k);
            X1(k)=0;
        end
        elseif PV_s(n,k)<LOAD_s(n,k)
            if Prices_s(n,k)>Delta_P_m(2,n)
                X2(k)=0;
            X1(k)=0.002-LOAD_s(n,k)+PV_s(n,k);
            X1(k)=X1(k)*-1;
            elseif Prices_s(n,k)<Delta_P_m(2,n)
                X2(k)=0.002-LOAD_s(n,k)+PV_s(n,k);
                X1(k)=0;
            end
        end
    end
end
%5pm to 00:00
for h=17:24
    if PV_s(n,h)>LOAD_s(n,h)
        if Prices_s(n,h)>Delta_P_m(3,n)
            X2(h)=0;
        X1(h)=-LOAD_s(n,h)+PV_s(n,h);
        X1(h)=X1(h)*-1;
        elseif Prices_s(n,h)<Delta_P_m(3,n)
            X2(h)=PV_s(n,h)-LOAD_s(n,h);
            X1(h)=0;
        end
        elseif PV_s(n,h)<LOAD_s(n,h)
            if Prices_s(n,h)>Delta_P_m(3,n)
                X2(h)=0;
            X1(h)=0.002-LOAD_s(n,h)+PV_s(n,h);
            X1(h)=X1(h)*-1;
            elseif Prices_s(n,h)<Delta_P_m(3,n)
                X2(h)=0.002-LOAD_s(n,h)+PV_s(n,h);
                X1(h)=0;
            end
        end
    end
end
BATTERY=size(none);
COST=size(none);

```

```
P_tot=size(none);

for y=1:24
    if X1(y)==0
        BATTERY(y)=X2(y);
    else
        BATTERY(y)=X1(y);
    end
    COST(y)=X1(y)*Prices_s(n,y)+X2(y)
    *Prices_s(n,y)+LOAD_s(n,y)*Prices_s(y)-PV_s(n,y)*Prices_s(n,y);
    P_tot(y)=BATTERY(y)+LOAD_s(n,y)-PV_s(n,y);
end
```

## 8.5 Data Tables

Here there are the used data for the simulations. First there are the hourly prices for Italy and Spain for each month, so in table 8.1. The unit is in €/MWh. The data were collected for Spain from OMIE site [26], instead for Italy from GME<sup>1</sup> site, [27].

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<sup>1</sup>**GME**: Gestore Mercato Elettrico.

**Table 8.1:** Hourly prices for Italy and Spain for each month. There is also the comparison between the two countries' values [€/MWh].

January			April		July		October	
Hour	Italy	Spain	Italy	Spain	Italy	Spain	Italy	Spain
1:00	48,48	38,50	50,84	54,50	74,34	60,70	49,01	49,01
2:00	48,68	60,01	42,53	42,53	83,04	60,43	44,07	40,00
3:00	44,75	47,43	41,84	37,69	68,94	50,85	41,07	38,40
4:00	44,12	45,94	41,00	34,20	60,56	49,46	39,18	37,00
5:00	44,08	43,77	40,74	30,45	60,02	47,98	38,00	36,50
6:00	44,10	42,00	40,24	31,10	60,02	47,98	37,52	36,00
7:00	44,31	42,88	41,00	34,11	60,56	48,80	40,18	37,94
8:00	50,88	46,04	44,66	41,36	67,40	56,47	46,87	43,43
9:00	56,46	59,82	50,52	48,10	73,50	61,57	60,00	49,97
10:00	67,36	62,33	54,23	51,76	85,18	64,50	67,89	55,51
11:00	62,64	65,69	50,05	53,30	86,13	66,60	64,17	56,11
12:00	62,67	67,75	48,17	56,10	80,00	68,10	58,68	56,18
13:00	57,69	65,01	46,30	55,62	77,39	69,48	57,16	54,99
14:00	52,66	59,01	44,88	56,02	71,86	69,69	53,95	54,10
15:00	51,93	52,60	35,34	55,01	73,20	69,48	52,50	52,50
16:00	52,72	45,13	42,35	52,48	80,00	67,03	51,35	49,97
17:00	54,30	44,95	45,46	50,31	79,70	65,51	52,01	49,61
18:00	54,68	46,25	46,46	51,50	82,16	65,51	53,13	49,85
19:00	61,48	55,47	50,63	52,60	83,84	65,51	53,46	49,85
20:00	64,13	59,82	54,08	52,48	83,27	65,32	59,06	54,13
21:00	58,76	58,34	56,36	52,60	85,35	63,71	73,94	56,70
22:00	53,90	55,02	77,60	57,49	83,87	62,89	59,63	59,50
23:00	52,04	45,00	63,17	64,40	87,00	65,10	53,59	56,00
00:00	50,76	42,00	55,84	59,20	85,38	65,51	50,33	49,85

In tables 8.2 and 8.3 we can find the power output of photovoltaic systems, these data were used for all the simulations. As already discussed in the previous chapters, where the PV model was described and all the formulas for calculating the power from irradiation values were presented, the data come from PVGIS software [20], but for script the power output value was used. Thus, in the tables the data are ordered in MW, all the power calculation were performed with DigSILENT, which from the irradiation and input data, it calculates the power output. In table 8.4 there

**Table 8.2:** Power generation of photovoltaic system in Spain.

Hour	January [MW]	April [MW]	July [MW]	October [MW]
1:00	0,000000	0,000000	0,000000	0,000000
2:00	0,000000	0,000000	0,000000	0,000000
3:00	0,000000	0,000000	0,000000	0,000000
4:00	0,000000	0,000000	0,000000	0,000000
5:00	0,000000	0,000000	0,000000	0,000000
6:00	0,000000	0,000000	0,000000	0,000000
7:00	0,000000	0,000000	0,000000	0,000000
8:00	0,000425	0,000000	0,000000	0,000190
9:00	0,001062	0,000404	0,000207	0,000757
10:00	0,001516	0,000909	0,000655	0,001252
11:00	0,001844	0,001327	0,001041	0,001637
12:00	0,002047	0,001633	0,001332	0,001903
13:00	0,002125	0,001822	0,001518	0,002048
14:00	0,002076	0,001892	0,001598	0,002074
15:00	0,001894	0,001846	0,001572	0,001977
16:00	0,001565	0,001685	0,001444	0,001752
17:00	0,001133	0,001422	0,001220	0,001395
18:00	0,000612	0,001042	0,000965	0,000929
19:00	0,000063	0,000526	0,000529	0,000380
20:00	0,000000	0,000001	0,000037	0,000000
21:00	0,000000	0,000000	0,000000	0,000000
22:00	0,000000	0,000000	0,000000	0,000000
23:00	0,000000	0,000000	0,000000	0,000000
00:00	0,000000	0,000000	0,000000	0,000000

are the data of power demand from the household during 24 hours both for Spanish and Italian costumers.

**Table 8.3:** Power generation of the PV system in Italy.

Hour	January [MW]	April [MW]	July [MW]	October [MW]
1:00	0,000000	0,000000	0,000000	0,000000
2:00	0,000000	0,000000	0,000000	0,000000
3:00	0,000000	0,000000	0,000000	0,000000
4:00	0,000000	0,000000	0,000000	0,000000
5:00	0,000000	0,000000	0,000000	0,000000
6:00	0,000000	0,000000	0,000000	0,000000
7:00	0,000000	0,000000	0,000000	0,000000
8:00	0,000367	0,000000	0,000000	0,000106
9:00	0,000948	0,000522	0,000433	0,000675
10:00	0,001428	0,001039	0,000894	0,001198
11:00	0,001781	0,001459	0,001275	0,001609
12:00	0,002001	0,001763	0,001555	0,001894
13:00	0,002091	0,001946	0,001728	0,002052
14:00	0,002049	0,002007	0,001793	0,002082
15:00	0,001877	0,001947	0,001749	0,001984
16:00	0,001573	0,001765	0,001596	0,001759
17:00	0,001138	0,001463	0,001337	0,001406
18:00	0,000588	0,001044	0,000975	0,000933
19:00	0,000026	0,000528	0,000526	0,000369
20:00	0,000000	0,000001	0,000040	0,000000
21:00	0,000000	0,000000	0,000000	0,000000
22:00	0,000000	0,000000	0,000000	0,000000
23:00	0,000000	0,000000	0,000000	0,000000
00:00	0,000000	0,000000	0,000000	0,000000

**Table 8.4:** Load data for Italy and Spain [MW].

Hour	Spain				Italy
	January	April	July	October	
1:00	0,000782	0,000793	0,001138	0,000935	0,0013013
2:00	0,000632	0,000640	0,000934	0,000680	0,0012047
3:00	0,000559	0,000566	0,000827	0,000564	0,0011734
4:00	0,000529	0,000536	0,000778	0,000493	0,0011653
5:00	0,000520	0,000527	0,000756	0,000445	0,0011692
6:00	0,000536	0,000543	0,000762	0,000447	0,0012358
7:00	0,000629	0,000635	0,000825	0,000517	0,0014698
8:00	0,000834	0,000845	0,000972	0,000733	0,0017547
9:00	0,001010	0,001024	0,001154	0,000966	0,0019304
10:00	0,001114	0,001129	0,001370	0,000960	0,0019876
11:00	0,001192	0,001211	0,001528	0,000934	0,0019815
12:00	0,001212	0,001232	0,001592	0,000979	0,0019690
13:00	0,001238	0,001259	0,001664	0,001025	0,0018502
14:00	0,001274	0,001296	0,001741	0,001101	0,0018232
15:00	0,001210	0,001228	0,001671	0,001218	0,0018517
16:00	0,001102	0,001119	0,001563	0,001209	0,0018854
17:00	0,001077	0,001091	0,001561	0,001156	0,0019752
18:00	0,001110	0,001125	0,001615	0,001152	0,0021067
19:00	0,001139	0,001157	0,001660	0,001121	0,0020673
20:00	0,001182	0,001204	0,001657	0,001124	0,0020177
21:00	0,001291	0,001315	0,001624	0,001256	0,0019036
22:00	0,001391	0,001411	0,001662	0,001445	0,0017670
23:00	0,001237	0,001254	0,001644	0,001534	0,0015833
00:00	0,001002	0,001016	0,001407	0,001300	0,0014171

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