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Demand side management for large scale integration of photovoltaic power plants.

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Master in Energy for Sustainability

Demand side management for large scale integration of photovoltaic power plants.

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Abstract

Nowadays, due to the abundance of sun light at earth surface and the decreasing cost of technology, the number of countries adopting solar electricity generation systems is constantly increasing, ensuring great benefits for the society, environment and economy. However, Photovoltaic (PV) energy imposes challenges to the Distribution and Transmission Grid Operators (DSO and TSO) due to its variability and intermittency. In large interconnected grids, short term fluctuations in PV power plants may impact utility operations by compelling generators to be operated in a less efficient manner. At the same time, there is the necessity to incorporate a higher penetration of variable solar electricity generation in the grid.

Additionally, in buildings, the PV generation and electricity consumption do not have the same variation profile and such mismatch brings the need to export to the grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption. These aspects are a source of inefficiency and create problems on the electrical grid management and can be even a source of economic losses.

However, for the problems caused by the mismatch between the PV generation and consumption, if properly controlled, several residential appliances can be used as Demand Response resource therefore contributing to minimize the mismatch between the generation and consumption. The objective of this Master thesis work is to analyze the photovoltaic generation power in order to minimize the grid integration issues through demand side management, using the control of residential appliances.

Keywords: Renewable Energy, Solar Photovoltaics, Grid Integration, Demand-Side Management, Demand Response.

Resumo.

Atualmente, devido à abundância de radiação solar na superfície terrestre e à diminuição dos custos de tecnologia, o número de países que adotam sistemas de geração de energia solar tem aumentado constantemente, garantindo grandes benefícios para a sociedade, meio ambiente e economia. No entanto, a energia solar fotovoltaica impõe desafios para os operadores das redes de distribuição e de transporte devido à sua variabilidade e intermitência. Em grandes redes interligadas, as flutuações de curto prazo em grandes centrais fotovoltaicas podem ter impacto nas operações de serviços das *utilities*, levando os geradores convencionais a operar de uma forma menos eficiente. Simultaneamente, é necessário incorporar nas redes uma penetração mais elevada de geração solar variável.

Adicionalmente, em edifícios, a geração solar fotovoltaica e o consumo de energia elétrica não têm o mesmo perfil de variação e tal desajuste leva à necessidade de exportar para a rede uma parte significativa da energia gerada localmente, apesar da mesma quantidade de energia necessitar de ser depois importada para assegurar o consumo local. Estes aspetos são uma fonte de ineficiência e criam problemas à gestão da rede elétrica e podem mesmo ser uma fonte de perdas económicas.

Contudo, para os problemas causados pelo desajuste entre a geração de energia fotovoltaica e o consumo de energia, algumas cargas em edifícios residenciais, se devidamente controladas, podem ser usadas como recurso de *Demand Response*, contribuindo assim para minimizar o desajuste entre a oferta e o consumo de energia. O objetivo desta Tese de Mestrado foi analisar a geração solar fotovoltaica de forma a minimizar os problemas de integração na rede, através de gestão da procura, usando o controlo das cargas residenciais.

Palavras-chave: Energia Renovável, Solar Fotovoltaico, Integração na Rede, Gestão da Procura, *Demand Response*.

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Finally I would like to thank my family, specially my mother and my father who always have been there to support me and to encourage me every day to go into the pursue of my goals.

“*Con enorme gratitud y amor para mis queridos padres Arturo y Melva*

Gracias por su incondicional apoyo y por darme las alas correctas para volar alto”.

”I’d put my money on the sun and solar energy. What a source of power! I hope we don’t have to wait until oil and coal run out before we tackle that.” -Thomas Edison, 1931

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Abbreviations

BESS – *Battery Energy Storage System*

CO_2 – *Carbon Dioxide*

DC – *Direct Current*

DER – *Distributed Energy Resources*

DG – *Distributed Generation*

DR – *Demand Response*

DRM – *Demand Response Management*

DSM – *Demand Side Management*

DSO – *Distribution System Operator*

ESS – *Energy Storage System*

GHG – *Greenhouse Gases*

GW – *Gigawatts*

ISO – *Independent System Operator*

kWh – *Kilo Watt Hour*

PV – *Photovoltaic*

PV-DSM – *Photovoltaic-Demand Side Management*

RGGI – *Regional Greenhouse Gas Initiative*

RPP – *Renewable Power Plants*

SPV – *Solar Photovoltaic*

Chapter 1 – Introduction

The research for environmental quality constitutes an ancestral tendency that aims for the establishment of harmonious equilibrium between the person and nature that surrounds him. Environmental quality considerations fell into disuse after the industrial revolution, in an era where man believed in his omnipotence without measure the resources in the planet. Likewise, the fast increase of the world population plus the struggle of humans for continuous rise of their biotic level and the poor awareness about the resources consumed or the energy reserves has led to a seriousness situation where actions are needed to change behaviors, processes and activities aimed to take care about the natural resources.

Electricity generation is responsible for a high share of the CO_2 emissions (about 40% in the US). The European Union, Switzerland, and the Québec province in Canada have also implemented cap-and-trade programs. As well, European Union climate targets are translated into renewable energy technology deployment scenarios [1]. Therefore, there is the necessity to incorporate a higher penetration of solar electricity generation in a transmission grid.

1.1 - Motivation

Due to its variability and intermittency, PV energy imposes a challenge to the Distribution and Transmission Grid Operators (DSO and TSO) and at large interconnected grids, short term fluctuations in PV power plants may impact utility operations by compelling generators to be operated in a less efficient manner. In buildings, the mismatch between PV electricity generation and consumption leads to export to the grid a significant part of the locally generated energy, even though the same amount of energy is later imported back for local consumption. Therefore, it is required more data to understand the variability of the different PV systems and new tools are needed to compensate it, in order to evade unnecessary barriers to the interconnection of those type of energy to the electrical grid.

However, the PV generation and consumption mismatch problems can be minimized if several appliances are properly controlled to be used as Demand-Side Management (DSM) resource. For the residential buildings, some appliances can be rescheduled to match the period with higher generation (load shifting strategy) and the thermal loads can be controlled to compensate the short term variations of the generation (curtailment strategy) and therefore energy storage can be used as a crucial tool in order to offset the unpredictable variation of the energy and to minimize the mismatch levels between renewable generation and demand.

With all this information in mind, it was a starting point for the development of this thesis work to fulfill the main arise topics regarding to identify proper strategies of Demand Side Management and Demand Response to minimize the mismatch caused at PV systems and allow them to have the best integration to the grid and to maximize the benefits from these PV systems.

The impact and the relevance of this research proposal work directly affects building owners, DSO (Distribution System Operators), TSO (Transmission System Operators), Universities, researchers and research organizations as well to a society in general (Environmental, economic and social benefits).

1.2 - Objectives

The main objective of this Master thesis work is to analyze the photovoltaic generation power in order to minimize the grid integration issues through demand side management, using the control of residential appliances.

The objective of the present work it is to assess the minimization of the mismatch that occurs between generation and consumption profile of PV solar energy through the application of strategies of DSM and DR techniques.

In this case, objectives are related with identification of DR potential in the residential sector, impact in the energy that is injected into the grid and likewise impact on costs.

1.3 - Thesis outline

The present thesis dissertation it is organized in the following way:

The second chapter is an introduction to the renewable energies and its benefits with main focus on the PV systems, its characterization and different technologies, as well as its advantages and challenges in order to be integrated at the large scale grid level.

Chapter three presents the intermittency issues, its characterization and challenges to the grid as well as the benefits that represent the aggregation of intermittent generation of PV solar power over large areas can represent a mitigation on their variability. At the fourth chapter it is analyzed the opportunities that DSM and DR can gives to PV systems for a better grid integration. During the chapter it is settled up the DSM strategies, its challenges and benefits, as well as other solutions to minimize the intermittence, such as energy storage and PV forecasting, in order to achieve higher grid penetration. Chapter fifth gives an introduction to data utilized as a basis to develop the two case studies for this master thesis work as well as the generation and demand profile information and the costs of energy are presented in an initial step.

The sixth chapter presents the analysis of the information given at chapter fifth but applying DSM techniques in order to reduce the amount of energy that it is injected into the grid. It is analyzed for each of the case studies, the results obtained at generation and demand profiles by applying the strategies are presented, likewise it is analyzed the economic changes at the energy costs due to the implementation of DSM.

And finally Chapter seventh presents the global conclusions for this Master thesis dissertation and similarly presents the recommendations for further work related to the integration of PV systems into the grid.

Chapter 2 – Renewable Energy Photovoltaic Systems

This chapter presents a general overview of the renewable energies and its main characteristics and benefits for the electric energy system, the characterization of PV systems, its technologies, challenges and benefits, as well as its integration to the electric grid system.

2.1 Renewable energy overview

Energy represents the most vital motor for the human activity and also for the human's survival. At the present time, energy is extremely connected at every activity of the worldwide societies, giving a fundamental contribution to the economic activity, contributing since basic human needs from food, housing, health, security and education. However, the relationship between society and energy relies on the complexity due to in one hand energy services can help to recover the environmental ideal state by for instance implementing machineries to reduce deforestation but at the same time the use of energy for maintain those machineries emit some pollution that can harm the ecosystems.

The supply of energy has direct effects on the social order and economic improvement due to energy consumption and economic improvement go hand-by-hand. Nevertheless, energy is not available in the same quantities for all countries, and due to our dependency on energy to supply our necessities, the energy resources had turn out to be progressively costly and scarce.

In this context, it is necessary to shift the electricity production from conventional energy sources to renewable sources, in order to have a relevant impact on the actual global warming situation, on the reduction of fossil fuel reserves and also on the need for countries to guarantee energy self-dependence. Between all the renewable energy sources, solar energy is one of the cleanest and a green source of abundantly available energy. Therefore one of the most feasible ways to do the previously mentioned it is through the generation of electricity through photovoltaic systems (PV) by using the most abundant renewable source that it is the sun.

2.2 Solar Photovoltaic Systems

Renewables also are an important element of climate change adaptation, improving the resilience of existing energy systems and ensuring delivery of energy services under changing climatic conditions. Heating capacity grew in a fast way and the production of biofuels for transport increased for the second consecutive year, following a slowdown in 2011–2012. The most rapid growth, and the largest increase in capacity, occurred in the power sector, led by wind, solar PV, and hydropower [2].

One of the major challenges for the area of electric energy systems it how to meet the increasingly demand from a worldwide growing population and at the same time address the climate change mitigation.

The sun provides an abundant energy resource which can be used to generate electrical energy, by using photovoltaic panels through direct conversion into electric energy. The potential environmental benefits obtained due to the implementation of photovoltaic power systems can be abundant. For grid connected PV systems, the most immediate opportunity is on the customer side or demand side of the meter, where the customer's peak demand can be partially met using PV systems [3].

However, there is a variability on the electricity production due to the intermittency of the solar energy during the day or seasons. Therefore, to compensate it, grid operators must play an important role by providing balancing techniques to ensure a higher grid flexibility. These techniques can embrace, for instance, additional generation and transmission capacity, better forecasting of renewable generation, Demand-Side Management (DSM), Demand Response (DR) or energy storage [4].

2.2.1 Solar Photovoltaic technology.

Solar energy conversion technologies are largely classified into 4 main types: solar to electricity, solar to heat electricity, solar to heat and solar to fuels. The most commonly used for the electric industry are the solar to energy and the solar to heat energy. At solar to energy generation in the sub classified group, are of tracking and non-tracking systems, which can even have been obtained through concentrating and non-concentrating systems using one or two axis tracking. At solar to heat commonly called solar thermal energy it is used even to heat water for consumption or to generate electricity using heat engines, heat exchangers and tracking and concentrating systems as parabolic through, parabolic dishes or solar towers.

In order to amplify the power generation capacity, solar panels are connected to form a PV system for residential, commercial, industrial or rural applications around which gravitates other components complex (inverters to convert direct current to alternating current, wiring, circuit breakers and a mounting structure, mainly in aluminum and steel for roof-top laminate panels) and additional accessories which vary according to the type of system. The combination of basic components and accessories constitutes the balance of the system [5].

The PV systems issues such as limited conversion efficiency, elevated temperatures and surface´s dust accumulation are considered critical due to their significant impact on the performance of PV cells, especially in sun-drenched hot climate regions according to [6]. With this in mind, it is required for the photovoltaic prediction the estimation of both the weather conditions and the PV modules parameters to evaluate the production efficiency[7].

PV panels, whichever been, flat, one or two axes, are most efficient depending on their location around the world, the season, weather, clouds existing in that area and the most accurate or feasible technology designed to improve the maximum absorbing solar power to generate electricity. Photovoltaic prediction requires the estimation of both the weather conditions and the PV modules parameters. To accommodate variable sources of electricity, grid operators will deploy load-balancing techniques that increase the grid flexibility.

2.2.2 Solar PV power efficiency and limits

To understand specific operation performance characteristics of solar cells better, users, owners, and finance and lending organizations must have a fundamental understanding of specific operation and performance characteristics of solar cells. Unlike any other technology, they are subject to numerous environmental parameters that affect power output production over a project life cycle.

Another parameter affecting power output is wind, when there are windy conditions the panels are cooled, so they may slightly improve their efficiency, one more parameter it is the reflection of sunlight from adjacent hills located in various locations (except in the front) and lakes, the local solar platform (called the albedo effect), as well as solar flares, may cause PV modules to produce more energy and finally another parameter it is the air mass which is the volume of air that occupies the space between solar power PV modules and the stratosphere so the larger the volume of air or the distance, the more particles, gases, and water vapor there are, resulting in more solar ray reflection.

Solar energy has the advantage of no pollution, low maintenance and no noise due to the absence of the moving parts. However, high initial cost and low conversion efficiency have deterred its popularity. Therefore, it is important to reduce the installation cost and to increase the energy conversion efficiency of PV arrays and the power conversion efficiency of PV system.

As the solar power output performance is directly proportional to the amount of solar irradiance that impacts the photovoltaic modules, therefore, any obstacle that blocks or refracts the solar rays will prevent photons from being absorbed and converted into electrical current. Most common of all such obstacles are airborne particulates such as dust and water particulate in the air that gradually settles on the surface of PV panels.

A factor that affects solar power energy production depends on the solar PV module frame assembly and the clearance band of the solar cells from the frame edges. In general, under rainy conditions the accumulated dust particles on the surface of PV modules are washed downward and gradually accumulate around the edges of the frame.

Nowadays, for a PV cell it is a tendency to decrease the thickness of the material by increasing the material absorption through light trapping increasing and this allows to the physical thickness can remain low and also allows carriers to be absorbed close to the junction and this increases their probability of collection.

Some barriers for PV systems are due to the solar radiation which depends on the geographic location, affecting the competitiveness of PV systems. The architectural dimension of the areas is also an important factor that can become a barrier to adoption. For urban areas, a key barrier is an inadequate installation space. PV panels need to be angled toward the right direction to maximize solar exposure. For rooftop integration, the surface can be too limited in old high-rise buildings. However, new buildings can be designed to integrate PV systems in their structure to maximize the installation space.

In some remote areas, lack of demand for electricity is also a barrier to the adoption of PV systems. Here, it can be distinguished the reasons for the lack of demand into two types. First, it is due to the lack of electricity-related activities, since in the low-income markets, some people have recently started to use household electrical appliances. In previous years, economic barriers were usually related to the high cost of solar PV modules and therefore PV systems were usually not profitable without policy support in many countries. In this manner, policy measures were of vital importance for rapid diffusion of environmentally friendly innovations including PV systems which recently have been involved in a huge decrease of costs and nowadays PV are already cost competitive [8].

2.3 Solar Photovoltaic Grid Integration

Nowadays, electricity suppliers have more awareness about Distributed Generation (DG) since it is an instrument to fulfill certain specific market areas. Each customer is looking for a specific electricity service that please their different amount of electric energy requirements and so then distributed generation can help to the electricity suppliers to satisfy the specific electricity service that the customer is demanding. Actually in energy economy markets it is important to act in flexible ways and distributed generation offer this flexibility due to their short construction times and small sizes compared with larger power plants.

Distribution generation technologies for solar energy can be flexible regarding to procedure, expandability or dimension and one prove of this is that the use of distributed generation can be helpful by react in a flexible way to the electricity price changes and evolution. Therefore, one of the most common ways to use distributed generation is in a continuous way and for peaking use.

The power quality can be affected in a negative way due to failures and switching operations in the network, which can produce interruptions, transients and voltage dips or also due to network disturbances from loads that result in a fast voltage variation. These disturbances have their origin in a short-circuit capacity which minimum value have to be guarantee by the network operators in order to maintain the system with an optimum power quality.

Distributed generation can make contributions to the facility of secondary services which includes necessary services to maintain a stable operation at the grid but not providing in a direct way to customers, for instance to stabilize a dipping frequency generated by an unexpected excess demand.

Small-scale generation is also called distributed generation, embedded generation or decentralized generation, there is not a specific definition because the concept encompasses many technologies and applications. The first power plants only supplied electricity to customers in the close neighborhood of the generation plant. According to [9] "since distributed generation is gaining popularity as it has a positive environmental impact and the capability to reduce high transmission costs and power losses, although the integration of renewable energy-based DG will help reduce greenhouse gas emissions, it will rely heavily on new ways of managing system complexity". As a traditional distribution networks were not designed to accommodate power generation facilities, various technical issues arise in the integration of distributed energy resources (DERs) into grids.

Grid integration of solar PV systems is gaining more interest than traditional stand-alone systems because of the following benefits: 1) Under favorable conditions, a grid-connected PV system supplies the excess power, beyond the consumption required by the connected load, to the utility grid; 2) It is comparatively easy to install as it does not require a battery system because the grid is used as a backup; 3) No storage losses are incurred; and 4) It has potential cost advantages.

It is expected that grid-connected PV systems in medium-voltage networks will be common in the near future. Therefore, it is necessary to accurately predict the dynamic performance of three-phase grid-connected PV systems under different operating conditions in order to make a sound decision on the ancillary services that need to be provided to utilize their maximum benefits without violating grid constraints. Thus, the spread and growth of solar and other distributed renewable energy has led to significant modeling and engineering analyses of distribution systems. Although DG has several potential benefits, the connection of it the existing distribution network will increase the flat level of the system.

Typical contingencies on a distribution network can occur in the form of single or multiple outages, such as unplanned losses of generators or distribution feeders. Several internal and external causes are responsible for equipment outages. The internal causes arise from phenomena, such as insulation breakdown, over-temperature relay action or simply incorrect operation of relays. The external causes result from some environmental effects, such as lightning, high winds and icy conditions or non-weather related events, such as a vehicle or aircraft coming into contact with equipment or even human or animal direct contact. These contingencies can result in partial or full power outage in a distribution network unless an appropriate control action is taken.

A higher PV penetration level could possibly cause instability problems when a large percentage of the system load is supplied by PVs. Therefore, it is becoming more important to understand the behavior of a DG-integrated system under disturbances with practical distribution network loads since variations in loads physically close to generators are a large fraction of the generation. Load modeling is qualitatively different from generator modeling in many aspects. Generally, only the aggregate behavior of load is required for power system stability studies rather than a whole collection of individual component behaviors.

Chapter 3. Solar power intermittency

As it can be seen at previous chapter, PV systems are a great option to be integrated into electric grids. Nevertheless, they are an intermittent energy source that presents challenges to the grid and such intermittency is analyzed at the present chapter where it is presented the intermittent generation, as well as its main challenges.

3.1 Intermittent generation

The fluctuations in the system load are fairly slow due to statistical smoothing and are quite accurately predicted on day-ahead and hour-ahead bases by system operators. Solar power, in contrast, is characterized by more rapid and less predictable fluctuations over time scales from minutes to hours. The mitigation of intermittency must address both variability and uncertainty.

In PV power plants, the short-term variability has two components:

- Predictable - the sun's apparent motion in the sky induces changes in the resource.
- Non-predictable - variability caused by the motion and evolution of cloud fields.

Predictable changes are generally not noticeable for very short time intervals, but become influential when the time interval extends beyond tens of minutes. Non-predictable have a strong influence on the grid operation.

Some of the intermittency metrics are capacity value or capacity credit of an intermittent generator, which is the ratio of the capacity of conventional dispatchable plant that can be retired to the capacity of the intermittent generation that is installed in its place to meet the load without compromising reliability. A capacity value can be determined by stimulating the system with a given capacity of the intermittent technology of interest while reducing the dispatchable plant capacity until a further reduction would compromise the reliability of the system.

Intermittent renewables can also be characterized by the cost associated with their integration into the grid. This intermittency cost includes any additional cost associated with real-time balancing of the load and maintaining any additional reserve margin that becomes necessary due to the renewable generators; it does not include the capital cost of the renewable plant or the cost of additional transmission to the plant. The cost of intermittency can be calculated using grid integration models by calculating the cost of electricity with the renewable technology and subtracting the expected cost of electricity were that plant to operate as a dispatchable generator.

While much of the literature in intermittent renewables has been devoted to qualifying the capacity value and cost of intermittency for a given renewable resource, there is little agreement on the precise values of these metrics. This is because both, capacity value and the cost of intermittency are functions of the resource quality, the system load characteristics and the composition of the conventional generator fleet, the strategies employed by and the controls available to the system operator, the electricity market structure, and finally the energy penetration of the technology of interest. The proper use of these metrics is therefore not to make general claims about the ability of intermittent technologies to supply electric loads, but to compare the behavior and reliability of intermittent renewables across different systems, and to identify the types of systems that best incorporate intermittent generation.

The difficulty in analyzing electric power systems with renewables like solar lies in accurately characterizing the resource intermittency and the ability of the system to accommodate this intermittency. Intermittency in an electric power system is comprised of both variability and uncertainty in the load or the availability of power. Conventional electricity systems exhibit both variability and uncertainty in the supply and the demand: thermal power plants introduce variability through unforced outages and uncertainty through forced outages; hydroelectric plants introduce variability due to seasonal changes in precipitation levels, snow melt, and human use; and the load fluctuates with human activity, which is both variable and uncertain.

By aggregating intermittent generation of photovoltaic solar power over large areas mitigates their variability [10]. However, the potential for high grid exports in the grid from high-regional penetration of PV generation during periods of low energy demand and high solar irradiance still exists and during these periods, if electric energy demand is not flexible, the grid infrastructure requires major investment to cope with the transfer of energy from one area to another [11].

In the other hand, some barriers for PV systems are due to the solar radiation which depends on the geographic location, affecting the competitiveness of PV systems. The architectural dimension of the areas is also an important factor that can become a barrier to adoption. For urban areas, a key barrier is an inadequate installation space [8].

Despite the promise of wind and solar power to reduce carbon dioxide emissions, the ability of these intermittent renewable resources to contribute to supplying a fluctuating electricity demand remains an open area of research. More recently, technical feasibility studies have been devoted to the issue of intermittency in integrating large capacities of wind and solar on the Western and Eastern Interconnects in the United States.

The Western Wind and Solar Integration Study (WWSIS) described the impacts of intermittency on system operation over the West Connect area for a portfolio of wind, solar photovoltaic, and concentrating solar power with energy penetrations between 11% and 35% [12].

This is illustrated in Fig. 1. Demand response has been proposed as a strategy for reducing these reserve requirements [13], but to date, grid integration studies have largely treated the load as exogenous. An endogenous load, while improving flexibility and efficiency, also introduces added complexity to the system and presents new modeling challenges. At small scales, when the variability and uncertainty in their power output is within the load-following capability of the existing system, wind and solar power may be treated as load modifiers [14], [15]. However, as the penetration increases, the power fluctuations begin to necessitate additional load balancing and regulation capabilities.

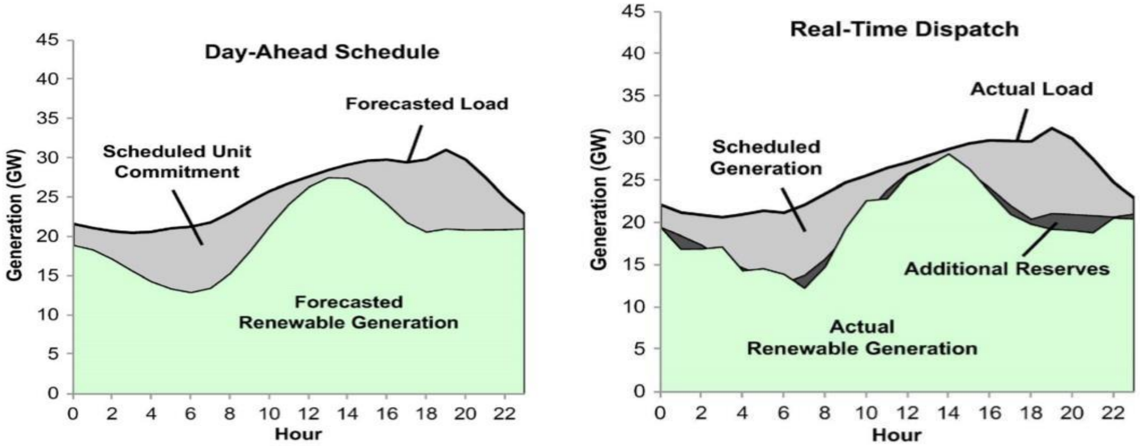


Figure 1. *Comparison of possible scheduled generation with the corresponding real-time dispatch. Figure adapted from [16]*

Other problem is the change on the net load variation introduced by the PV generation. Regarding such issue, the California ISO "duck chart" shows a duck's growing belly highlights the near-term potential for "over-generation" (Fig. 2)" [17]. As solar penetration increases, net load starts to bump up against the minimum generation levels of other grid-connected generators and at some point, system operators have to start curtailing solar to balance the grid.

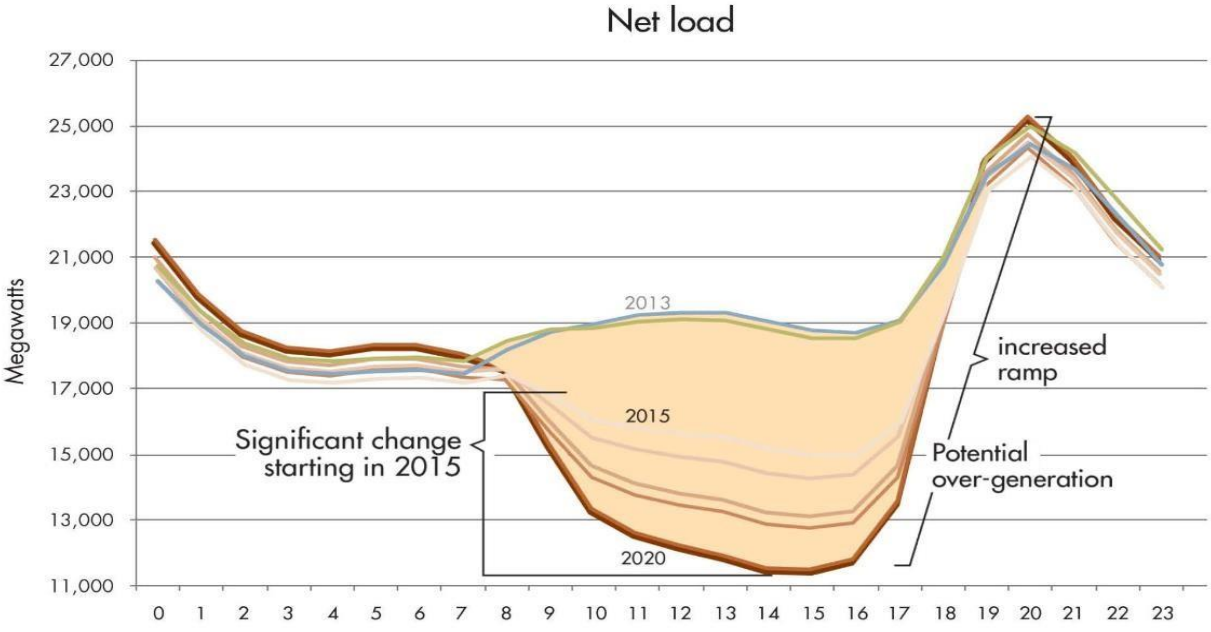


Figure 2. *Growing need for flexibility starting in 2015 [19]*

In general, if a household uses own electricity, it saves money which otherwise has to be paid for retail price [17]. The presence of a long memory of behavior in renewable energy consumption is addressed in [18]. In [19], the impact of PV generation system on energy demand is analyzed from an economic point-of-view. The study in [20] applied Self-Organizing Map (SOM) clustering to household demand curves based on time of peak demand. Distinct peak- shifting behaviors were observed which indicate a deliberative shift in consumption behaviors.

Utilities are concerned about the safe, efficient, and reliable operation of the power grid. There are many examples of high penetration PV installations that are operating well, but some cases which illustrate the general concerns with this issue. In Germany 80% of the PV power is interconnected on the distribution network [21]. The distribution networks historically have been designed to transfer energy from higher voltage levels down to the residential load which is connected at the low voltage level. Detailed measurements are available at the connection points between the distribution system (DSO) and the transmission system (TSO) and visible at the distribution grid control centers. The fluctuations of load at the residential level are estimated by standardized load profiles. With the integration of decentralized power generation such as PV into the low voltage level, the distribution control centers lose visibility and control over the grid, as network operators have no measurements at the low voltage level today.

There are several important considerations in the integration of high penetration levels of PV into the utility grid. These include the operation of the utility grid including balancing and control, the interaction of the PV equipment with the grid as required by grid codes, and forecasting of the PV power generation. For the integration of photovoltaic systems into the low-voltage network, grid extension is the most expensive way but still the standard solution. Solar inverters providing reactive power, can be a more cost effective way to increase the possible fraction of renewable power input to the distribution grid. However, operational strategies and market structure changes are still needed to address increased levels of uncertainty that high- penetration of renewable resources presents to utility companies and grid operators due to their intermittent nature. Forecasts of future solar energy system output allows grid operators and utilities to proactively manage variable output, and thus integrating solar resources into the existing grid at lower costs to society [22].

Also, with the rising prices of the retail electricity and the decreasing cost of the PV technology, grid parity with commercial electricity is already a reality in several Europe countries. This fact, together with less attractive PV feed-in tariffs in the near future and incentives to promote self-consumption suggest that new operation modes for the PV distributed generation should be explored, differently from the traditional approach which is only based on maximizing the exported electricity to the grid.

3.2 Intermittency challenges.

The electrical grid in the twenty-first century is experiencing major changes all over the world in order to become smarter, cleaner, more efficient, and reliable. Among different sources of renewable energy, wind and solar energy are gaining popularity in most countries. Due to the variable nature of renewable energy sources, in terms of power including real and reactive power, output voltage, and frequency, it is a major challenging issue for the current power industry to integrate large-scale wind and solar photovoltaic (PV) energy into the grid.

However, with the increasing size of generation, direct interconnection at transmission level was required and hence rules were being developed by different TSOs and regulators. The first part of the grid code focuses on the static requirements. A few of these requirements contain time limits or operate within fixed time frames. The values are however, still constant within the mentioned time frames.

Voltage regulation in a power system is dependent on flow of reactive power, as well as on short circuit capacity and impedance of the network. By operating in a wide range of power factors, conventional generation units have traditionally provided reactive power to support system voltage. Voltage regulators on their excitation systems provide the primary voltage control function. However, lack of this capability leads to problems such as under-voltages and excessive voltage fluctuations.

Regarding to the power quality, the power system needs to run in a stable state and be able to deliver power to consumers at an acceptable quality. Harmonic and flicker at PCC (point of common coupling) are two major power quality disturbances, which need to be taken care of while harnessing power through RPPs. Sources, which contributes in harmonics injection in RPP include generator technology, dynamic reactive power compensation equipment, collector system feeders and electric grid itself.

To accommodate variable sources of electricity, grid-operators will deploy load balancing techniques that increase grid flexibility [23]. In lieu of grid flexibility, variable resources can be curtailed during periods of oversupply or of strong market disincentives [24], but curtailing renewable resources results is an immediate and obvious forfeiture of energy. However, flexible grid technologies can also consume significant amounts of energy in their manufacture and operation.

Chapter 4. Mitigation of the Generation Variability

In the previous chapter it was observed that it is feasible and efficient to aggregate intermittent generation of photovoltaic solar power over large areas in order to mitigate their variability. Nevertheless, there is a lot of work to do in order to minimize the challenges that the intermittency represents for the electric grid systems. So then, at present chapter it is presented Demand Side Management strategies that if applied in a proper way can give positive results for a best integration of the PV systems into the grid.

4.1 Demand-Side Management

Demand-Side Management (DSM) is the planning, implementation and monitoring of utility activities that are designed to influence customer use of electricity, resulting in changes on the time pattern and magnitude of utility´s load [25]. In an energy consumption context, Demand-Side Management [26] is defined as deliberative household actions to achieve savings and higher energy efficiency using variations of renewable energy technology, retailer products, choices for electrical appliances and time of use [27]. Usually, the main objective of demand side management is to encourage users to consume less power during peak times or to shift energy use to off-peak hours to flatten the demand curve. Sometimes, instead of flattering the curve it is more desirable to follow the generation pattern.

Demand side management techniques are extensively used to modify the manner in which the energy is consumed. The use of DSM can provide many benefits such as: reduce the generation reserve margin (decreasing the need for backup generation), improve transmission-distribution grid investment (adjusting the size of the lines to local demand) and operation efficiency (decreasing the need for energy transport). DSM may also be used to mitigate the variations in production of renewable energy, being able to make greater use of these technologies [27]. It can reduce building peak demand, decreasing the transport losses through the grid and the pollutant emissions [28].

In order to accommodate variable sources of electricity, grid-operators can use load-balancing techniques that increase grid flexibility.

The main objectives of DR techniques are the reduction of peak load and the ability to control the consumption according to generation [29] in order to decrease the amount of assets needed to fulfill current demand using existing methods of power generation and would significantly increases the load factor [30]. Demand response will be best placed to provide flexibility in the period of several minutes to several hours [31].

Reliable operation of power grid is primarily dependent on perfect balance between supply and demand at each given time. This is not an easy task and gets even harder when distributed energy generation increases, since as previously described, renewable generation varies with weather conditions and it is not generally easy or desirable to modulate the output of renewable in order to follow a particular load shape [32]. By using DSM techniques, it is possible to maximize the matching between the generation and consumption. One of the most usual methods in DSM implies the use of the forecasting of solar resource in order to schedule the local consumption, using strategies of DSM. However, due to the PV forecast uncertainty, this method has limitations for introducing this technology into the grid, creating a wide challenge at the design and operation areas of the PV generation.

Photovoltaic DSM systems can have both energy and capacity value (in the form of coincident peak demand reduction). The energy value credited to a PV DSM system is a function of the PV array´s size and efficiency and the availability of the solar resource. By producing energy on sunny days, rooftop systems can directly displace at least a portion of a building´s needs from the utility. Coincident peak demand savings from the deployment of PV DSM systems depend on the type of system used and its management rules [33].

Demand side management will serve as a great option to provide and improve power system flexibility in the period of several minutes to several hours [34]. DSM can be used as a tool to accomplish different load shaping objectives, [35] and to mitigate the variations in production of renewable energy [36]. It can reduce building peak demand, decreasing the transport losses through the grid and the GHG emissions [37].

Electric utility infrastructure costs are driven primarily by the need to serve the load during the peak demand period. Therefore, it is desirable to shave peak demand in order to defer generation, transmission and distribution equipment upgrades, and reduce or avoid the necessity to purchase much higher cost generation assets. However, the use of DSM also has to face different challenges such lack of infrastructure because the absence of monitoring, communication and control systems in the grid, lack of understanding of the benefits and the difficulty to evaluate them, increase the complexity of the system, etc. [38].

DSM can be primarily based on a household's decision making behaviors (e.g., under a demand response signal), or can be actively controlled (dynamic demand) known as active DSM [39, 40]. In [41], distribution feeders with high penetration levels of renewables are analyzed to address the relationship between electricity demand of different consumer segments and different types of renewable resources.

[42] Demonstrated that due to the high PV penetration in Germany peak demand in both winter and summer has shifted toward the midday hours, matching with hours of peak solar electricity generation. This is due to the 'self-consumption' of own site-generated electricity [43]. However, in most other cases, peak demand does not coincide with peak solar generation; therefore, the positive correlation between solar electricity generation and midday self-consumption is often overlooked. This is due to the often negative correlation between aggregated diurnal demand curves and diurnal solar generation curves [44], and illusively due to electricity generation at a particular time, often being higher than the level of consumption at the same time [45].

Smart grids are designed not to change the way that the actual electricity grid system is working, but for create an expansion of perspective and do more of the actually is doing nowadays by sharing communications infrastructures and introducing a developed level of integration by leveraging current technologies and filling in product gaps. Smart grids offers high expectations and confidence to the electricity network system by working through on a long-term and integrated work frame and the smart grids are increasing their advantages, soon will provide a large range of benefits to the operational areas of the power utilities worldwide due to the afford of a wide platform of solutions for deliver benefits to utilities and their final customers.

Distribution grid optimization can be improved by the continuous development of new technologies and applications in distribution. It is not sufficient to only integrate smart-grid technologies, it is necessary to increase and implement applications and structures to maintain the proper operation of the grid while it is introduced at the new environment of smart electricity consumption by end customers, clean energy use and distributed generation. The distribution management requires to have an increase at the Distribution Management System (DMS) for the smart grid in order to generate advances on its functionality.

In a general new perspective, final customers are now going to be able to not only be consumers but then buyers or even sellers, also a major uncertainty to the distributed generation is the electricity consumption of particular customers at the moment that they respond to the power utilities rewarding polices and real-time pricing for economic reimbursements.

In this context at the household level, consumers are increasingly using intelligent appliances and smart meters which can control loads and perform a better monitoring of the consumption of electricity at homes. It is here, at household level, where DSM can be implemented to empower the use of solar photovoltaic systems of a smart meter, and this result in an increased consciousness of electricity consumption.

4.2 Demand response

In order to accommodate variable sources of electricity, grid-operators will deploy load-balancing techniques that increase grid flexibility. Demand response will be best placed to provide flexibility in the period of several minutes to several hours [46]. Indeed DR will play a key role in electricity balancing act in the future.

Peak load or also called peak demand refers to a load profile period at which the maximum electric demand occurs at customer’s side. So then, due to the growing population in the last decades and its lead to increase the arise of new technologies the peak demand has been increasing and consequently in order to meet these peak demand the increasing on generation level by utility companies has increased or even the buy of electricity at a dynamic pricing structure from the wholesale market. As a result, a low load factor becomes present and utility companies has to offer Demand Response programs to reduce the peak demand at peak hours in order to increase such load factor, and consequently those DR programs encourages to end users to shift from peak hours to off hours their demand with the objective of target the fluctuating wholesale market price either by day by day or distributed it into predefined price [47]. Likewise since demand response main driving it is to avoid the high peak load which comes from demand side management, therefore there is the necessity to study and coordinate the usage of large electric power-consuming appliances.

Nowadays there are different DR programs and the most used are the price-responsive method and the incentive-based programs. At the first one, in order to reduce the peak, the utility company can change the price during the day nonetheless can either change every hour in a day or be stable for some times during the day and new peaks can be perceived at this new arrangement. Hence through this method it can be obtained results through two ways which are Real-time price (RTP) and Time-of-use (TOU). For the real-time-price it is stablished that the utility defines the price in advance so this creates a pricing policy at the whole sale market but requires a very reliable and efficient communication between the customers and the utility by the use of smart meters. At the TOU method exists a fixed price for at least two years which is based on off-peak and in-peak time periods.

For the incentive-based programs, residential customers are required by utility to have PV and storage, the price it is defined on a yearly basis and it is flat. The main purpose of this program consists on curtailment or scheduling method which gives incentive to the utility by reducing the peak demand through having a control for the charging time and then the customers gets credits or discounts for their bills [48].

At the DR method, in order to link the demand into the supply besides the smart meters exists the Advanced Metering Infrastructure (AMI). Smart digital meters achieve real time data accessibility to consumer and electricity supplier, at end consumer perspective, these smart

meters allows them to schedule the PV energy consumption at their homes and therefore to reply to tariff signals. The consumers are more able to evade energy consumption during the peak hours due to at these hours electric kWh prices are high and at off peak hours kWh prices are low.
Thus DR technology support peak shaving objectives and supply in order to match demand through the use of AMI and smart meter arrangement.

The dynamic pricing application and the real time energy usage are the two main steps in order to achieve DR. By installing at customers' homes and offices one display that combine these two steps, it is going to be able to create a communication between smart meter installed outside and the display at home or office and henceforth customers can decide if they are going to curtail at peak hours their electricity usage or if they are going to buy electricity at higher prices.

Established as a promising method, demand response looks to increase power system flexibility and consequently facilitate the integration of renewable energy. However, significant investment is required to establish a communication, control and monitoring infrastructure if demand response is to be provided on a continuous basis from all sectors of electrical demand. Advances in modeling and IT capabilities have made demand response an attractive option to increase power system flexibility. This will consequently allow a more efficient use of system assets and resources. Since a limitation to manipulate the electricity's wholesale price for large producers is given by the time varying price and a locational differentiated DR strategy it is important that supplier and locational market power meet their reduction by allowing that DR strategy. Therefore some benefits can be that the volatility of peak prices can be reduced as well as the average of wholesale prices [47].

Currently consumers have no means of receiving information that would reflect the state of the grid thus cannot react to reach the balance and increase efficiency. Due to the nature of renewable, it is not possible to control or request power when it is needed. The main objectives of DR techniques are reduction of peak load and the ability to control consumption according to generation [49].

4.3 Energy Storage

At the same stage, energy storage systems (ESS) is other the important component of integrated systems in order to offset the unpredictable variation of the energy supplied by intermittent renewable energy sources like solar or wind power. Energy storage systems help in peak shaving, smoothing out load fluctuations, making up for intermittent variation in renewable energy sources so as to make an efficient energy management in integrated systems [50]. A PV system in which storage is not included, would achieve demand reductions based on the output of the PV system only at the time that the utility or the building is experiencing peak demand [33]. However, energy storage compensates the mismatch between renewable power generation and demand which is important for both economic and technical reasons [51]. With battery energy storage systems (BESS) the load leveling involves storing electric energy in a battery during the off-peak period, and extracting it during the peak period [52].

Load profile of an isolated area is sharp peaked during evening time. Various generator sizes have to be increased in integrated system in order to meet evening peak load, and this raises the system cost. In integrated system, energy storage system helps in reducing peak power demand. During peak power demand, deficit energy is supplied by the storage systems. A simplified generation profile (with and without storage system) is given in Fig. 3.

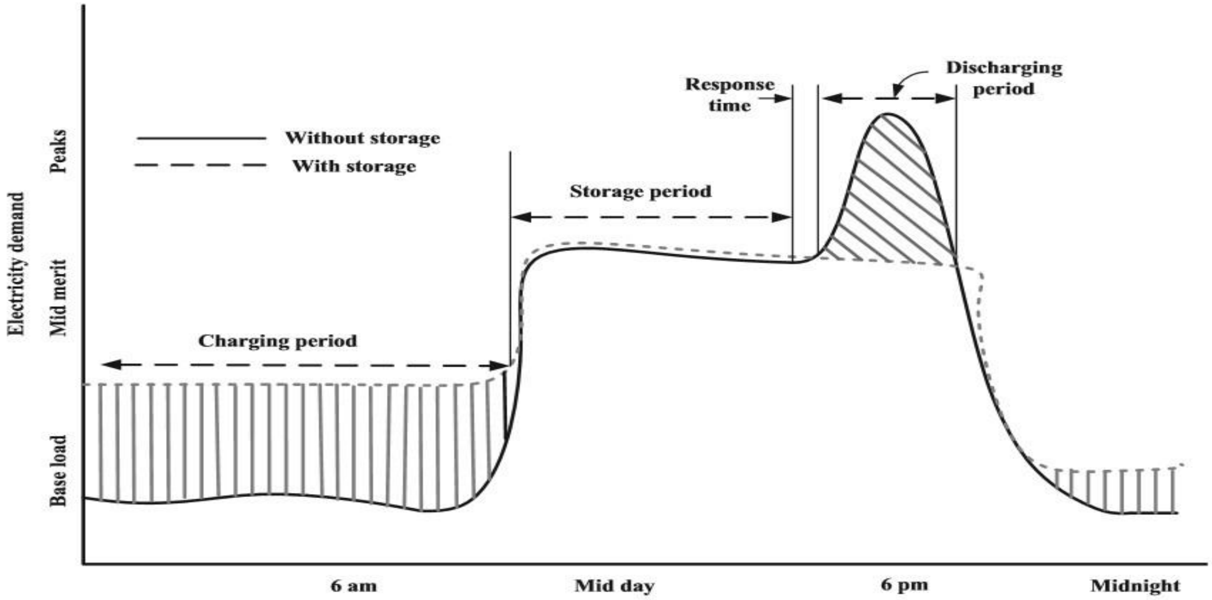


Figure 3. *Energy generation management using energy storage [56].*

In addition to load leveling, energy storage systems can provide a wide array of solutions to other key issues that affect the power system which include, but are not limited to, spinning reserve, frequency control, voltage regulation, relief of overloaded network components, capacity release, and the possibility of temporary islanding operations [53][54][55].

As mentioned in [57] "the rising retail prices for grid electricity and declining costs for solar PV and batteries mean that grid-connected solar-plus-battery systems will be economic within the next 10-15 years for many customers in many countries. So then utilities could see significant decline in energy sales that would support needed grid investment".

4. 4 Forecasting for a grid integration

The forecasting methods applied in the field of renewable energy can be classified into different categories: the physical model, the conventional statistical model, the spatial correlation model, and the artificial intelligence. Some of these prediction models are more accurate at short-term prediction while others are better in long-term prediction.

The advancement of photovoltaic energy into electricity market requires efficient photovoltaic power prediction systems. Furthermore, the analysis of PV power forecasting errors is essential for optimal unit commitment and economic dispatch of power systems with significant PV power penetrations. Generation forecasting has always been a key issue in power system operation, but with the use of renewable energy, the forecast becomes difficult due to the high variability of the electricity production of this new system.

Operational strategies and market structure changes are needed to address increased levels of uncertainty that high-penetration of renewable resources presents to utility companies and grid operators due to their intermittent nature. The use of advanced forecasting of variable generation is one of these essential strategies. Forecasts of future solar energy system output allows grid operators and utilities to proactively manage variable output, and thus integrating solar resources into the existing grid at lower costs to society.

Photovoltaic forecasts have only recently been introduced into electricity system operation, and forecasting rapid solar ramp rates is also garnering attention among electricity system operators. Likewise, the advent of the smart grid with predictive control of buildings and electricity loads will place its own requirements on PV forecasting and help spur new developments. Although the solar forecasting industry is in the early stages of market development and acceptance, several companies currently offer solar forecasting services. Benchmarking efforts have been conducted to compare the accuracy of various solar and PV forecast models against common datasets. Such benchmarking is critical to assessing forecast accuracy, since this accuracy depends on numerous factors, such as local climate, forecast horizon and whether forecasts apply to a single point or cover a wide geographic area. In the latter case, which is often the main interest of electric system operators, higher accuracies can be achieved since random errors at distant locations tend to be largely uncorrelated and to partially cancel out.

Chapter 5. Case Studies for DSM and DR

At chapter 3 it was settled up that in order to accommodate variable sources of electricity, it is necessary that grid-operators deploys load balancing techniques that increase grid flexibility and some of these techniques include energy storage and demand-side management. At chapter 4 it was shown that DSM can be used as a tool to accomplish different load shaping objectives, such as flexible load shape and to mitigate the variations in production of renewable energy and reduce building peak demand. It was also concluded that by applying DR programs the high peak load from the demand side can be avoided. For the present chapter are used the Demand Response method of rescheduling in order to decrease the mismatch between PV generation and demand.

5.1 Electricity Demand

This sections presents the two case studies for this master thesis work. Both of them are focused to analyze the PV residential sector generation and demand for weekdays and weekends for all the Portuguese residential buildings, considering a 50% of the buildings with PV generation.

The electricity consumption breakdown in EU households provided by the REMODECE project was used to characterize the load profile of the different loads [58]. A survey made by the National Institute of Statistics and the Direction-General for Energy and Geology, considered for Portugal an average consumption of electricity per house hold as 3673 kWh/year. It is also shown the ownership rates of each type of appliance in the Portuguese households. Then, considering the ownership rates of each appliance and the total number of households (3.9 millions), each load profile was adapted to the Portuguese reality.

Figure 4 presents the considered load profile to the residential sector in Portugal during week days and Figure 5 presents the same load but for the weekends.

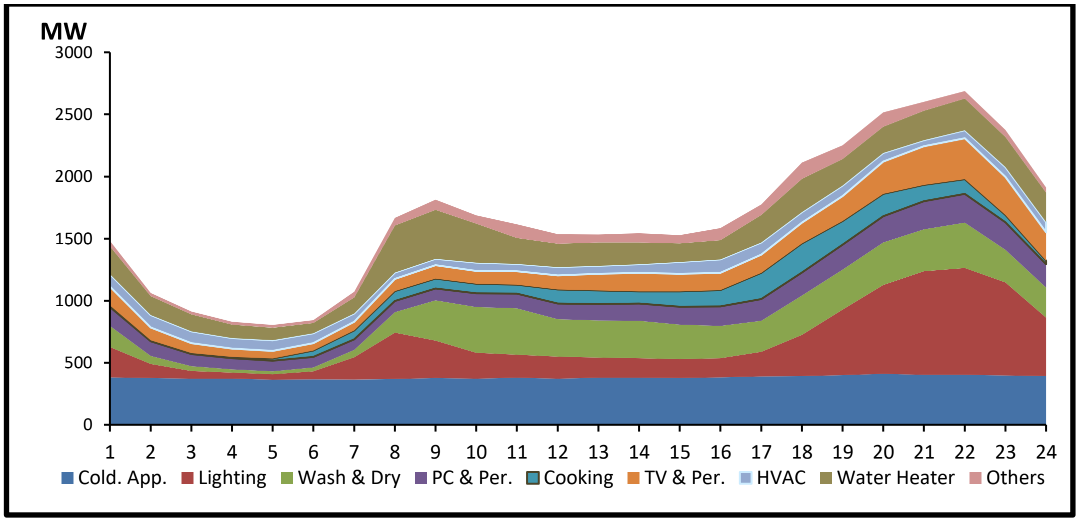


Figure 4. *Load profile per type of use for the residential sector in Portugal for weekdays.*

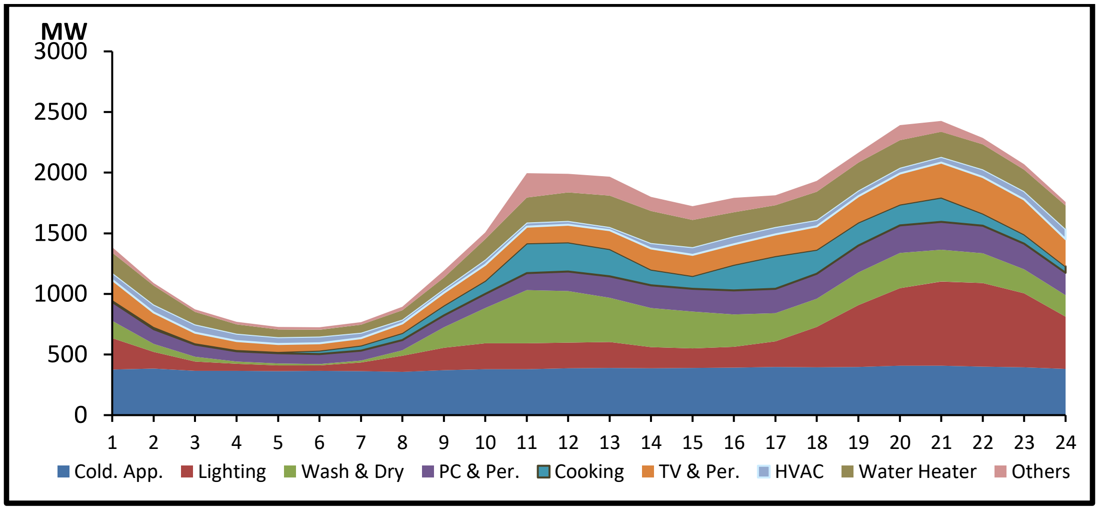


Figure 5. *Load profile per type of use for the residential sector in Portugal for weekends.*

At Figures 4 and 5 for weekdays and weekends respectively, it is projected the 8 types of load profile appliances (cold appliances, lighting, washing and drying, ICT, cooking, audiovisual, HVAC and others) and these ones are classified into 3 main categories in order to apply further DR strategies for the minimization of the PV mismatch between generation and demand as shown in Figure 6. Such appliances can be divided into two main groups: controllable and non-controllable appliances. The non-controllable appliances use depends mainly on the user behaviour and its operation cannot be changed without a negative impact on the comfort level. This group includes appliances such has lighting, ICT, cooking or audio-visual appliances.

The controllable appliances can in turn be divided into two groups: reschedulable appliances and interruptible appliances. In the reschedulable appliances the start of the operation can be delayed or anticipated based on the load management requirements. This group includes mainly the washing and drying appliances. The limitations for this operation are mostly set by consumer preferences, but also by technical constraints (e.g., the noise during night operation should be avoided and wet clothes should not be left too long in the washing machine).

In the interruptible appliances, the appliances are already in operation and under certain conditions it may be possible to interrupt the cycle of operation for a certain period. This is typically done with thermal loads such as cold appliances, water heaters and HVAC, which can be turned OFF during several minutes without a major change on temperature.

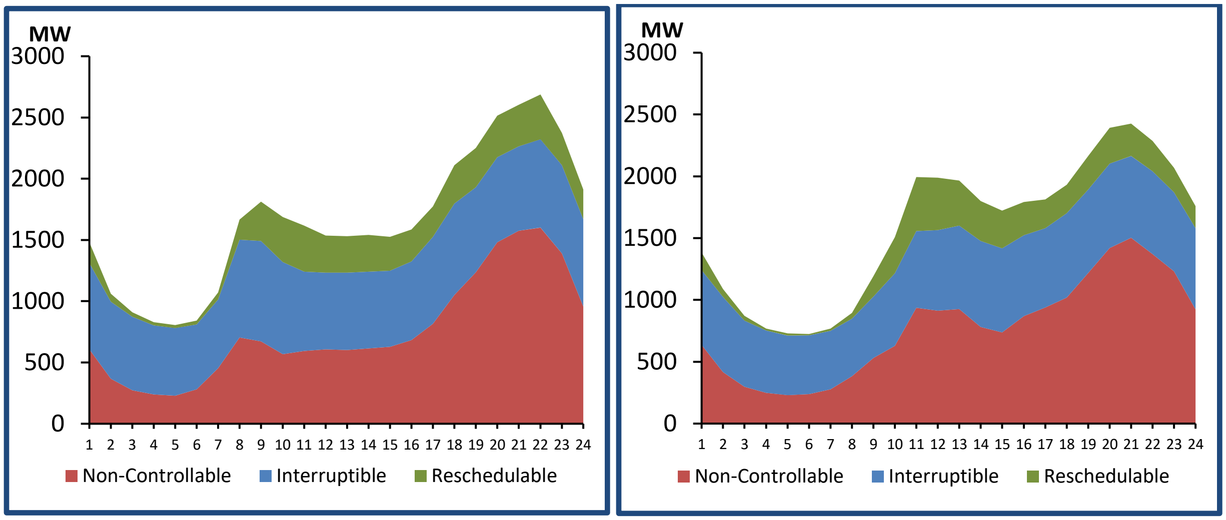


Figure 6. *Load profile diagram for Non-controllable, Interruptible and Reschedulable appliances without reschedule of loads for weekdays (left) and for weekends (right).*

5.2 Electricity Generation

The PV generation considers the average radiation in Coimbra and a yearly generation level of the average household of 3673 kWh. This is ensured with 2.4 kW of PV installed by building. However, a scenario that considers PV generation in all buildings is not realist. Therefore, it such generation was considered to 50% of the Portuguese buildings (the data was extrapolated to about 2 millions of households). In order to represent different conditions, it was selected data from 3 months: August (higher generation), October (almost the same level of generation and consumption) and December (higher consumption).

Figures 7-9 presents the generation profile, the demand profile and the exchange of energy with the grid (difference between the generation and consumption levels) during week days.

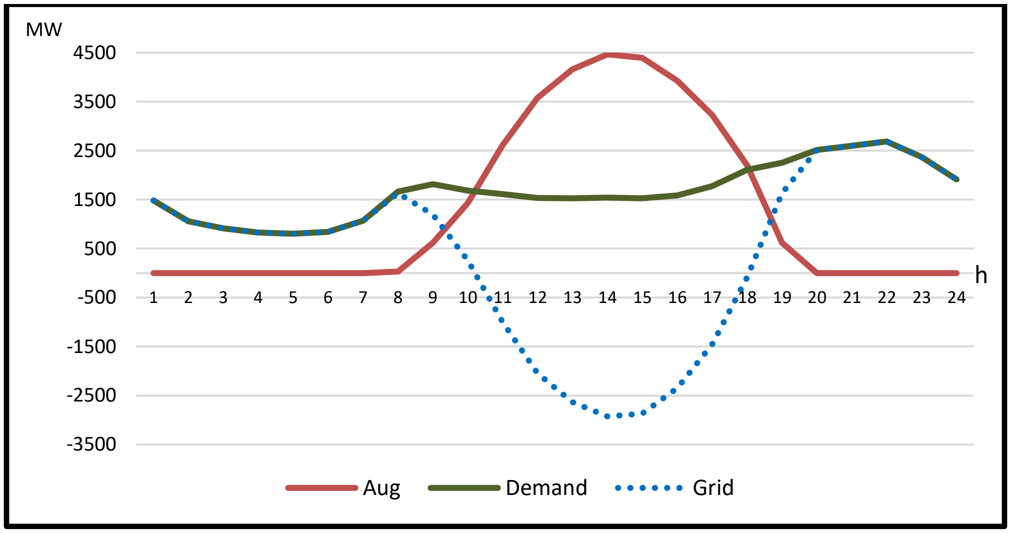


Figure 7. *Generation, demand and exchange with the grid during August weekdays.*

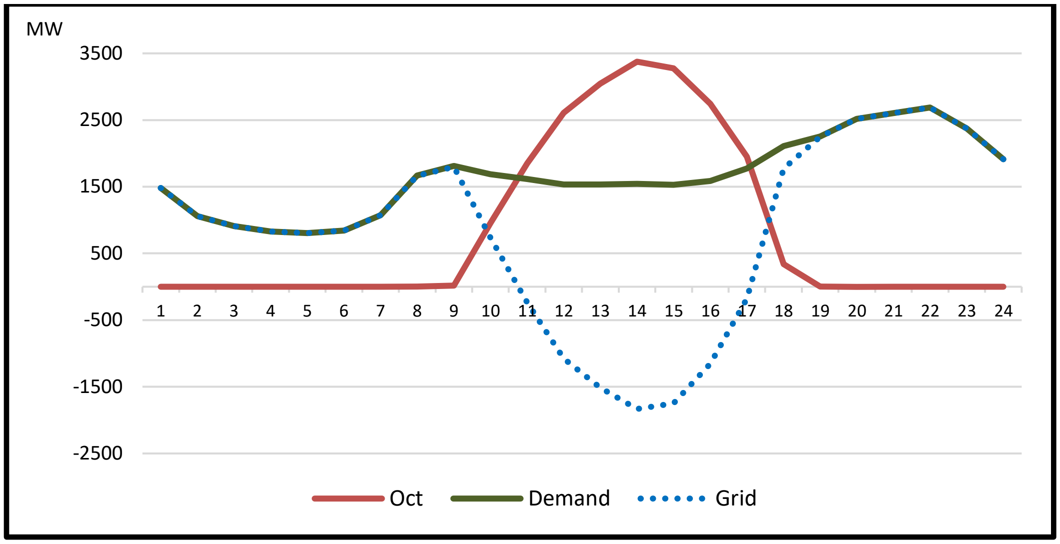


Figure 8. *Generation, demand and exchange with the grid during October weekdays.*

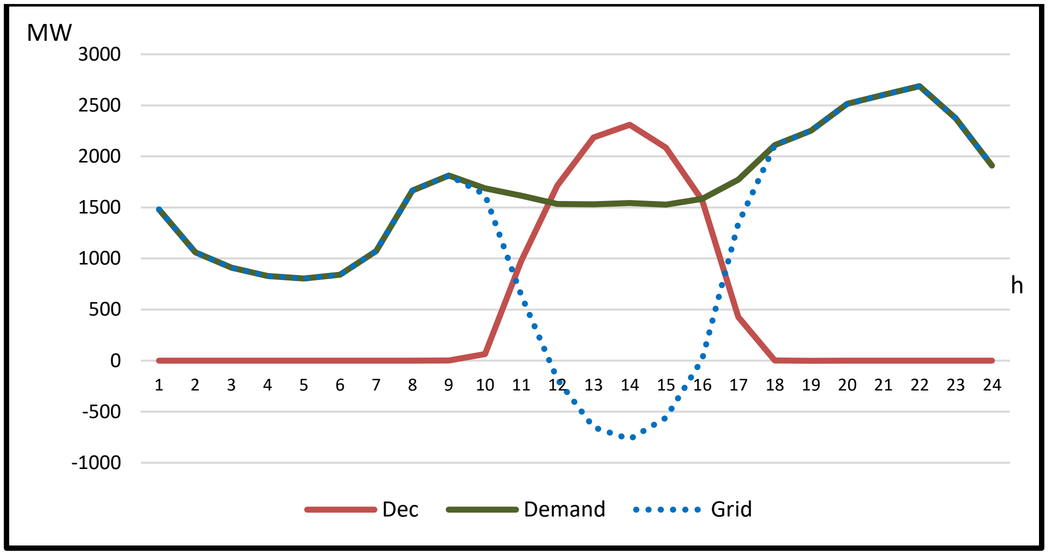


Figure 9. *Generation, demand and exchange with the grid during December week days.*

Figures 10-12 present the generation profile, the demand profile and the exchange of energy with the grid during weekends.

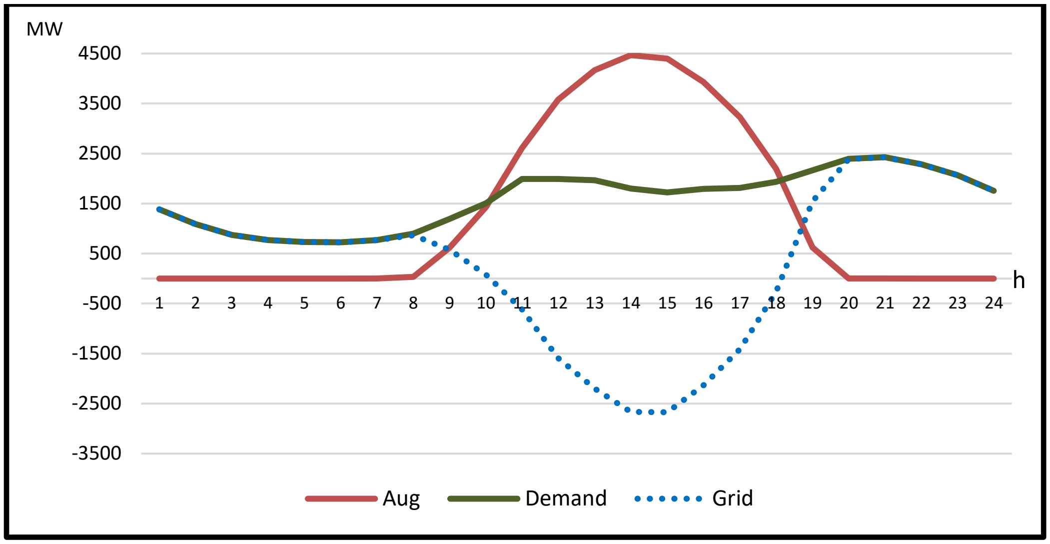


Figure 10. *Generation, demand and exchange with the grid during August weekends.*

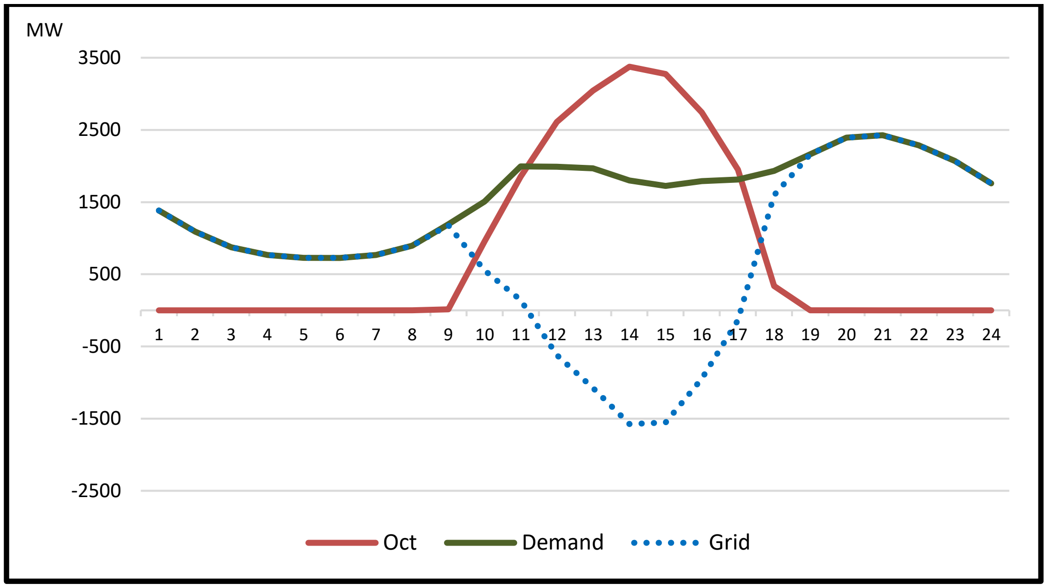


Figure 11. *Generation, demand and exchange with the grid during October weekends.*

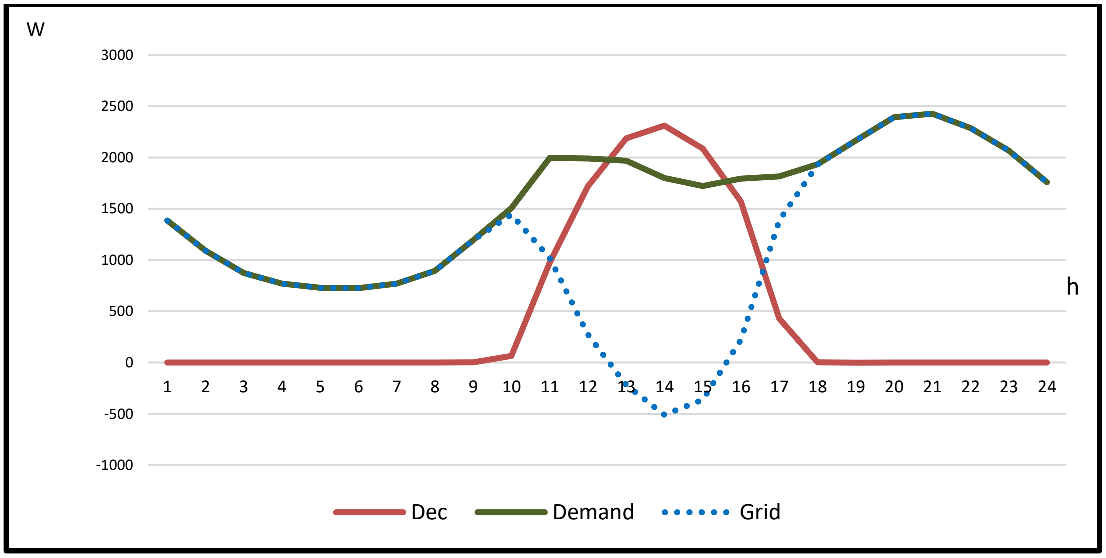


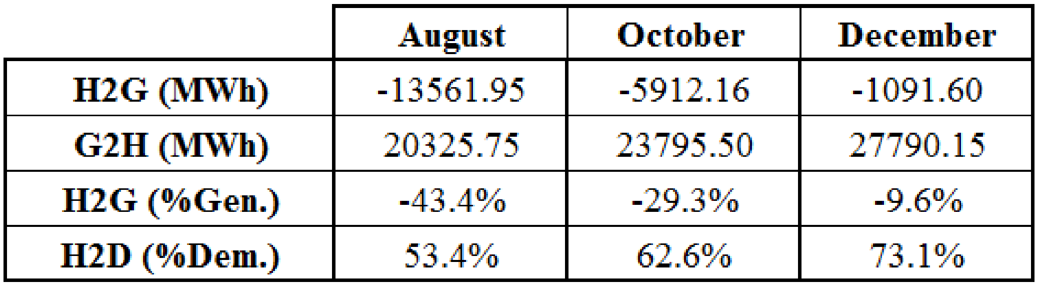
Figure 12.*Generation, demand and exchange with the grid during December weekends.*

In a household that does not have control of loads, constantly there is a power flow between the grid and the household and during these power flow it is sent to the grid the most of generation leading to receive from the grid all the energy that it is needed during the night. As can be seen in Table 1, in such conditions for weekdays for the total residential buildings, between 19.1% and 49.1% of the generated energy is injected into the grid (H2G) and, simultaneously, between 59.9% and 76.9% of the consumed energy must be requested to the grid (G2H).

	August	**October**	**December**
H2G (MWh)	-15350.02	-7736.02	-2160.80
G2H (MWh)	23809.81	27315.35	30555.33
H2G (%Gen.)	-49.1%	-38.4%	-19.1%
H2D (%Dem.)	59.9%	68.7%	76.9%

Table 1. *Energy exchange between the households and the grid during week days without rescheduling.*

At Table 2 it can be seen that for weekends, the percentage of energy injected into the grid is between 9.6% and 43.4%, these differences represent a less energy injected into the grid due to the higher energy consumption during the day in weekends and the percentage of energy requested to the grid is between 53.4% and 73.1% this means that less energy it is being consumed from the grid due to a lower global consumption in weekends.

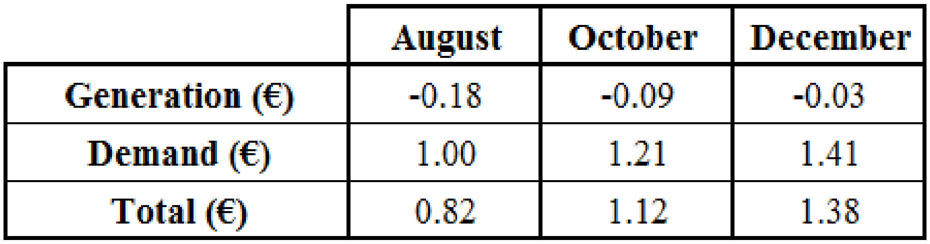


	August	October	December
H2G (MWh)	-13561.95	-5912.16	-1091.60
G2H (MWh)	20325.75	23795.50	27790.15
H2G (%Gen.)	-43.4%	-29.3%	-9.6%
H2D (%Dem.)	53.4%	62.6%	73.1%

Table 2. *Energy exchange between the household and the grid during weekends without rescheduling.*

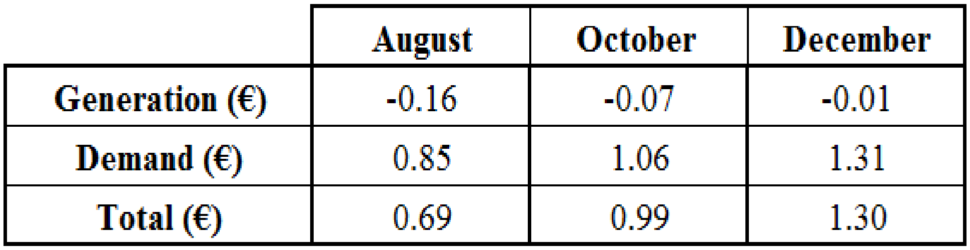
These high power flows have technical impact and also an economic impact. In Portugal, based on the Portuguese regulation to self-consumption of locally generated electricity, the price of electricity injected into the grid is paid at the price of 90% of the monthly average price of the Portuguese spot electricity market. In 2015 the mentioned average price of the Portuguese spot electricity market was 0.0503 €/kWh and consequently the price paid by the electricity injected into the grid it was in average 0.0453 €/kWh. In the other hand there is a high cost of the energy that it is received from the grid (0.2395 €/kWh during on-peak periods and 0.1242 €/kWh during off-peak periods). Therefore, any energy that is injected into the grid and not used to self-consumption leads to economic losses for the users.

As can be seen in Table 3, for weekdays there is an average daily cost per building between 0.82€ and 1.38€, and for weekends it can be seen at Table 4 that the average daily cost per building is between 0.69€ and 1.30€.



	August	October	December
Generation (€)	-0.18	-0.09	-0.03
Demand (€)	1.00	1.21	1.41
Total (€)	0.82	1.12	1.38

Table 3. *Energy costs without reschedule for Generation and Demand during the week days.*



	August	October	December
Generation (€)	-0.16	-0.07	-0.01
Demand (€)	0.85	1.06	1.31
Total (€)	0.69	0.99	1.30

Table 4. *Energy costs without reschedule for Generation and Demand during the weekends.*

Chapter 6. Case studies impact analysis

In the previous chapter it was presented the data for the PV generation and consumption for weekdays and weekends, as well as their respectively costs of energy. In this chapter, the impacts of applying DR strategy of rescheduling the appliances for both of the case studies, weekdays and weekends, is going to be assessed.

6.1 Weekdays

The rescheduling method of Demand Response program allows the utility to controls the times in which the appliances are going to be used in order to reduce the peak demand. Customers who use this method of incentive to the utility, can receive credits or discounts for their bills.

Figure 13 presents the load profile diagram for week days presented in Figure 6 but now considering a reschedule of average consumption for the three type of appliances. The strategy used it was to concentrate the consumption on reschedulable appliances in hour with generation surplus.

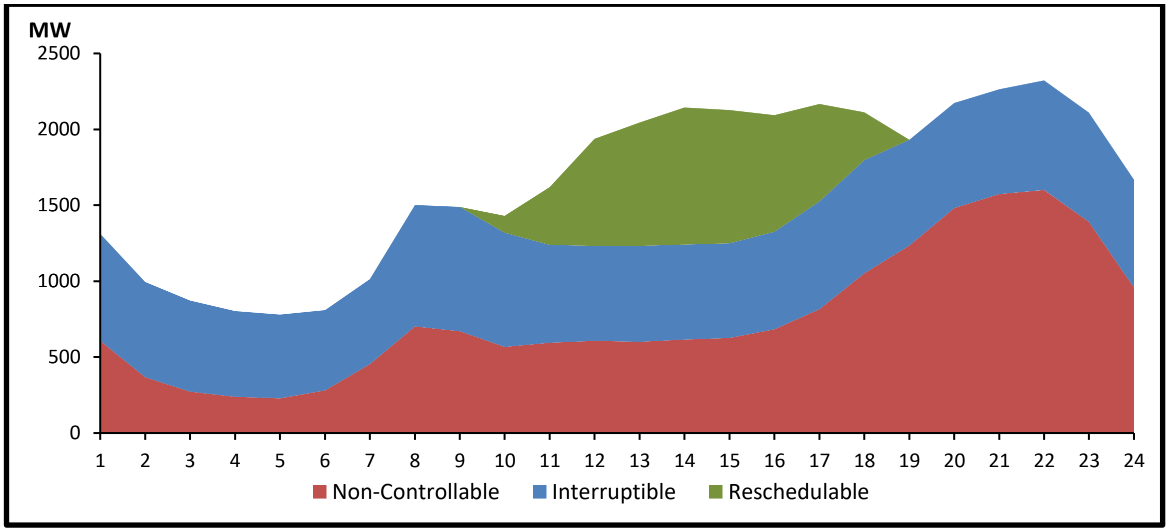


Figure 13. *Load profile diagram for Non-controllable, Interruptible and Reschedulable appliances with reschedule of loads for weekdays.*

Figures 14-16 presents the impact on exchanges between the household and the grid for the weekdays, due to the applied reschedule for the months of August, October and December. The figures present the generation profile, the demand profile with rescheduling and the exchange of energy with the grid.

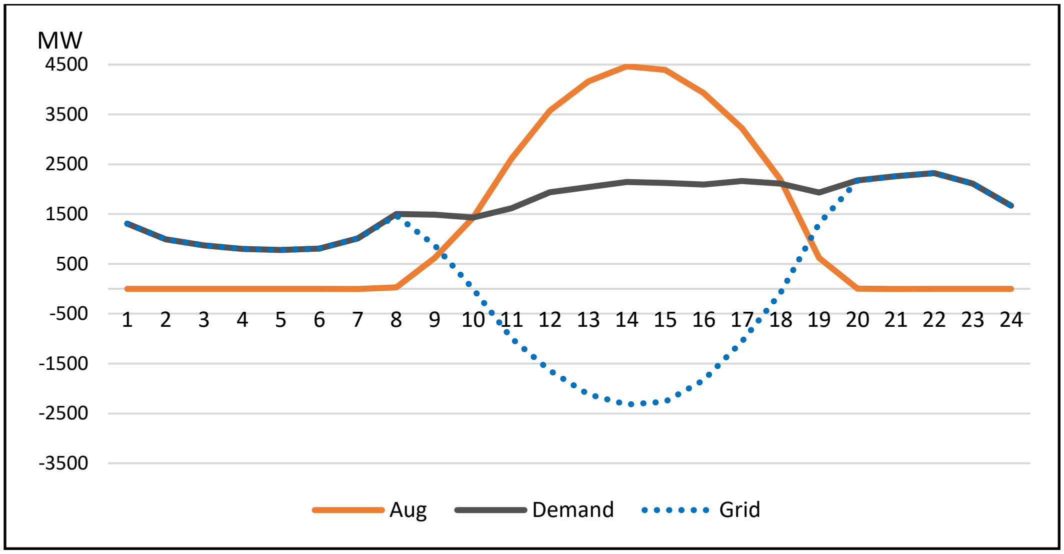


Figure 14. *Generation, demand with rescheduling and exchange with the grid during week days in August.*

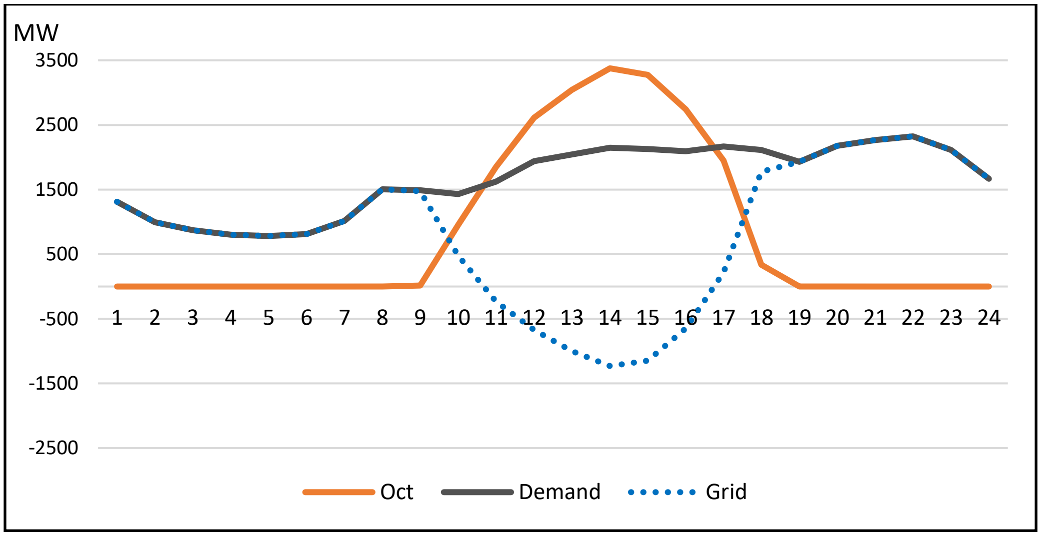


Figure 15. *Generation, demand with rescheduling and exchange with the grid during week days in October.*

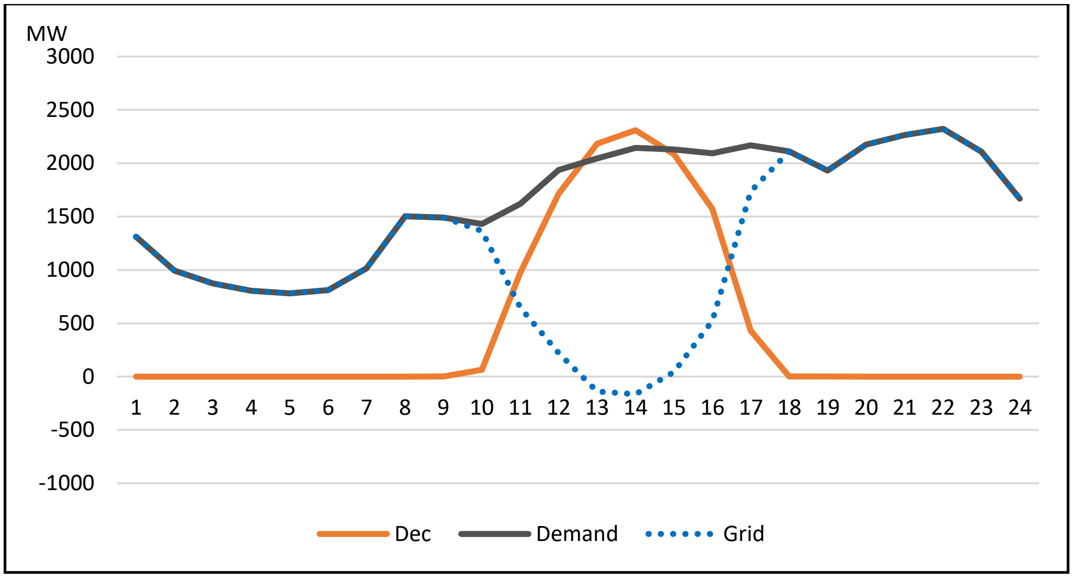


Figure 16. *Generation, demand with rescheduling and exchange with the grid during weekdays in December*.

By using DSM measures, it is possible to maximize the matching between the generation and consumption. Reliable operation of power grid is primarily dependent on perfect balance between supply and demand at each given time and it is not an easy task to maintain balance assuming there is very little control on the demand side (generation side can be controlled according to the load).

Figures 17 -19 presents for the weekdays of August, October and December, the generation profile and the demand profile with and without rescheduling and the exchange of energy with the grid, in the scenarios with and without rescheduling.

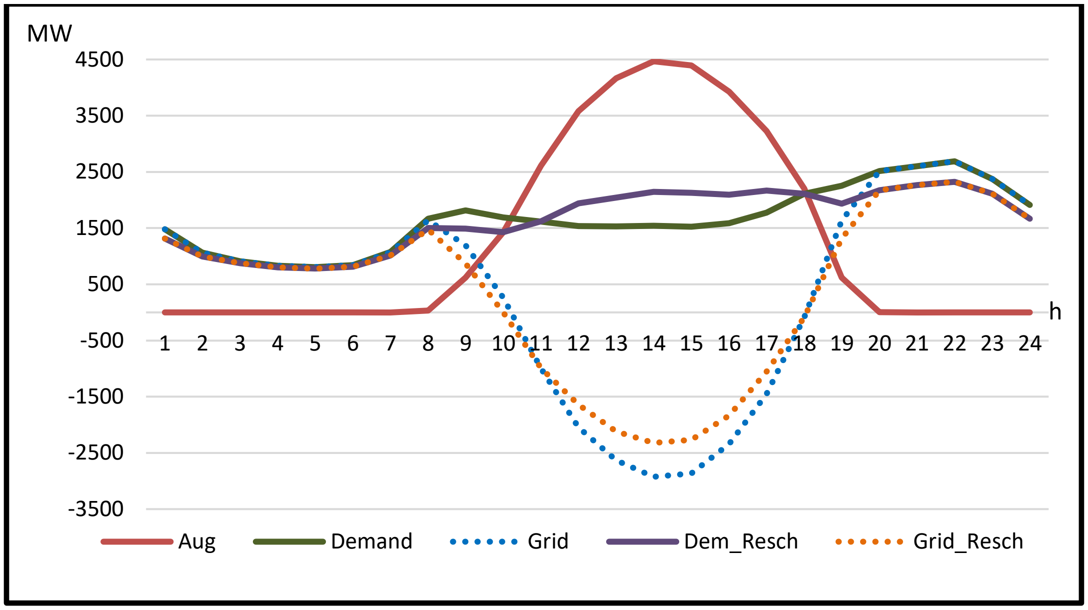


Figure 17. *Generation, demand and exchange with the grid during week days in August with and without reschedule of appliances.*

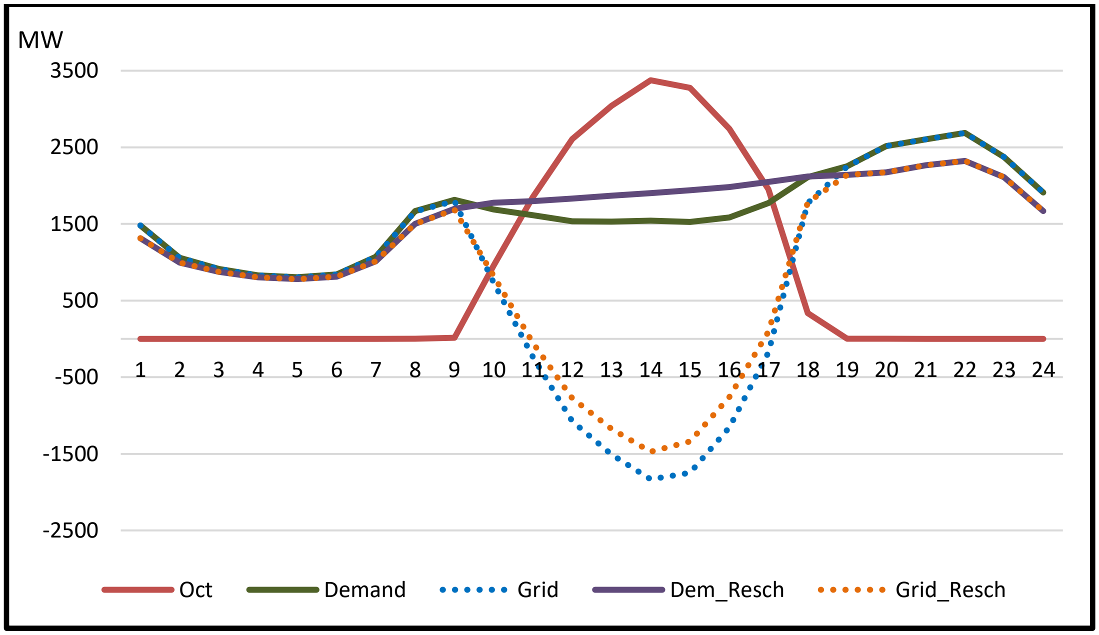


Figure 18. *Generation, demand and exchange with the grid during week days in October with and without reschedule of appliances.*

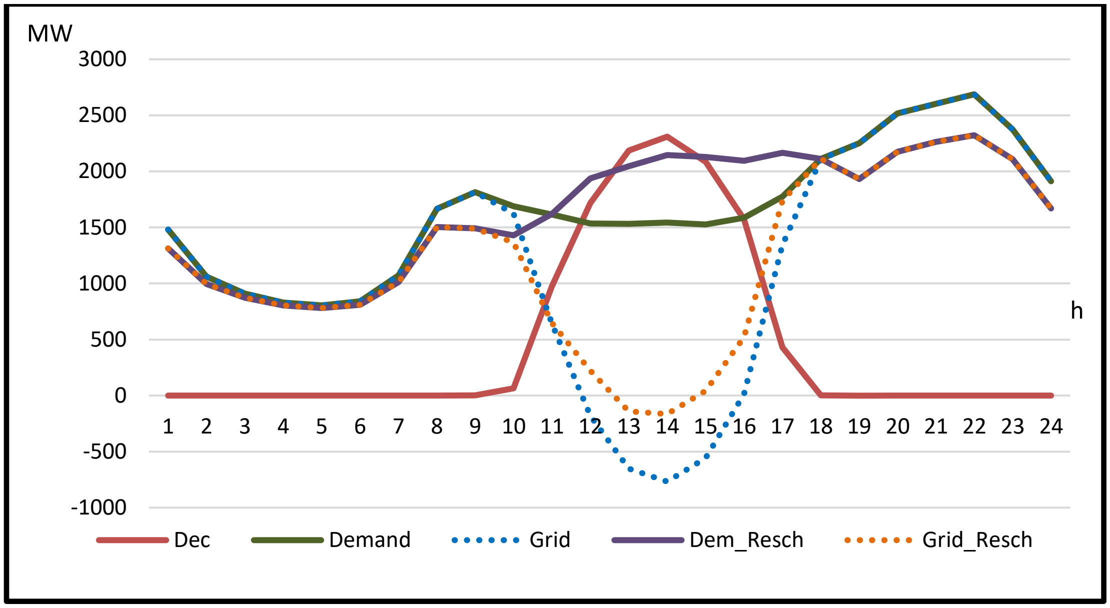


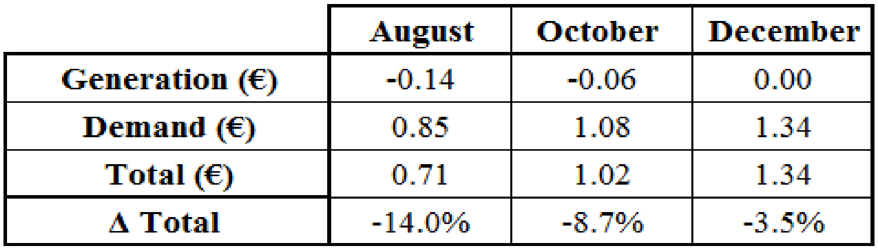
Figure 19. *Generation, demand and exchange with the grid during week days in December with and without reschedule of appliances.*

At Table 5 it can be seen that this strategy of rescheduling leads to a decrease between 19.7% and 85.9% on the energy that it is sent into the grid and, at the same time, a reduction between 6.1% and 12.7% on the energy that it is consumed from the grid.

	August	**October**	**December**
H2G (MWh)	-12320.48	-4923.44	-304.32
G2H (MWh)	20780.32	24502.81	28698.91
H2G (%Gen.)	-39.4%	-24.4%	-2.7%
H2D (%Dem.)	52.3%	61.7%	72.2%
Δ2G%	19.7%	36.4%	85.9%
Δ2H%	12.7%	10.3%	6.1%

Table 5. *Daily energy exchange between the household and the grid considering reschedule of appliances during week days.*

During December there is 72.2% of the energy demand ensured by the grid. This is justified by the lower generation level during the winter leading to a higher need of energy consumed from the grid. The reduction impact on the energy exchanged between the household and the grid also have as impact a reduction between 3.5% and 14% on the daily costs, as can be seen in Table 6.



	August	**October**	**December**
Generation (€)	-0.14	-0.06	0.00
Demand (€)	0.85	1.08	1.34
Total (€)	0.71	1.02	1.34
Δ Total	-14.0%	-8.7%	-3.5%

Table 6. *Daily energy exchange between the household and the grid considering reschedule of appliances during weekdays.*

6.2 Weekends

The case study for weekends was done following the same structure as presented for the weekday's case study, but having in mind that due to the different consumption profile during weekends it is going to be presented differences on the results. Figure 20 presents the load profile for weekends in which it was applied the strategy of concentrate the consumption on reschedulable appliances in hour with generation surplus for the three main types of appliances: non-controllable, interruptible and reschedule appliances, in order to ensure the generation and consumption matching objectives, the reschedule appliances can be changed in its operation period in order to match the period with higher generation.

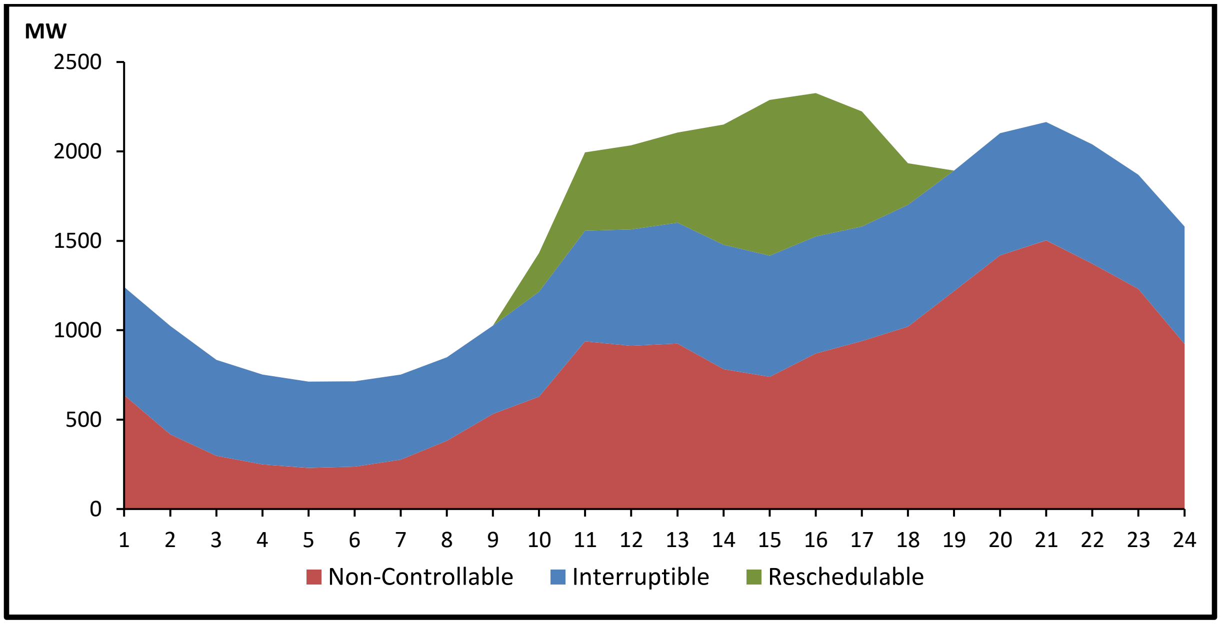


Figure 20. *Load profile diagram for Non-controllable, Interruptible and Reschedulable appliances without reschedule of loads for weekends.*

Figures 21-23 presents the impact on exchanges between the household and the grid for the weekdays, due to the applied reschedule for the months of August, October and December. The figures present the generation profile, the demand profile with rescheduling and the exchange of energy with the grid.

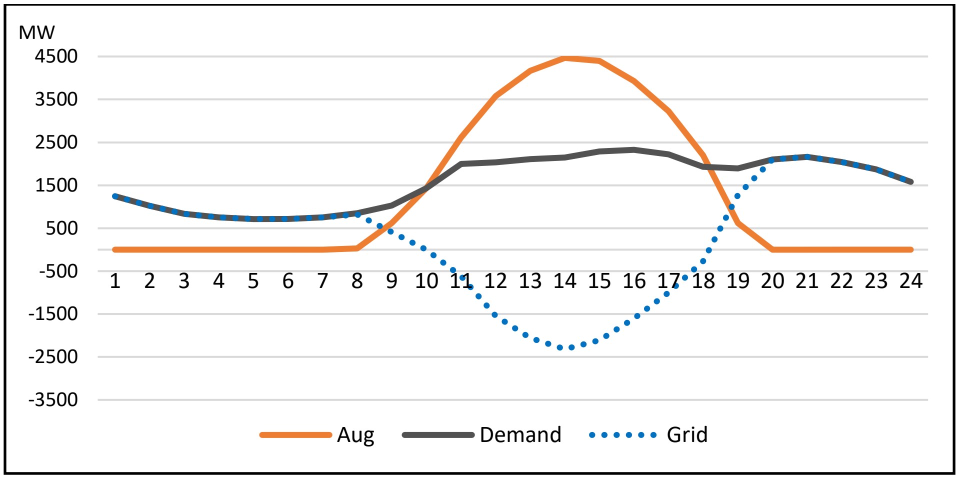


Figure 21. *Generation, demand and exchange with the grid during weekends in August.*

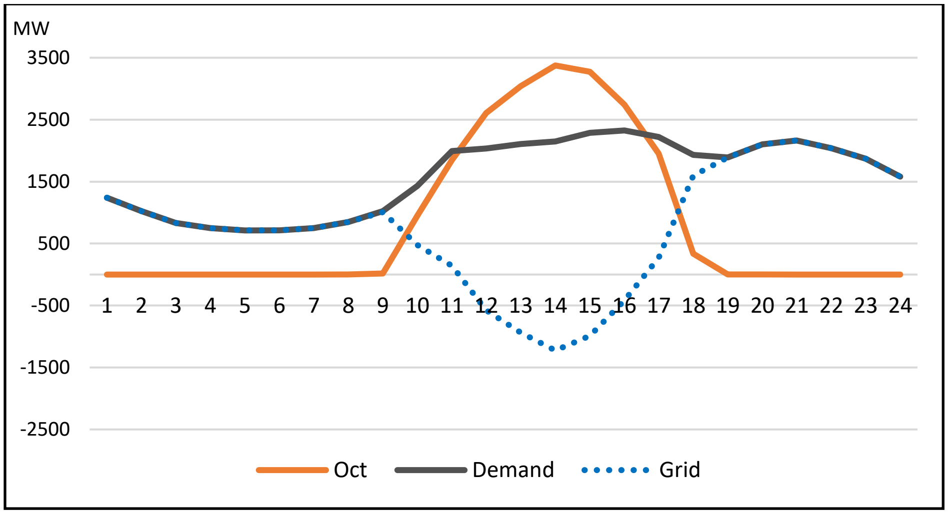


Figure 22. *Generation, demand and exchange with the grid during weekends in October.*

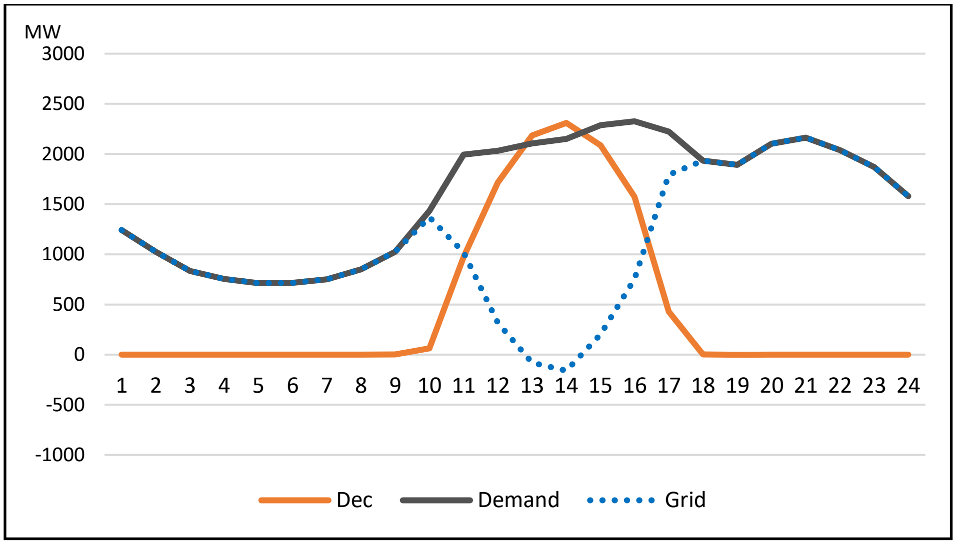


Figure 23. *Generation, demand and exchange with the grid during weekends in December.*

It can be seen that due to the applied rescheduled it is possible to reduce the amount of energy that it is injected into the grid during the hours with generation, as well as to decrease the amount of energy that it is requested from the grid in the hours without generation.

Figures 24 -26 presents for the weekend of August, October and December, the generation profile and the demand profile with and without rescheduling and the exchange of energy with the grid, in the scenarios with and without rescheduling.

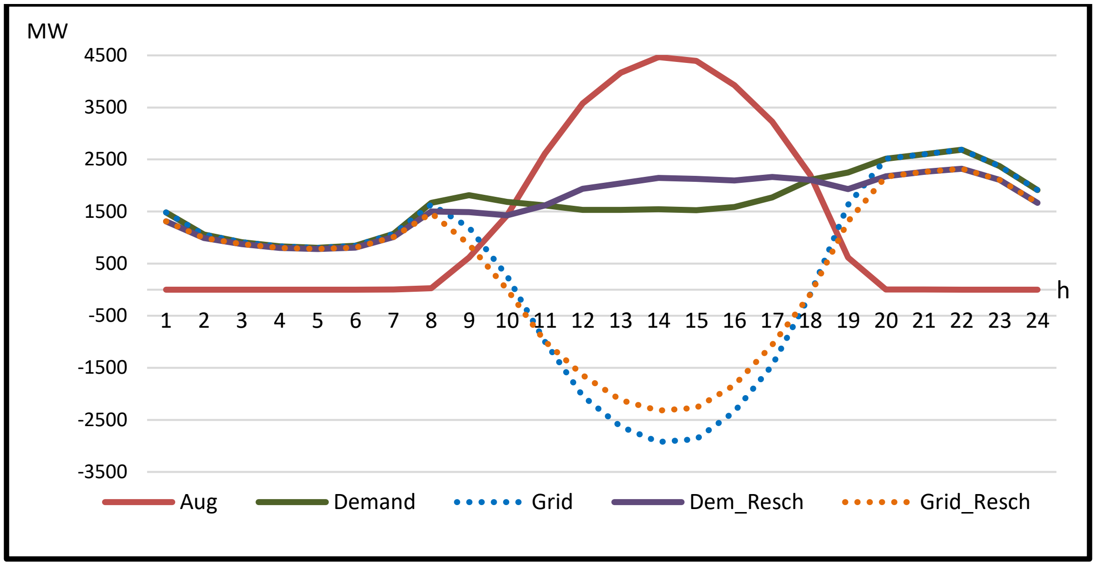


Figure 24. *Generation, demand and exchange with the grid during weekends in August with and without reschedule of appliances.*

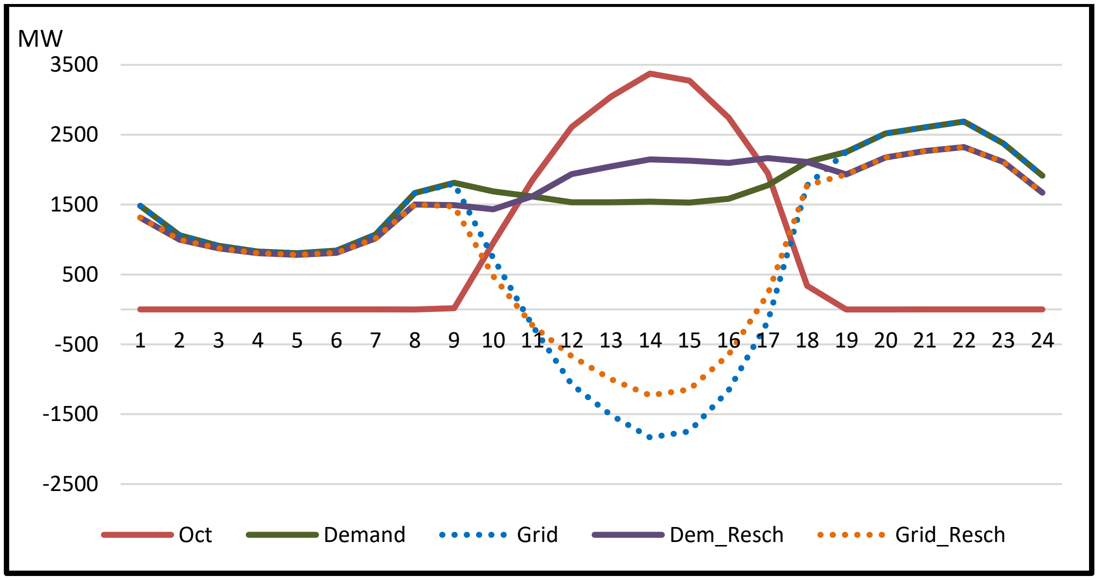


Figure 25. *Generation, demand and exchange with the grid during weekends in October with and without reschedule of appliances.*

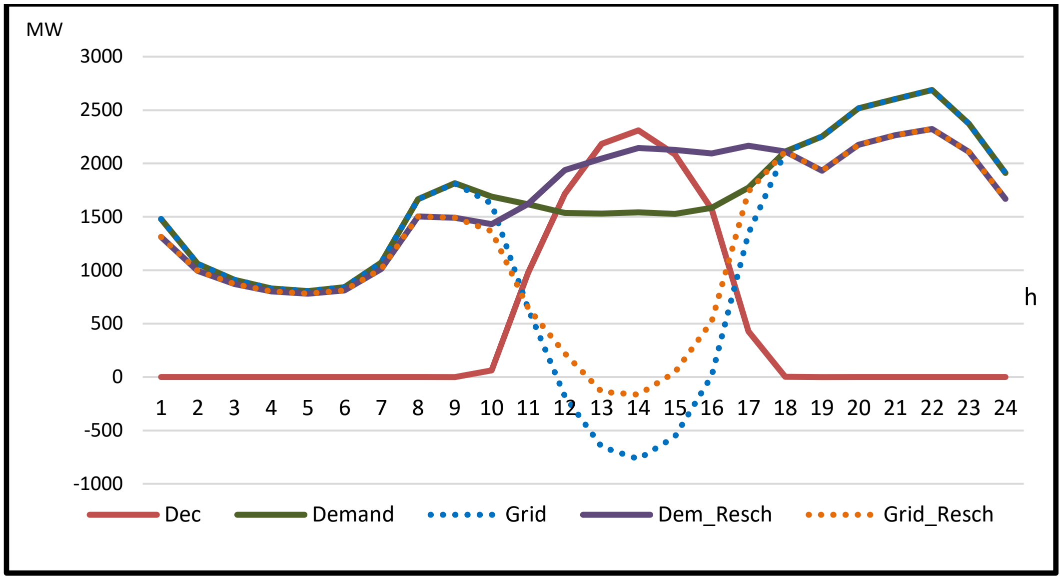
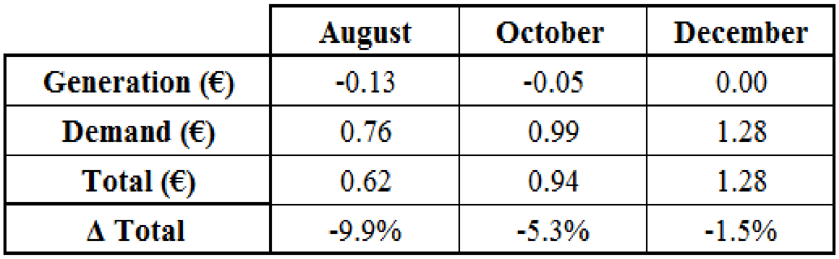


Figure 26. *Generation, demand and exchange with the grid during weekends in December with and without reschedule of appliances.*

The strategy of rescheduling during weekends primes to a reduction among 15.1% and 78.1% on the energy sent into the grid and at the same time, a decrease among 3.1% and 10.1% on the energy that it is consumed from the grid. Table 7 presents the daily energy exchange between the household and the grid considering reschedule of appliances during weekends. Such reduction also have as impact on the daily costs with a reduction between 1.5% and 9.9%, as can be seen in Table 8.

	August	**October**	**December**
H2G (MWh)	-11518.91	-4141.98	-239.52
G2H (MWh)	18282.71	22025.31	26938.07
H2G (%Gen.)	-36.8%	-20.6%	-2.1%
H2D (%Dem.)	48.1%	57.9%	70.8%
Δ2G%	15.1%	29.9%	78.1%
Δ2H%	10.1%	7.4%	3.1%

Table 7. *Daily energy exchange between the household and the grid considering reschedule of appliances during weekends.*



	August	October	December
Generation (€)	-0.13	-0.05	0.00
Demand (€)	0.76	0.99	1.28
Total (€)	0.62	0.94	1.28
Δ Total	-9.9%	-5.3%	-1.5%

Table 8. *Energy costs considering reschedule of appliances during weekends.*

Chapter 7. Conclusions and further work

7.1 Conclusions

The objective of this thesis it is to analyze photovoltaic solar generation in order to minimize the grid integration issues through Demand Side Management measures, using Demand Response as tool for compensate the mismatch between generation and demand at the residential buildings sector in Portugal.

For the problems produced by the mismatch between the PV generation and consumption, several appliances can be used as Demand-Side Management (DSM) resource minimizing that disparity. Usually, the main objective of demand side management is to encourage users to consume less power during peak times or to shift energy use to off-peak hours to flatten the demand curve. However, sometimes, instead of flattering the curve it is more desirable to follow the generation pattern. In each case, there is a need of control over customer energy use.

At the present thesis the PV generation and consumption was analyzed in order to obtain the best way to compensate the mismatched caused by PV systems by using strategies of DSM and DR. Therefore, for the two case studies of weekdays and weekends the generation and consumption profile for three months of the year, representing a higher generation in August, almost the same level of generation and consumption in October and higher consumption in December were assessed. Subsequently, the impact of DSM measures were assessed by comparing the energy injected into the grid and the associated costs.

The PV residential sector generation and demand for weekdays and weekends was assessed for all residential buildings in Portugal, considering a 50% of the buildings with PV generation. It was demonstrated that by applying a DR Rescheduling technique it is possible for the weekdays to decrease between 19.7% and 85.9% the energy that it is sent into the grid and, at the same time, to reduce between 6.1% and 12.7% the energy that it is consumed from the grid Considering a price paid by the electricity injected into the grid as 0.0453 €/kWh and the prices for the energy that it is received from the grid at 0.2395 €/kWh during on-peak periods and 0.1242 €/kWh during off-peak periods, a reduction between 3.5% and 14% on the daily costs was achieved.

At the same way, it was proven that for the weekends period it can be achieved a reduction among 15.1% and 78.1% on the energy sent into the grid and at the same time and a decrease among 3.1% and 10.1% on the energy that it is consumed from the grid. It was also achieved a reduction on the daily costs between 1.5% and 9.9%.

Finally, it can be concluded the existence of feasibility on the analysis and characterization of the Demand Side Management and Demand Response strategies. With the control of demand, it is possible to reduce the energy injected into the grid in order to ensure a more efficient matching between the generation and consumption.

7.2 Future work

The study performed during this thesis can be improved by performing a research for achieve the best combination of PV system plus energy storage to install in buildings in order to reduce the energy exchange between the household and the grid, as well as the associated costs. Furthermore, it can be assessed which load shifting, curtailment and storage management strategies increases the feasibility and efficiency of the PV system integration at the grid to compensate the mismatch that occurs at the grid due to loads fluctuations. So it can be assessed and simulate for the small and large scale integration of PV systems, the impact on the electrical grid (power flows, losses and load diagram), costs (for the grid and users) and GHG emissions. For this, different control rules to the energy storage and demand control can be defined with different objectives from the user and from the grid point of view and considering different generation and consumption profiles and case studies in order to ensure an efficient level of generation and consumption matching.

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