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PROVISION OF ADVANCED ANCILLARY SERVICES THROUGH DEMAND SIDE INTEGRATION

Miguel Luís Delgado Heleno

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Thesis Supervisor: Manuel António Cerqueira da Costa Matos
Thesis Co-supervisor: João Abel Peças Lopes
Full Professors at the
Department of Electrical and Computer Engineering
Faculty of Engineering, University of Porto

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“We are all mortal until the first kiss and the second glass of wine,
which is something everyone knows, no matter how small his or her
knowledge.”

Eduardo Galeano, *in “The Book of Embraces”*.

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Abstract

The penetration of generation coming from renewable sources has been growing significantly during the last decades in order to achieve the CO2 emissions targets. However, renewables bring more uncertainty and variability to the system by changing the predicted balances between generation and demand, which increases the need for ancillary services. Currently, the majority of these services are provided by the generation units that establish bilateral contracts with the system operator and/or participate in the ancillary services markets.

However, on the demand side, home energy management solutions and smart appliances are starting to be offered to the electricity consumers. These solutions comprise a set of functionalities – such as appliances control and monitoring – enabling a variety of new services to the end users. This emergent load control infrastructure creates the conditions for demand response techniques and for the provision of ancillary services from the demand side.

Thus, this thesis conceptualizes and develops a technical framework for the provision of ancillary services by residential consumers, starting at the appliances level and ending at the markets level. This work is based on a structured approach, where demand response is treated as service/resource chain towards ancillary services. An architecture that identifies the main entities participating in the provision of ancillary services through residential consumers and establishes, from a technical point of view, the main interactions among them is presented.

At the residential level, a set of methods and tools allowing Home Energy Management System to quantify and maximize the demand response services is proposed. These tools take into account the smart appliances' control functionalities and physical characteristics as well as the behavior of the end-user.

Furthermore, a comprehensive methodology for the provision of flexibility services by demand side aggregators participating in tertiary reserve serve is presented. This methodology transforms the demand response services at the residential level into flexibility bids that can be offered in the reserve market. The objective is to maximizing the remuneration of the aggregator's bids in this market, considering the uncertainty of the reserve dispatch.

This research ends with a discussion about economic, social and regulatory aspects related to the provision of ancillary services through demand response. This aims at identifying the main drivers and barriers that can enable or limit the demand side flexibility services as well as evaluating the economic viability of the provision of those services.

Resumo

Nas últimas décadas, a produção de energia elétrica através de fontes renováveis tem aumentado com o objetivo de diminuir as emissões de CO2. No entanto, este tipo de produção de energia acarreta um grau de incerteza e variabilidade consideráveis para o sistema elétrico, alterando permanentemente o equilíbrio entre a oferta e a procura e aumentando as necessidades de serviços de sistema. A grande maioria destes serviços são fornecidos pelo lado da geração, através da participação em mercado ou pela via de contratos bilaterais com o operador de sistema.

Todavia, do lado do consumo residencial, têm surgido um leque de soluções tecnológicas, como os eletrodomésticos inteligentes ou as plataformas de gestão doméstica de energia, que fornecem um conjunto diversificado de serviços ao consumidor final, através da monitorização e do controlo eficiente dos seus consumos. A existência desta infraestrutura tecnológica de controlo ao nível doméstico cria as condições para que os serviços de sistema possam ser fornecidos também pelo lado da procura, através de técnicas de gestão dos consumos.

Assim, objetivo desta tese é conceber e desenvolver um conjunto de ferramentas que permitem o fornecimento de serviços de sistema pelo lado da procura. Este trabalho propõe uma abordagem estruturada às técnicas de gestão dos consumos, descrevendo-as como uma cadeia de recursos e serviços que começa nos eletrodomésticos inteligentes e acaba nos mercados de serviços de sistema. Por outro lado, é também apresentada uma arquitetura que identifica os principais agentes envolvidos no fornecimento destes serviços.

Ao nível da casa, são apresentados um conjunto de métodos e ferramentas que permitem às plataformas de gestão de energia quantificarem e maximizarem a disponibilidade dos consumos domésticos para o fornecimento de serviços de sistema. Estes métodos têm em consideração as características físicas e a capacidade de controlo dos aparelhos, assim como o comportamento dos consumidores.

Para além disso, este trabalho apresenta uma metodologia que permite aos agregadores participarem nos mercados de reserva terciária. Esta metodologia converte as disponibilidades dos consumidores em serviços de flexibilidade que podem ser oferecidos em mercado. O objetivo é maximizar os proveitos do agregador, considerando as incertezas associadas à mobilização da reserva.

Este trabalho termina com uma discussão sobre os aspetos económicos, sociais e regulatórios relativos ao fornecimento de serviços de sistema pelo lado da procura. Aqui, são identificadas as principais barreiras e os fatores que podem potenciar o fornecimento destes serviços pelo lado dos consumos e é avaliada a viabilidade económica dos mesmos.

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List of Acronyms and Abbreviations

AC	Air-conditioner
AGC	Automatic Generation Control
AMI	Advanced Metering Infrastructure
AMM	Automatic Meter Management
AMR	Automated Meter Reading
CVR	Conservation Voltage Reduction
DER	Distributed Energy Resources
DG	Distributed Generation
DLC	Direct Load Control
DRES	Distributed Renewable Energy Sources
DSB	Demand Side Bidding
DSI	Demand Side Integration
DSM	Demand Side Management
DSO	Distribution System Operator
EB	Energy Box
ENTSO-E	European Network of Transmission System Operators for Electricity
ETS	Electric Thermal Storage
EV	Electric Vehicles
EWH	Electric Water Heater
FAPER	Frequency Adaptive Power-Energy Re-scheduler
GUI	Graphical User Interface
HAN	Home Area Network
HEMS	Home Energy Management System
HMI	Human Machine Interface
ILC	Indirect Load Control
LAN	local area networks
LC	Load Control
LM	Load Management
MG	Microgird
MILP	Mixed Integer Linear Programming

MPC	Model Predictive Control
NIALM	Non-Intrusive Appliance Load Monitoring
PB	Payback
PBLM	Physically based load models.
PEV	Plug-in Electric Vehicles
RS	Reserve Services
RTP	Real Time Pricing
SG	Smart Grids
SM	Smart Meters
SS	System Services
ToU	Time-of-Use
TSO	Transmission System Operator
WAN	Wide Area Network

Chapter 1 – Introduction

1.1 Motivation for the Thesis

In the past few years, Demand Response (DR) started to be included in the list of energy efficiency targets towards the reduction of CO2 emissions. For example, in 2012 Energy Efficiency directive, the European Parliament and the Commission recognize that "demand response is an important instrument for improving energy efficiency, since it significantly increases the opportunities for consumers or third parties nominated by them to take action on consumption and billing information and thus provides a mechanism to reduce or shift consumption, resulting in energy savings in both final consumption and, through the more optimal use of networks and generation assets, in energy generation, transmission and distribution" [1]. In fact, within the Smart Grids paradigm, it is expected that DR enables end-users participation in energy markets (through aggregators and retailers) and profit from optimal price conditions, contributing to the efficiency of the grid and the integration of renewable energy sources.

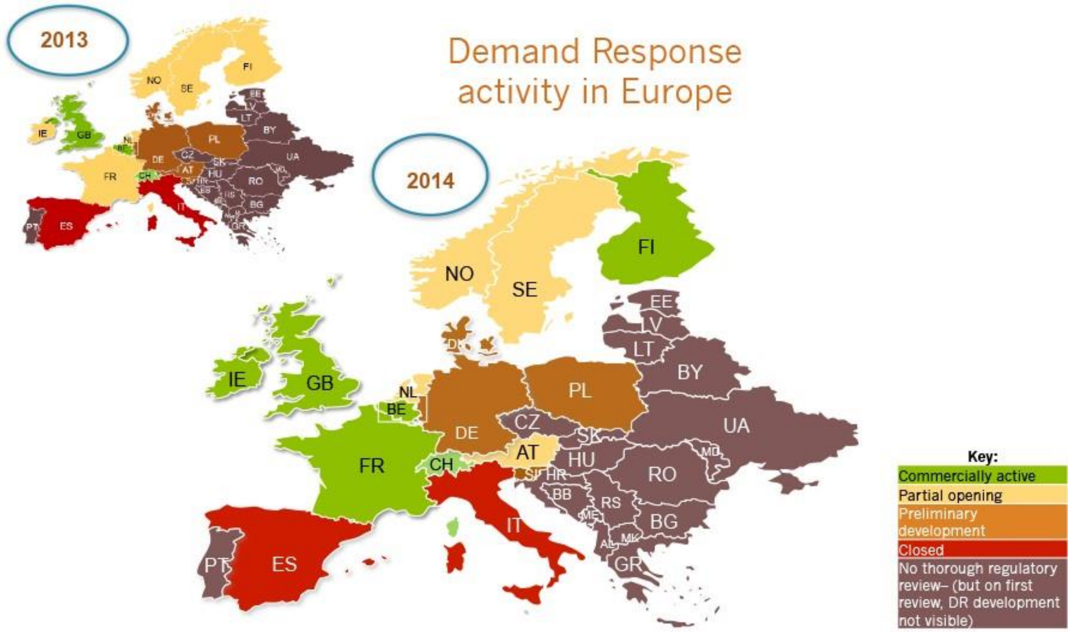

Figure 1-1. Demand Response activity in Europe [2].

Nevertheless, in Europe, DR implementation has been going at a tardy pace in comparison with the United States, where, in 2013, businesses actors and homeowners earned over $2.2 billion in revenues from DR [2]. As presented in Figure 1-1, only a small share of European countries have commercial available DR solutions offered to few segments of the electricity consumers. In contrast, other countries, such as Spain and Italy, did not approved yet all the legislation needed to allow the provision of DR services. Finally, a significant part of the central European countries have some regulatory conditions to the deployment of DR but no commercial available solutions are offered to the consumers.

Indeed, despite the recent efforts in defining the new role of Distribution System Operators and preparing the networks to receive demand side flexibility services [3], currently DR is facing technical, regulatory and market barriers to the emergence of business opportunities and wide-scale uptake solutions, particularly in residential sector. These obstacles are related not only to the capability of engaging end-users through in-house services but also to the development of commercially viable aggregation applications, *e.g.* establishing clear rules for the technical validation of flexible DR transactions [4].

In the regulatory field, the recent report of the Smart Energy Demand Coalition[1] concluded that "in the majority of Member States today, Demand Response is either illegal or impossible due to regulation" [2]. The report suggests 10 rules that should be included in the new regulatory framework for the deployment of the DR in Europe:

1. The participation of aggregated load should be legal, encouraged and enabled in any electricity market where generation participates.
2. Consumers should have the right to contract with any demand response service provider of their choosing, without interference.
3. National regulators and system operators should oversee the creation of streamlined, simple contractual and payment arrangements between retailers, Balancing Response Parties (BRP) and aggregators. These should reflect the respective costs and risks of all participants.
4. The aggregated pool of load must be treated as a single unit and the aggregator be allowed to stand in the place of the consumer.
5. Create unbundled standard products that allow a range of resources to participate, including demand side resources.
6. Establish appropriate and fair measurement and communication protocols.
7. Ensure Demand Response services are compensated at the full market value of the service provided.
8. Create market structures which reward and maximize flexibility and capacity in a manner that provides investment stability.
9. Penalties for non-compliance should be fair and should not favor one resource over the other.
10. Create and enforce requirements for market transparency within the wholesale and balancing market.

Besides the regulatory barriers, the creation of a DR business in Europe (and its expansion in the U.S.) depends on the promotion of end-users' participation in flexibility services and on the capability of aggregators to leverage the value of this flexibility in the markets. From the technical point of view, the research and innovation on the DR field should create the conditions at the building level that allow end-users to change their electricity consumption and, at the

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[1] The Smart Energy Demand Coalition (SEDC) is a not-for-profit industry group created in 2011. Its mission is to promote the participation of demand side response in the EU electricity markets, ensuring that consumers can actively engage on par with the traditional supply side and get benefits out of their participation.

market level, develop new bidding strategies that transform end-users' consumption changes into flexibility products that can be traded in the electricity and ancillary services markets.

However, it is important to stress that the research and innovation towards the deployment of DR are not starting from scratch. In fact, as will be discussed further on this thesis, the load management initiatives launched by the utilities during the 20th century consist in a valuable experience and some developments from that time can be adapted to the current organization of the electricity systems and to the future smart grids paradigm.

On the other hand, nowadays several automation, Information and Communication Technologies (ICT) are available in residential buildings, creating a favorable environment for the deployment of DR in residential sector. This Smart Home market has been drawing the attention of a wide range of industry leading players from different sectors, as displayed in Figure 1-2, and it is expected to grow 12 percent per year until 2020 [5].

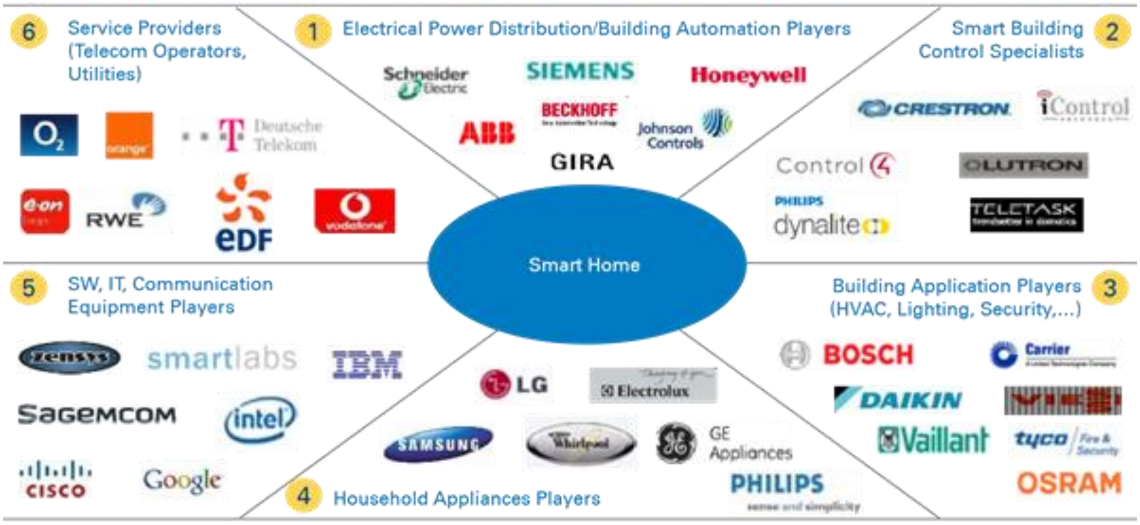


Figure 1-2. Leading companies with Smart Home products [5].

The main segments of the current Smart Home market are home assistance, home cloud, e-health and home automation/security [5]. Particularly, in this last segment, home energy management systems and smart appliances commercial solutions are starting to be offered in the market, some of them comprising automation and load control functionalities capable to interact with the end-user and provide a variety of energy services. This new control infrastructure creates the conditions for a new era of DR.

Therefore, the technical barriers for DR are not on the side of the load control and automation solutions. In fact, DR platforms can be designed to interoperate with the current and future buildings' automation and communications systems, taking advantage of the existing appliances' control. In contrast, the main challenge is to transform this load control into DR services (or flexibility services) that can be offered by the end-users to the aggregators and by the aggregators to the markets. This requires a comprehensive technical framework that includes a set of tools capable of quantifying and maximizing the flexibility of residential consumption as well as a set of bidding methods that enable the participation of aggregators in the markets.

This thesis aims to contribute to this technical framework towards the mass adoption of DR solutions. Consequently, this research work was driven by the three research questions presented below:

- *How can DR services at the level of residential consumption can be quantified, taking into account smart appliances control?*
- *How demand side aggregators can use residential load control in their participation in ancillary services markets?*
- *What are the main barriers and drivers for the provision ancillary services through the demand side?*

It is important to stress that the development of this technical framework needs to be compatible with the vision of smart grids as well as with the expectations of the different agents involved in DR services, namely system operators, aggregators, smart appliances manufacturers, ICT providers and end-users. Furthermore, the flexibility services encompass multiple time frames (from real-time up to the day ahead) and physical scales (from the appliances level to the markets level).

In this thesis these diverse perspectives of DR stakeholders as well as the multiple scales of the problem are taken into account. Nevertheless, in definition and quantification of DR services, a particular attention is given to the developments within home domain as well as to the new problems regarding the aggregators' bidding activity in the reserve services markets. Although the approach and the conceptual architecture include the multiple time scales of DR, a special emphasis is given to the provision of day ahead ancillary services, namely tertiary reserve.

In order to explain in detail the options made during the development of this research, a special section was created in Chapter 3.

1.2 Objectives of the Thesis

The general objective of this thesis is to conceptualize and develop a technical framework enabling the provision of ancillary services through DR, assumption that demand side aggregators are allowed to participate in the these markets offering flexibility bids and representing a significant number of the residential consumers.

This general objective was divided into three specific parts:

- To propose a set of methods and algorithms capable of quantifying the day ahead DR services that can be provided at the building level, from an active control of smart appliances performed by a Home Energy Management System. This means, the evaluation of the potential changes in residential consumption, considering different types of appliances and different consumption patterns of the end-users.

- To propose a bidding method to be used by demand side aggregators in their participation in day ahead ancillary services markets. The method should take into account the uncertainty of the market as well as the flexibilities of the residential consumers presented in the aggregator's portfolio.

- To identify, from a technical perspective, the main barriers and drivers that can incentive or discourage participation in flexibility services by end-users and aggregators as well as to discuss the economic viability of the provision the ancillary services through DR.

1.3 Structure of the Thesis

The research developed within the scope of this PhD thesis is presented into seven chapters (including the present one).

The current Chapter 1 presents the general context and the motivation to this thesis as well as the research questions and the objectives of this work.

The literature review related to the topics of this research is presented in Chapter 2. Thus, this chapter provides a summary of the context and the main findings on DR techniques, starting from the traditional demand side management programs launched by the utilities during the 20th Century. Moreover, it also characterizes the current ancillary services as well as the DR deployment environment within the Smart Grids and the Smart Home that enables future researches and developments on this field.

Chapter 3 presents the approach used in this thesis towards the objectives and the research questions. A conceptual architecture summarizing the functional relationships between the DR agents participating in the provision of ancillary services is presented. Furthermore, in this chapter, the choices made in this thesis concerning to the type of ancillary services and loads evaluated during this research as well as the main assumption on the DR deployment environment will be detailed.

Chapter 4 describes the methodology to quantify the availability services that residential consumers can provide to the aggregators. Methods capable of maximizing the provision of this services for the day ahead, considering diverse end-users' consumption patterns, and different characteristics of the appliances, are presented. A particular attention is paid to the situations where the appliances control is used to provide other type of flexibility services within the home domain.

Chapter 5 discusses the characteristics of the demand response flexibility services and formulates the problem of the aggregators' participation in the day ahead ancillary services market (namely for the provision of tertiary reserve) representing a group of residential consumers. A bidding method to maximize the aggregators' remuneration in these markets is presented.

The methods developed in chapters 4 and 5 are used in Chapter 6 to identify the main drivers and barriers to the provision of ancillary services through the demand side in the current regulatory framework. In this chapter, an economic evaluation of the flexibility services is performed and the economic viability of the demand side aggregators business is discussed.

The document ends with chapter 7, where the main contributions and findings from this thesis as well as the topics for future work are described.

Chapter 2 – State-of-the-Art

The centralized and vertical structures of electricity systems have been changing during the last decades. In the end of the 20th century, European electricity systems moved to operate under an unbundling model [6]. Although transmission and distribution network operation are still monopolies, competition appeared in generation and retailing sectors. Producers and retailers are nowadays trading energy through bilateral contracts and participating in the wholesale electricity or in the ancillary service markets, making bids for the day-ahead and the intraday time span.

Simultaneously, due to the technological evolution as well as the investments made in the renewables sector, the penetration of electricity generation coming from renewable sources has been increasing significantly in the last decades [7]. In the future, it is expected that the share of renewables continue to increase, namely under the form of microgeneration located along the electricity distribution networks. Undoubtedly, these variable and dispersed generation sources will bring new challenges to power systems operation and management. An example of these challenges is the provision of ancillary services – namely reserve services – for renewable integration [8]. In fact, renewables bring more uncertainty and variability to the system due to the unexpected changes in power output, which requires the dispatch of reserve resources.

The advent of Smart Grids (SG) and the current efforts to add sensing, automation and communication systems to the existing network infrastructure aim at creating a conceptual and technical vision of the grids operation for the new reality of renewables integration. The smart metering systems are an example of this intelligence and real-time information flowing down to the level of individual consumers. Besides the advantages of Smart Meters (SM) in providing real-time measurements to the system operator, these devices will be capable to send signals to the end-user, such as real-time prices, that enable an intelligent load management on the consumer side. These load management (LM) activities within the SG context can be viewed as permanent distributed energy resources (DER) that can be traded in the wholesale energy and ancillary services markets. Mostly in the residential sector, where the size of individual LM resources is insignificant in comparison with the total demand, load aggregators and flexibility agents will play a crucial role by facilitating the integration of the demand side into the energy and ancillary services markets.

Important experiences on LM activates through the demand side occurred in the past in the context of a verticalized paradigm in the electricity sector. In fact, a significant part of the approaches and methods that are nowadays being proposed under the framework of demand side integration (DSI) into the SG are inspired by the vertical LM programs launched during the last thirty years of the 20th century.

This chapter presents a literature review about the LM deployment from its beginning up to the present. In order to perform such review, three aspects were taken into account: (1) the policy and regulatory organization of the electricity system driving the LM development, *i.e.*, vertical electrical systems or smart grids paradigm; (2) the deployment environment, *e.g.* control and communication systems that allowed the implementation of LM; (3) the type of LM. Thus, the experiences and scientific developments regarding LM were treaded according to these three dimensions of the LM deployment. Figure 2-1 presents the contents of this chapter divided by subsections.

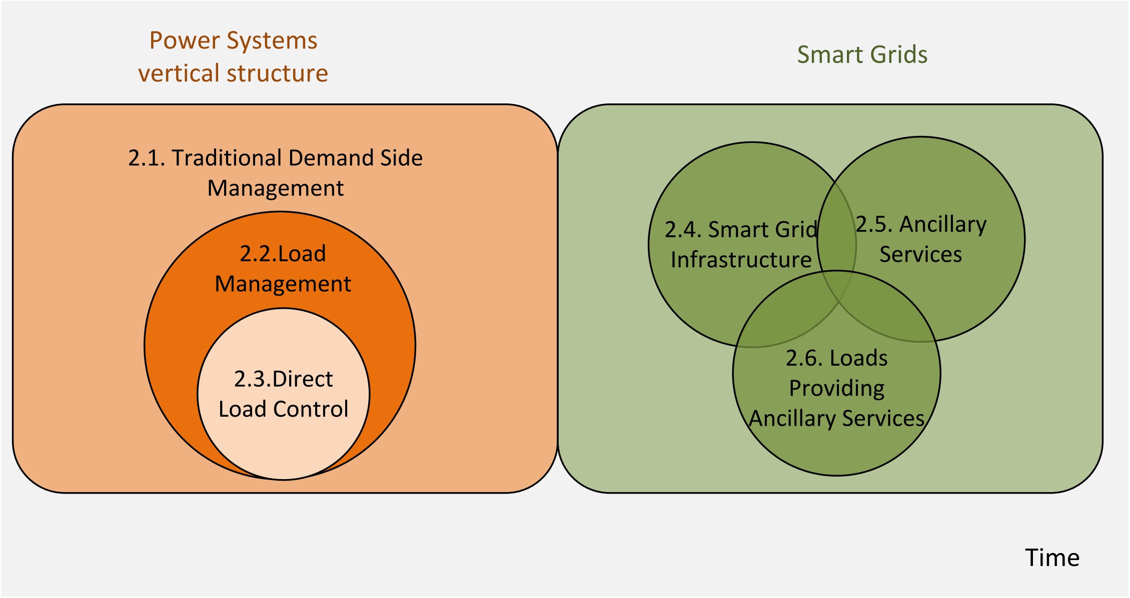


Figure 2-1. Contents of the state of the art

Section 2.1 presents an overview of the electricity demand side management in the context of a vertical organization of the power systems. Under this vision, the programs were launched by integrated public utilities that were responsible to the whole system management and operation as well as security of supply. At the same time, due to the strategic nature of the power systems, these utilities were also viewed as instruments to achieve macroeconomic and political objectives. Hence, the oil crisis of 70's had a relevant impact on the promotion of demand side management programs. Within this traditional form of demand side management, section 2.2 gives a special emphasis to the LM programs and section 2.3 focus on the specific case of Direct Load Control (DLC).

In a SG environment, the concept of an integrated demand side management is not compatible with the unbundling in the electricity sector. Hence, the literature review of the LM in the context of SG is presented in according to the current market paradigm. Section 2.4 lays emphasis on the deployment environment for load management provided by the SG infrastructure. Rather than presenting a discussion about abstract vision of the forthcoming grids, the objective of this section is to highlight the technical developments associated with SG that enable LM. Therefore, a special focus on the deployment of smart metering infrastructures is given. Section 2.5 presents an overview of the current ancillary services, namely the main characteristics of the reserve services. Section 2.6 summarizes the current state of the provision of ancillary services through LM. In this section, the technical methodologies to perform LM, the participation of loads in the electricity and reserve services markets as well as related projects and initiatives are presented.

The main conclusions of this literature review are presented in the section 2.7.

2.1 Traditional Demand Side Management

After the oil embargo in 1973, loads started to be taken as possible solutions to deal with security of supply problems in the electricity sector. At that time, Demand Side Management (DSM) was considered interesting from the technical point of view and it made economic sense, due to the momentary increase of the energy prices. Simple measures to incentive efficiency in the consumption and to promote waste reduction were implemented by the electric utilities. The first phase of DSM was born under the form of energy conservation [9]. Later, Boshell and Veloza [10] defined DSM as a relation of three terms: Energy Efficiency, Demand Response and Energy Conservation. However, the first definition of Demand Side Management was presented by Gellings [11]. According to the author, *"Demand side management is the planning, implementation, and monitoring of those utility activities designed to influence customer use of electricity in ways that will produce desired changes in the utility's load shape, i.e., changes in the time pattern and magnitude of a utility's load."*

2.1.1 Goals and Measures

Demand side management actions, taken either by regulators and policy makers or by the utilities in electricity field aimed to save energy and peak power through the flexibility and the efficiency in the consumption. Objectives regarding load shape were also summarized by Gellings [11]. Six different goals for demand side measures became well known:

- <u>Peak clipping</u>: consists in the reduction of the peak load using direct load control, for example the interruption and curtailment rates applied to the industrial and commercial loads.

- <u>Valley filling</u>: aims to increase the load during the off-peak periods. This is desirable when the generators starting costs are very high and it is more profitable to keep them running during the valley hours instead of stop and start them later.

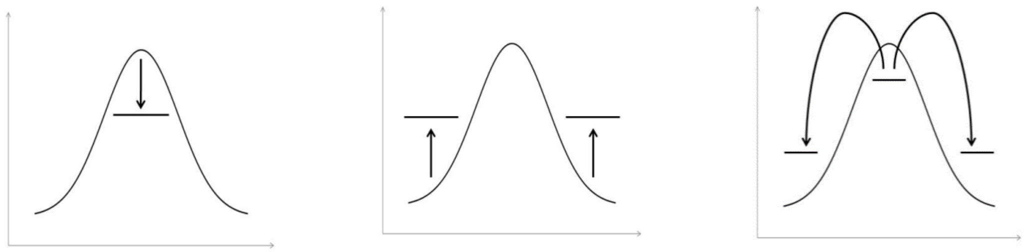
- <u>Strategic conservation</u>: is related with the incentivized energy conservation by utilities programs. These programs normally lead to a decrease in the load shape either in valley or peak periods.

- The same happens in the <u>strategic load growth</u>, but in this case the load reshaping causes an overall increase in the demand.

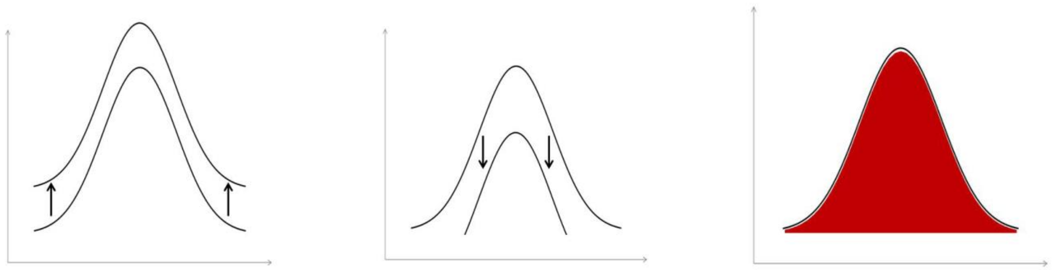
- <u>Load shifting</u>: is used to change the load profile by moving power demand form peak hours to off-peak periods, in order to avoid huge variations in the diagram.

- Flexible load shape: is a concept that is used for reliability evaluation and it is related with the flexibility characteristics of the load. Thus, it does not consider the load magnitude but the availability of the load to be curtailed or interrupted.

Figure 2-2 illustrates the demand side management objectives proposed by Gellings.



Peak clipping **Valley Filling** **Load shifting**



Strategic Load Growth **Strategic Conservation** **Flexible Load Shape**

Figure 2-2. Demand Side Management: objectives regarding load shape

From the implementation point of view, a set of traditional DSM measures – that can be applied in order to achieve the load shape objectives summarized by Gellings – were presented by Lee Willis [12]:

- Appliance Upgrade

  Appliance upgrade measures are those procedures that improve the appliances efficiency and reduce the total load. The improvement in efficiency can be obtained using two types of measures: one is through the electromagnetic efficiency of the device, which is associated to energy conversion into electricity, and the other is associated to the environment and equipment usage (for example computers can "shut down" memory activity when they are not being used). Several programs on appliances upgrade were promoted by the integrated utilities after the oil crisis.

- Distributed Generation

  In the past, distributed generation was associated with the backup generators that were normally installed in commercial and industrial companies' facilities, which use to deal with high costs of interruptions. In the beginning of the 21st century, distributed generators, such as cogeneration and renewable units, are widely used to provide energy in a regular basis avoiding energy losses associated with the transmission.

- Building Insulation

Programs regarding buildings envelope provide energy savings as well as peak power reduction. However these programs were not common since they are difficult to implement without significant costs, which cannot be allocated neither to the consumers nor to the electric companies.

- End-use Storage

End-use storage allows the consumers to shift load from peak to off-peak hours. For example domestic water heaters can be used for that purpose, since they can store a great amount of hot water, heated during the load valley periods, and keep it ready to be used during the day.

- Fuel-Switching

Fuel switching measures consist in moving electrical energy uses (cooking, cooling, space and water heating, etc.) to other energy carriers, such as oil or natural gas, in order to reduce the electrical peak load. Moreover, in most cases, fuel-switching can also reduce substantially the losses associated with the energy uses since it avoids thermal to electricity conversion.

- Interlocking

Interlocking is a simple load control mechanism that avoids the operation of two or more appliances at the same time, which has also an impact on peak reduction. Figure 2-3 illustrates a simple case where a water heater device and an air conditioner are interlocked.

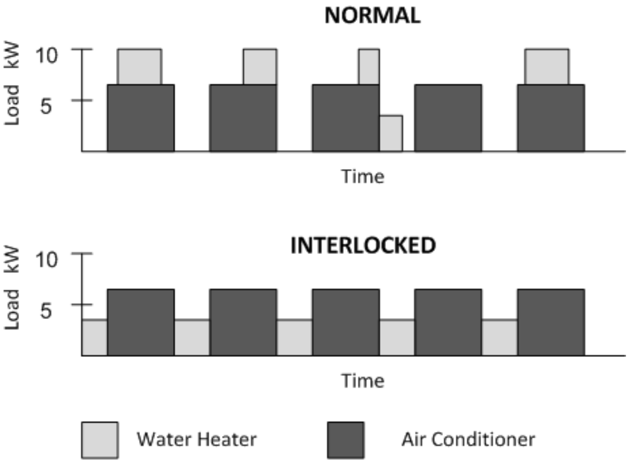


Figure 2-3. Interlocking (adaptation from [12]).

- Lighting Efficiency and Motors/Equipment upgrade;

Lighting efficiency programs and motors upgrade programs are implemented in order to minimize the losses in the use of electricity. In fact, it is a specific case of the "appliance upgrade" measures. However, motors and lighting upgrade played an important role in the utilities' demand side management strategies.

- Load Control;

Load control measures represent a direct and indirect control of the residential, commercial and industrial loads performed by the utilities. Thus, some home appliances, such as air conditioners and water heaters, can be directly managed in a centralized way from the utility. Normally, customers receive a financial incentive to allow this type of control. Load control was the most popular measure of the traditional DSM and it will be analyzed further in this chapter.

- UPS and PQ devices;

More recently, small automation devices are being used to disconnect some appliances during the peak periods. On the other hand, appliances such as Uninterruptible Power Supply (UPS) and other harmonic mitigation equipment can be included in DSM programs, due to their impact in reliability and power quality.

- CVR (Conservation Voltage Reduction):

Conservation Voltage Reduction (CVR) is a measure taken by the utility that consists in lowering the voltage on distribution system, so that the total load power can decrease. This is particularly relevant in residential zones that can be represented by pure impedance loads, which makes the power consumed equal to the square of voltage. Although CVR was started to be implemented 30 years ago, nowadays the benefits of this measure are still being discussed and tested [13][14].

2.1.2 Programs

In the previous subsection, the general traditional DSM goals and measures in the electricity sector were presented. In the following paragraphs, the implementation of such measures by the utilities worldwide is analyzed. Rather than an exhaustive review of the demand side initiatives taken by electric utilities during the last decades of the twentieth century, the main objective of the following review is to highlight some examples of different measures applied and different schemes used to promote DSM. For that purpose three types of measures – that are fully reported in [15] – will be summarized: appliance upgrade programs, lighting efficiency programs and high efficiency motors programs. Within the appliance upgrade, two programs were considered: *Appliance Turn-In* and *Power Smart Refrigerator Buy-Back pilot*. In lighting efficiency field, three programs were studied: *Operation LBC, Residential Lighting Program* and *CFB and CFL Manufactures' Rebates.* Finally, three efficiency motors programs were taken into account: *Northern Sates Power High Efficiency Motors & Drivers*, *Niagara Mohawk* and *British Columbia Hydro Power high efficiency Motors.* All these programs were running many years, leading to different results.

Appliance Turn-In (APTI) was developed by *Wisconsin Electric*, an American utility covering Wisconsin, Michigan as well as Milwaukee metropolitan zone. The program aimed to replace the old and inefficient refrigerators and air-conditioners of residential customers, through the application of a buy-back strategy. The customers were requested to choose between a check ($25 for air conditioner and $50 for refrigerators) and savings in bonds ($50 for AC and $100 for fridges). It occurred between 1987 and 1991 and a significant variation regarding the number and type of appliances turned-in during the different years of the program was found.

Power Smart Refrigerator Buy-Back pilot was a two years program (1990-1991) launched by *British Columbia Hydro*, an utility that provides electric services to more than 13 million customers in the province of British Columbia in Canada. In this program, the customers were paid ($ 50) to replace their old refrigerator, defined as "any refrigerator that had a door and a compressor at the time of pick-up". Essentially, the program was conducted in two phases: the first phase included only two small communities located 40 miles outside the Vancouver and it was restricted to residential sector, while in the second phase the project developed towards 5 new communities and all customers were allowed to participate.

Operation LBC was a program from *Electricité de France* (EDF) in collaboration with ADEME[2], French environmental and energy agency, to the islands of Guadeloupe and Martinique during 1992 and 1993, respectively. This program aimed at incentivizing the use of CFLs (Compact Fluorescent Lamps). 100.000 lamps were leased by the consumers to EDF and installed at the consumers' facilities. The costs of the investment were recovered through the energy savings achieved by the customer. This project resulted in a significant decrease of the evening peak consumption, which allowed the utility to avoid investments in a new generation infrastructure during the project lifetime.

Residential Lighting Program was launched by *Madison Gas and Electric Company*, a utility located in Madison, Wisconsin, with more than 117 000 customers. The program began in 1991 and it finished in 1994. In the first phase, this program consisted in distributing coupons to the end-users, in order to incentive them to buy CFLs. Afterwards, the strategy changed and the customers bought the lighting equipment first and then sent the receipt to the utility, which mailed them back a rebate.

CFB and CFL Manufactures' Rebates program was launched by *SCEcorp*, which is a parent corporation of *Southern California Edison* company and three non-utility subsidiaries collectively known as the Mission Companies that serves 4.1 million customers. Although it was a DSM program on light efficiency, it had a different approach regarding the bulbs subsidizing. While in other programs the utility paid the lighting equipment directly to customers (totally or partially), in this project the rebates were applied to the manufacture, in order to decrease the prices. On the other hand, this program was both commercial and residential oriented.

Northern Sates Power High Efficiency Motors & Drivers was led by Minneapolis utility, a city in the state of Minnesota. The program aimed to incentivize the use of high efficiency motors and adjustable speed drivers. Two types of rebates were given: lower incentives to the motors for new applications and higher rebates for existing application. The main objective of this measure

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[2] Agence de l'environnement et de la maîtrise de l'énergie. Website: http://www.ademe.fr/

was to force customers to change the technology of their motors by an indirect sharing of the investment. Furthermore, the value of per horsepower rebates were specified according to the size of the motors and drivers, in order to achieve better results in high power equipment, which tend to represent the majority part of the consumption.

A similar program was launched by *Niagara Mohawk Power Corporation*, which is a utility that has the largest service share in New York State, providing both gas and electricity to 1.5 million customers. Although the program started with low rebates, they increase substantially over the years. For example, the rebate in 1991 for a 125 horsepower motor with a minimum efficiency of 95% was 457$, while in 1992 the amount for the same motor was 1200$.

In 1989, *British Columbia Hydro* also presented a DSM program on high efficiency motors. The first year of the project was led by a customer rebates policy, similar to those applied in previous cases. Nevertheless, in 1990, the utility decided to add a vendor incentive to encourage stocking and sales of high efficiency motors. This type of incentive can be seen as the same approach used by *SCEcorp* in *Manufactures' Rebates* program.

2.2 Load Management

In the beginning, LM programs were established with the objective of managing appliances consumption for lowering the average cost of electricity. At that time, strategies and methods were developed taking into account the existing integrated and vertical structure of the electric power systems. For instance, the addition of LM to the economic dispatch formulation was a clear example of such type developments. Le *et al*. [16] proposed a method to include LM in the dispatch formulation so that system production costs could be minimized. A similar approach based on economic dispatch was proposed in [17] to address the specific case of fuel costs minimization. The use of dynamic programming to solve this type of multi-period optimization problems was proposed in several studies, such as [18] and [19]. The viability of LM to operational costs savings was assessed in [20]. Later, a multi-period minimization was proposed in order to achieve those savings [21].

From the implementation point of view, three types of strategies concerning LM programs can be found: the Direct Load Control (DLC), the Indirect Load Control (ILC) and Electric Thermal Storage (ETS). ILC consists in the use of economic incentives (or disincentives) to encourage voluntary changes in the end-user consumption pattern. Normally, the objective of ILC is to reduce the demand during the expected daily peak periods by shifting the appliances' use to the off-peak hours. In contrast, DLC involves the active control of electric devices by the utility in order to defer loads during peak periods. The direct consumption management by the utility may restrict the appliances use, which provoke discomfort situations to the end-user.

DLC and ILC strategies were implemented in many programs with the objective of reducing the average cost of electricity and decreasing the need for new generation capacity. In 1981, a working group on load management summarized the main initiatives until that date on DLC and ILC [22]. Besides the direct load control and indirect (or voluntary) load control strategies, the document highlights a “third class” of load management: Electric Thermal Storage. ETS consists in storing heat for space and water heating during the off-peak periods for the use during the peak periods, without utility intervention neither responding to economic incentives. For some years, ETS was performed only at the customer side of the meter through time-clock control of air-conditioners and water heaters and it had a considerable acceptance especially in Europe.

Load management is the capability to perform a deliberate shifting in time of the electric power and energy associated with loads. ILC, DLC and ETS are alternative ways of provoking changes in the demand profile either controlling the appliances or influencing the end-users to change their consumption patterns. The differences on management approaches between these three LM strategies are represented in a two axes chart, in Figure 2-4. The horizontal axis corresponds to the management type, *i.e.*, the nature of the action that provokes the consumption modification, and the vertical axis correspond to the source of the management action.

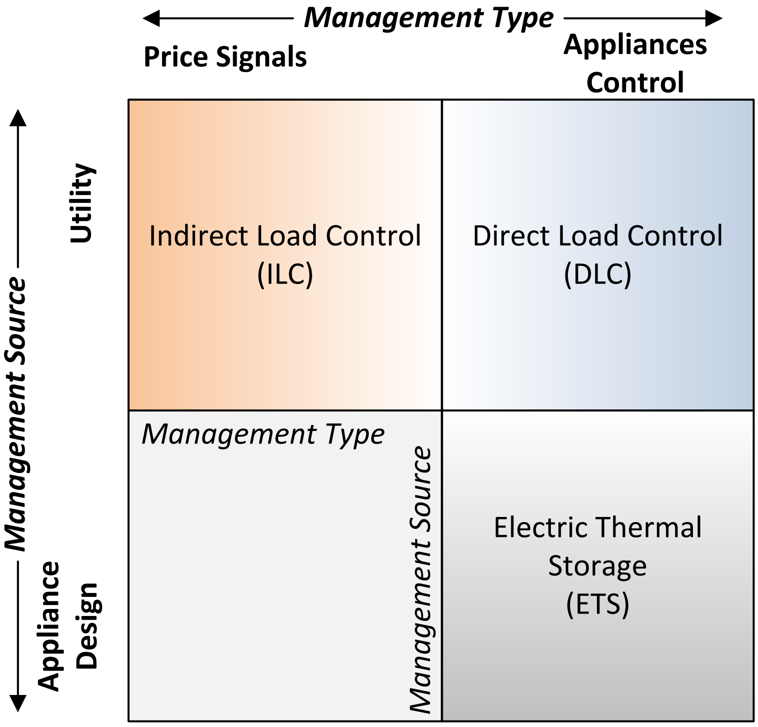

Figure 2-4. Load Management Strategies

As shown in Figure 2-4, ILC management consists in price signals sent by the utility in order to influence the end-user behavior. It differs from the DLC in terms of management type. In fact, DLC is performed via intrusive control orders that have a direct impact on the consumption as well as on the comfort of the end-user.

In this section a detailed description of ILC and ETS is presented. Due to the special relevance of DLC for the objectives of this thesis, the review of DLC programs and methods will be performed in section 2.3.

2.2.1 Electric Thermal Storage

Although ETS involves appliances control, it does not affect the comfort of the end user. In fact, the ETS management procedures are integrated in the appliance design and the control orders are expected by the end user. ETS devices are conceived to avoid consumption during typical peak periods (previously defined) and, hence, their behavior can be easily predicted. For instance, in [23], the authors discuss some design aspects of forced-air electric furnaces to be used as ETS devices. A control circuit is added to the furnaces so that the devices can charge only in off-peak periods. The starting point and duration of off-peak period is adjustable in the electronic control.

Similar approaches were used in the thermal domestic appliances. Miller and Coleman [24] presented a four-year field demonstration project conducted by the AEP[3], testing several ETS devices in 71 homes of seven different states in the US. After collecting information regarding end-users' comfort, the water heating devices were designed to charge during the off-peak period (between 11 p.m. and 7 a.m.), which reduced 6.5 kW to the total peak demand. The success of the results encouraged AEP to extend the ETS program to a larger scale [25]-[27]. However, in this second part of the project, ETS was combined with time-of-use (ToU) rates in order to encourage end-users to purchase ETS devices and taking advantages of the appliances control.

Actually, despite the success of ETS programs, it was clear from the beginning that ETS strategies were not enough. In other words, these programs demonstrated the load shifting capability of thermal appliances, but for the potential implementation in large scale, a combination with other strategies was needed. A more cost-effective result could be obtained if the local control of ETS devices could be taken by the utility either directly or through price signals and ToU rates. In fact, ETS had a very short life as a sole strategy of load management. Throughout the time, it was gradually integrated in ILC and DLC programs as a central resource with special potential for load shifting. In this section, a particular attention was paid to ETS due to relevance of domestic thermal loads in this work. However, hereinafter it will be discussed within ILC and DLC strategies.

2.2.2 Indirect Load Control

Indirect Load Control (ILC) aims at modifying the load profile through the structure of the electricity rate. This LM strategy started to be implemented during the 70's and 80's of the twentieth century by several utilities, particularly in the US. Furthermore, the development of ILC programs was accompanied by an intense debate over electricity rate structures involving economists and engineers in the utility sector. Nowadays, when the LM is being presented as a resource of the future Smart Grids, recovering this discussion on electricity rates carried out some decades ago, can contribute to establish a regulatory framework for the new era of the DER management. Therefore, besides the presentation of some examples of ILC programs, this subsection summarizes the debate over electricity rate structures carried out in the 80's.

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[3] American Electric Power (AEP) is an electric utility in the US, nowadays operating in 11 states.

Indirect Load Control Programs

One of the first experiences of ILC was launched by the Arizona Public Service Company in the US. The utility conducted an experiment in order to observe the effect that the ToU rates would have on the household electricity consumption. 19% of residential consumers, from Yuma and Phoenix metropolitan areas, were voluntarily included in this program. From May to October 1976, the utility allocated to each consumer one of 28 ToU rates (with different prices) and compared the consumption profile with the same period in 1975. These 28 different rates were divided into three groups distinguished by the length of the peak rating period (3, 5 and 8 hours). In this experience [28], two aspects were analyzed: the magnitude of the rate and the duration of the peak rating period. It was concluded that the peak consumption reduced by 7 to 16% according to the peak rating duration. However, the comparative results regarding the 28 ToU rates encompassing different electricity prices were not conclusive. Although the consumers shifted their consumption form peak rating to intermediate rating periods (and similarly from intermediate to base rating periods), the consumers' behavior did not changed significantly with the magnitude of the energy price. This fact demonstrated that the residential consumption was sensible to the variation of the tariff during the day. Nevertheless, in general, it did not have significant margin for energy conservation.

One year later, a program was launched by the Pacific Gas and Electric Company. In 1977 the utility developed a ToU tariff to be applied to the consumers with a peak demand higher than 4 kW, in a first phase, and 500 kW, in a second phase. The majority of the consumers involved in the first phase of the program were industries, although a considerable number of commercial companies were also affected by the tariff. Appropriate meters were installed in order to apply the three types of differentiated energy rates (2.25, 2.45 and 2.65 cents/kWh). The tariffs peak and off-peak periods changed according to the typical winter (October - April) and summer (May - September) consumption profiles. Reynolds and Creigthon [29] discussed the effect of these rates on the load profile as well as on the individual consumers. The analysis encompassed measurements of the electricity demand in different industrial sectors (cement, paper production, steel and industrial gases). Clear changes provoked by the ToU tariffs were registered in the load shape of individual consumers which caused a significant reduction in the total system peak load.

In New York, Orange and Rockland Utilities developed an ILC program based on Peak Activated Rate in the summer of 1982 [30]. This program aimed at encouraging peak shaving by consumers through economic incentives. 100 small commercial and 150 residential consumers were free to use electricity without any charge. However, during the system peak periods (when the load exceed 90% of the forecasted summer peak), a signal was sent to the metering devices changing the tariff to three times (for residential consumers) and four times (to commercial consumers) the normal electricity rate. Thus, instead of applying ToU tariffs for daily peak reduction, this program was focused on lowering the total system peak that occur approximately 60-100 hours during the summer. This approach was demonstrated to be successful since the average load reduction during the peak periods was around 0.5 kW per consumer.

The debate over rate structures

The structure of electricity rates has been discussed since the end of nineteenth century. However, the considerable increase of the oil prices in the 70's raised again the debate regarding two main approaches on tariff schemes: the Hopkinson tariffs and the time-of-use (ToU) tariffs. The next paragraphs will summarize the elements of this discussion within the load management perspective.

A simple form of Hopkinson tariff consists of an energy rate (*Er*) per kilowatt hour applied to the electricity consumption (e_c) plus a fixed monthly demand charge (*Dc*) applied to the maximum kilowatt demand (m_d) measured over an interval of half an hour or less. Under this tariff, the end-user electricity bill is calculated according to the equation (2-1):

$$Elect. bill = Er \cdot e_c + Dc \cdot m_d \tag{2-1}$$

This tariff was widely accepted by the utilities during the major part of the twentieth century. Nevertheless, the increase of the oil prices led some economists to criticize this rating approach since a fixed electricity price could not represent the marginal costs associated with the electricity generation [31]. Moreover, a charge applied to the maximum demand has the effect of discouraging individual peaks but it gives no incentive to reduce the consumption coincidental with the system peak. Hence, ToU tariffs started to be considered as an alternative, since they could represent the growing costs of electricity generation (in a hourly basis) and promote system peak shaving and load shifting. Although some intermediate rating levels could be added, the simple form of ToU, presented in equation (2-2), is composed by two prices: a peak rate (*Pr*) that allocates the fixed costs of the utility to the end-user consumption in peak periods (e_p); an off-peak rate (*Or*) that allocates the additional generating costs to the end-user consumption in the other periods (e_o). Different costs allocation proposals for ToU were explored in other studies, such as [32].

$$Elect. bill = Pr \cdot e_p + Or \cdot e_o \tag{2-2}$$

In the context of load management through ILC, the ToU approach was extended to the limit of real time pricing (RTP), also named in the literature as homeostatic control pricing, spot pricing, load adaptive, flexible pricing and responsive pricing. For instance, Schweppe *et al*. [33] proposed different schemes for RTP. According to the authors, no single set of RTP formulation will be universally agreed, hence they suggested some potential goals for designing RTP schemes:

- The Marketing System should minimize operating costs;
- To prevent monopolistic pricing and guarantee a fair rate of return on capital, regulation may be necessary;
- The present and future reliability and availability of power should be ensured;
- Demand levels and patterns should be influenced to take on desirable characteristics.

Garcia and Runnels [34] presented a study of the application of RTP theory to the utility operation and Flory and Parker [35] addressed some challenges of RTP regarding communication and metering equipment.

Some years later, after the stabilization of the oil prices, new versions of Hopkinson tariffs – including a price for the maximum capacity subscription (contracted power) – started again to be suggested. For instance, Seeto *et al*. [36] concluded that Hopkinson rates were a better option for electricity distribution companies regarding the effectiveness in cost recovery, prevention of uneconomic bypass, welfare implications and service reliability. The authors criticized the metering costs associated with ToU and RTP.

Nowadays, different tariff schemes and costs allocation can be found in the electrical systems worldwide encompassing, Hopkinson rates, ToU rates, RTP and hybrid approaches with several combinations among them. However, the debate over the electricity rates during the twentieth century raised some arguments that can help to define a regulatory framework for the future incentives to load management within the Smart Grids. This topic will be addressed further on this thesis.

2.3 Direct Load Control

Direct load control (DLC) consists on the control of the consumers' appliances performed by the electricity utility for an efficient use of the resources in order to minimize the costs of energy delivery. These consumers' loads are cycled or deferred in case of local or system peak loads or in case of emergencies [22]. The residential loads most often considered for DLC include space and water heaters and air conditioning systems. Some inconvenience or discomfort to the consumer may result when direct load control is used. Therefore, economic incentives may be offered to consumers in order to encourage the participation and to compensate the discomfort that can be caused.

Many DLC programs were launched by the electric utilities in the US motivated by the increase in oil prices. The majority of them achieved successful results: the efficiency of DLC allowed utilities to decrease the generation costs, reduced system peaks which avoided investments in generation and distribution systems, improved system load factors and provided a high speed load shedding that contributed to the reserve capacity. Bhatnagar and Rahman [37] analyzed the main DLC programs launched in this period. Three of those programs are summarized in this section in order to exemplify the impact of DLC and the technologies used.

DLC required a significant knowledge by the utility of the appliances that were being controlled. In fact, utilities should estimate the number of appliances that were operating in each period so that the available interruptible power capacity could be calculated. Therefore, the DLC programs were accompanied by considerable developments in load modeling. Furthermore, the payback consumption associated with the control actions was also a concern of some DLC programs, due to the impact of this actions on the consumption in the subsequent hours. Hence, a review of load modelling developments as well as payback estimation models are addressed in this section.

2.3.1 Direct Load control Programs

An example of the implementation of DLC actions can be found in [38] and [39]. These papers present the experiment of a DLC program applied to 450 electric water heaters (EWH) by Wisconsin Electric during the 70's and 80's. The load control orders were given manually into the data dispatching computer at the system control center. The commands were sent to the substations through telephone lines. Afterwards, the substation communicated with the loads using code messages. Once receiving an interruption order, the devices staid disconnected during a 12 minutes period, after which they were automatically reenergized, unless another order was given. The utility planned to expand this program to all EWH operating in the system. In that case, the peak reduction caused by the direct control of 150 000 EWH was estimated to be around 105 MW in summer and 150 MW in winter.

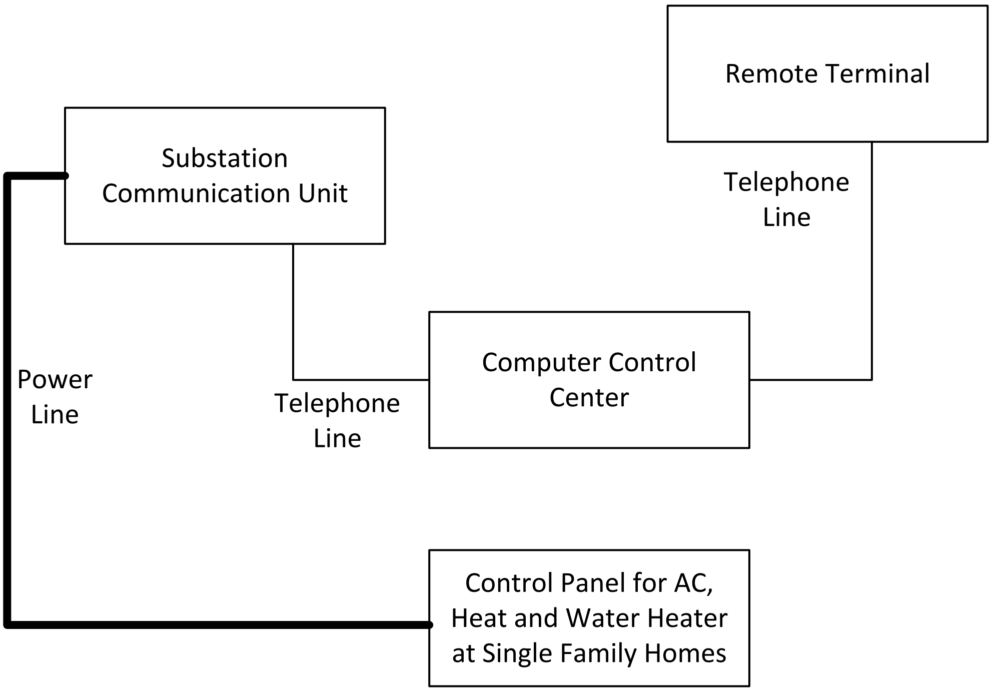

Figure 2-5. Basic Elements of Florida DLC system (adapted from [40])

A similar program was developed in Florida [40], when the local utility decided to install a remote control of EWH, central air conditioning and water heating systems in 120 residential consumers. The same type of communication was used: the central dispatch center communicated with the substations via telephone lines and the substation transmitted orders to the devices over the power distribution lines, using a transponder to send those signals. The basic elements of this DLC system are displayed in Figure 2-5. Considering DLC orders during a day operation, utility observed between 7.7% and 9% of load reduction in summer season and 2.5% in winter season. This difference occurs since, in summer periods, more than 50% of the total load corresponds to air-conditioners consumption. Therefore, the available range to reduce energy demand was more significant during summer months.

In 1968, Detroit Edison utility started to switch off the 200 000 electric water heaters (EWH) during the peak period via radio control signal [41]. The radio control system sent a coded audio signal via FM to the EWH installation. 10 different audio control tones were available in the transmission substation and each EWH respond only to 1 tone. The utility divided the EWH receivers among the 10 tones so that a 10% control step is available for managing the system water heaters load. This ability to control EWH via radio signals was used by the utility for two main reasons. First, if the daily reserve forecast show that an insufficient operating reserve would occur, the utility used the EWH capacity to provide additional operating reserve. In contrast, when sufficient operating reserve was forecasted, the appliances LM capacity was used to reduce the fuel costs, namely by interrupting the EWH before the night valley allowing an earlier shutdown of the high cost generation units. For instance, 1978, the appliances were interrupted 101 times which led to \$5,300 savings in capacity needs and \$4,854 savings in high cost fuel.

In Europe, the centralized direct load control initiatives launched by the utilities during the 60's and 70's were not integrated in specific programs. Therefore, specific data and results of DLC experiences are difficult to find in the literature. However, for example in Portugal, the vertical utility at that time used frequency-based load control (between 400 and 1200 Hz) to shift the consumption of domestic appliances, namely EWH [42].

2.3.2 Load Modelling

The first experiences on DLC motivated the development of load models capable of anticipating the consumption of the appliances controlled within these programs. A variety of models can be found in the literature from that time up to the end of the twentieth century. As shown by the DLC programs reviewed previously, the type of loads selected to be controlled by the utility were essentially thermostatically controlled loads (TLC), namely electric water heaters (EWH), space heating devices such as air-conditioners (AC) and, in some cases, refrigerators. The load models review performed by Molina *et al*. [43] divided these models in three categories: empirical models, models based on historical data and physically based load models (PBLM).

Empirical load models were developed in situations where the information regarding loads operation was clearly insufficient. For instance, Walker and Pokoski [44] proposed a load model based on the customer behavior. The model comprises the combination of two functions: availability function (that estimates the number of people in a household available to use the appliance) and the proclivity function (that calculated the probability of the appliance usage by each person). These two functions are computed based on pure empirical relations between the aspects of the consumer behavior, such as "normal sleeping hours" or "normal travel hours to work". In [45], the authors presented a model to assess the average hourly load reduction potential per AC device. The estimation of load reduction was dependent on the ambient temperature. For the maximum temperature registered in the summer (105^{o}F), the potential for load reduction was estimated to be 1010 Watts per AC device. In contrast, when the ambient temperature was equal to the typical space heating comfort temperature (75 ^{o}F), it was expected that the AC systems were disconnected with no load reduction potential. Hence, the hourly reduction potential for each AC device was related to the ambient temperature (T_m) by a linear relation expressed in (2-3).

$$\overline{HR} = 101\frac{(T_m - 75)}{3} \tag{2-3}$$

A model based on historical data for AC operation can be found in [46]. Authors measured the active and reactive power characteristic of the devices using several points of operation. Analogously, Virk and Loveday [47] proposed a model for AC that models the room temperature as a function of the ambient temperature and humidity. The model inputs are the heating, cooling and humidification powers. The coefficients of the model (time constants) were obtained after several tests performed in real conditions.

Physically based load models (PBLM) for thermal appliances are based on energy balance that occur inside a thermal chamber, which can be a room in the house, a refrigerator cabin or a hot water cylinder. Kupzog and Roesener [48] described the thermal process of an AC using a comparison with an RC circuit. This equivalent of electrical circuits and thermal processes was also used in [49]. The objective of this approach relies on establishing 4 relations between electrical circuits and the thermal balance inside a room in which and AC device is operating:

1- Electric current and thermal power of the AC heat pump – *i.e.* the quantity of heat over time (*Q/t*);
2- The electric resistance and the total thermal resistance of the room walls;
3- The capacitance of the electric capacitor and the thermal capacity of the room, which depends on the volume of the space as well as on the air composition;
4- The voltage and the temperature (θ) inside and outside the room.

Figure 2-6 presents the equivalent between RC electric circuit and the thermal process of the AC appliance operation.

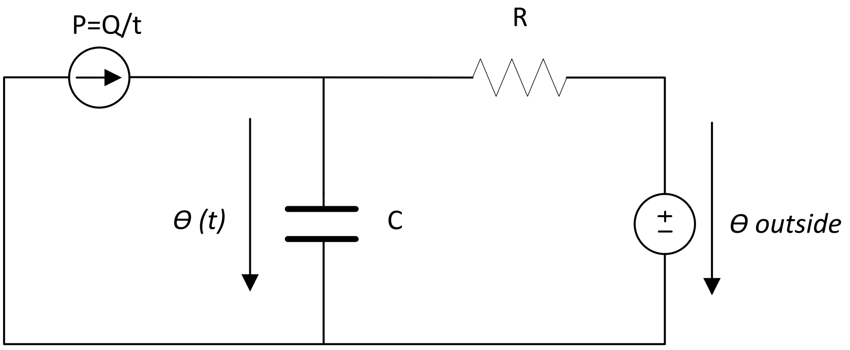

Figure 2-6. Equivalent between RC electric circuit and AC thermal process (adapted from [48])

The equivalence between thermal processes and RC circuits are also observed in the differential equations used in PBLM for thermal loads. A model describing the energy balances regarding a domestic AC is presented in [50]. The similarities of this model with the RC circuit equations are evident, as shown in equation (2-4).

$$\frac{\partial \theta}{\partial t} = -\frac{1}{CR}\left[\theta(t) - \theta_O + m(t)RP + W(t)\right] \tag{2-4}$$

Besides the thermal capacity and resistance of the room where the AC appliance is located, *P* represents the power of the AC equipment. θ_o refers to the outdoor ambient temperature (assumed constant in this case) and (θ) is the temperature inside the room. *W(t)* represents the thermal losses coming from external factors, such as a door opening as well as the presence of computers or any other loads that may influence the energy balance. Although the model presented above can establish a simple relation between the temperature of the room and the power of the AC unit in a time period, more complex models can be found in the literature. For example, Bargiotas and Birdwell [51] proposed a very complete description of a house thermal behavior including AC units. The temperature variation inside the room as well as its relation with the relative humidity of the air was considered in this model. In [48], some refinements were introduced in the PBLM for AC, by adding the possibility of splitting the overall thermal resistance into the resistance of each wall. However, it is important to stress, the use of more complex models also requires specific data, which is more difficult to obtain.

Similar differential equations are used to characterize other types of thermal loads, namely refrigerators and EWH. In case of refrigerators, the thermal model is equivalent to the AC representation presented in equation (2-4). A model that does not consider the losses associated with external factors – *W(t)* – is used in [52] and [53].

EWH models are very diverse, each one accounting for different constructive characteristics of this type of appliances. For instance, [54] presents water heaters modeling with two pairs of a heating element. On the other hand, the authors of [55] used an exponential model that considers the water demand required by the consumer. A differential equation to characterize the EWH behavior was proposed by Chong and Debs [56] and it is shown in equation (2-5). This equation is similar to the one presented for AC – (2-4). However, instead of a resistance, it includes a heat loss constant (α). The term *v(t)* is added to the model in order to represent the water energy demand, which is associated with the difference between the temperature desired for hot water usage (θ_d) and the inlet temperature (θ_i) entering in the EWH tank. In this case, the ambient temperature is indoors (θ_a).

$$C\frac{\partial \theta}{\partial t} = -\alpha\left[\theta(t) - \theta_a\right] - v(t)\left[\theta_d - \theta_i\right] + P(t) \tag{2-5}$$

Considering the characterization of thermal behavior presented in the models above, different levels of detail were found, depending not only on the context in which the model was used, but also on the information available in each case. Nevertheless, nowadays PBLM are widely used to describe the thermal appliances behavior. A common point between the different PBLM is the fact that they all come from energy balance, often written as first order differential equations. However, utilities used these models to perform discrete simulations of the temperature with, four example, 5 min, 15 min or 1 hour time step. In that case, two possibilities exist in temperature representation through these differential equations: it can be done either using an exact formulation of the exponential form or considering a linearized approximation. Typically, in DLC programs the models presented in equations (2-4) and (2-5) are linearized in the discrete representation of the temperature values. The error related to this approximation depends mainly on the time step used and also on the magnitude of the thermal capacity. A typical error for the linear representation of the AC temperature was estimated to be around 3% [57], *i.e.*, less than 1^oC, if one considers the room temperatures around 25^oC.

The load models presented in this section are commonly used in the context of direct load control programs, in order to simulate actions taken by the utilities. In most cases, these models are aggregated so that the total load profile can be characterized and used in simulation studies. These simulations are focused on the impact of the appliances management either on the final load curve or on the specific thermal behavior of the appliances, in order to assess the comfort levels. For instance, Gomes and Martins [58] simulated the impact of peak clipping actions on the final load diagram using EWH. Stadler *et al.* [52] studied the influence of some control measures on the thermal behavior of cooling devices. In [49], the impact of AC control on peak load reduction as well as on thermal comfort levels is analyzed. Moreover, in [59], the authors proposed a simulation-based methodology that uses PBLM and load aggregation.

2.3.3 Payback Modelling

In the context of DLC implementation, the payback (PB) consists of a sudden increase of power demand after a period of load interruption. A typical example of the PB phenomenon can be observed in thermal appliances control. When the power is curtailed, the temperature associated with the appliance operation suffers a significant deviation in relation to the comfort temperature. The deviation increases with the time of the curtailment. Within the objectives of the Wisconsin Electric DLC program presented before, Bischke and Sella [39] established an empirical relationship between the magnitude of the payback associated with the EWH curtailment and the time of interruption. This empirical relationship was defined according to the equation (2-6).

$$Pb(t) = 3 - 2x0.798^{t} \tag{2-6}$$

The maximum time of interruption considered in this modeled was 4 hours. For this duration of EWH interruption, the average payback estimated was 3 times the appliance power capacity. From the observations done in this study, the increase of the payback ration with the duration of the interruption was concluded to be in the form a^x. Figure 2-7 presents the evolution of the payback ratio taking into account this empirical model. As shown in the figure, the payback may be up to three times the capacity interrupted, which can provoke significant peaks in load consumption after an interruption order.

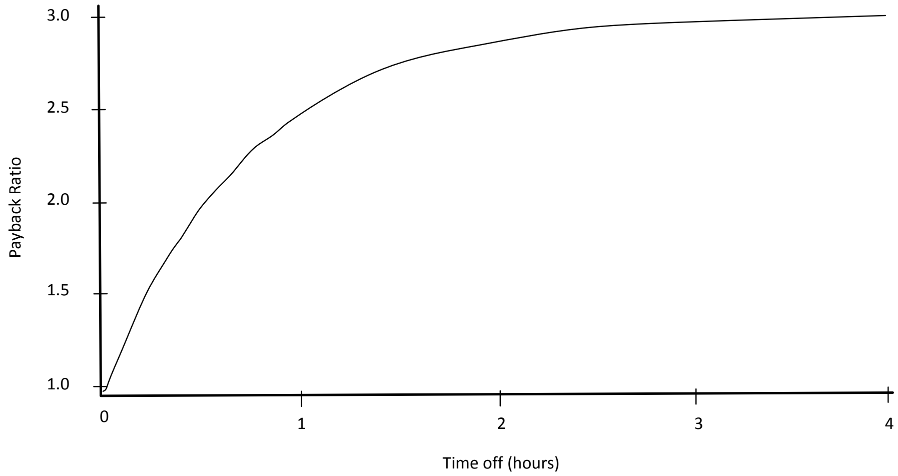

Figure 2-7. Payback ration (adapted from [39])

Wisconsin Electric tried to minimize the impact of the payback associated with the EWH load control operations. The utility divided the controllable appliances in different groups and sent the interruption signals for each group separated by a small time step [39]. Figure 2-8 presents the daily load consumption of the EWH appliances with DLC orders sent separated in two and four groups. Comparing these two situations presented in the figure, it is possible to conclude that dividing the controllable load in groups decreases the payback peak. On the other hand, not all the appliances are interrupted at the precise moment of the system capacity needs. Furthermore, although the segmentation of load interruption reduces the peak load, it also increases the duration of the payback effect.

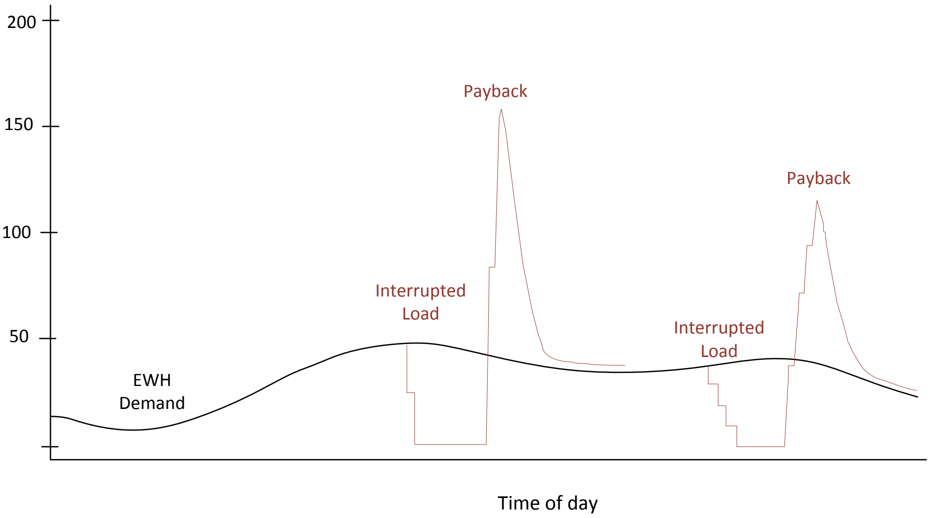

Figure 2-8. Payback effect (adapted from [39])

Energy PB depends on the control strategy, users' behavior and other external factors (such as weather conditions). It is associated with the need to meet the comfort requirements of the end-user after the load interruption. In the implementation of DLC strategies, the problem of PB was identified but it was rarely quantified. In [60] a generic model for PB quantification is used. It consists in a 3 stage-model including percentages (α, β and γ) related to the capacity interrupted in the periods before. These percentages depend on the control strategy, type of appliance and comfort requirements of the end-user. Equation (2-7) illustrates this generic approach considering 3 periods of interruption.

$$Pb(n) = \alpha IC_{n-1} + \beta IC_{n-2} + \gamma IC_{n-3} \tag{2-7}$$

Unlike the model (2-6), in equation (2-7) the relationship between the payback and the duration of the interruption results from the combination of the coefficients α, β and γ instead of a dependence in the form α^x. Both approaches are derived from empirical observation – none of them considers the dependencies from thermal factors that really affect the consumption of the appliances (for instance, the ambient temperature) – and it is difficult to assess their accuracy as well as their applications in different conditions.

2.4 The Smart Grids Infrastructure for Load Management

2.4.1 Smart Grids vision and challenges

The Smart Grids (SG) concept relies on a common vision of the electric grids of the future raised from the interest in electricity market opportunities after the unbundling of the electricity sector as well as in new services associated with distributed energy resources (DER), such as Distributed Generation (DG), storage and the flexibility of the consumption.

In Europe, these objectives require an interoperability of the European electricity networks and innovation initiatives regarding the modernization of the grid infrastructure by adding sensing, automation and communication systems to the existing network [61]. The SG encompasses new products and services together with intelligent monitoring, control, communication and self-healing technologies in order to: provide a user-centric approach and allow new services into the market; enable DG and utilization of renewable energy sources; better facilitate the connection and operation of generators of all sizes and technologies; maintain security of supply, ensure integration and interoperability; allow consumers to play a part in optimizing the operation of the system through the demand side management; provide consumers with greater information and choice of supply; significantly reduce the environmental impact of the whole electricity supply system.

It is expected that the technological developments and applications within SG will be capable to prepare the grids to cope with the expectations of different participants and to operate under new scenarios. Hence, the transition to SG brings new challenges to electricity sector [62]. For instance, the increasing penetration of variable resources (such as wind and solar) affects the adequacy and stability of the system, and requires new operational and forecasting tools capable of ensuring security, reliability and quality of supply [63]-[65]. On the other hand, the integration of a large-scale DG and micro-generation [66] increases the variability of the resources at the distribution level, introducing different flows patterns in the networks and demanding new deverticalized approaches in grid operation, such as microgrids [67].

In 2005, the Smart Grids European Technology Platform for Electricity Networks of the Future[4] (ETP Smart Grids) was established in order to meet the challenges seen by network owners, operators and particularly users, across the Europe. The main aim of this platform was to formulate and promote a vision for the development of European electricity networks looking towards 2020 and beyond. In 2010, the ETP Smart Grids elaborated a strategy for the deployment of SG in Europe [68]. In this document, six priorities were identified: optimizing grid operation and usage; optimizing grid infrastructure; integrating large scale variable generation sources; ensuring interoperability with information and communication technology; developing active distribution networks; enabling new market places, users and energy efficiency.

These six priorities established by ETP Smart Grids require important changes in the distribution grid infrastructure and management systems. Fan and Borlase [69] summarized a set of functional challenges to the present distribution management systems that will pave the way to the SG paradigm. Besides the extension of actual monitoring, control and data acquisition systems, the authors also emphasized the need for an enhancement of current Volt/Var Control by gathering detailed information about the operating conditions of capacitor banks and tap changer transformers. Furthermore, improvements in Fault Detection, Isolation and Service Restoration (FDIR) will also be necessary by adding new functionalities such as multi-level feeder reconfiguration and multi-objective restoration strategies.

2.4.2 From Smart Metering to the Home Energy Management Systems

The Smart Metering and the Automated Metering Infrastructure

The SG paradigm encompasses the replacement of traditional domestic energy meters (Ferraris meter) by Smart Meters (SM). SM is an advanced energy meter that measures the energy consumption of a consumer and provides real-time information to the utility [70]. SM is capable of collecting energy consumption data from each customer in a regular basis, which allow the utilities to manage electricity demand more efficiently and also to inform the customers about the prices and to use their appliances. Figure 2-9 presents the difference between conventional energy meters and SM regarding metering system architecture.

Wissner [71] highlights some advantages of using SM in order to improve energy efficiency. The possibility of the consumer to gather information regarding his/her domestic consumption profile allows him/her to take measures to avoid inefficiency. Moreover, if the consumers can have access to real-time energy metering and electricity price, they will be aware of their main electricity consumption, which allow them to identify possible changes in habits towards economic and energy savings. From the utility point of view, the use of SM bidirectional

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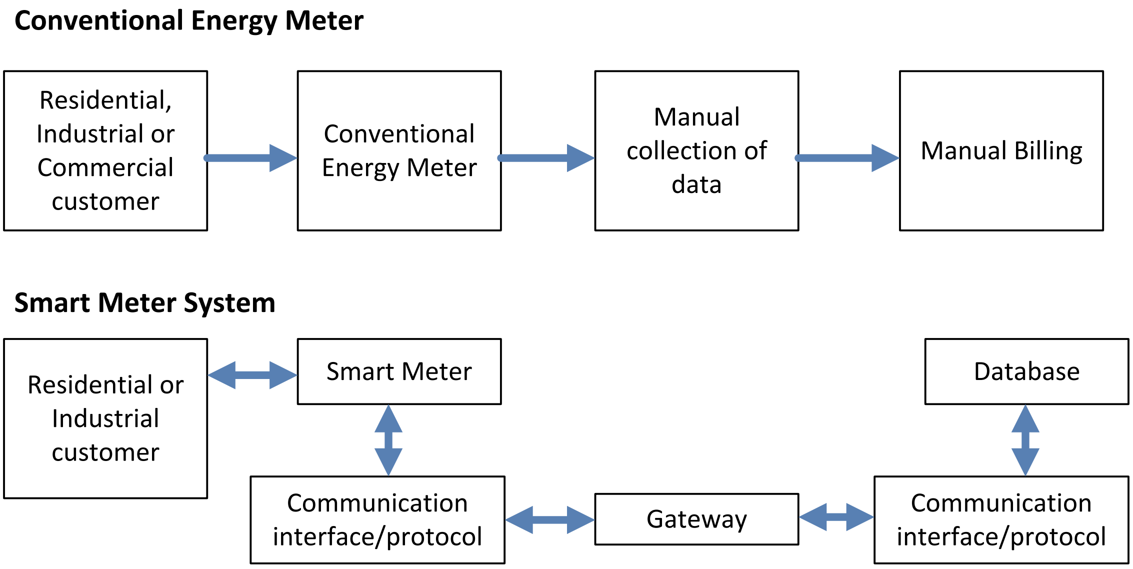
[4] The European Commission Directorate General for Research developed the initial concept and guiding principles of the Technology Platform. For more information see http://www.smartgrids.eu/

communications avoids manual metering which improves the accuracy of the measures and decreases the operational cost.



Conventional Energy Meter

Smart Meter System

Figure 2-9. Conventional vs Smart Metering System (adapted from [70])

The advantages summarized by Wissner assumes a bidirectional communication, *i.e.*, the utility sends the real-time prices to the SM and this devices send back real-time power measures to the utility. This type of communication opened new possibilities regarding, for instance, consumption monitoring and load control. Thus, the use smart metering platform were commonly associated with diverse energy metering nomenclature with different concepts and phases.

According to [72], the development of energy metering experienced three phases: Automated Meter Reading (AMR), Automatic Meter Management (AMM) and Advanced Metering Infrastructure (AMI).

AMR consists on the remote reading without physical access to the meter [73], *i.e.*, the simple application of the SM characteristics as they are described in [70]. AMM comprises an extension of AMR in order to include data management and, more recently, the possibility of load disconnection which requires a bidirectional communication with appliances.

Nowadays, AMI is the most accepted infrastructure in the context of metering systems since it extends both AMM and AMR. AMI are capable of establishing communication with domestic appliances, collecting data and monitoring the power consumption (through smart meters) as well as controlling and optimizing the energy usage [74].

Many studies have been considering AMI as a central element of the SG architecture in the context of Demand Response (DR), *e.g.* [75] and [76]. In fact, AMI consists not only on data measurement in a regular basis but also on continuously available remote communications.

Furthermore, AMI combines frequent information collection and transmission with exhaustive and detailed data metering. AMI refers to the full measurement and collection system that includes meters at the consumer site, communication networks between the consumer and a service provider [77]. Additionally, it also includes data reception and management systems that make the information available to the service provider.

A survey on case studies and policies regarding SM installations in many countries can be found in [78]. Gerwen *et al.* [79] summarized the common characteristics of smart meters: real-time or near real-time registration of electricity use and electricity generated locally *,e.g.,* local photovoltaic units; offering the possibility to read the meter both locally and remotely (on demand); remote limitation of the throughput using specific commands of the meter (in the extreme case curtailing the electricity to the customer); interconnection to premise-based networks and devices (*e.g.,* distributed generation); ability to read other, on-premise or nearby commodity meters (*e.g.*, gas, water).

European Commission endorsed a set of recommendations on smart metering systems [80], written under Mandates M/441, M/468 and M/490 as well as best practices in European countries. These recommendations established the minimum requirements regarding smart meters' functionalities:

- Provide readings directly to the customer and any third party designated by the consumer;
- Update the readings frequently enough to allow the information to be used to achieve energy savings;
- Allow remote reading of meters by the operator;
- Provide two-way communication between the smart metering system and external networks for maintenance and control of the metering system;
- Allow readings to be taken frequently enough for the information to be used for network operation and planning;
- Support advanced tariff systems;
- Allow remote on/off control of the supply and/or flow or power limitation;
- Provide secure data communications;
- Fraud prevention and detection;
- Provide import/export and reactive metering.

Minimum functionalities of SM established in [80] only consider data collection and control at the residential level. In other words, it does not take into account the communication and control specifications regarding home appliances. However, this component is not excluded. Although appliances control does not represent a mandatory characteristic of the SM in Europe, the EU recommendations recognize "a significant consensus on provision of standardized interfaces which would enable energy management solutions in 'real time', such as home automation, and different demand response schemes" [80].

Therefore, regarding SM functionalities, it is possible to distinguish two main groups: a first group related to the metering and data collection functionalities, which fulfill the basic requirements to define a SM, and a second group that includes more advanced technologies, such as load control and home automation, that allow the provision of ancillary services using domestic loads and generation.

In fact, the main potential of using SM relies on the capability for LC and home automation, integrated in a SG environment. In contrast, the data collection through SM has been dominated by recent technologies, due to economic and technical aspects. The installation of thousands of SM may lead to considerable high costs. A report conducted by the Office of Gas and Electricity Markets (OFGEM) [5] in Great Britain analyzed the additional cost of a SM beyond that required to replace the current meters [81]. OFGEM report reveals that SM cost varies considerably depending on the type of meter. However, it estimates a cost range in the region of £30 to £150 per meter, which includes the cost of the meter, installation, data transmission costs and maintenance.

Although SM mass production can decrease these costs, they are still significant in comparison with other technologies. For instance, Non-Intrusive Appliance Load Monitoring (NIALM) [82] can gather appliances information and avoid SM installation. For NIALM only a set of voltage and current sensors, which are installed at the power service entry, are needed. By analyzing the current and voltage signals, the NIALM systems are capable of identifying the operation status as well as the power consumptions of individual appliances [83].

Thus, metering functionalities are required but not enough to motivate the use of SM, due to the existence of better alternatives such as NIALM. However, taking into account that SM are the SG elements located at consumers' place, they should be capable of establishing communication with home appliances in order to enable control procedures that allow the provision of ancillary services.

Home Energy Management Systems

Home Energy Management Systems (HEMS) [84] emerged from this broader viewpoint of the SM. Besides the capability of being interoperable with smart meters, HEMS are also responsible for managing local distributed generation as well as consumption devices inside the house, which demands compatible functions on the side of the appliances. According to [74], "smart appliances" are capable of generating and share consumption information and obtaining management instructions. These appliances will be programmable devices that can be switched off automatically at peak hours [85]. On the other hand, Mathieu and Callaway [86] studied scenarios of real-time data regarding load management of TCL. The authors considered real-time scenarios regarding data collection, considering the possibility of TCL to report their current temperature and on/off state to the house central controller (HEMS). Temperature and appliances' time of use variables are related with the consumer comfort. It is expected that the consumer communicates his/her preferences to the HEMS, specifying an accepted range

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[5] Office of Gas and Electricity Markets (OFGEM) is the government electricity and natural gas regulator in Great Britain.

regarding these comfort variables. The HEMS gateway interface are designated by Energy Box (EB) in some studies [87]-[92].

Recent projects have been incorporating this broader viewpoint of the SM. For instance, in Portugal, the InovGrid project [87] proposed a reference architecture for smart grids consisting of a hierarchical control scheme supported by a communication infrastructure. The European project ADDRESS ("Active Distribution networks with full integration of Demand and distributed energy RESourceS") [89] proposed an architecture for load management [90] in which EB works as an interface between the consumer and the aggregator. Thus, the EB receives information about home appliances (including communication with temperature sensors) and it is responsible for the supervision and control of the loads related to the comfort of the end-user [91].

Livengood [92] developed and conceptualized an automated response model for the EB, based on real-time pricing. In this work, the EB is capable of performing an optimized control in order to minimize the energy costs. This optimization also takes into account the weather conditions, which influence DG units (such as rooftop wind turbines and photovoltaic generation), as well as the thermal model of the house and the outdoor temperature. Additionally, a decision-making process was also incorporated into dynamic programming algorithm, in order to bring to the model the cost/comfort preferences of the consumer. The uncertainty of the forecasted values regarding weather conditions was also included. The EB simulation process, developed by Livengood, is shown in Figure 2-10.

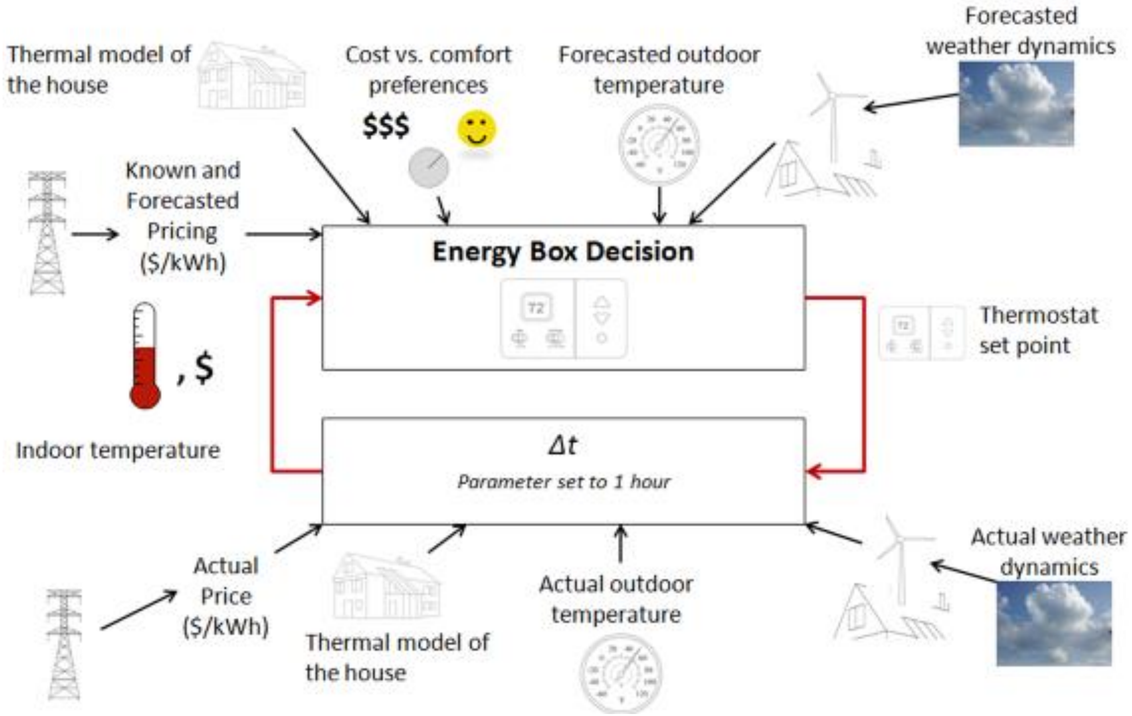

Figure 2-10. Energy Box model input data ([92])

Communication with the appliances

In general, the communication in the domestic domain, *i.e.*, between the HEMS and the generation/consumption electricity devices operating within the home area is established via Ethernet or wireless protocols such as Zigbee and Wireless Fidelity (Wi-Fi) [93]. Although these are the most popular technologies, it is important to stress that specific power-line communication (PLC) protocols for home automation are also being used [94]. HomePlug[6] is probably the most relevant example of a PLC protocol designed to perform communications between HEMS and smart appliances [95][96].

Ethernet is a widespread communication technology which is commonly used in the short-range network such as local area networks (LAN). Several devices within home domain come with Ethernet interfaces, including personal computer, laptops, servers, printers, media console, tablets, smart phones, etc. However, according to the home area network (HAN) technology assessment presented in [97] "Ethernet may not be appropriate for connecting all devices in the HAN (especially appliances) due to the high cost and power requirements plus the need for separate cabling back to a central".

Wi-Fi is a high-speed wireless Internet and network communication technology based on the IEEE 802.11 standard for wireless local area networks (WAN). Several HEMS applications are being considering this technology to communicate with smart appliances. For instance, Saha *et. al.* [98] executed air-conditioners load control actions through a Wi-Fi thermostat and in [99] a design of a smart home system based on Wi-Fi is provided.

ZigBee is a low power, open standards-based wireless networking technology that specifies a set of higher layer network and application protocols over IEEE 802.15.4 standard. These layers enable functionalities like initialization, device association/disassociation, security management and address management, among others [100]. The ZigBee protocol is managed by ZigBee Alliance[7]. The technology defined by the ZigBee specification is intended to be simpler and less expensive than other wireless premises area networks, such as Wi-Fi [93]. Applications of ZigBee include wireless switches, meters for a HAN and other equipment which requires short-range wireless data transfer at relatively low rates. Smart domestic appliances are included on this equipment. A variety of publications in the literature are considering ZigBee communications within the HEMS architecture. For instance, in [101], the smart home device descriptions and standard practices for demand response using ZigBee are presented and, in [102], a HEMS model capable of gathering real-time energy usage information coming from ZigBee hubs connected to the domestic appliances is proposed. In [103], a performance model of Smart Energy Profile protocol of a Zigbee HAN regarding SG functions (AMI and demand response) is presented.

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[6] Home Plug Alliance HomePlug Alliance is developing technology specifications and certification & logo programs for power-line networking. Website: http://www.homeplug.org/

[7] ZigBee Alliance was formed in 2002 and currently has 400 members and more than 600 certified products. Website: http://zigbee.org/
The Smart Energy Profile 2 is the forthcoming standard for applications that enable home energy management via wired and wireless devices that support Internet Protocol.

2.5 Ancillary Services

2.5.1 Concept and Definition

The liberalization of the electricity sector led to the identification and separation of Ancillary Services (AS). In fact, previously, these services were integrated into the centralized and vertical structures of the electrical systems that were responsible for generation, transmission and distribution of the electricity. The Unites States Federal Energy Regulatory Commission (FERC) established that AS are those services necessary to support the energy transmission from resources to loads while maintaining reliable operation of the system [104]. However, in [105], a distinction is made between AS and System Services (SS) from a technical point of view: while SS are the services provided by the system operator to all users of the network, AS are the services supplied by some of the users of the network to the system operator. Moreover this document also refers a sub-classification, which consists on the separation between the services that support system integrity (SS) and the ones that are linked with the power transfer (Transmission Services). Figure 2-11 shows how these terms are related with the user and the system.

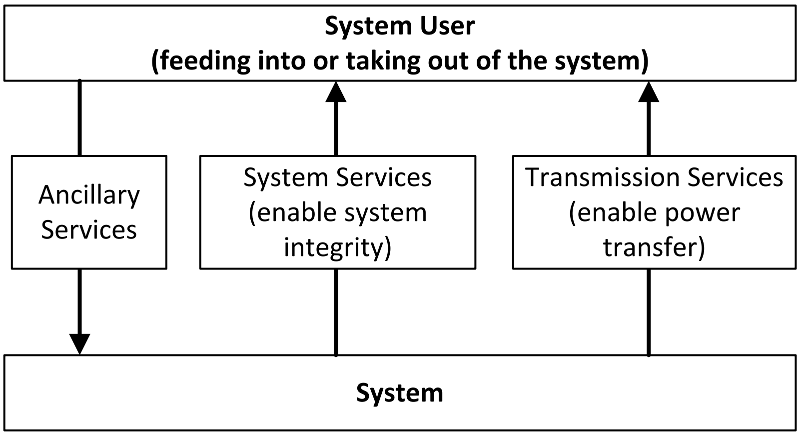

Figure 2-11. Ancillary Services ([105])

As shown above, many interpretations exist regarding the definition of AS. Similarly, different views are also proposed for its classification and categorization. For instance, Gjerde [106] divides AS into three groups: Interconnection, Generation/Demand balancing and Local Services. Interconnection services are related with the frequency response services between different areas. Balancing services consist on regulation responses to imbalances in the system, as well as load following and contingency reserve. Finally, Local Services involve not only voltage and reactive power control to support the active power transmission, but also other local services, such as Black Start. On the other hand, [105] highlights a classification based on the system needs in terms of operating requirements. Thus, four categories are proposed: Frequency Control, Voltage Control, Stability Control and System Restart.

As shown in the Table 2-1. , the stability and frequency are associated with similar AS. As a matter of fact, these services correspond to the objective of keeping balance between generation and demand, on different time scales. This balance is preserved due to Reserve Services (RS), traditionally provided by generators.

Requirements	Ancillary Service
Frequency Control	• Automatic Generation Control • Governor Control • Operating Reserve • Emergency Control
Voltage Control	• Voltage Control through reactive power.
Stability Control	• Governor Control • Operating Reserve • Emergency Control
System Restart	• Black Start

Table 2-1. Ancillary Services

2.5.2 Reserve Services

Although RS are presented in the electrical systems worldwide, the nomenclature used to describe them may change from country to country. The European Network of Transmission System Operators for Electricity (ENTSO-E) divides RS in three levels: Primary Control Reserve, Secondary Control Reserve, and Tertiary Control Reserve. A description of the ENTSO-E vison about these tree types of reserve control can be found in [107]. The main characteristics of each control level are transcript below:

- Primary Control Reserve: "*The objective of primary control is to maintain a balance between generation and consumption (demand) within the synchronous area. By the joint action of all interconnected parties / TSOs, primary control aims at the operational reliability of the power system of the synchronous area and stabilizes the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but without restoring the system frequency and the power exchanges to their reference values* […] *The time for starting the action of Primary Control is a few seconds after the incident, the deployment time for 50 % or less of the total Primary Control Reserve is at most 15 seconds and from 50 % to 100 % the maximum deployment time rises linearly to 30 seconds*".

- Secondary Control Reserve: "*Secondary Control makes use of a centralized and continuous Automatic Generation Control (AGC), modifying the active power set points / adjustments of generation sets/controllable load in the time-frame of 30 seconds (at the latest) up to typically 15 minutes (at the latest) after an incident. Secondary Control is based on Secondary Control Reserves that are under automatic control. Adequate*

Secondary Control depends on generation resources made available by generation companies to the TSOs"

- Tertiary Control Reserve: "*is usually activated manually by the TSO in case of observed or expected sustained activation of secondary control. It is primarily used to free up the secondary reserve in a balanced system situation, but it is also activated as a supplement to secondary reserve after larger incidents. […] Schedule activated tertiary control reserve is activated with relation to the predefined timeframe of exchange schedules, e.g. 15 minutes. A special exchange scheduling procedure is used. It may include exchange rescheduling between TSOs, a special kind of exchange schedule is used*".

In short, primary control consists on local automatic control, responding to the frequency changes. Secondary control manages the available reserve in order to bring back frequency to the target levels. On the other hand, this automatic control also reestablishes the scheduled flows in the interconnection branches. Finally, the Tertiary control comprises the unit commitment and dispatch orders that are sent by the Transmission System Operator, in order to restore the Secondary control and to compensate the difference between the forecasted and actual generation/demand. Table 2-2 presents a summary of these three levels of frequency control.

	Primary control	**Secondary control**	**Tertiary control**
Why is this control used?	To stabilize the frequency in case of any imbalance.	To bring back the frequency and the interchange programs to their target	To restore the secondary control reserve, to manage eventual congestions, and to bring back the frequency and the interchange programs to their target if the secondary control reserve is not sufficient.
How is this control achieved?	Automatically		Manually
Where is this control performed?	Locally	Centrally	
Who sends the control signal to the source of reserve?	Local sensor	TSO	Generation Company (the TSO in the case of a pool market)
When is this control activated?	Immediately	Depends on the system	
What sources of reserves can be used?	Depends on the system: partially loaded units, loads, fast-starting units.		

Table 2-2. Frequency control levels [108]

Rebours and Kirschen [108] developed a framework in order to compare different meanings and terms used to define RS. The authors examined the requirements of different types of RS in many countries and established a relation with the UCTE/ENTSO-E terminology. This comparison demonstrated that the nomenclature used in European countries, in general, corresponds to the UCTE/ENTSO-E terminology, in spite of some variations related with the starting and duration times of the reserve. Nevertheless, in other systems, different names for RS were found.

In the North America region, reserves are characterized by their response speed (ramp rate and start time), response duration, frequency of use, direction of use (up or down), and type of control (*i.e.*, control center activation, autonomous/automatic, etc.). Recently, González *et al.* [109] analyzed six different markets within the North American Electric Reliability Corporation (NERC). The authors identified four types of reserve services that are nowadays generally accepted within the North America region: Regulation and frequency response; Spinning Reserve; Non-spinning reserve; Replacement Reserve. Figure 2-12 presents a comparison between these usual American reserve services and European classification provided by ENTSO-E.

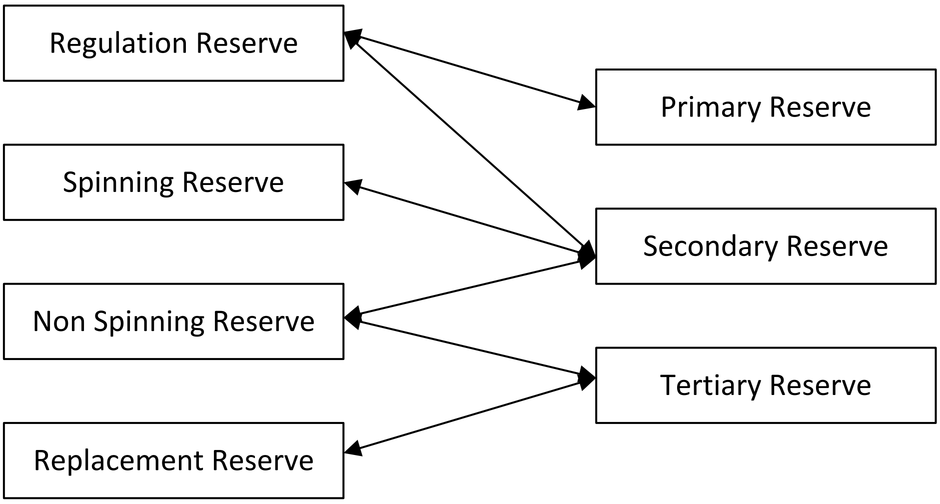

Figure 2-12. Comparison between American and European classification on reserves ([109])

Regulation and frequency response covers the continuous fast and frequent changes in load and generation that create energy imbalances and frequency fluctuations. In fact, Regulation corresponds to the primary and secondary control of the ENTSO-E nomenclature, since it is controlled by the automatic governor of the turbines and by the AGC, and must respond almost instantaneously to frequency changes and areas interconnection flow changes [109].

Rebours and Kirschen tried to clarify the meaning of Spinning Reserve [110]. The authors concluded that "*spinning reserve is the unused capacity which can be activated on decision of the system operator and which is provided by devices that are synchronized to the network and able to affect the active power*". In [109], more detailed definitions of spinning and non-spinning reserve are provided: Spinning reserve "*responds almost simultaneously (within seconds) to a contingency, but it is only required to be fully available within 10 min and maintained for 2 h*" and the non-spinning reserve "*does not require the permanent synchronization of the unit to the grid, but rapid start up and total availability must be guaranteed within 10 min*".

Replacement reserve or in some cases called supplemental reserve aims "*to substitute faster and more expensive reserves, so as to reduce costs and guarantee security against subsequent contingencies, and must be supplied within 30 min at the latest*" [109].

In 1996, the Federal Energy Regulatory Commission of the USA (FERC) groups the ancillary services into six classes: Scheduling, System Control and Dispatch Service; Reactive Supply and Voltage Control from; Regulation and Frequency Response Service; Energy Imbalance Service; Operating Reserve - Spinning Reserve Service; Operating Reserve - Supplemental Reserve Service [111].

Kirb [112] categorized these services in terms of normal and contingency operation. Regulation and Energy Imbalances services (similar to the regulation but slower, bridging the regulation services and the energy markets) are responsible to keep the balance between the supply and demand under normal conditions. Spinning, non-spinning and replacement services are responsible to provide "*reserve stand ready to respond in the event of a power system contingency*". Figure 2-13 illustrates how these services are differentiated in response time and duration.

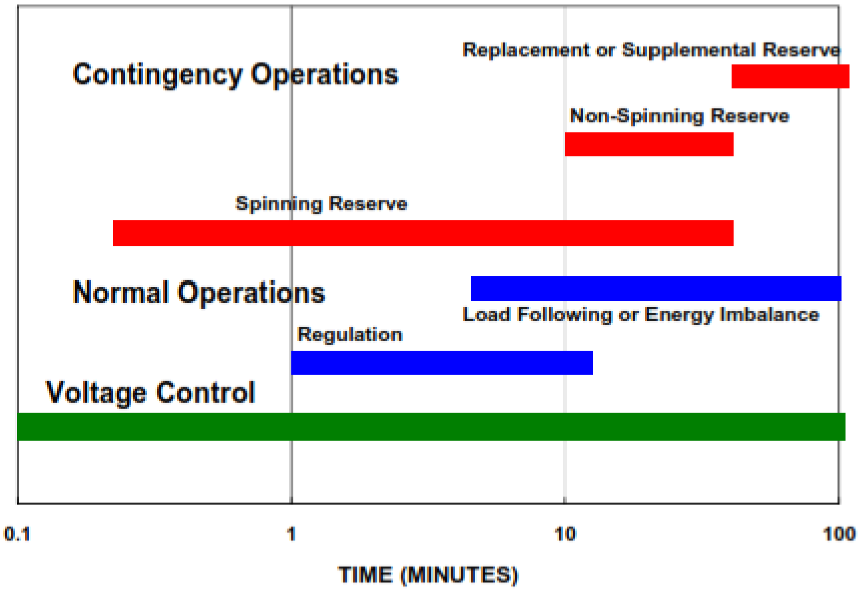

Figure 2-13. Response time and duration for normal and contingency reserve services ([112])

2.6 Loads Providing Ancillary Services

In this thesis the provision of tertiary control reserve will be explored through the day ahead flexibility of loads. This option will be explained in this section, by reviewing a set of developments from the literature related to the provision of ancillary services through the demand side.

Subsection 2.6.1 focus on the system restoration and voltage control services provided by the demand side; Subsection 2.6.2 presents the technical developments that enable loads to respond to frequency imbalance in a small time span; Subsection 2.6.3 presents the most relevant demand response (DR) models that allow the loads to participate in the secondary and tertiary reserve services via an aggregator; In 2.6.4, the current state of demand side integration into energy and ancillary service markets is discussed; Finally, in subsection 2.6.5, modern DR projects and initiatives from industry are presented.

2.6.1 System restoration and voltage control services

The integration of load management procedures in system restoration strategies, namely in microgrids context, has been considered in recent black start approaches [113]. For instance, Barsali *et al.* [114] recognize that "a signal to the meter for reducing the available capacity can help restore the service more quickly, in terms of number of re-powered users, even with lower power availability". Nevertheless, the participation of loads in system restoration should not be treated as an independent practice. In fact, it is integrated into the low level operation strategies combined with generation side, which is particularly relevant in isolated systems.

From the point of view of the demand response (DR) of load devices, receiving orders from the local emergency control is not different than responding to other services' requests. Therefore, the potential scientific development to enable load management participation in black start and emergency system restoration relies on the strategy design itself, rather than on DR improvements.

Moreover, the decision processes regarding strategies for load curtailment and demand limitation in emergency situations are related with other aspects rather than pure technical capability of loads to provide the service. In several situations, these decisions involve discomfort to the consumer and, hence, welfare and social commitment aspects of the consumption become dominant. For example, the curtailment of a space heating system in a hospital, in a public building or in a residential neighbourhood is treated differently even if the characteristics of the load devices are similar. Thus, although the strategies design comprising load management for black start and emergency recovery are viewed as a relevant topic, it is out of the scope of this thesis.

The provision of voltage control through the demand side has been also addressed by some authors in the literature. In [115], the effect of DR in the voltage of the radial distribution network nodes is evaluated. The authors concluded that DR has a great potential to boost the distribution system voltage at most of the critical nodes and it should be integrated in the current Volt/Var control. In fact, recent studies have been addressing this integration of DR in voltage regulation [116] [117].

In this thesis, the participation in system restoration and voltage control services was not explored due to two main reasons: (1) similarly to the black start, the potential developments in this topic are more on the identification of critical nodes and the integration into current Volt/VAR control as well as on the communication systems rather than on DR models; (2) the voltage regulation through DR suggests that the control is performed directly by the DSO at these critical nodes. Excluding equipment with significant capacity (such as industrial or large commercial loads) the idea that DSO performs a direct control of system loads is not aligned with the vision of this thesis, as will be explained further on this document.

2.6.2 Primary Control Reserve

The use of system frequency as an input signal to a load-controller was patented in 1979 in the U.S. by Schweppe [118], under the name of Frequency Adaptive Power-Energy Re-scheduler (FAPER). The concept can be applied to any electrical consumer which needs electrical energy to function but which is not critically dependent on when the energy is supplied, such as space and water heating and cooling appliances. In case of these appliances, the approach aims at integrating local frequency measurements in the thermostat control, *i.e,* making the set point temperature of the heating and cooling devices dependent on the frequency values so that the control of individual appliances could help on managing frequency disturbances in the grid.

In [119], the authors investigated the effects on a power grid of a large aggregation of frequency-responsive loads similar to FAPER. Refrigerators aggregated load were used to provide primary frequency control in situations of sudden loss of generation and during periods of fluctuating wind power. The study demonstrated how real-time operation could be like with a significant amount of active frequency-sensitive fridge/freezer load for the National Grid system in Great Britain. They also provide evidence of the usefulness of increasing the proportion of these types of loads when power systems have to integrate large penetrations of wind generation.

A similar study, presented in [120], simulated the potential of space heating appliances for primary frequency control. In this paper, a diagram of the thermostat action is provided in order to demonstrate the relationship between the frequency response and the temperature control. In a conventional thermostat action, the set point oscillates around a desired temperature (T_{des}) – selected by the end-user – within a dead band defined by the appliance manufacturer. The manipulation of the conventional thermostats to allow frequency response consists in replacing the dead band by a temperature tolerance up to a maximum deviation defined by the end-user (ΔT_{max}) and configuring the set point temperature to operate as a function of the local frequency.

Figure 2-14 illustrates the difference in the operation between a conventional and a modified thermostat of a heating appliance. If the frequency is above the nominal value (f_n), the set point temperature remains the same as in conventional thermostats. However, if the frequency drops below a pre-defined frequency (f_1), the set point temperature is lower so that the appliance consumption could be interrupted and the frequency restored back to the nominal value.

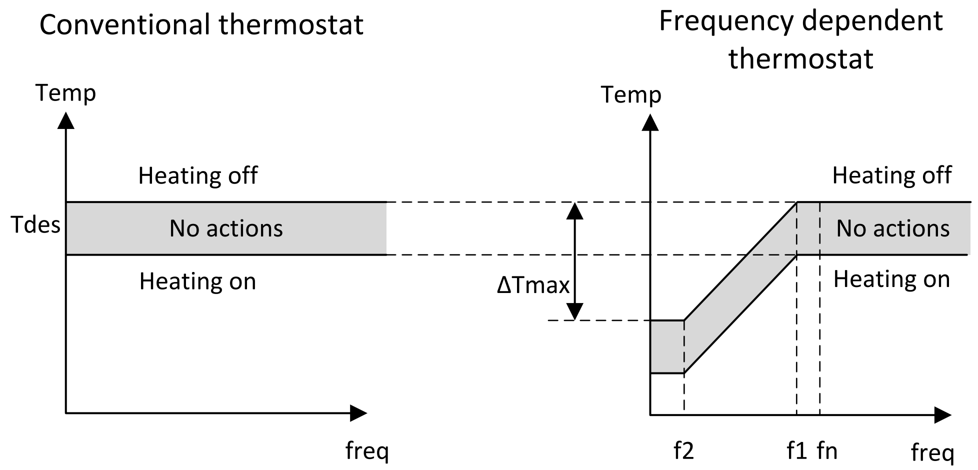

Figure 2-14. Conventional Thermostat and Frequency Dependent thermostat (adapted from [120])

A frequency response load control algorithm in the domestic sector was developed and tested in [121]. When the system frequency falls, this algorithm switches off domestic loads at different frequencies. In order to perform this selective control, the domestic appliances were divided into five groups: (I) electric space and water heaters, refrigerators and freezers; (II) dish and clothes washing machines, Tumble dryers; (III) Cooking appliances; (IV) electrical in-line heaters; (V) Lighting loads.

The switch off and reconnection control orders of these loads were designed according to the degree of disturbance that such action would cause to the end-user. Hence, the space and water heating and cooling appliances were disconnected a higher rate during the frequency drop (49.7 Hz). In contrast, lighting loads (group V) were switched off only in case of a severe disturbance in the frequency stability (48.9 Hz). An analogous approach was used to the reconnection periods. Due to the thermal storage characteristics of heating and cooling appliances, these appliances can remain disconnected longer than the lighting loads which have significantly lower off time periods.

The frequency-responsive load controllers based on FAPER and used in the studies previously presented turn a load on or off when the frequency goes above or below some threshold values. In [122], an improvement to this controlling approach was proposed. According to the authors, besides the deviations of the measured frequency from the nominal value also the evolution over time of such frequency deviation should be considered. Thus, for each load controller, a time characteristic determines when the load starts taking part in the control of frequency. As long as the frequency deviation does not exceed a certain threshold for a certain time, the load controller remains passive and the load follows its intrinsic evolution. The inclusion of time characteristic parameters regarding the frequency deviation in load control permits that larger frequency deviations trigger a faster reaction of the controllers while smaller deviations are allowed to persist for a longer time before the load starts contributing to frequency regulation.

In spite of the differences regarding the control approaches, the works presented above ([118]-[122]) share a common vision, *i.e.*, the primary frequency control provided by the demand side should be performed through a decentralized approach not requiring explicit communications. However, other studies have been pointed out a more centralized (or aggregated) vision of the primary frequency control. For instance, Pourmousavi and Nehrir [123] presented a central demand response algorithm for frequency regulation in a smart microgrid. The frequency regulation strategy consists in a central controller that selects the percentage of responsive loads that will turn on and off based on the evaluation of the frequency deviation. The controlling orders are sent to the loads through a wireless network with latency of less than 20 milliseconds [124]. On the other hand, Vrettos *et al* proposed a centralized frequency control through a population of thermostatically controlled loads (TCL) [125]. Since the time for performing such type of control does not allow the central unit to collect the state of operation of the appliances and, consequently, to forecast the interruptible load, the authors developed a moving horizon state estimation to assess this information [126] [127].

Besides the traditional domestic appliances, new loads such as plug-in electric vehicles (PEV) are being considered capable of providing primary frequency regulating services. For instance, in [128] the authors evaluated the participation of electric vehicles in the frequency regulation in an isolated system. A droop control was adopted to manage the PEV loads. This control was capable of changing the operation point of the vehicles charging for a deviation of 1 Hz. It was considered that in normal situations, the PEV is at the normal operating charge. In case of severe frequency disturbance, the vehicle can increase its load up to its maximum rated power (1 C) or reduce it up to 0.2 C. Recently, Izadkhast *et al*. [129] proposed an aggregated model of PEV for the provision of primary frequency control based on participation factors that defines the PEV availability to provide the service. The participation factors incorporate three possible stages regarding the electric vehicles charging (disconnected, idle and charging). In case of being at the charging stage, the PEV constant voltage and constant current operation modes were taken into account.

As discussed in this subsection, loads can participate in primary control reserve by responding to the grid frequency variations. In case of thermal appliances, frequency dependent thermostats can be installed in the devices to implement such control. Temperature-frequency relations in the thermostat design can be included in order to perform a selective disconnection and reconnection of loads according to their usage and the comfort off-time requirements ([118]-[122]). From the first patent on this domain [118] up to the present, the capability of loads to participate in primary frequency regulation became mature enough from the technologic point of view.

The implementation at the low voltage level becomes especially relevant in case of small scale or isolated systems (such as microgrids) and it depends on regulatory aspects of end-users' remuneration as well as on the private or public investments in frequency-dependent thermostat installation. In this thesis, the topic regulatory aspects will be addressed integrated in the context of other reserve services.

Therefore, this provision of primary frequency control reserve is out of the scope of this work.

2.6.3 Secondary and Tertiary Control Reserve

As discussed in the previous section, the secondary and tertiary control require a central management of the generators' power output. This type of reserve is activated either automatically – through the AGC signal in secondary control – or manually in tertiary control reserve. From the technical point of view, the provision of such reserve services through the demand side is very similar. In fact, both services require the capability of loads to respond to a central power deviation signal. Hence, from the point of view of demand response strategies, the difference between secondary and tertiary reserve relies on the time frame within which the loads are capable to respond to those signals in order to meet the activation time required for each type of reserve service. Unlike the generation side, where the response to power deviation requirements depends on the capability to change the kinetic energy, the demand response (DR) to a central controller can be limited mainly by the communication system.

The recent PG&E[8] pilot program on load control for ancillary services evaluated the ramp speed response to central signals aiming at interrupting a population of residential air-conditioners (AC) devices [130]. The aggregated response of the 129 AC devices involved in the study was the following: by the second minute 65% of the load reduction was attained; by the third minute, on average, 80% of the AC load was switched off; the total demand reduction took up to seven minutes. Although the control signals were sent within few instants, the communication between the load control operating system and the AC devices faced considerable delays. In some cases the signals were re-sent five minutes after the initial transmittal in case of individual AC devices did not receive the initial curtailment instructions.

The evaluation performed in the PG&E pilot program reveals clearly the current limitations of a large scale integration of DR into the secondary control. However, conceptual approaches and simulation studies are being developed in this topic. Recently, Ravindran *et al.* [131] presented a simulation study of an AGC scheme that includes price based DR. A load model of TCL was developed to be included in the AGC. However, the most relevant contributions on the provision of secondary control services through the demand side occurred in the field of electric mobility. For example, in [132] a methodology to make PEV able to contribute to secondary frequency regulation is proposed. The authors developed control functionalities to be provided by the PEV in order to keep the scheduled system frequency and establishes interchange with other areas within predefined limits. A comparison between the electric power system behavior to a given disturbance with normal AGC operation and with an AGC control that includes PEV is performed. Similarly, in [133] a study involving a two-area system AGC simulation demonstrated that an aggregated population of PEV can significantly suppress the frequency deviation and reduce the traditional regulation of AGC units.

Besides the earliest publications on the participation of DR in AGC, the most relevant technical advances occurred in the topic of aggregation of individual loads – namely TCL – to respond to power deviation signals for the provision of load following, regulation and replacement reserve, *i.e.*, encompassing response time frames between 1 and 15 minutes. For instance, Callaway [134] presented a first-order linear controller that generates broadcast temperature set point

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[8] Pacific Gas and Electric Company (PG&E): utility that provides natural gas and electricity in the California, U.S.

offsets in order to regulate the aggregate power output of a population of AC. The controller was applied to balance the power output of a wind farm. In this paper, the probability of an AC device being operating at a certain time was determined based on a model developed by Malhamé and Chong [135] that estimates the probability density distribution of a temperature in a population of similar heaters conditioning identical spaces. An improvement to this controller was proposed by Perfumo *et al*. [136] by modelling the aggregated control of a population of AC through a linear time-invariant second order approach.

In [137], a centralized load controller applied to TCL for the provision of regulation reserves is proposed. The control method consisted in switching off thermal appliances based on a merit order until the global power deviation required is achieved. This merit order was conceived by dividing the TCL in five groups according to their temperatures. If a heating device is closer to the upper bound of the thermostat, it belongs to the group 1 and it is in the top of the queue to be turned off. In contrast, if the appliance is closer to the lower bound of the thermostat, it is in the state 5 which indicates that it is switched off only in extreme situations. This controlling method has two evident advantages: first, it reduces the impact of appliances control on the end-user comfort; second, it minimizes the risk of payback. This central control approach was used in [138] to evaluate the potential of space heating loads to provide balancing reserve using direct load control.

2.6.4 Markets and Demand Side Bidding

Current State of demand response integration in AS markets

A study conducted by the Consortium for Electric Reliability Technology Solutions (CERTS) examined the experiences of loads providing AS in five electricity markets: Australia, the United Kingdom, the Nordic market and the ERCOT[9] and PJM[10] markets in the United States [139]. Authors studied load participation in four types of reserve services: Continuous Regulation, Imbalance Management, Instantaneous Contingency Reserve and Replacement Reserves. The first two RS are required in normal conditions whereas the other two are required in contingency/disturbance conditions. Continuous Regulation reserve is automatically provided in order to maintain the balance between generation and demand (in a minute basis) and to control the inter-area power flow. Imbalance Management is similar to but slower than Continuous Regulation. Instantaneous Contingency Reserve, in general, corresponds to Primary Frequency Control in the UCTE/ENTSO-E nomenclature. Analogously, Replacement Reserve is similar to Tertiary Reserve in terms of full availability time. However, in some cases, it can be activated automatically. The study also found load participation in three of these four RS. In fact, although the possibility of loads providing Continuously Regulation Reserve is being considered by some System Operators, nowadays this service is still being provided exclusively by generators. In general, Replacement Reserves are the RS with higher load participation.

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[9] ERCOT market is the electricity wholesale and ancillary services market operated by the Electric Reliability Council of Texas.

[10] PJM is a regional transmission organization (RTO) that coordinates the movement of wholesale electricity in all or parts of 13 states and the District of Columbia, in the US.

Nevertheless, for instance in United Kingdom, there is a considerable provision of Contingency Reserve through loads (around 30% of the reserve needed).

The evolution of DR programs within PJM and NYISO[11] markets is described in [140]. In NYISO market, a demand side ancillary service (AS) program was launched in 2009, including the provision of regulation, synchronous reserve and non-synchronous reserve. In PJM, since 2006, the frequency regulation is open to demand side bidding. However, the participation of loads in the provision of such services is insignificant. Therefore, in [141], market and policy barriers for DR providing AS in the United States were identified. Measures to enable the deployment of DR as a AS product and to be implemented at different entities levels (such as regulators, balancing authorities, utilities, etc. were detailed.

The impact of DR on electricity markets has being studied during the past few years. A report to the United States Congress [142] evaluated the benefits of the DR in Electricity Markets through the analysis of some traditional demand side management measures. The report concluded that the resource-efficiency of electricity production improved due to closer alignment between customers' electricity prices and the value they place on electricity. On the other hand, it also suggested some measures to increase the performance of electricity market, such as improving incentive-based DR and strengthening its analysis and evaluation.

In 1996, a European Commission directive [6] launched a general framework on liberalized markets for electrical systems in member states. One of the major changes was the introduction of a retailing activity in the structure. This market-oriented model emerged in many countries; for instance in Portugal it was integrated in 2006 with the Decree-Law 172/2006 [143]. Thus, although companies in retailing sector are nowadays playing a commercial role, in future they may also incorporate the aggregation function and start bidding AS, through DR, in electricity markets. This change in retailing activity functions has already started. For example, according to the Portuguese Decree-Law 39/2010 [144], retailers can be also players for energy trading regarding electric mobility. Toritti *et al* [145] evaluated the demand response programs in European markets, namely in the UK, Italy and Spain. The authors concluded that, currently, DR programmes are focused mainly on industrial sector through interruptible load contracts. In most cases, these contracts are agreed directly with the System Operator.

In NEM[12], loads are allowed to participate in eight types of AS presented in the market comprising frequency control, network control and system restart [146]. The participation is implemented through a demand response aggregator (DRA). The rules for the DR participation in the markets, detailed in [147], highlight the responsibility of DRA to ensure the feasibility and reliability of the AS offers:

> *"Loads are generally not able to provide ancillary services if the load is out of service. As with a Market Customer, a DRA will be responsible for ensuring it does not offer ancillary services that cannot be physically delivered […] there will be no provision for a mechanism to 'claw back' ancillary service payments made to a DRA that is found to be*

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[11] NYISO market is the electricity market operated by the New York Independent System Operator in New York State's electricity system.

[12] National Energy Market is the Australian wholesale electricity and ancillary services market, operated by the Australian Energy Market Operator (AEMO)

> *unable to provide the service. Instead, this would be a rule breach and the DRA may incur penalties if this occurred."*

Bidding Methods

In the following paragraphs, recent developments enabling the participation of loads in the markets will be discussed. First a review of bidding methods applied to the wholesale electricity markets will be presented and, afterwards, we will focus on the specific case of the participation in reserve service markets.

Demand Side Bidding (DSB) is the possibility of demand side to participate in electricity trading markets. Nowadays, there are two general types of DSB: bid the total demand or bid a change in the demand [148]. The first category relies on demand side participation in bilateral contracts and in the bids offered in the day-ahead spot markets. The second category means the possibility of demand side players to bid in the intraday markets an increase or a decrease amount in relation to the first offer.

Kiani and Annaswamy [149] proposed a model with market agents in order to simulate perturbations on the market equilibrium conditions, caused by the generation running on renewable sources. The impact of the DR on this problem was assessed and the effect of the uncertainties associated to the renewables in the market equilibrium was quantified. It was concluded that the presence of demand response can mitigate the consequences of the perturbation for the market.

In [150], the consequences of DR for the electricity market were analyzed, considering the location in the network for demand response and applying a Location Marginal Price (LMP). It was concluded that LMP is not a good solution, since DR may affect the lines' congestion and influence prices of those nodes far away, due to the presence of loops in network.

Shayesteh *et al.* [151] present a method to include aggregated DR as a solution for the bottlenecks that occur when a spot market is run. The authors concluded that the congestion management by generation and demand re-dispatch can considerably reduce congestion and decrease the auction price.

In fact, it is expected that aggregators will be capable to make reliable bids in the electricity and AS markets. Recently, demand side bidding methods have been proposed in order to accelerate the DR integration into these markets. For example, in [152], the demand bidding is discussed and a method to generate demand bids including price forecasting is developed and simulated taking into account data regarding California power market. In [153], a demand-price model is developed and two optimal bidding functions for electricity power markets (must-serve and price based demand) are provided.

Alvarez *et al.* [154] proposed a methodology to generate demand side bids to be offered by large customer (commercial/services). The methodology uses a forecast of the consumption of the electric devices located at customer's facilities combined with a cost analysis to generate the bids. In [155], a price-based optimization model for aggregating DR contracts to allow the aggregator to bid in the day-ahead electricity markets is proposed.

The particular case of a Microgrid (MG) aggregator that trades energy in the pool market and produces energy from local distributed generation to serve MG customers is analyzed in [156]. In the paper, a model for power scheduling and bidding operation of an aggregator was proposed, including risk management associated to the bidding activity. The objective of the model development was to determine the optimal bidding strategy for the MG aggregator in the day-ahead energy market and schedule the energy dispatch in real time to maximize the profit of the aggregator.

Liu and Tomsovic [157] developed a demand side bidding model to participate in both energy and spinning reserve markets. The model includes different characteristics for a price responsive shiftable demand bids for electricity markets and for the bids that a DRA can submit to the spinning reserve market. Table 2-3 summarizes these characteristics that were included in the developed model. Furthermore, the authors proposed a co-optimized day-ahead energy and spinning reserve market clearing process based on the maximization of social welfare.

Shiftable demand bids in electricity markets	Bids in spinning reserve market
• Minimum energy consumption at any period; • Maximum energy consumption at any period; • Total energy consumption over the scheduling horizon; • Demand pickup / drop rate • Minimum up/down time lines	• Price-volume bid at a specific period; • Maximum spinning reserve at any period; • Maximum daily curtailment • Demand pickup / drop rate

Table 2-3. Shiftable demand bids in electricity and spinning reserve markets (adapted from [157]).

The developments on the demand side participation in AS markets also occurred in the field of electric vehicles (EV). For instance, Sortomme and El-Sharkawi [158] presented an optimal combined bidding method to allow EV to participate in the regulation and spinning reserve markets via an aggregator. Bessa and Matos [159] formulated a day-ahead optimization problem for the participation secondary reserve. The paper also includes an operational management algorithm capable of coordinating the EV charging in order to minimize differences between contracted and realized values. The same authors also proposed algorithm regarding the participation of an EV aggregator in manual reserve bids [160]

2.6.5 Related projects and initiatives from the industry

OpenADR and OpenADR Alliance

The OpenADR project[13] has been carried out by the Demand Response Research Center (DRRC) which is managed by Lawrence Berkeley National Laboratory (LBNL). The initial goal of the OpenADR research was to explore the feasibility of developing a low cost communications infrastructure to improve the reliability, robustness, and cost-effectiveness of DR in commercial buildings. In 2006, DRRC performed a technology evaluation for the Pacific Gas and Electric Company (PG&E) Emerging Technologies Programs [161]. The program was designed to evaluate the feasibility of deploying automation systems that allow customers to participate in critical peak pricing (CPP) with a fully-automated response.

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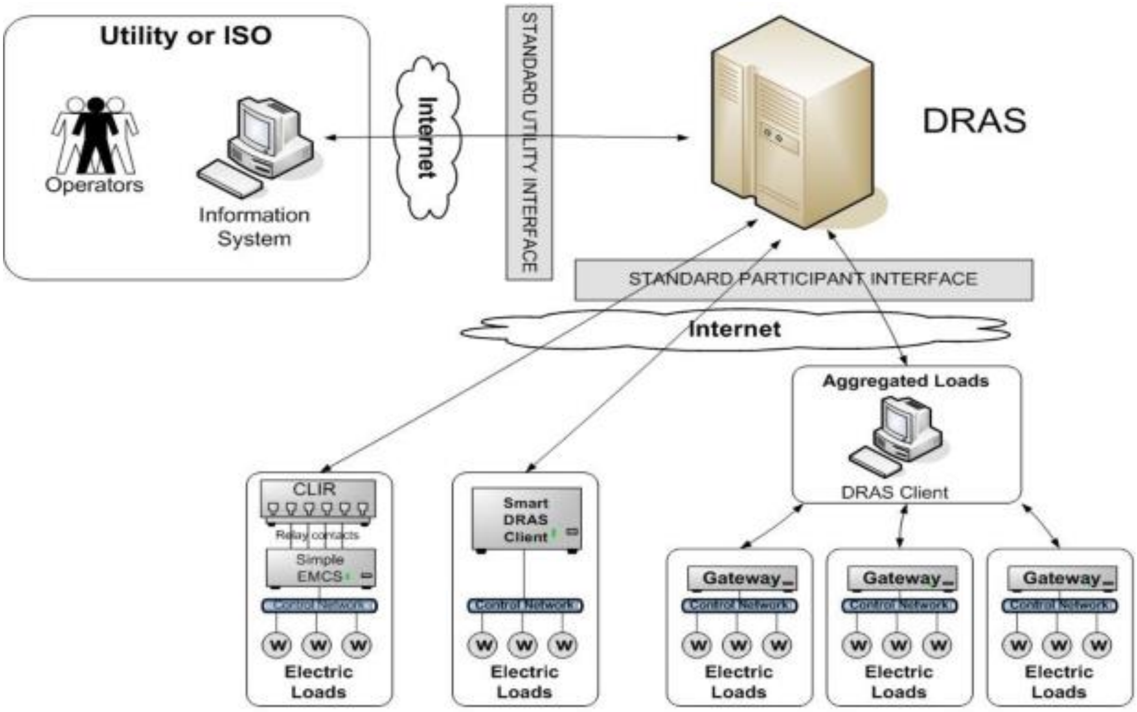

Figure 2-15. OpenADR architecture ([162])

The concept of OpenADR is to develop an architecture specification and a communication platform that uses open internet protocols which are interoperable with different building and industrial control systems. Through this platform, utilities can send signals to their costumers when the grid is operating at nearing the capacity. At the consumers' facilities, an Energy

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[13] Project website: http://openadr.lbl.gov/

Management System is capable of delivering an automated response to the utility requesting signals. Within the OpenADR architecture [162], a central element of to enable the automated response of the customers' load is the Demand Response Automation Server (DRAS). The DRAS is designed to generate, manage and track signals between the utility and the participants in the DR programs. The participants can communicate directly with DRAS or via an aggregator. Figure 2-15 illustrates the role of DRAS into the architecture of OpenADR.

OpenADR project also encompassed an effort for standardization of the various DRAS interfaces in order to provide benefits in lowering the effort and cost of implementing DR programs and thus increasing the level and reliability of participation in them [162]. Moreover, in 2010 the project created the *OpenADR Alliance*[14] initiative aiming at industry leveraging the OpenADR specification and methodologies to contribute to more effective deployment OpenADR to the market. Products related with demand response has being developed in the framework of this initiative such as the Demand Response Optimization and Management System (DROMS), an advanced demand management system created by one of the members of the alliance, AutoGrid[15].

ADDRESS

ADDRESS ("Active Distribution networks with full integration of Demand and distributed energy RESourceS") was a 2008-2012 FP7 EU funded project, composed of 25 partners spanning from electricity suppliers, R&D institutions, manufacturers, as well as distribution and transmission network operators. The main objective of this project was to develop a commercial and technical framework towards the active participation of domestic and small commercial customers in electricity markets considering also the provision of services to participants in power grids. Within the project development, this main objective was divided into seven specific goals described below:

1) Define an innovative communication architecture that ensures interoperability between the various devices that provides the services necessary to deploy Smart Grids with Active Demand in an efficient and economical way.
2) Describe the conceptual technical and commercial architectures developed to enable de Active Demand and exploit its benefits.
3) Develop algorithms for the Aggregator, taking into account the following functionalities:
    a. Consumption and flexibility forecasting;
    b. Market forecasting;
    c. Market and consumer portfolio management;
    d. Operational optimization;
    e. Settlement and billing.
4) Develop algorithms for the Energy Box, taking into account the following functionalities:
    a. Communication with the aggregator;
    b. User interface;

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[14] Initiative website: http://www.openadr.org/

[15] AutoGrid is a start-up company on the smart metering big data analytics. http://www.auto-grid.com/

    c. Optimization algorithm module;
    d. Information center (memory);
    e. Appliances Management.
5) Establish a DSO Functional Architecture, divided in three main Control Levels (for network management in the presence of active demand):
    a. DSO Central Control level
    b. HV/MV substation level
    c. MV/LV substation level
6) Development of an architecture acting as an abstract layer between the communication network and the applications interfaces, assuring interoperability.
7) Describe market mechanisms which enable active demand participation in the power systems. Recommendations:
    a. Technical Validation;
    b. Remarks on balancing and measurement;
    c. Recommendations for regulation.

The ADDRESS reference architecture [90] – presented in Figure 2-16 – introduces a new element at the consumers' facilities capable of communicating with the aggregators and with the system operator. This Energy Box (EB) acts at the consumption level by managing loads and other energy resources (such as electric vehicle and microgeneration). In fact EB has the capability of establishing a bidirectional communication with the appliances, in order to perform local automation and control. For example, EB should incorporate some strategies to limit the energy payback effect at the level of the house and to carry out control actions on the controllable equipment taking into account this information, the signals sent by the aggregators, and its own internal technical and economic optimization criteria.

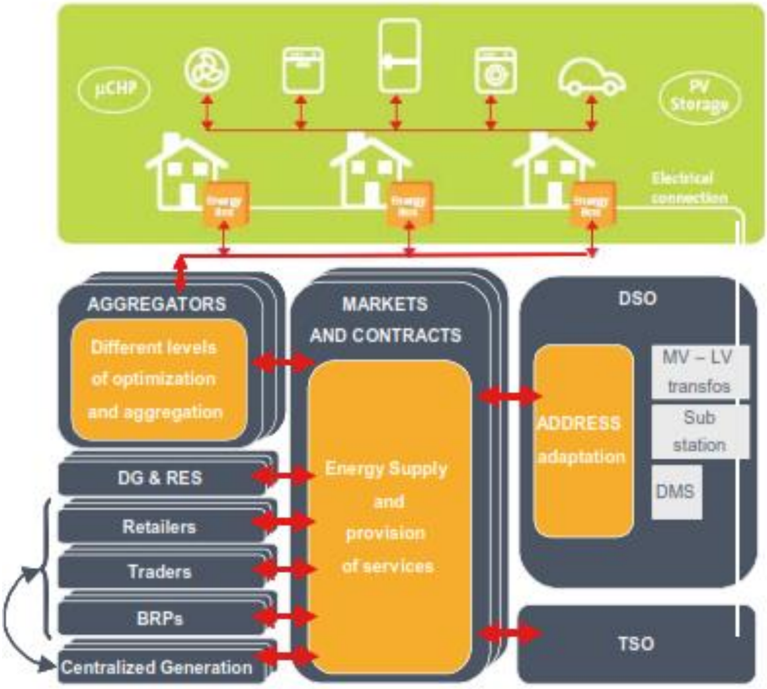

Figure 2-16. ADDRESS reference architecture ([90])

The Aggregator has a role of mediator between the consumers, the market and the other participants. The aggregator collects requests and signals for DR services and gathers the flexibilities of the consumers. These consumers' flexibilities are provided by the EB as the form of "modifications of the consumption profile". The main functions of the Aggregator are specified in the ADDRESS are the following:

- Gather the flexibilities of domestic and small commercial consumers to build the AD products;
- Be aware of the active demand requests and opportunities;
- Maximise the value of consumers' flexibility;
- Manage risks associated with the uncertainties.

The participation of Aggregators in the market requires the capability of delivering active demand products to provide a service over a specific timeframe requires. A relevant contribution of the ADDRESS project consisted in establishing a basic delivery template of active demand products. Two main products were identified in the project: Scheduling Re-Profiling (SRP) and Conditional Re-Profiling (CRP). In SRP "the aggregator has the obligation to provide a specified demand modification (reduction or increase) at a given time to the product buyer" whereas in the CRP "The aggregator must have the capacity to provide a specified demand modification during a given period. The delivery is called upon by the buyer (similar to a reserve service)". The active demand product template is displayed in Figure 2-17.

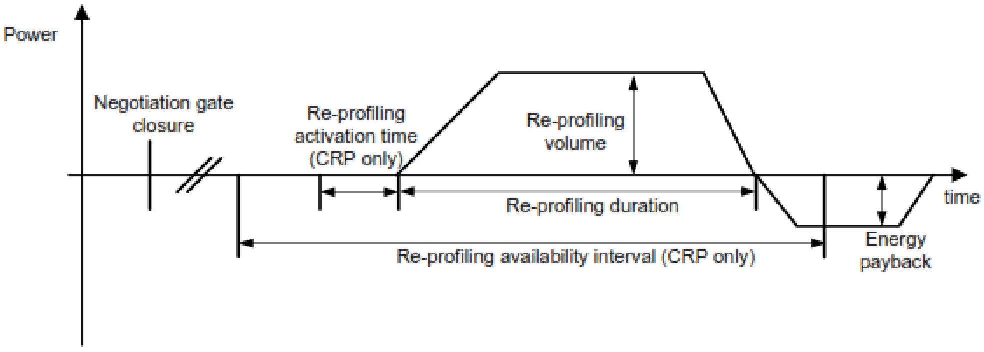

Figure 2-17. ADDRESS active demand product: power delivery template ([90])

As shown in the figure, the power delivery consisted in two parts. A first part involving a re-profiling volume, which can be positive and negative, that corresponds to the magnitude of the power increase/decrease due to the demand modification of the consumers. Then, a second part encompassing the energy payback (assumed as a consequence of the active demand product delivering) whose tolerance limits should be also included in the description of the product.

The results and the reports regarding the field tests of the ADDRESS can be found in the website of the project[16].

Energy@home

Energy@home is a project and a non-profit association (founded by *Electrolux*, *Enel Distribuzione*, *Indesit Company* and *Telecom Italia*) that aims to develop and promote home based technologies and services for energy efficiency. Energy@home targeted the increase of energy efficiency of a house system through the information exchange related to energy usage, energy consumption and energy tariffs between smart devices and domestic appliances. A home residential gateway, with several interfaces (Wi-Fi, ZigBee and cable/ADSL), was used to coordinate the exchange of information between devices. It allowed end-users to receive market information and according to their needs and restrictions define different starting times of smart appliances to take advantage of advantageous energy prices or tariff schemes.

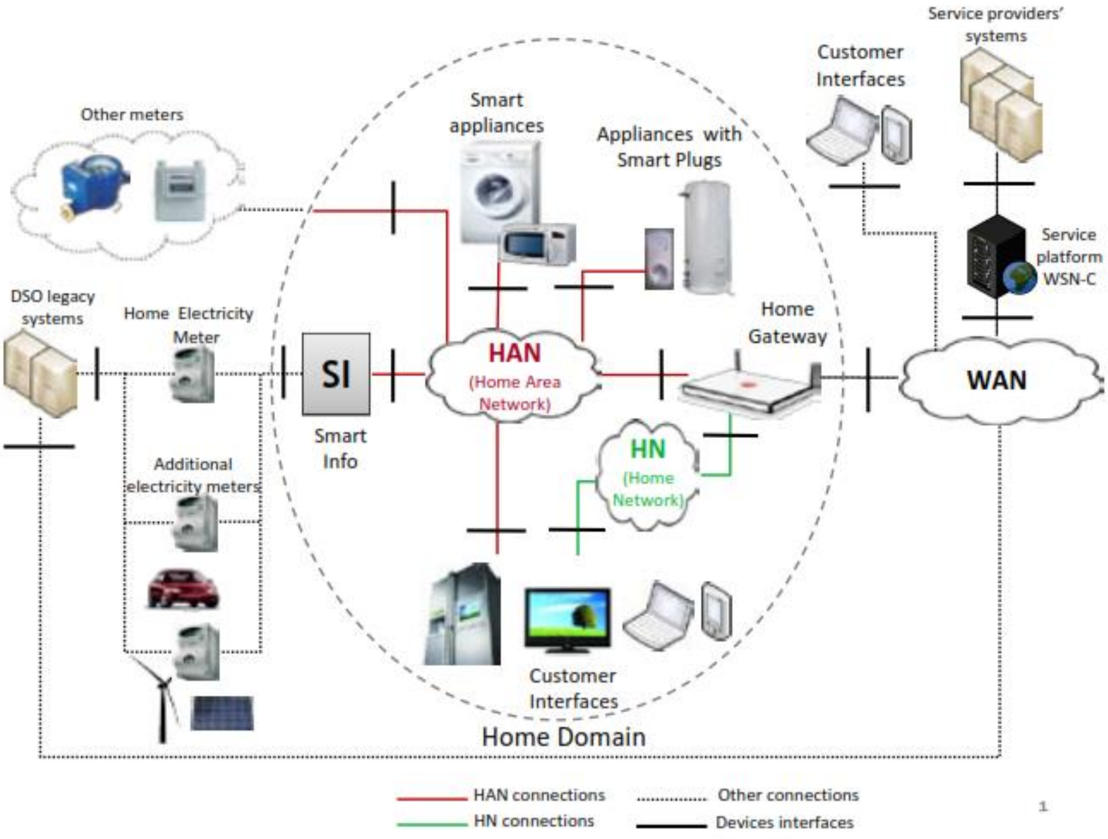

Figure 2-18. Energy@home architecture [163].

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[16] ADDRESS webpage: http://www.addressfp7.org/

The Energy@home viewpoint clearly distinguishes the communications within the residential building from the communications with the DSO and with the service providers [163]. At the "Home Domain", the communications with the appliances are established via the Home Area Network (HAN) – encompassing technologies such as ZigBee – and the communication with customer interfaces is performed through a Home Network (HN) involving existing infrastructures, *e.g.* IP/HTTP. The Home Gateway represents the link between the HAN, the HN and the communications with external service providers. The Smart Info is the element, provided by the DSO (Distribution System Operator), which enables the interoperability between the HAN and the electricity meter – and other existing metering systems associated with electric vehicle or local microgeneration.

Withus and EDP Comercial

Withus[17] is the Prime Contractor for the main Portuguese Retailer (EDP Comercial), for the development and manufacturing of an innovative HEMS solution, **re:dy,** presented in Figure 2-19. This is a home automation system, compatible with the SG, allowing energy consumption awareness and electric device management in real time. This system comprises four products: re:dy plug (smart plug with ZigBee communication); re:dy box (home gateway with HomePlug GP and ZigBee); re:dy meter (panel module with 3 phase metering and HomePlug GP interface); re:dy modem (EB modem with HomePlug GP interface).

Figure 2-19. Re:dy solution (Withus / EDP Comercial).

There Corporation Oy

There Corporation[18] offers Energy Efficiency and Home Energy Management solutions for electricity consumers, including real-time energy monitoring, energy load aggregation for demand management purposes, energy use optimization and substantial cost savings for the

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[17] Withus is a technological oriented company setting its core business on outsourcing and custom design and delivery. Company website: http://www.withus.pt

[18] There Corporation was founded in 2009 by combining Nokia Smart Home business program and Comsel Systems knowledge of smart metering and energy efficiency.
Company website: ttp://www.therecorporation.com

end-users and utilities. There Corporation's products are distributed to the end-users by energy utilities and service providers in Europe, namely in Scandinavia.

There Corporation developed an innovative technology platform for home energy management that includes: controlling home energy balance with optimization algorithms; consumer data aggregation; energy consumption visualization; demand side management.

The platform can be utilized to provide the consumer home energy management solutions without lowering comfort levels. The platform connects the home to the cloud, makes the consumer aware of his/her consumption and makes it possible to control heating systems and other energy devices connected in the home. All data can be visualized and consumption aggregated for demand response purposes.

Home Connect

In June 2014, two European leading industries in the smart appliances manufacturing sector (*Bosch* and *Siemens*) launched Home Connect, a solution to allow end-users to control home appliances from the existing smart phones and tablets. The particular contribution of Home Connect platform relies on the fact of being open to other appliance brands than Siemens and Bosch [164]. In fact, these two manufacturers aim at establishing an industrial standard capable of providing information and electricity consumption managing tools to the end-user and, simultaneously, ensuring the interoperability among the appliances within the home domain, such as ovens, dishwashers, refrigerators, washing machines and dryers, coffee machines, etc.

Open Energi

Open Energi is an aggregator of demand response operating in the United Kingdom (UK). The company provides demand side frequency balancing services to the UK National Grid through a virtual power plant that performs load management activities within large commercial and industrial customers. At the consumer's facilities, a meter is installed to measure electricity consumption on a second-by-second basis. All activity is wirelessly reported to the Open Energi secure servers. Figure Figure 2-20 depicts the technical diagram of typical hardware and communications infrastructures installed at the consumers' facilities.

This aggregator has an energy analytics service that informs the consumer with instant online reporting and can also be adapted to provide the ability to remotely control the industrial or commercial equipment. A software based technology which operates with a range of equipment including heaters, pumps, chillers, refrigerators and air conditioning units and turns them into smart devices which can react instantaneously to changes in electricity supply and demand across the UK network. If it detects that the system is imbalanced, *i.e.* including frequency deviations from 50 Hertz, it will temporarily adjust the equipment's power consumption up or down to help balance the grid.

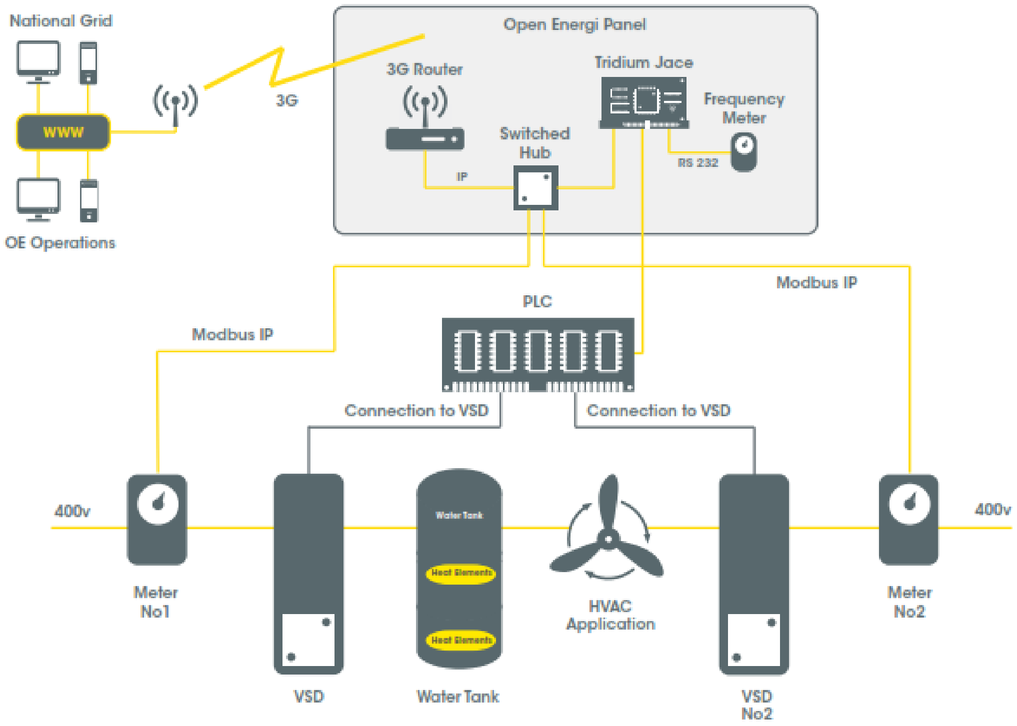

Figure 2-20. Open Energi: technical diagram ([162])

Nowadays, the participation of loads in the primary frequency control through the Open Energi system is still a marginal part in comparison with the generation side. Currently, the total loads capacity own by the aggregator is around 80 MW: However the real available capacity is significantly less (around 12 MW), since the normal operation of loads does not allow their use for demand response activities.

2.7 Summary and Main Conclusions

At the time of vertical organization of power systems, load management programs were developed to accomplish the general objectives of the utilities in order to yield benefits to the system as a whole. In this context, the possibility of a centralized control (managed by the utilities) of end-users' appliances, known as direct load control, was an important instrument to achieve those goals.

The deverticalization of the electricity sector raised the need for ancillary services in power systems provided by independent entities. The advent of smart grids and the current efforts to add sensing, communication and automation systems to the traditional network infrastructure paved the way for the provision of ancillary services from the demand side. In this new paradigm, three main conclusions can be drawn from the state of the art:

- Nowadays, the existing ancillary services markets (in most cases secondary and tertiary reserve) are not yet prepared to accommodate large scale demand side bidding. A new regulatory framework is essential in this field, namely in European countries where a diversity of markets designs can be found. On the other hand, mature demand side bidding approaches have been proposed in the electric vehicles field. Nevertheless, new improvements are required to extend these methods to the other loads in the system, such as domestic appliances.

- Recent developments on load management are taking into account the technological functionalities of the smart grids, such as advanced metering infrastructure. However, from the conceptual point of view, the load control strategies are still considering a vertical organization of the electricity sector. Section 2.6.3 revealed that present-day approaches are comprising centralized load control scenarios, in which a central entity ("utilities", aggregators or system operators) send direct load control signals to the individual appliances and incorporate concerns regarding end-user comfort. This vision ignores that intelligent energy management systems are also expected at the building level. Energy@Home [163] and Home Connect [164] are two examples of initiatives in this field.

- A conceptual architecture and high level functionalities enabling the provision of ancillary services in the smart grids paradigm should be define. This conceptual framework should express a vision of interconnection and interoperability among different intelligent systems from the smart appliances towards the ancillary services.

Chapter 3 – Approach and Conceptual Architecture

This chapter aims to conceptualize a technical framework for the provision of ancillary services through demand response (DR) within the smart grid paradigm. The approach of this thesis as well as and the conceptual architecture identifying the entities participating in the provision of ancillary services through residential consumers and establishing, from a technical point of view, the main interactions among them are presented.

Hence, this chapter is divided as follows: section 3.1 present the choices made in this thesis in what concerns to the type of ancillary services and loads in the scope of this work as well as the main assumption on the DR deployment environment; section 3.2 presents the approach of this research on the load management enabling tertiary reserve services in the current electricity sector organization; finally, section 3.3 presents the reference architecture developed in this thesis that resumes the functional relationship between the participant entities in provision of DR services.

3.1 Choices and Assumptions

3.1.1 Tertiary Reserve Services

As described in Chapter 2, ancillary services (AS) encompass reserve services (primary, secondary and tertiary control reserve) as well as other services such as voltage control and black start. Due to the reasons mentioned throughout the section 2.6, in this thesis only the provision of tertiary control reserve will be addressed.

Nowadays, tertiary reserve services may include demand side contribution, mainly through the interruptible load contracts established directly between the larger consumers and the system operator. However, as discussed in section 2.6.4, this participation is not integrated in the ancillary services markets. In fact, since tertiary reserves are centrally activated, an aggregation agent is required in order to allow the massive participation of small loads on these services.

Recently, aggregators started to be recognized by the legislation as important agents capable to ensure the extension of the centralized reserve services to the demand side [147]. On the other hand, the load management and aggregation methods described in section 2.6.3 have launched the basis for a technical framework that enables aggregators to participate in centrally activated reserve services.

Thus, this thesis aims to contribute to this framework by developing a conceptual approach, where active demand response is used by the aggregators for the purpose of delivering ancillary services.

3.1.2 Residential Thermostatically Controlled Loads

A variety of loads associated with different systems and uses are connected to the distribution grids. Managing demand profiles for participating in reserve services requires a detailed knowledge about load devices, their installation environment and their main uses. Performing such evaluation for all type of loads in all the possible environments (industrial, services/commercial and domestic) demand an exhaustive analysis. Therefore, choices had to be done in selecting the appropriate and representative devices capable of demonstrating the approach and load management solutions presented in this document.

In general, electric loads in industrial and commercial/services sector have a significant power capacity. Hence, some authors have been arguing that these loads should participate in electricity and reserve services markets without an aggregation agent [154]. In fact, each industrial/commercial application has its specific electricity uses and consumption patterns, which disable a generic approach for DR in this sector. On the other hand, the lack of information and disaggregated data regarding industrial/commercial consumption is a barrier to the development of load management strategies. Furthermore, considering the commercial/industrial equipment lifetime, the modifications in legacy devices to allow DR require significant investments. Thus, in spite of the potential of industrial and commercial/services electric loads to provide reserve services, the load management strategies in this sector should be addressed in a case-by-case basis and, therefore, they were not considered in this thesis.

In contrast, residential sector is characterized by a large number of small size electric loads with typical uses and well-known consumption patterns. A domestic facility is unable to participate in the electricity and reserve service markets on its own. However, in a large scale, it is expected that residential consumers can yield important contributions to these services through an aggregator. Moreover, from the implementation point of view, the costs to bring intelligence to residential loads allowing DR should not be put only on the side of power systems' services. For example, smart appliances initiatives, such as Home Connect [164], that include new control and interoperability features have been launched from the appliances manufacturers in order to add competitive characteristics to their products portfolio. Similarly, home area communication technologies, such as Wi-Fi, are widespread across the residential buildings ready to be used in DR activities.

Thus, the conditions of the domestic sector pave the way for the developments on load management and aggregation solutions within the objective of this work. Among the diversity of residential appliances, this thesis is focused on thermostatically controlled loads (TCL), namely air conditioners, electric water heaters and refrigerators, due to their potential to be controlled without major impact on the end-user comfort. Nevertheless, the conceptual approach and the methods presented in this thesis can be extended with minor modifications to other domestic appliances as well as other loads in the industrial and commercial/services sector.

3.1.3 Deployment Environment Assumptions

From the implementation point of view, the main differences between the traditional direct load control initiatives and the load management in the context of smart grids (SG) relies on the existence of an advanced communication infrastructure capable of connecting the participant entities in the DR activities: Distribution System Operators (DSO); Aggregators; Market Operators; end-users, through the Home Energy Management Systems (HEMS).

The uncertainty surrounding the possible services provided by DR in a SG environment as well as the lack of a comprehensive regulatory framework on this field led to different interpretations about the functional requirements regarding communication infrastructure. For instance, this problem is recognized in a report on SG communication conducted by the U.S. Department of Energy [165]. The report considers a wide range for communications latency concerning DR activities – from 500 milliseconds up to several minutes – depending on the type of service. The objective of this thesis is not to discuss the communication requirements neither to propose technical developments to the communication infrastructure. However, the conceptual architecture presented in this chapter is based on a set of assumptions on the area of communications that should be highlighted.

In the approach presented in this work, a wide area network (WAN), a home area network (HAN) and an Advanced Metering Infrastructure (AMI) are considered. A literature review about the theoretical and implementation aspects associated with these infrastructures was addressed in Chapter 2.

The communications between DSO and HEMS is established via the AMI including the installation of a smart meter at the end-users domestic facility. Despite the wide range of functionalities that can be endorsed to the smart metering devices, in this work they are assumed to be aligned with the minimum requirements recommended by the European Commission [80]:

- Provide readings directly to the customer and any third party designated by the consumer;
- Update the readings frequently enough to allow the information to be used to achieve energy savings;
- Allow remote reading of meters by the operator;
- Provide two-way communication between the smart metering system and external networks for maintenance and control of the metering system;
- Allow readings to be taken frequently enough for the information to be used for network planning;
- Support advanced tariff systems;
- Allow remote on/off control of the supply and/or flow or power limitation;
- Provide secure data communications;
- Fraud prevention and detection;
- Provide import/export and reactive metering.

The communications between the HEMS and the aggregators as well as the data exchange between system/market operators and aggregators are transmitted over long distances via the WAN, using the current internet service networks, for example. It is assumed that communication characteristics – namely in terms of latency and reliability – allow the aggregators to place bids in the day-ahead and intraday secondary and tertiary reserve services markets as well as to send signals to the various HEMS to activate such bids.

In the home domain, it is assumed that HAN ensures the interoperability among several systems including smart appliances, smart meters, microgeneration systems, existing home automation and end-user interfaces. Furthermore, the conceptual approach presented in this thesis assumes that HEMS are capable to establish bidirectional communications with smart appliances and with the end-user through the common HAN technologies: Zigbee and/or Wi-Fi. The following functional requirements within the home domain are assumed in this work:

- Smart thermostatically controlled appliances are capable to receive on/off signals from the HEMS (the coexistence of an exterior control and the appliance thermostat are detailed in Chapter 4);
- These thermal appliances report their current temperature, on/off state and power output to the HEMS;
- HEMS receive information (one way communication) regarding the actual power consumption of the uncontrolled load as well as the power injected by microgeneration units – such as photovoltaic or micro wind turbine – located in the home domain;
- HEMS can have access to local microgeneration forecasts for the next hours up to the day-ahead by communicating with this service providers through the WAN;
- HEMS receive information (via smart meters and/or aggregator gateway) about real time electricity prices as well as remuneration for the provision of tertiary reserve services in a 15 minutes time step;
- HEMS report the actual smart appliance state operation, uncontrolled load consumption and microgeneration power output to the end-users;
- End-user can define consumption preferences through the HEMS interoperable software installed in the interface devices.

3.2 A Structured Approach to Load Management

3.2.1 The integrated vision of Load Management

The Load Management programs (LM) under the power systems' vertical structures were implemented by electricity utilities (most of them public owned) that were responsible for the transmission and distribution network infrastructures, system operation and reliability, generation investments and maintenance, security and quality of supply, billing activities, etc. Due to the strategic nature of the power systems, these utilities were also viewed as instruments to achieve welfare as well as macroeconomic and political objectives.

The LM programs launched in this context reflected this integrated vision of the electricity systems. In fact, the system was treated as a whole in the implementation of LM strategies. Regarding the objectives of LM, some programs were designed to "avoid investment in generation sector", to "minimize fuel costs" or to "minimize the operational costs" [16]-[21].

Strategies such as direct load control – based on signals sent directly by the utility to the end-user's appliances whenever they "benefit the system" – are an example of a vertical approach to the LM. Figure 3-1 presents the vision of an integrated approach to LM programs carried out under the vertical structures of power systems.

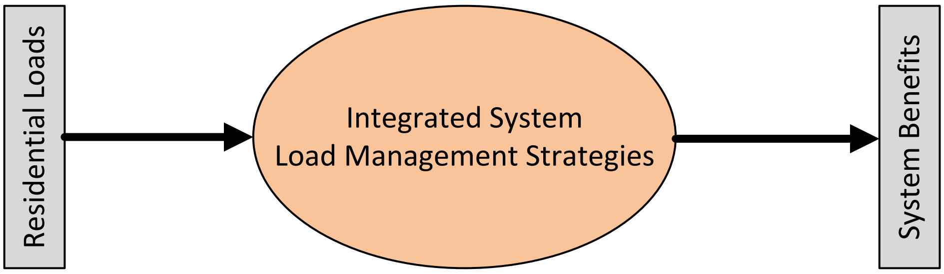

Figure 3-1. Integrated approach to Load Management

Nowadays, after the deverticalization of the electricity sector and the emergence of the electricity and ancillary services markets, the power systems sector was divided in different activities and new entities were created to accomplish different goals. Transmission and distribution grid operators, aggregators, market operators, generation companies and regulatory entities are looking at the demand side participation in ancillary services from different perspectives.

In general, the objective of the system operators is to decrease the operational costs of the transmission and distribution networks, avoid congestions in their grids, ensure satisfactory levels of reliability and quality of supply; aggregators aim at maximizing the profit of their bids in electricity and ancillary services markets as well as at increasing the income from bilateral contracts established with the system operators; generation companies are competing with the demand side aggregators in the ancillary services markets; regulatory entities are responsible to supervise the activities of the sector according to political objectives and remove the barriers for competition in generation and retailing activities.

In fact, the idea of single objective LM programs yielding benefits to the electricity system as a whole for a "common good" is no longer compatible with the current regulatory framework neither with the SG paradigm. In contrast, public entities or private companies committed to the different activities in power systems sector have their own objectives, decision making processes, resources and tools to deal with LM.

3.2.2 A Load Management approach in the SG paradigm: achieving controllability

The major barrier for the implementation of LM initiatives in current regulatory framework relies on the lack of consensus regarding loads controllability (*i.e., the capability of controlling loads*). Actually, the existence of several entities with direct or indirect interest in the potential DR services provided by appliances control and management within the buildings domain raised a new question: *who manages what?* or *who controls what?*.

Recent developments on LM, such as those presented in section 2.6, reveal a diversity of answers to this question. Some new load control methods still incorporate an integrated vision of power systems, in which the system operators perform a direct load control (DLC) of the devices, such as thermostatically controlled loads (TCL), located at the end-users' residences in order to accomplish with system operation objectives. For instance, Lu [138] evaluated the provision of regulation and load following services to the system through the demand side, assuming that "the power consumption of loads is controlled directly by a utility or a system operator".

The inevitability to adapt DLC implementation methods to the technological infrastructure of the SG communications is recognized by Callaway [134]. Even so, the author argues that with the recent advanced metering infrastructures "system operators will have the ability to control TCL by manipulating the thermostats' set points, rather than directly interrupting power, as in traditional direct load control programs".

Vrettos *et. al.* [126] [127] proposed a set of methods to allow the provision of ancillary services by managing residential TCL. The authors considered "an aggregator controlling a TCL population to provide power system services" [126]. In the proposed architecture, the aggregator is the centre of LM actions: it is capable to send control signals to the loads and, ideally, it "would have access to high frequency state measurements from each individual TCL".

Achieving controllability of loads is a key factor to enable LM for the provision of demand side ancillary services. Evidently, all the entities participating in these services would take advantages of controlling consumption at the appliances' level. Increasing the control margin of their resources is always beneficial to a system operator or an aggregator. Nevertheless, as demonstrated above, the current perspectives in the literature about "who controls what?" are clearly conflicting. In fact, it is not expected that residential appliances will receive control signals from an aggregator and, at the same time, from a system operator.

Furthermore, the vision of smart appliances manufacturers (such as Home Connect [164] launched by Bosch and Siemens), does not involve scenarios where system operators "manipulate set point thermostats" or aggregators receive "state measurements from each individual TCL". Obviously, constructive and operational characteristics of the appliances should be respected, internal control and design should be preserved, lifetime must not be shortened and the main functional requirements should be prioritized, *i.e.*, residential appliances have their primary uses besides being a hypothetical resource for ancillary services. Above all, the LM approaches within the SG paradigm should take into account the end-user's comfort and privacy concerns.

3.2.3 Addressing privacy concerns on Load Management

The access to end-users' private information has been a recent concern regarding smart metering and load management procedures. In fact, in the context of traditional power systems, the consumption was usually metered over long time span (*e.g.*, one month), which did not raise any privacy problems. However, smart meters are capable to provide up-to-date and accurate detailed information about the electricity consumption of the end-users. This frequent measurement of electricity gives to the utility the possibility of analyzing sudden power variations on the residential consumption, which allows the identification of the appliances' power signatures [166]. For instance, Molina *et al.* [167] demonstrated the potential for power consumption patterns to reveal private information about end-users. Through the aggregate household electricity metering every second, the authors easily obtained the consumption of typical residential appliances and identified patterns according to their characteristics. With this method, private information (such as how many people are at home, sleeping routines, eating routines, etc.) was easily recognized.

Several methods have been proposed in the literature to achieve data privacy in the SG communication networks. For instance, in [168], a method for anonymizing frequent consumption data sent by a smart meter is presented and in [169] a communication architecture encompassing the encryption of individual measurements is discussed. Recently, traditional privacy enhancement approaches have been applied to the smart grid infrastructures, such as differential privacy [170] as well as random noise and perturbation techniques [171]. Although privacy enhancement methods are essential to ensure the protection of end-users' personal information, they are out of the scope of this thesis. Even so, privacy concerns are addressed in the architecture proposed in this chapter, not from a technical point view, but from the perspective of controllability.

Indeed, the control of residential appliances requires a significant amount of information regarding private life (room occupancy, shower time, comfort patterns, etc.). Typically, this fact leads to a superficial conclusion – *control reduces privacy* – that is commonly used by several end-users as an argument to disapprove control systems within the home domain. However, in some cases the opposite is also true, *i.e.*, the residential appliances controllability is a way of ensuring privacy. For example, the identification of living patterns is more challenging in case of "self-controlled" or automated appliances. In the study performed by Molina *et al.* [167] aiming at infer about the personal behavior through frequent electricity measurements, the authors "filtered out the power signatures of automated appliances" in order "to obtain only power segments associated with human activity".

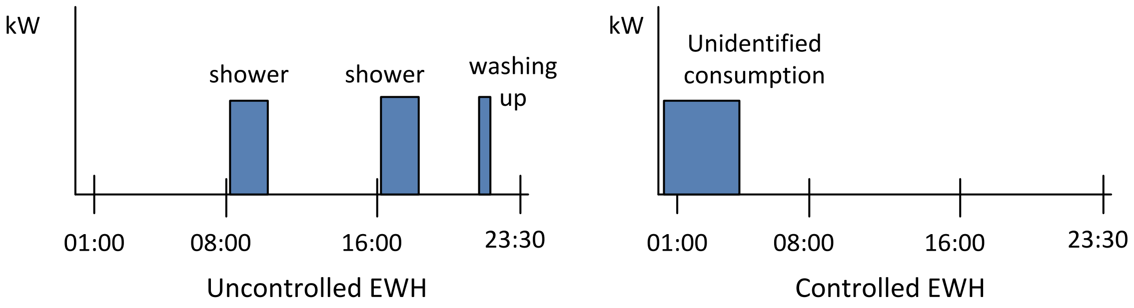

Figure 3-2. Private information through water heating appliance operation

The idea that "controllability enables privacy" can be proved through the analysis of a water heater device operation. In case of an uncontrolled appliance, the power demand is driven by the thermostat and normally the electricity consumption occurs immediately after the hot water usages. Thus, for instance, a minute based metering of the appliance power demand allows the identification of human life patterns, as illustrated in Figure 3-2. In contrast, if the end-user owns a local control to move electricity consumption to the night period (*e.g.*, to take advantage of lower electricity tariffs), the identification of hot water usages is practically impossible. Actually, the control disables the time-dependent characteristic of the appliance consumption which yields benefits in private information protection.

The example presented in Figure 3-2 clearly demonstrates that the existence of residential appliances control does not necessarily facilitates the access to private data. A conclusion that can be drawn from this example is that privacy concerns are not a matter of controllability itself; rather, they are a problem of "who controls what", already discussed in this section. In fact, if a suitable control of domestic appliances requires a significant amount of private information, then, from the privacy perspective, only one entity can perform such control: the end-user.

Therefore, in the architecture presented in this chapter, the appliances control is performed exclusively within the home domain. Hence, scenarios comprising the possibility of system operators and aggregators to take the control of domestic loads are not considered in this research, due to the reasons already mentioned. Furthermore, only minimum required information to enable the provision of metering and ancillary services is sent to external entities.

3.2.4 A structured approach to Load Management

As previously discussed, the traditional LM programs launched in order to yield benefits to the electricity system "as a whole" are no longer compatible with the existence of several entities in electricity sector. Moreover, the current conflicting definitions regarding controllability as well as privacy concerns emphasize the need for a new LM approach compatible with the present organization of the (unbundled) electricity sector that addresses these aspects.

The structured approach proposed in this thesis conceives the LM strategies for the provision of tertiary reserve services in agreement with the SG (unbundling) vision. Consequently, the reference architecture and LM methods presented in this thesis were developed taking into account the different perspectives and the management resources related to each type of activity within the electricity sector.

Therefore, entities are viewed as independent structures with interactions among them. As presented in Figure 3-3, three types of structures are considered in this thesis: Home Domain Structure; Aggregator Structure and Distribution System Operator Structure. Each structure is composed by three elements: resources, management methods and services. The role of the regulatory agents relies on establishing rules and supervising the interactions between the structures.

In the Home Domain, the HEMS can use resources (sensors, Home Area Network communications, data acquisition and processing units, interface with the end-user, etc.)

capable of controlling smart appliances. As previously discussed, these resources are owned by the end-user and are managed by the HEMS in order to provide internal services (for example, to improve the energy efficiency within the residential building) or external services (*e.g.*, to the aggregator). However, the HEMS acts according to the perspective of the end-user, *i.e.*, its management methods aim at minimizing the energy bill, maximizing the remuneration from the provision of services and avoiding discomfort situations.

It is assumed that the Aggregator is associated with a group of residential consumers that sell services coming from appliances control at the Home Domain. The Aggregator buy these services and establishes bilateral contracts with the system operator and/or offers bids in the tertiary reserve markets. The quantification of controllable services purchased from the Home Domain and the size of the bids (or the services offered) are defined by the aggregation methods according to the perspective of the Aggregator, *i.e.*, maximizing its profit in the bidding activity.

The procedures adopted by the System Operator use the Aggregator's services to improve grid operation. On the other hand, although these services are economically provided by the Aggregator, from the physical point of view they are delivered by the Home Domain, where the controllable resources are located.

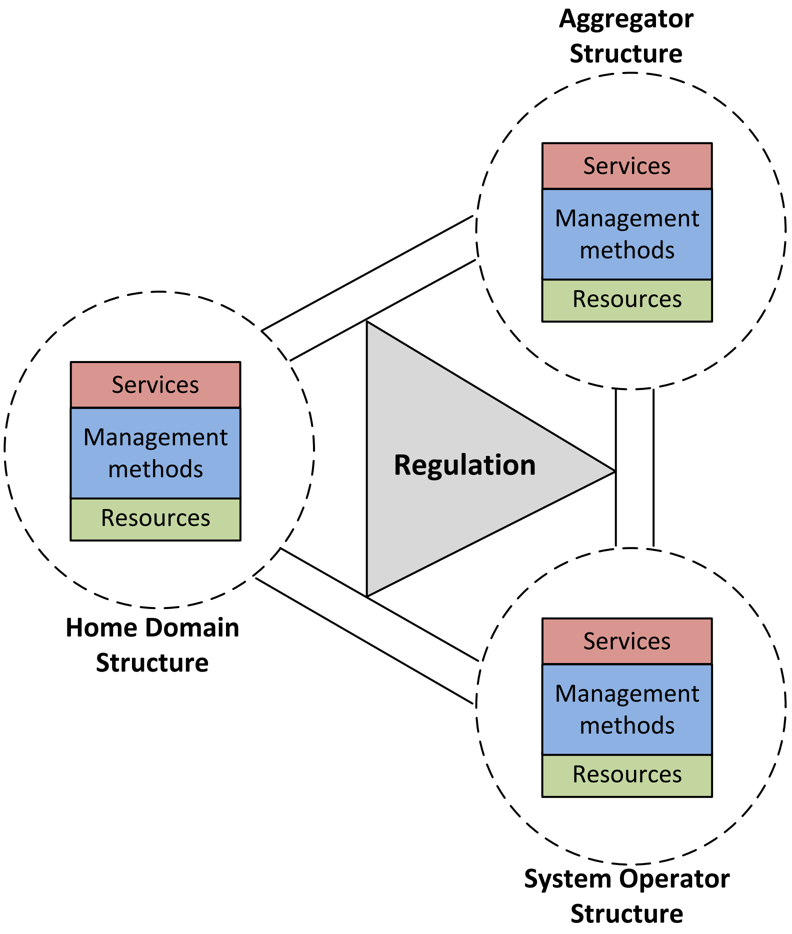

Figure 3-3. Structured approach to Load Management

3.2.5 Services/resources chain towards ancillary services

As stated above, the architecture and the methods presented in this thesis are based on a structured approach. The ancillary services (AS) are enabled by a sequence of interactions between services and resources of each structure (representing entities in the electricity sector). Figure 3-4 presents the perspective of this thesis regarding the services/resources chain from residential appliances towards the provision of AS.

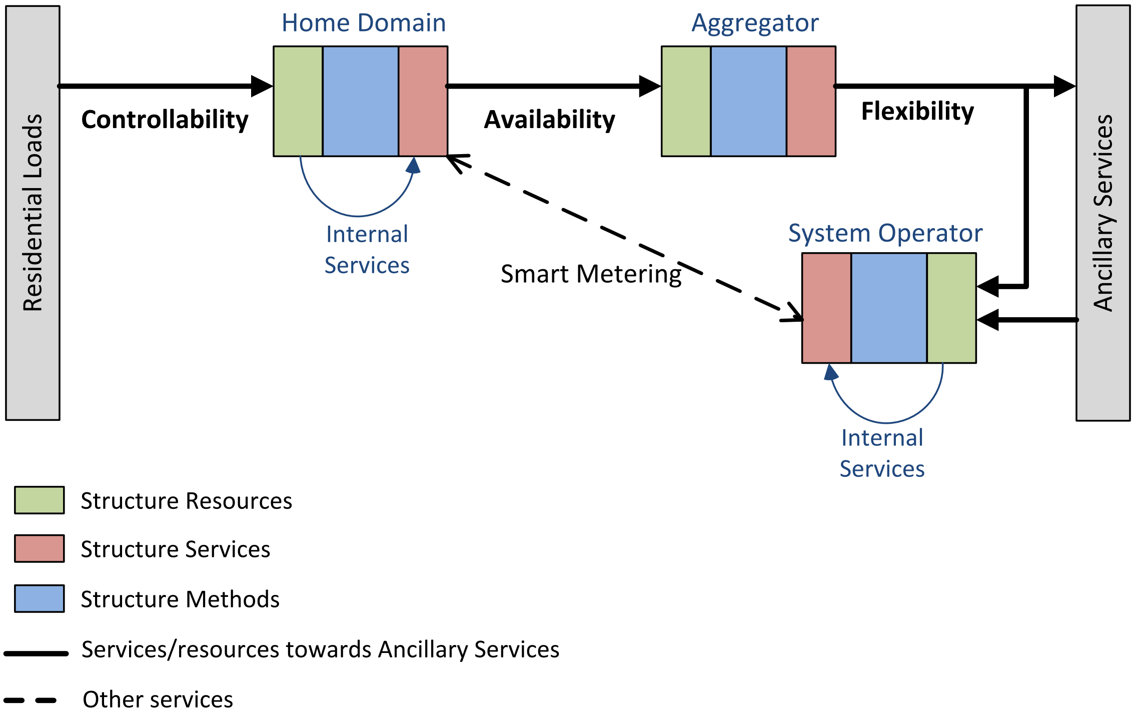

Figure 3-4. Services/resources chain towards ancillary services

Controllability is the basic unit of the ancillary services chain and it is the low level resource of the home domain structure. It consists on the capability to control loads taking into account the comfort of the end-user. Controllability can be achieved either by existing control and automation in the house and/or by the interoperability systems developed by the appliances manufacturers. As discussed previously, private information to enable a suitable control is provided and treated within the home domain structures in order to protect the end-user's personal data.

As a resource for the provision of flexibility services, controllability depends on two main factors: (1) the characteristics of the smart appliances, including their physical parameters as well as the capability of reporting their state of operation and receive control orders by an external energy management system within the home domain; (2) on the end-users acceptance of this control as well as on their willingness to increase the degree of controllability, for example through the relaxation of their normal comfort patterns.

Within the home domain, a set of methods should be developed, taking advantage of the appliances control and monitoring to provide internal and external services. The internal services are those that yield benefits directly to the end-users: disaggregated consumption information, prevention of discomfort situations, local load management enabling electricity costs reduction or comfort improvement, optimal load scheduling to maximize self-consumption, etc. The external services are those provided to the aggregator in order to enable AS. In this thesis, the term “availability” is used to define the type of service provided by the home domain to the aggregator.

At the level of the aggregator, availability resources are transformed into flexibility services to be offered directly to system operators (through bilateral flexibility contracts) or in the participation in reserve services markets (demand side bidding). The difference between availability and flexibility will be explained in the following chapters. Shortly, availability consists in the potential consumption changes related to the typical baseline consumption (including energy payback) of the end-users whereas flexibility is the aggregated upward and downward power capacity that can be offered directly to the market or to the system operator by the aggregator.

System operators are service takers and corresponds to end of the chain. Usually, these entities are responsible for the technical dispatch of flexibilities offers – both from generation and demand sides – in order to execute the centrally activated ancillary services. Furthermore, it is assumed that Distribution System Operators (DSO) can establish bilateral contracts with aggregators that deliver load flexibility at pre-defined nodes in the distribution grid. Besides the flexibility of the aggregators, DSO has their own controllable resources connected to the distribution network, such as capacity banks, on-load tap changers. These flexible resources can be used by DSO to improve management and operation of the distribution grid as well as to provide services to the transmission system operator.

An interaction between system operator and home domain structures can be observed in the figure. In fact, although the flexibility services are provided by the Aggregator, these services are physically delivered at the DSO connection point with the residential building. Furthermore, the smart metering devices owned by the DSO and physically located within the home domain can play an indirect role in facilitating the provision of ancillary services (e.g., informing end-users about real-time prices, measuring consumption to verify the availability services event).

3.3 Proposed Architecture

The architecture proposed in this section aims at describing the relationships between the entities of the electricity sector that participate in the provision of ancillary services (AS). Privacy and controllability aspects highlighted in section 3.2 were key inputs of the concept that is presented in the following paragraphs. Additionally, the architecture development was based on the structured approach previously discussed. Hence, the interactions among the abstract structures, the role of the regulation, the relation with the electricity and AS markets are detailed.

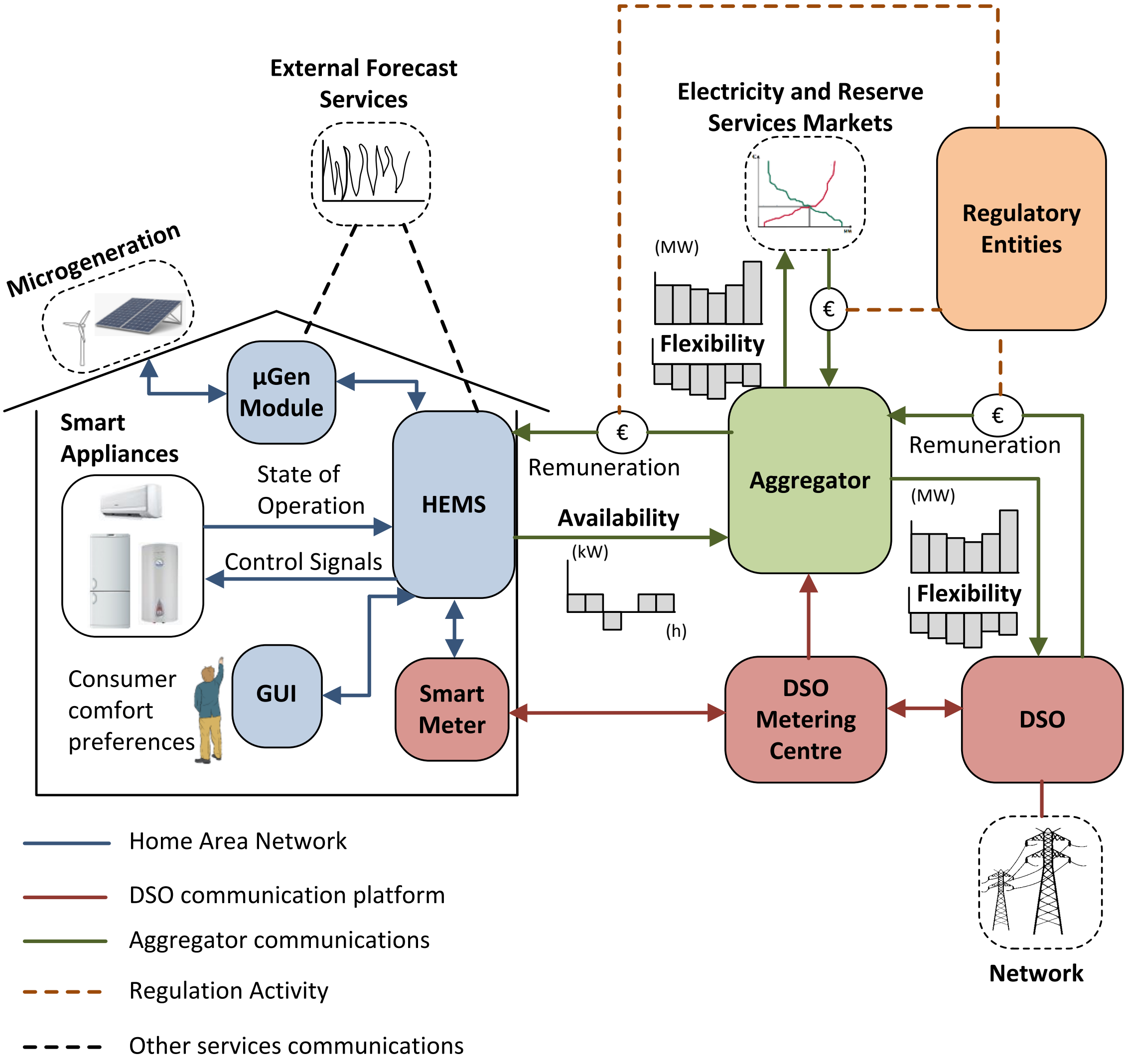

Figure 3-5. Reference Architecture

3.3.1 Main interactions towards the provision of ancillary services

The home domain structure comprises the end-users, the home energy management system (HEMS), smart appliances and microgeneration units. In the provision of ancillary services for the day ahead, the HEMS receives the remuneration for the availability for the day ahead that is sent from the aggregator and it communicates back the home domain availability profile that corresponds to consumption changes in each period. The HEMS is also connected to the distribution system operator (DSO) through the smart metering device, which is capable of metering the consumption and providing information regarding real time electricity prices. With the availability profiles received by each HEMS, the aggregator can offer flexibility services either directly to the DSO or to the electricity markets. In opposite way, DSO provides end-user's meter readings to the aggregator so that the availability services provided within the home domain can be quantified.

As already mentioned, this thesis is focused on the services/resources chain towards flexibility services. Hence, in the subsequent chapters, a special attention is given to the procedures within the home domain that maximize the availability of the end-users as well as to the role of the aggregator.

Although the interactions between the aggregator and the HEMS will be clarified during the Chapter 4 and Chapter 5, in this section the sequence of events towards the provision of tertiary reserve services is summarized below:

- During the previous day, the aggregator communicates the remuneration of availability services for each hour of day ahead to the HEMS;
- Until the last hour of the previous day, the HEMS communicates the availability profile, *i.e.*, the potential changes in the residential consumption for each hour of the day ahead;
- During the last hour of the previous day, the aggregator build its flexibility bids, based on the availability services received form the residential consumers included its portfolio, to be offered for each hour of the day ahead tertiary reserve market. Depending on the market conditions that are forecasted by the aggregator, some availability services are purchased to the end-users and others are rejected;
- Afterwards, the flexibility bids are placed in the market and the purchasing decisions are communicated to the HEMS.
- The HEMS, whose availability profile was accepted by the aggregator, will activate the appliances control mechanisms during the day ahead to provide this service. In contrast, the HEMS, whose availability profile is not accepted, do not perform any type of control.

3.3.2 Entities participating in the flexibility services

Although this research is focused on the interactions between the HEMS and the aggregator, in the definition of the conceptual architecture, the DSO, the regulation and the markets were included, since they are taken in to account in the development of methods that enable the provision of ancillary services.

A brief description of the role of entity participating in the provision of ancillary services through the demand side is presented in this subsection.

HEMS

The HEMS is a central element of the Home Domain structure and it aims at managing the electricity resources at the home level and sending residential availability curves to the aggregator. The HEMS contains a processing unit – where the energy management algorithms are run – as well as interoperability modules capable of establishing communication with the smart appliances and with micro generation modules. The communication with the smart appliances is bidirectional, *i.e.*, the HEMS sends on/off control signals and receives the current state of operation of the loads. As stated in section 3.1.2, in this thesis, only thermostatically controlled loads (*TCL*) will be analyzed, namely water heaters, space heating, cooling devices and refrigerators. Hence, the current state messages consist on temperature and power consumption frequent updates. Moreover, HEMS is capable to access external servers that provide day-ahead local ambient temperature forecasts in order to use them in the space heating control algorithms.

The communication between the HEMS and the microgeneration is performed through the µGen Module. This module may comprise interoperability functions that allow HEMS to collect real-time values regarding the operation of microgeneration and to send signals to the units' controllers. In this work, the possible controlling functionalities of µGen Module are not explored. In contrast, the capability of reporting to the HEMS the current local power generation as well as the forecasts for the day-ahead (provided by an external service) is taken into account.

HEMS are also responsible for gathering end-user information, namely consumption habits and comfort requirements. Consumption habits comprise the typical daily routines and human behavior patterns associated with the electricity uses of TCL: *house occupancy*, *shower time*, *normal desired temperature for hot water*, etc. It is assumed that HEMS have algorithms capable to forecast, store and protect this type of data. In contrast, comfort requirements are the end-user preferences regarding appliances operation, for example the *maximum and minimum temperature of the refrigerator*. The main difference between comfort requirements and consumption habits is that comfort requirements cannot be forecasted, since they do not depend of the past data. Rather, they are comfort boundaries that reflect the end-user willingness to allow appliances controllability. Therefore, comfort requirements are defined by the end-user through the HEMS graphical user interface (GUI).

Aggregator

The aggregator is responsible to gather the availability of a significant number of residential customers and to deliver flexibility services. Availability consists in potential upward and downward power deviations from the usual baseline consumption that residential customers are "available" to accomplish. Due to the reasons explained in Chapter 4 and Chapter 5, availability curves are not ready to be offered to the system operators. Therefore, the aggregator methods aim at converting these potential deviations into hourly flexibility services.

Given that aggregators buy availability services from their consumers, they should verify that the residential consumption actually was deviated (upward or downward) from the expected baseline. In this thesis, the verification process is not explored. However, it is assumed that it can be performed considering the update metering data sent by the DSO. In fact, nowadays it is a common procedure in the unbundling electricity systems. The owner of the meters installed in residential facilities – DSO – frequently collects the consumption values and report them to the retailers so that they can charge their customers. A similar situation is expected regarding the forthcoming demand side aggregators. Nevertheless, since smart meters will be widespread, the verification time should be shortened up in the DSO metering centre to an hourly based period.

It is assumed that aggregators can participate in the electricity and reserve services markets by offering upward and downward flexibility as power capability bids. Another option is to deliver flexibility directly to the distribution system operator in some nodes of the distribution grid. From the point of view of the aggregator methods – turning availability into flexibility – these two situations are similar. Specific issues regarding local aggregation will not be explored in this thesis.

Distribution System Operator

Typically, as already mentioned, the system operators are service takers since they can buy load flexibility services from the aggregators to use in their network operation and management responsibilities.

In the approach presented in this thesis, DSO are not taking control of the loads due to the privacy reasons and controllability aspects already mentioned. Therefore, smart meters do not incorporate controllability functions. Nevertheless, that smart metering platforms still have an important role in smart grids by enabling grid monitory function that improve network operation. Also, they play a decisive role in the smart grids environment, for instance, ensuring real-time electricity metering and providing electricity real-time prices.

It is important to stress that the Smart Grids paradigm is based on the premise that all existing resources and assets are managed in an intelligent way because they respond to network limitations and capabilities. Thus, it is expected that the HEMS will be able to interact with DSO, through the smart meter, as a resource that can support a suitable integration of DER in the distribution grids.

In fact, recent research projects have been establishing these new role of the DSO in the integration of distributed energy resources (DER), for example FP7 European project EvolvDSO[19] which was followed during this thesis. This project explored some approaches where DSO can provide flexibility services to the transmission system operators (TSO).

One example of these services is the possibility of DSO to estimate the flexibility at the DSO/TSO boundary nodes. This service can be provided through the services that is purchased from the aggregators (via bilateral contracts) and delivered in the MV/LV substation and/or via controllable resources connected to the distribution network and owned by the DSO, *e.g.*, capacity banks, storage, on-load tap changers. These type of new services can be seen as internal

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[19] EvolvDSO (FP7): defines future roles of distribution system operators (DSOs) and develop tools required for these new roles on the basis of scenarios which will be driven by different DRES penetration levels, various degrees of technological progress, and differing customer acceptance patterns.
Project website: http://www.evolvdso.eu/

services within the System Operator structure, as shown in Figure 3-4 presented in the section 3.2.5.

Regulatory Entities

Regulatory entities aim at supervising the activities of the different stakeholders acting on the provision of ancillary services through demand side management. As discussed in Chapter 2, the regulatory framework to allow such type of services is not defined yet. Therefore, one of the main objectives of regulatory entities in this phase is to suggest changes to the current regulation and legislation in order to facilitate the integration of demand side aggregators in the reserve service markets as well to accelerate the end-users' engagement in load management activities. In this context, the remuneration of availability and flexibility services is a decisive aspect. Indeed, if the deverticalization of the electricity sector turned theses services into a business, then all participants should take economic advantages from their participation. Thus, as illustrated in the architecture presented in Figure 3-5, concerning regulatory entities, this work will focus not only on technical aspects, but also on remuneration schemes capable of ensuring the economic viability of the demand side ancillary services business.

3.4 Summary and Main Conclusions

In this chapter, the choices made in this thesis concerning to the type of ancillary services and loads evaluated during this research as well as the main assumption on the DR deployment environment were presented. Moreover, the approach towards the objectives of this thesis was presented, paving the way for the methodologies and methods that will be developed in the subsequent chapters. A conceptual architecture summarizing the functional relationships between the DR agents participating in the provision of ancillary services was proposed.

The main options made during this thesis were related with the type of services that will be explored and the type of loads that will be used:

- Provision of tertiary reserve services in the day ahead tertiary reserve markets;
- Residential loads, namely electric water heaters, air-conditioners and refrigerators will be considered in this research.

It is important to stress that, despite these assumptions, the developments proposed in this thesis can be adapted to other types of loads and services. Furthermore, the different scales of the flexibility services will be addressed, *i.e.*, this thesis will propose methods both for HEMS and aggregators, taking into account the different perspectives of each of these entities.

The methods of the system operators are out of the scope of this thesis. However, these entities were integrated into the conceptual approach and architecture presented in this chapter, since they are the flexibility services takers and they guarantee that these services are physically delivered. In particular the DSO, which have the responsibility of managing in an intelligent way the DER in response to network limitations and of measuring the consumption of the end-users.

The approach of this thesis consists in a services/resources chain towards the provision of ancillary services form the demand side, involving different players of the powers systems sector. This service chain is enabled by the possibility to control domestic appliances, which is considered to be performed within the home domain. This means that other approaches from the literature, where the appliances are directly controlled by external entities, such as the system operator the aggregator, are not taken into account. Thus, HEMS use the appliances control to provide availability services to the aggregator. By receiving the availability profiles form different consumers in their portfolio, the aggregators can prepare their flexibility bids to present in the ancillary services markets.

Chapter 4 – Home Domain

In the services/resources chain towards ancillary reserve services, presented in Chapter 3, the Home Energy Management System (HEMS) is responsible to convert controllable resources into availability services that are offered to an aggregator so that it can participate in reserve services markets. This chapter aims at defining and quantifying availability and describing the processes to achieve it.

In this thesis, "controllability" is considered the basic resource to allow load management (LM) actions taken by the HEMS. It can be viewed as a service enabled by the capability of smart appliances to communicate their state of operation and to respond to control signals sent by this central control entity located at the home level. As discussed in Chapter 3, the HEMS uses the load control actions to provide availability services to the aggregators. However, additional functions are currently addressed by the HEMS solutions developed in the industry. The economic scheduling of appliances' consumption allowing end-users to take advantage from the real-time prices or the self-consumption optimization that permits a smart management of the local energy resources are examples of alternative services that require load control. Thus, at the home level, a single resource (controllability of loads) is used to provide a variety of services either external (such as the availability that is offered to the aggregator) or internal (related to the local energy management). Figure 4-1 presents a conceptual scheme of the resources (green) and services (red) associated with the Home Domain structure.

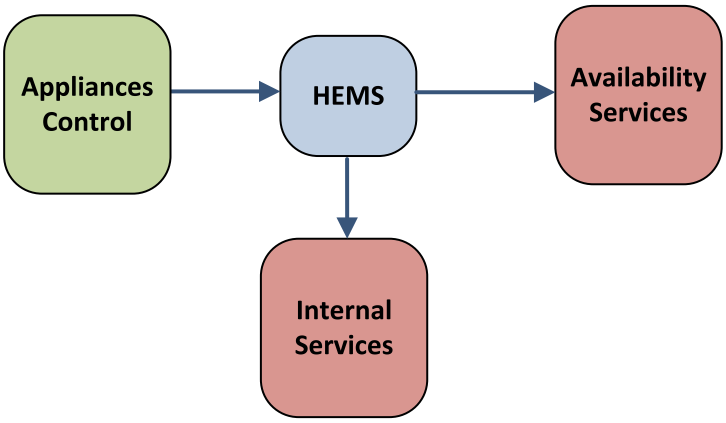


Figure 4-1. Conceptual scheme of the Resources and Services in the Home Domain

As displayed in the figure, the availability and internal services share the same domestic resource, appliances controllability. Consequently, the availability services that can be provided to the aggregator and the internal services cannot be treated independently. Indeed, the use of controllable loads to achieve internal services has an impact on the provision of availability services and vice-versa. For example, the consumption of a controllable washing machine can be scheduled to the night (when the electricity rates are lower), to the afternoon (to benefit from photovoltaic self-consumption) or to the evening (when the needs for downward flexibility services are higher). However, it cannot be scheduled simultaneously to the three periods since the end-user only washes his/her clothes once a day. Therefore, the services that are provided by the HEMS depend on the decisions regarding the usage of controllable resources.

Thus, although the focus of this chapter relies on the definition and quantification of availability services at the HEMS level, the internal services that requires controllability should be also taken into account. The example of a self-consumption optimization service integrated into the HEMS will be presented in order to illustrate the impact of internal services on the availability services.

Figure 4-2 shows the contents of this chapter. Section 4.1 is focused on the controllability resources, namely the appliances modelling, and it discusses how HEMS can deal with these models; section 4.2 describes the concept of availability and presents a method to quantify the amount of availability services that can be provided to the aggregators; section 4.3 discusses the integration of internal services into the availability calculation considering the example of the optimal self-consumption; section 4.4 presents a case study as well as a laboratory demonstration of smart appliances control.

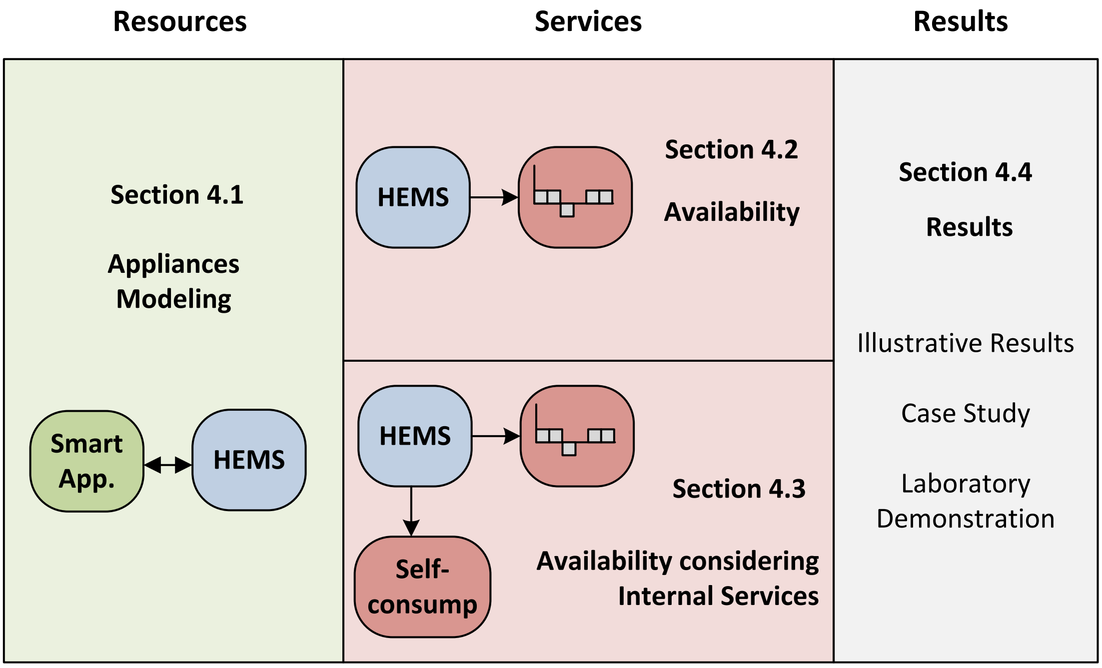


Figure 4-2. Contents of Chapter 4.

The main contributions of this chapter are the following:

- A discussion on the adaptation of appliances Physically-Based Load Models in real conditions;
- Development of a methodology to enable automatic learning of appliances thermal parameters by the HEMS in real environment;
- Definition and quantification of the availability services provided by the HEMS to the aggregators;

- Laboratory demonstration of the appliances control;
- Calculation of the availability at the appliances level;
- Calculation of the availability services at the home level considering scenarios where the load control is also used for the provision of other services within the home domain;
- Evaluation of the availability services considering a case study involving 1500 typical end-users;

4.1 Appliances' Modelling

4.1.1 Physically-Based Load Models

Several load models representing the behavior of thermal appliances were proposed in the literature to be used under the traditional demand side management programs. In section 2.3.2 the most relevant developments in this field were discussed and three main types of models were identified: empirical models, models based on historical data and physically-based load models (PBLM). Although these models were developed at the time of vertical organized load management programs, they are still being applied to current load control methods in a smart grid (SG) paradigm.

The empirical and statistical models consist in a description of an aggregated load consumption of a significant number of appliances and, therefore, they are not adequate to applications concerning single appliance modeling at the HEMS level. Thus, in this thesis, PBLM were used to characterize the behavior of residential thermostatically controlled loads (TCL). As stated in section 3.1.2, three representative types of domestic TCL were chosen: electric water heaters (EWH), Air-conditioners (AC) and refrigerators.

Model for AC and refrigeration devices

PBLM for thermal loads are based on energy balances that occur inside a thermal chamber, which can be a room (in case of space heating devices), a refrigerator cavity or a hot water cylinder. The AC model considered in this thesis is similar to the one presented in equation (2-4). However, the term $W(t)$ – that represents the thermal losses coming from external factors, such as a door opening as well as the presence of computers or any other loads that may influence the energy balance – is ignored. In fact, it is assumed that this type of temperature perturbations can be neglected, since this work comprises a 15 min time-step analysis.

Due to the same reason, as shown in equation (4-1), a linearized formulation of the model was chosen. There is an error associated to this approximation that depends on the time step used and on the magnitude of the temperature required for the AC operation. Typically, temperature error for a linearized representation an AC was estimated to be around 3% [51], *i.e.* less than 1^{o}C, as discussed in section 2.3.2.

The negative signal on the right hand side of equation (4-1) indicates that when the power consumption of the appliance (P) increases, the temperature inside the room decreases. It is important to stress that it occurs because the AC is used in a cooling mode. Hence, this formulation can also be applied to other cooling appliances. In this work, the same model is used for refrigerators since their energy balances are conceptually analogous to the AC. Obviously, the magnitudes of thermal capacity (C) and thermal resistance (R) values are different.

$$\theta_t = \theta_{t-1} - \frac{\Delta t}{CR}\left[\theta_{t-1} - \theta_{et} + \eta RP\right] \tag{4-1}$$

C	[kWh/°C]	Thermal Capacity
R	[°C/kW]	Thermal Resistance
P	[kW]	Electric power
η		Coefficient of performance of the AC and refrigerator.
Δt	[h]	Time step
θ	[°C]	Temperature inside the room
θe	[°C]	Average exterior temperature during the time step: it corresponds to the ambient temperature, in case of a space heating system installed inside the room; it corresponds to the house indoor temperature, in case of a refrigerator.

Model for EWH

Regarding the characterization of EWH thermal behavior, the PBLM proposed by Chong and Debs [56], presented in equation (4-2) is considered. A particular characteristic of EWH thermal modeling in comparison with the AC/refrigerator relies on the hot water consumption that also influences the energy balance. Hence, in Chong and Debs model, the term *v* is added in order to represent the water energy demand, which is associated with the difference between the temperature desired for hot water usage (θ_d) and the inlet temperature (θ_i) of the EWH tank. However, in order to understand the term *v* in the model, three aspects should be clarified:

- 1) In power systems studies, some interpretations of this model have been considering *v* as a "real hot water consumption rate" (*e.g.* liters per second). Nevertheless, it is not an accurate approach from the thermal energy balance point of view. Formally, the arithmetic multiplication of hot water consumption (liters) by the temperature range (θ_d-θ_i) is not equivalent to a thermal energy loss. Therefore, in order to keep the original meaning of *v* in the model, the water specific heat constant (c_p) should be added to the equation.

- 2) Since the water specific heat is described in terms of kilowatt hour per kilogram degree Celsius, it is important to highlight that an approximation concerning *v* is implicit in the model (1 kilogram = 1 liter). Although the temperature and the pressure inside the EWH are not at standard conditions, the impact of this approximation is not relevant in comparison with magnitude of imprecision associated to the values of hot water consumption. Furthermore, it is important to highlight that, in real conditions, the temperature of the water in the water tank is not homogenous, which means that different temperatures exist according to the height of the water in the tank. This model is based on the energy balance and, hence, the average temperature is assumed.

- 3) The term *v* can represent either the actual hot water that is really removed from the EWH or the amount of water (hot plus cold mix) required by the end-user, depending on the value of (Θ_d). Normally, *v* refers to the water usage (*e.g.* amount of water demand for a shower) and Θ_d is the desired mix temperature. However, it is important to stress that these parameters are acceptable if the inlet water temperature of the EWH is equal to the cold water temperature of the mix, which is the case of the majority of EWH installations.

$$\theta_t = \theta_{t-1} + \frac{\Delta t}{C}\left[-\alpha\left(\theta_{t-1} - \theta_{et}\right) - c_p v_t\left(\theta_d - \theta_i\right) + P\right] \tag{4-2}$$

C	[kWh/^{o}C]	Thermal Capacity
α	[kW/^{o}C]	Thermal admittance (or Thermal losses coefficient)
P	[kW]	Electric power
Δt	[h]	Time step
Θ	[^{o}C]	Average temperature inside the EWH tank
Θe	[^{o}C]	Average exterior temperature during the time step: house indoor temperature.
v	[ltr/h]	Water consumption
Θd	[^{o}C]	Desired temperature for water consumption
Θi	[^{o}C]	Inlet water temperature
cp	[kWh/(ltr.^{o}C)]	Water specific heat

As presented above, PBLM require a significant amount of information regarding different aspects of appliances and consumption. In this work, the PBLM input data was divided in four categories.

I. The first group comprises the physical characteristics of the appliances and installation environment: thermal capacities, thermal resistances/admittances and nominal electric power.
II. The second group is related with consumption habits, for instance, the periods when AC is running or the typical end-users' shower hot water usage (time and quantity);
III. The third category involves the comfort requirements of the consumer regarding the appliances operation: the set point temperature of the thermostat, the maximum and minimum temperature admissible in each period and the temperature desired for hot water;
IV. The fourth group encompasses the external and environmental variables, such as the water inlet temperature and the ambient temperature (in case of AC) and house temperatures (in case of EWH) as well as time step of the simulation,

Information regarding group III and IV are provided to the HEMS by external entities. In fact, the comfort requirements can be chosen directly by the end-user through the graphical User Interface (GUI), as illustrated in the reference architecture (Figure 3-5). The indoor temperature can be communicated to the HEMS in real-time by thermal sensors located at home. Furthermore, forecasted values of the ambient temperature can be reported by an external meteorological station.

The physical characteristics of the appliances (I) and consumption habits (II) are directly or indirectly obtained by HEMS methods. In the subsection 4.1.2 a special attention to the consumption habits is given while in subsection 4.1.3 two methodologies for estimating the physical parameter of the appliances are proposed.

4.1.2 Consumption Habits

Consumption habits comprise the typical daily routines and human behavior patterns related to the use of appliances. In case of TCL, information such as *house occupancy*, *shower time*, *normal desired temperature for hot water*, etc., is assumed to be frequently collected by the HEMS via the real-time communication with smart appliances as well through interoperability modules with existing home automation. Afterwards, HEMS can store this information and provide forecasts of the consumption habits for the day-ahead.

The functionalities of recent smart appliances sensing and communication platforms (such as Home Connect [164]) will facilitate the acquisition of consumption habits by the HEMS. Automatic learning algorithms as well as privacy and cybersecurity data protection techniques are expected to be integrated in the HEMS.

Typical Values

The hot water energy demand (v) can be obtained by multiplying the water specific heat (C_p) by the quantity of water used. The typical water consumption for a shower depends on the consumer. In Sweden, for instance, it is around 40 liters and the typical temperature for the EWH set point is around 55ºC [54]. The period when the hot water demand occurs also varies according to the end-user habits. For example, in Australia, several end-use residential consumptions were measured in different parts of the South East Queensland region [172]. The hot water demand for shower was evaluated throughout the 24 hours of the day and the probability of shower occurrence was calculated for each hour. Figure 4-3 presents the result of the study.

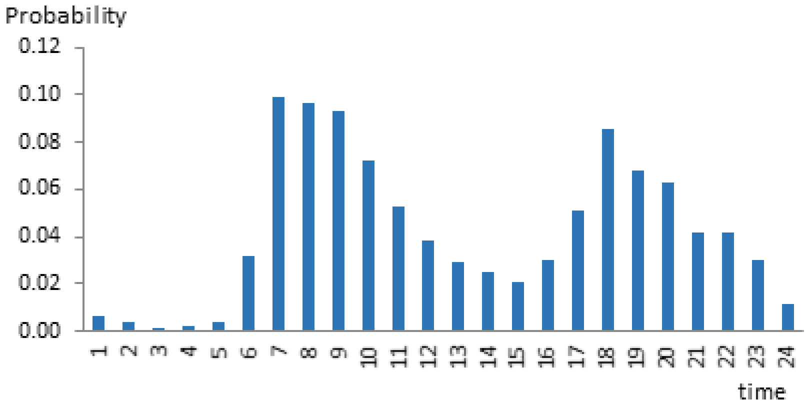


Figure 4-3. Hourly probability of hot water uses [172].

The time when AC is running depends on many aspects, but mainly on the house occupancy during the day and the comfort temperature that is required by the end-user. In [173] typical house occupancy curves are provided. Similarly to the shower occurrence, the same probability curves can be determined for house occupancy. Furthermore, the AC running time also depends on set point defined by the consumer, which is related with the ambient temperature, the air humidity and the air speed. Dear and Brager [174] observed that the temperature range of indoor comfort is typically concentrated between 22ºC and 25ºC.

In cooling devices, such as refrigerators and freezers, the comfort habits are only related to the thermostat set point. Although the freezing and refrigerating temperatures differ according to the type of food that is stored in the appliance [175], the average set point vales are 5^{o}C for refrigerators and -18^{o}C for domestic freezers.

4.1.3 Installation and Constructive Parameters

The physical parameters of domestic TCL, such as thermal capacities and thermal resistances are not available in the installation guides provided by the appliances' manufacturers. First, because these values are not commercial information; second, because some of thermal parameters do not depend on the appliances constructive characteristics. For instance, in space heating and cooling systems the thermal capacity and resistance are related to the physical characteristics of the room where the AC system is installed and not with the device itself.

Therefore, methodologies to estimate the PBLM thermal parameters in real world are necessary. In this thesis proposed in this subsection:

- A methodology based on physical information;
- A methodology based on automatic learning.

The first methodology aims at estimating the parameters based on characteristics typically available in the appliances manual as well as on information related to the appliances installation. The second methodology consists in learning the parameters of the TCL by examining the power and temperature values reported in a real-time basis to the HEMS.

Parameters Estimation based on Physical Information

Some parameters of the TCL are not available on the installation documents provided by manufacturers. In the following paragraphs, simple calculations of the PBLM parameters are presented, taking into account information that can be manually provided to the HEMS by the end-user.

Instead of making available the heat loss constant (α) and the thermal capacity (*C*), usually the EWH manufacturers provide the volume (V), the type and the insulation thickness (*l*) as well as the dimensions, such as the base radius (*r*) in case of a cylinder water tank.

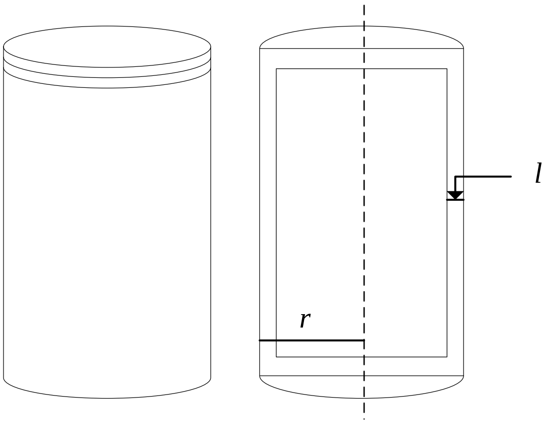


Figure 4-4. EWH radius and insulation thickness

The heat loss constant of the EWH (*α*) can be calculated using the thermal conductivity (*k*) of the insulation material, the area of the appliance walls (*A*) and the insulation thickness (*l*), as shown in equation (4-3). In the majority of EWH, the volume can be approximated to a cylinder, as shown in Figure 4-4. Hence, it is possible to express (*A*) in terms of volume and the base radius. However, in (4-3), *A* refers to the internal surface are of the EWH tank. Thus, considering the representation presented Figure 4-4, it is possible to conclude that the internal radius corresponds to the difference between the base radius (*r*) and the insulation thickness (*l*).

Equation (4-4) presents the expression of the internal surface area for the computation of the heat loss constant. The thermal conductivity (*k*) depends on the type of insulation. In [176], three types of blowing agents used in polyurethane insulation foam are compared. The thermal conductivity for this widely used type of insulation varies between 0.0214 and 0.0324 W/m°C.

Equation (4-5) shows that thermal capacity (*C*) can be obtained by multiplying the EWH volume by the water specific heat (c_p=0.00117 kWh/kg°C).

$$\alpha = k\frac{A}{l} \qquad [{}^{kW}\!/_{^oC}] \tag{4-3}$$

$$A = \frac{2}{(r-l)} V + 2\pi (r-l)^2 \qquad [m^2] \tag{4-4}$$

$$C = C_p V \qquad [kWh/{}^{o}C] \tag{4-5}$$

In an AC installation, the thermal resistance (*R*) and the thermal capacity (*C*) are associated with the room characteristics. Thermal capacity depends on the dimensions of the room and the thermal resistance is related with the material of the walls, windows and roof. Hence, the provision of these parameters to the HEMS can be a problem to the end-user. However, typical values available in the literature may provide a good approximation. For instance, in [134] typical values for room capacity per square meter (around 0.065 kwh/^{o}C) is used. On the other hand, Kupzog and Roesener [48] presented different values of thermal resistance per square meter according to the type of material of the building (concrete or wood) as well as the thickness and the presence of cavity in the walls. Considering these values, the end-user only has to provide the room volume as well as the type of material of the walls to the HEMS.

The refrigerator parameters are similar to the AC. However, the thermal resistance only depends on the dimensions of the refrigerator walls (provided by the manufacturer) as well as the type of insulation and it can be calculated using the following equation [175]:

$$R = \frac{1}{l/k} \qquad [\mathrm{kW}/\mathrm{m}^{2o}C] \tag{4-6}$$

Analogously to the EWH, the thermal resistance depends on the type of insulation. Polyurethane is widely used material and it corresponds to 23 kW/m^{2o}C. In the equation (4-6), *l* is the polyurethane thickness, which is usually 75 mm for refrigerators and 100 mm for freezers [175]. Although the food preserved in the cooling device strongly influences the thermal capacity, general average values can be related to the volume: between 0.03 kWh/ºC (for smaller refrigerators) and 0.07 kWh/ºC (for larger refrigerators).

Automatic Learning of Parameters

This section aims to contribute with a methodology allowing HEMS to automatic learn the thermal parameters of the appliances during their normal operation.

In case of EWH, the method used to estimate C and α is based on a set of temperature readings from the EWH during its regular operation. By analyzing the EWH's PBLM (4-2), it is possible to conclude that, when the EWH is off, P_{EWH} disappears from the equation and the temperature decreases ($\Delta\theta_{down}$) inside the tank. By reading the temperature before and after the temperature decreasing period (Δt_{down}) it is possible to write α as a function of C:

$$\alpha = -\frac{\Delta\theta_{down}}{\Delta t_{down} \times \Delta\theta e_{down}} C \tag{4-7}$$

Where $\Delta\theta e_{down}$ is the average difference between the temperature inside the tank and the ambient temperature.

Similarly, when the EWH is connected, the value of P_{EWH} is equal to the nominal power of the appliance and the temperature increases inside the tank ($\Delta\theta_{up}$). Reading the temperature before and after the heating time (Δt_{up}) it is possible to write C as a function of α. By replacing α – using equation (4-7) – C can be obtained by:

$$C = \frac{\Delta t_{up} \times P_{EWH}}{\Delta\theta_{up} - \dfrac{\Delta t_{up}}{\Delta t_{down}} \dfrac{\Delta\theta e_{up}}{\Delta\theta e_{down}} \Delta\theta_{down}} \tag{4-8}$$

Thus, from equation (4-7) and (4-8) the EWH thermal parameters can be found. It is important to stress that only four temperature readings are required (two during the heating period and the other two during the thermal losses period).

The thermal resistance (R) and the thermal capacity (C) of the AC and refrigerators can be automatic learnt by the HEMS following an analogous procedure. When the nominal power of the appliance switches off, the term ηRP disappears from the PBLM equation (4-1) and the temperature starts to increase (in case of refrigerators or air-conditioners in the cooling mode). Thus, the value of RC can be obtained by measuring the temperature increase ($\Delta\theta_{up}$) before and after a certain period (Δt_{up}) during which the appliance remains disconnected, as shown in (4-9).

$$RC = \frac{\Delta t_{up} \Delta\theta e_{up}}{\Delta\theta_{up}} \tag{4-9}$$

Where $\Delta\theta e_{up}$ represents the difference between the appliance controlling temperature and the external temperature, which can be the house temperature (in case of refrigerating appliance) or the ambient temperature (in case of a space cooling system).

When the appliances switches on, the power demand is equal to the nominal power (P_n) and the temperature starts to decrease. By reading the temperature before and after the temperature decreasing period, the thermal resistance (R) is given by the equation (4-10).

$$R = \frac{\frac{\Delta\theta_{dw}}{\Delta\theta_{up}}\frac{\Delta t_{up}}{\Delta t_{dw}}\Delta\theta e_{up} - \Delta\theta e_{dw}}{\eta P_n} \tag{4-10}$$

4.2 Availability

The word "availability" has been widely used in the context of demand side management. For instance, according to Callaway and Hiskens [177], the potential contribution of loads to provide services to the system can be described "in terms of its availability and willingness to respond" to load management (LM) requirements. The authors argue that availability metrics refers to "the amount of load available for switching in or out by the control action" [177].

Under the concept of this thesis, comprising the services/resources chain that was discussed in Chapter 3, this "availability to respond to LM" is defined as a service (called availability) that the end-users provide to the aggregators. The way how availability is used by the aggregators for the participation in ancillary services markets in discussed in Chapter 5. This section aims at defining and quantifying the volume of this availability service, taking into account the possibility of controlling smart appliances, whose models and parameters were previously presented.

For the definition of availability services, it is assumed that the control of the appliances is performed within the Home Domain. According to the structured vision of the LM presented above, the objectives of this control should be aligned with the criteria defined by the end-user, rather than yielding benefits to abstract entities, such as the "system as a whole", that no longer exist after the unbundling of the electricity sector. Economic and comfort criteria are assumed to represent the end-user objectives in the control, *i.e.*, the end-user willingness to maximize his/her remuneration for the provision of availability service without violating the comfort preferences that he/she defines. Figure 4-5 presents the interactions between the end-user, the smart appliances, the HEMS and the aggregator in order to enable the provision of availability services.

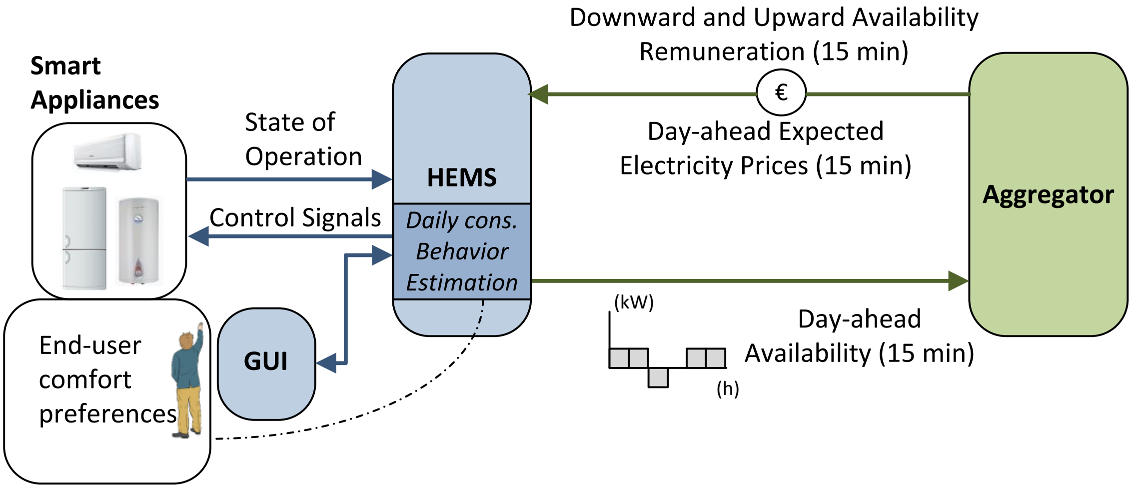


Figure 4-5. Home Domain and Aggregator interactions enabling Availability

Smart appliances communicate their state of operation to the HEMS and receive control signals. In case of the appliances considered in this thesis – refrigerators, EWH and AC – the state of operation relies, at least, on the actual temperature and on the on/off state of the devices that are communicated to the HEMS in real-time. Thus, after some days receiving this information, it is assumed that HEMS is capable of estimating the typical daily electricity consumption end-users, called "baseline demand" in this work. The variables of the appliances models (presented in section 4.1) regarding typical daily consumption are the following:

Electric Water Heaters	**Model variable**
Shower time and quantity	v_t
Desired temperature for water consumption	θ_d
Set point temperature of the EWH	$\theta_{SP\|ewh}$
Refrigerator	
Set point temperature of the refrigerator	$\theta_{SP\|ref}$
AC	
Set point of room temperature	$\theta_{SP\|ac}$
Room occupancy	$\theta_{SP}=\theta_e$ *when the room is empty*

As shown in Figure 4-5, the end-user specifies his/her preferences in terms of comfort through the graphical user interface (GUI) of the HEMS. These preferences consist in minimum and maximum temperatures, for each period, associated with the appliances operation. It is assumed that the end-users allow load control operations as soon as the temperature is kept within these ranges.

It is also assumed that end-users have contracts established with the aggregators for the provision of availability services. The aggregator informs the HEMS about the upward and downward availability remuneration – in a 15 min time basis – for the day-ahead. Furthermore, if the aggregator is also a retailer, it can communicate the electricity prices to the HEMS in a similar time span and period. If not, the HEMS can receive this information via smart meter (see section 3.3). Given this information, until the last hour of the previous day, the HEMS should be capable to calculate the upward and downward availability services that can be provided to the aggregator for each period of the day ahead, assuming the maximization of the end-user economic benefits.

During the last hour of the previous day, the HEMS is informed by the aggregator if their availability profile is accepted for the provision of ancillary services (this will be discussed in Chapter 5 where the problem of aggregator is formulated). If the availability profile is included in the aggregator's flexibility bids, the HEMS start controlling the appliance in order to accomplish with the changes in the consumption that were agreed. If not, the HEMS does not perform any type of control and the appliances consumption correspond to the baseline demand.

4.2.1 Availability Concept

The analysis of the home domain resources as well as the interactions with the aggregator leads to a definition of the availability services:

- *Availability service consists in consumption changes, in relation to the baseline demand, enabled by appliances control actions that are taken locally and with the objective of maximizing the remuneration of the end-users.*

Thus, availability services require the control of the appliances located within the home domain. As discussed in section 3.2.2, a significant number of recent studies are still assuming that the appliances control is performed by external entities (aggregator or system operator). Normally, this type of vertical load control is motivated by a system need. Therefore, appliances control actions are taken in a direct response to services requirements in a top-down approach.

In contrast, if the control is performed within the home domain, the aggregator should have first an estimation about the possible modifications in the consumption. In fact, these modifications (or availability) are offered in the market by the aggregators in a form of flexibility services. If the system needs such flexibility, these services are activated. In contrast, if the system is not facing operational problems, the flexibility is not activated. In any case, in the previous day, the aggregator needs to have an estimation about the amount of possible flexibility services for the day ahead so that it can prepare its market bids.

Thus, at the home domain level, a bottom-up approach is necessary to convert the possible load control into availability profiles that are communicated to the aggregator. By receiving all the availability profiles from the consumers, the aggregator can estimate the total flexibility of its portfolio. Hence, the availability estimation is essential to enable the participation of aggregators in the ancillary services markets. Nevertheless, it requires to look at the appliances control in a bottom-up perspective, completely different from the top-down approaches of the vertical load control. Figure 4-6 illustrates the difference between the vertical load control and the HEMS load control approaches.

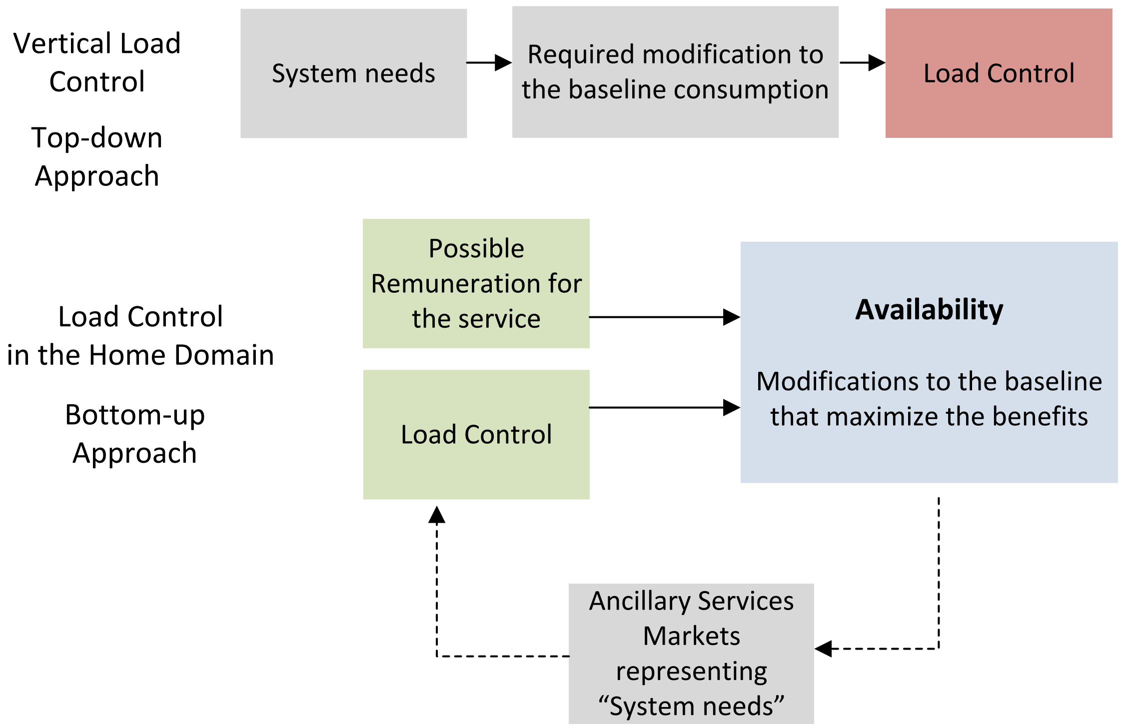


Figure 4-6. Bottom-up and top-down approaches to load control

Taking into account this conceptual difference, it is possible to derive a mathematical formulation for availability from the vertical load control methods. For example, Kondoh *et al.* [54] developed a load control strategy to respond to reserve balancing signals using EWH, in which the control signal (P_{LC}) is given by:

$$P_{LC} = P_{BL} + \Delta P_{RS} \tag{4-11}$$

where P_{BL} is the total power consumption without considering any active control – baseline demand – and ΔP_{RS} consists in the required load modification to provide the reserve the system needs.

As already stated, availability consists in modifications to the baseline consumption that maximize the benefits for the end-user. Mathematically, it consists in looking at equation (4-11) in a bottom-up perspective, *i.e.*, the modification to the baseline (ΔP_{RS}) is unknown – it represents the availability that we want to quantify – and P_{LC} should be such value that leads to the highest remuneration of the end-user. Thus, ΔP_{RS} is replaced by availability (A) and P_{LC} by the modified consumption (P_{MC}) that leads to the maximum benefits to the end-user. In each period t, the availability can be written as in (4-12).

$$A_t = P_{BLt} + P_{MCt} \tag{4-12}$$

Figure 4-7 illustrates the definition of availability taking into account the baseline demand as well as the consumption modification during 8 periods time span. As depicted in the figure, the availability is represented as a power/time curve with the potential deviations regarding the regular consumption, called baseline.

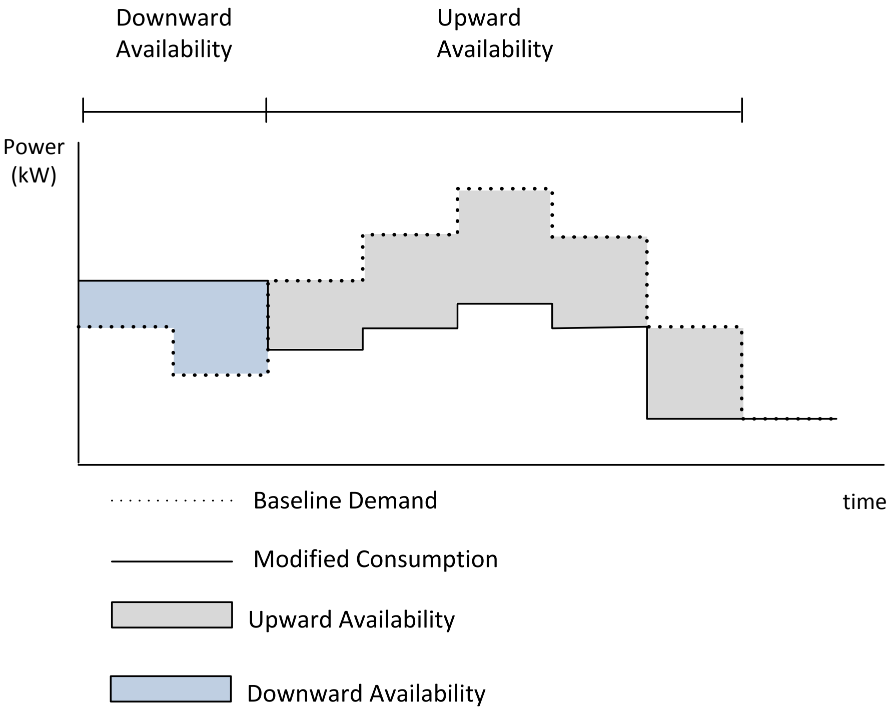


Figure 4-7. Availability.

In the first and second periods, the modified consumption is above the baseline, which means that the residential load demand is higher than the regular consumption in these periods. In contrast, from period 3 up to period 7, the modified consumption is below the baseline, which means that the domestic appliances are consuming less than in the regular conditions during these periods. Finally, in period 8, the consumption is equal to the baseline and, hence, no availability exists.

In this thesis it is assumed that **downward availability services** occur when the modified consumption is above the baseline. Analogously, the **upward availability services** occur when the modified consumption is below the baseline. This nomenclature is chosen in order to match with the existing reserve demand in current ancillary services markets. Thus, the downward availability services are those that allow aggregator to prepare bids for downward reserve. Similarly, the upward availability services are those that are used by aggregator to offer upward reserve services in the markets.

The provision of upward and downward availability services to the aggregator lead to different economic benefits (remuneration) and different comfort limitations to the end-user. The provision of downward availability services requires extra electricity costs for the end-user (since the appliances demand is above the regular consumption). In contrast, upward availability services lead to electricity costs savings.

Regarding the behavior of thermostatically controlled loads (TCL), a consumption above the baseline leads to an increase of the temperature in heating systems and a decrease in the temperature in cooling systems. It may provoke discomfort situations: exceeding low temperatures in the refrigerator or uncomfortable warm indoor temperatures in winter caused by the space heating systems. The opposite occurs in the provision of upward availability services. The temperatures tend to increase in cooling devices and to decrease in heating systems. Discomfort situation due to lower electricity consumption may happen, for example cold water in EWH tank.

Table 4-1 summarizes the impact on the end-user of the provision of availability services.

	Downward Availability Services	**Upward Availability Services**
Definition	When the modified consumption is above the baseline	When the modified consumption is below the baseline
Economic impact on the end-user	Remuneration for the provision of downward reserve services; Electricity costs associated with the increase of electricity demand regarding the regular consumption (baseline).	Remuneration for the provision of upward reserve services; Electricity costs reduction due to the decrease of consumption.
Comfort limitations (TCL)	The temperatures tend to increase in heating appliances and to decrease in cooling appliances.	The temperatures tend to decrease in heating appliances and to increase in cooling appliances.

Table 4-1. Upward and Downward availability

4.2.2 Availability at the level of appliances

The previous subsection presented a conceptual representation of the availability services in terms of a power/time curve containing the potential modified consumption in relation to the baseline. Equation (4-12) expresses the availability in terms of each period of the baseline and modified consumption profiles. The methods to calculate these two curves at the level of appliances are detailed in this section.

Baseline Demand

Baseline demand (P_{BLt}) consists in the regular consumption, *i.e.*, without any external control actions. System operators and aggregators use to estimate the baseline consumption in an aggregated scale using load forecast methods. At the level of single appliances, forecast becomes inappropriate, due to the variability of a single consumer behavior. Therefore, in TCL, the baseline demand can be obtained by simulating the temperature behavior as well the consumption profile that results from the thermostat control.

The temperature behavior can be calculated using Physically-Based Load Models (PBLM) presented in section 4.1.1. These models relate the temperature variation in each period with the appliance power demand as well as other variables, such as ambient temperature and end-user consumption habits.

It is expected that after some days receiving information from the smart appliances, HEMS is capable of estimating the typical daily consumption behavior of the end-users. Indeed, PBLM variables regarding shower time and water consumption, desired temperatures for hot water, room occupancy as well as average set point temperatures are available can be obtained by the HEMS. Furthermore, end-users can also complete and update this information through the human machine interfaces (HMI) or graphical user interfaces (GUI).

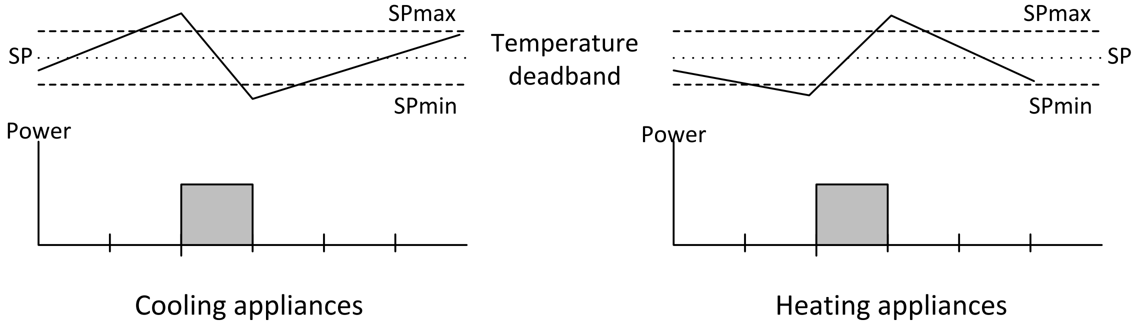


Figure 4-8. Cooling and heating appliances baseline estimation.

Equation (4-13) displays the normal on/off thermostat control in a cooling device: when the maximum admissible temperature (θ_{SPmax}) is exceeded, the appliance is switched on and the power demand is equal to its nominal capacity (P_{cap}). If the temperature is below the minimum set point deadband (θ_{SPmin}), the consumption is zero. Analogously, the on/off control of the heating appliances is presented in equation (4-14): when the minimum temperature of the thermostat deadband in achieved, the appliance switches on (turning demand equals P_{cap}) and when the temperature is higher than θ_{SPmax} the appliance switches off. Figure 4-8 illustrates the behavior of the heating and cooling appliances.

In order to estimate the baseline consumption, the HEMS needs to simulate the temperature associated with the TCL. Equation (4-15) presents the abstract PBLM that enable the appliances thermal behavior simulation. According to the type of appliance the correspondent model should be selected (see section 4.1.1).

$$P_{BLt} = \begin{cases} P_{cap} & if\, \theta_{t-1} > \theta_{SPmax} \\ 0 & if\, \theta_{t-1} < \theta_{SP\min} \end{cases} \tag{4-13}$$

$$P_{BLt} = \begin{cases} P_{cap} & if\, \theta_{t-1} < \theta_{SPmin} \\ 0 & if\, \theta_{t-1} > \theta_{SPmax} \end{cases} \tag{4-14}$$

$$\theta_t = f(\theta_{t-1}, \mathrm{P}_{BLt}, \ldots) \tag{4-15}$$

Modified Consumption

As stated above, the baseline consumption is used as a reference for the availability calculations. At the appliance level, the baseline is calculated based on PBLM as well as on the typical daily consumption behavior of the end-users. The temperature of TCL is kept within the appliance thermostat deadband since no additional control actions are included.

The modified consumption profile can be obtained through an external on/off control performed by the HEMS. Thus, from the implementation point of view, it is assumed that the thermostat control is disabled either electronically (in recent smart appliances) or by manually changing its temperature to the upper/lower bound limits. Hence, the actual control temperatures are no longer the thermostat deadband. Instead, it is asked to the end-user to choose in the GUI his/her admissible comfort limits, within which the temperature should be kept by the HEMS control. Figure 4-9 illustrates the control modifications in a cooling appliance. The thermostat set point was moved to the lower bound limit and the new comfort temperatures selected by the end-user were included.

In general, it is expected that the comfort range chosen by the end-user is wider than the normal deadband of the thermostat. In fact, this relaxation of the temperature boundaries allows the HEMS to modify the consumption profile without violating the comfort limits. Furthermore, the potential consumption modification should be done with the objective of maximizing the economic benefits of the end-user. Hence, the availability remuneration and the electricity prices (see Table 4-1) should be taken into account.

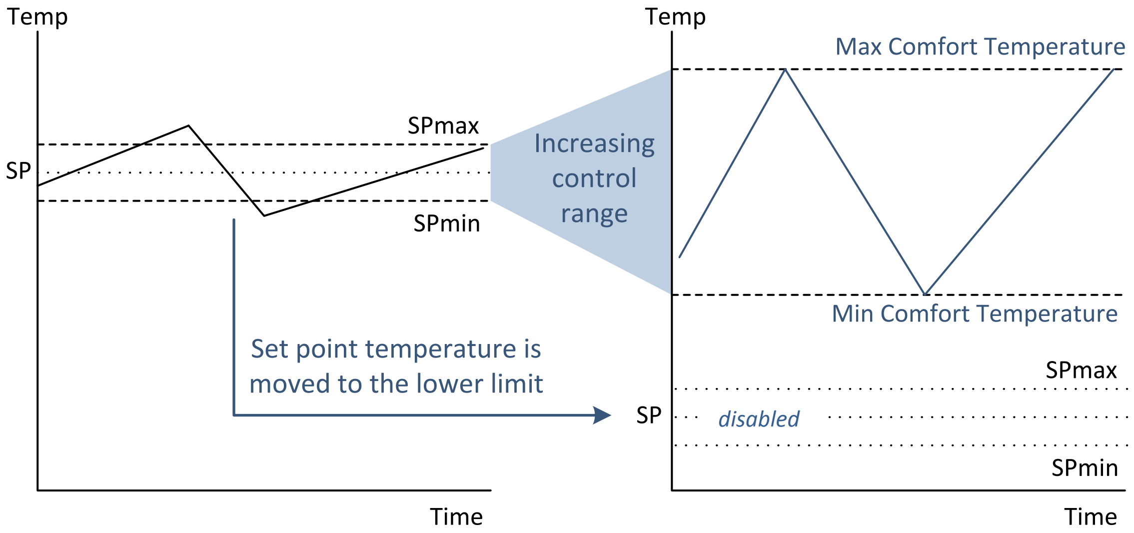


Figure 4-9. Cooling and heating appliances control temperature change.

Equations (4-16)-(4-19) present the multi-period optimization problem associated with the consumption modification. For a certain time span (*e.g.* one day), the objective function (4-16) aims at maximizing the remuneration of the end-user for the provision of upward and downward availability services. As summarized in Table 4-2 the extra costs and savings of electricity (λ_{Et}) in the provision of downward and upward availability, respectively, were considered in each period. Moreover, different remuneration values for upward and downward availability (λ_{RUPt}, λ_{RDWt}) were included in the function. As shown in equation (4-16), if the baseline is higher than the modified consumption the appliance is providing upward reserve. Therefore, the end-user is remunerated by the aggregator the provision of this service (λ_{RUPt}) and, at the same, it saves energy costs since it consuming below the baseline. In contrast, if the baseline is lower than the modified consumption the appliance is providing downward availability and, hence, although it is remunerated for that service (λ_{RDWt}), the extra electricity costs (λ_{Et}) are also proportional to this difference.

The comfort limits imposed by the end-user are constraints of the model. Equation (4-17) presents the lower bound temperature limits and equation (4-18) represents the upper bound comfort temperature chosen for each period. Again, PBLM presented in section 4.1.1 are used to estimate the temperature evolution during the time span (*n* periods). The equation (4-19) presents an abstract formulation of the equations (4-1) and (4-2).

$$\max \sum_{t=1}^{n} R_t \begin{cases} R_t = -\lambda_{Et} P_{MCt} + \lambda_{RUPt}\left(P_{BLt} - P_{MCt}\right), if\ P_{BLt} > P_{MCt} \\ R_t = -\lambda_{Et} P_{MCt} - \lambda_{RDWt}\left(P_{BLt} - P_{MCt}\right), if\ P_{BLt} < P_{MCt} \end{cases} \tag{4-16}$$

$$\theta_t \geq \theta_{mint} \tag{4-17}$$

$$\theta_t \le \theta_{maxt} \tag{4-18}$$

$$\theta_t = f(\theta_{t-1}, \mathrm{P}_{BLt}, \ldots) \tag{4-19}$$

The modified consumption values in each period (P_{MCt}) are the binary decision variables of the problem representing the two states of the on/off control: 0 and P_{CAP} (nominal power). At the same time, the modified consumption profile is one of the results of the optimization allowing the availability calculation (see equation (4-12)). Obviously, the total remuneration of the availability is also another important outcome of the model since it quantifies the economic benefits of the end-user regarding the provision of availability services to an aggregator.

It is important to stress that the time span of the optimization depends on the type of availability services required by the aggregator. Therefore, the multi-period objective function (4-16) is written in the generic form (*n* periods). In this chapter, the day-ahead availability services are explored. However, the aggregator can require modifications in the consumption profile for the next hours. From the methodological point of view, the procedures and calculations presented in this section remain the same.

This section proposed a method to characterize the availability of thermal appliances connected to a HEMS capable of sending control signals as well as receiving information regarding the state of operation of those appliances. Summarily, the availability at the level of appliances depends on:

- The baseline demand, *i.e.*, the consumption in regular operation conditions, which takes into account the normal consumption patterns of the end-user as well as the physical characteristics of the appliance. These physical characteristics can be estimated by the HEMS using the automatic learning methodology that was presented in section 4.1.
- The end-user willingness to allow control, described in terms of comfort specifications through the GUI;
- The economic benefit of the end-user that includes the remuneration for the provision of upward and downward availability services as well as the extra costs of electricity associated, since this information is communicated in the previous day.

4.2.3 Linear Formulation of the Modified Consumption Optimization

The quantification of the appliances availability services involves solving the multi-period optimization problem that lead to the modified consumption, described in equations (4-16)-(4-19). The computational capacity required at the HEMS processing unit to run this optimization problem may be significant, especially in situation that involve large number of periods. For example, the calculation of the availability curve for the day ahead considering 15 minutes time step result in 96 periods for the next 24 hours. As described in the previous section, each appliance is associated to a binary decision variable per period (P_{MCt}), two comfort constraints (maximum and minimum temperature) as well as an equality constraint (4-17)-(4-19). Thus, a small group of appliances can lead to a considerable dimension optimization problem.

As previously discussed, the comfort constraints (4-17)-(4-19) consist in abstract representations of appliances PBLM. However, the integration of these models – (4-1) and (4-2) – contain a recurrence relation between the decision variables (P_{MCt}), *i.e.*, the consumption in each period depends on the consumption in previous periods. This fact leads to a significant number of comfort constraints, comprising this recursive sequence. Obviously, the number of constraints increases with the time frame that is being considered.

Furthermore, the computational burden is even more demanding since the objective function (4-16) formulation in written in two branches, which does not allow the direct application of Mixed Integer Linear Programming (MILP) techniques.

Thus, in this section, a linearization of the optimization problem is proposed so that MILP techniques can be applied to solve it in order to reduce the computational effort of the HEMS. The formulation changes encompass:

- Innovative transformations of the objective function so that MILP techniques can be applied.
- A detailed formulation of the multi-period recurrence associated with PBLM in order to write the comfort constraints in the linear form: $Ax>b$ or $Ax<b$.

The transformation of the objective function was inspired by equivalent developments in the literature applied to similar functions. Absolute value functions are typical examples of branch formulation. In [178], Bisschop demonstrates how these functions can be transformed so that they can be solved by linear programming.

The transformation of objective function (4-16) developed in this thesis is presented in equations (4-20)-(4-23). Decision variables X_t^+ and X_t^- were included in order to represent the positive and negative deviations in relation to the baseline. The decision binary variable y_t and the large positive constant M are used in (4-22) and (4-23) in order to impose an either/or constraint to represent the appliances on/off states.

For n periods, the comfort constraints can be presented in a linear matrix inequality ($Ax<b$ and $Ax>b$), as shown in (4-24) and (4-25). The elements (a_{it}) of the matrix represent the influence of period i on the consumption of period t. Since i is a period from the past, A becomes a lower triangular matrix. A and b are obtained through the replacement of θ_t in (4-17) and (4-18) by the appliances PBLM (4-1)(4-2). Hence, as shown in (4-26)-(4-30), the temperature constraint in each period is written as function of the temperature in the first period (θ_0).

$$\max \ -\lambda_{Et}P_{MCt}+\lambda_{RUPt}X_t^{+}+\lambda_{RDWt}X_t^{-} \tag{4-20}$$

Subject to:

$$X_t^{+}=X_t^{-}+P_{BLt}-P_{MCt} \tag{4-21}$$

$$X_t^{+}\le y_t M \tag{4-22}$$

$$X_t^{-}\le (1-y_t)M \tag{4-23}$$

$$\begin{bmatrix} a_{11} & 0 & \dots & 0 \\ a_{12} & a_{22} & \dots & 0 \\ \dots & \dots & a_{it} & \dots \\ a_{1n} & a_{2n} & \dots & a_{nn} \end{bmatrix}\begin{bmatrix} P_{MC1} \\ P_{MC2} \\ \dots \\ P_{MCn} \end{bmatrix}\ge\begin{bmatrix} b_{min1} \\ b_{min2} \\ \dots \\ b_{minn} \end{bmatrix} \tag{4-24}$$

$$\begin{bmatrix} a_{11} & 0 & \dots & 0 \\ a_{12} & a_{22} & \dots & 0 \\ \dots & \dots & a_{it} & \dots \\ a_{1n} & a_{2n} & \dots & a_{nn} \end{bmatrix}\begin{bmatrix} P_{MC1} \\ P_{MC2} \\ \dots \\ P_{MCn} \end{bmatrix}\le\begin{bmatrix} b_{\max 1} \\ b_{\max 2} \\ \dots \\ b_{\max n} \end{bmatrix} \tag{4-25}$$

AC and refrigerators:

$$a_{it}=\begin{cases} \eta R\left(\dfrac{\Delta t}{CR}-1\right)^{t-i} & ,\forall t\ge i \\ 0 & ,\forall t<i \end{cases} \tag{4-26}$$

$$b_{mint}=\frac{CR}{\Delta t}\theta_{mint}+\sum_{\substack{j=1\\ j\in N}}^{t}\left[\left(\frac{\Delta t}{CR}-1\right)^{t-j}\theta_{ej}\right]+\left(1-\frac{CR}{\Delta t}\right)\left(1-\frac{\Delta t}{CR}\right)^{t}\theta_0 \tag{4-27}$$

$$b_{\max t}=\frac{CR}{\Delta t}\theta_{\max t}+\sum_{\substack{j=1\\ j\in N}}^{t}\left[\left(\frac{\Delta t}{CR}-1\right)^{t-j}\theta_{ej}\right]+\left(1-\frac{CR}{\Delta t}\right)\left(1-\frac{\Delta t}{CR}\right)^{t}\theta_0 \tag{4-28}$$

EWH:

$$a_{it}=\begin{cases} \left(1-\alpha\dfrac{\Delta t}{C}\right)^{t-i} & ,\forall t\ge i \\ 0 & ,\forall t<i \end{cases} \tag{4-29}$$

$$b_{mint} = \frac{C}{\Delta t}\theta_{mint} + \sum_{\substack{j=1 \\ j\in N}}^{t}\left[\left(1-\alpha\frac{\Delta t}{C}\right)^{t-j}\left(-\alpha\theta_{ej} + v_j\left(\theta_d - \theta_j\right)\right)\right] + \left(\alpha - \frac{C}{\Delta t}\right)\left(1-\alpha\frac{\Delta t}{C}\right)^{t-1}\theta_0 \tag{4-30}$$

$$b_{\mathrm{max}t} = \frac{C}{\Delta t}\theta_{\mathrm{max}t} + \sum_{\substack{j=1 \\ j\in N}}^{t}\left[\left(1-\alpha\frac{\Delta t}{C}\right)^{t-j}\left(-\alpha\theta_{ej} + v_j\left(\theta_d - \theta_j\right)\right)\right] + \left(\alpha - \frac{C}{\Delta t}\right)\left(1-\alpha\frac{\Delta t}{C}\right)^{t-1}\theta_0 \tag{4-31}$$

4.3 Residential availability considering internal services

As previously discussed, the availability profile depends on the baseline as well as on the modified consumption that yields an optimal remuneration from the aggregator. However, the HEMS can use this capability of modifying consumption (controllability) to provide other internal services that can be more lucrative than the remuneration offered by the aggregator for the availability services. For example, one of the most relevant services that can be provided within the home domain consists is the optimal scheduling of TCL to maximize the Photovoltaic (PV) based self-consumption. Thus, in subsection 4.3.1, a model to maximize the PV based self-consumption at the HEMS level is proposed.

The provision of services directly to the end-user (such as PV based self-consumption) affects the availability of the residential load. Therefore subsection 4.3.2 presents the overall model for the home domain encompassing a multi-objective function that aims at maximizing the remuneration coming from availability services as well as the PV based self-consumption.

4.3.1 Appliances providing internal services: the example of PV based self-consumption

The Photovoltaic (PV) self-consumption is being adopted in Europe with the objective of promoting energy efficiency and avoiding grid problems, such as voltage rise during PV generation peak periods [179]. In some countries (*e.g.*, Belgium, Denmark and the Netherlands) PV based self-consumption measures encompass net metering schemes aiming at balancing endogenous generation and local consumption for large time periods. In contrast, in countries like Germany and Portugal, a new policy is being implemented to encourage instantaneous consumption. For instance, the recent Portuguese legislation for small PV installations announces lower remuneration for PV energy fed into the grid in comparison with the retailing energy price for the consumption, thus reducing the number of PV units under feed-in tariffs [180]. This makes self-consumption always more profitable (or less expensive) than injecting PV into the grid.

However, daily profiles of PV generation are not correlated with the consumption, namely in the residential sector, since a significant part of the households are not at home during daylight hours. Therefore, a modification of the consumption profile is required at the local level so that loads can be shifted to the periods when PV generation is higher. Battery storage systems have been presented as a solution for matching consumption with PV generation [181] but, in most cases, this type of installation may represent an additional cost that affects the rate of return of PV investments.

Alternative resources within the domestic environment, such as appliances' load management, can be used to force this correlation between consumption and PV generation. Recently, particular attention has been paid to the TCL namely space heating and electrical hot water systems in the context of PV based self-consumption [57]. For instance, Sossan *et al.* [182] proposed a Model Predictive Control (MPC) for scheduling EWH consumption with the objective of following PV generation.

The HEMS Module for PV based self-consumption uses existing functionalities of the HEMS as shown in Figure 4-10. The microgeneration module collects data regarding real-time PV generation. Furthermore it is capable of accessing external online services that provide local forecasts for sun irradiance from 3 days to 1 day ahead [183]. The HEMS incorporates functions capable of identifying the uncontrollable load as well as ensuring interoperability with the existing controlling systems of the smart appliances. As previously discussed, HEMS receives the state of operation of TCL and performs an on/off control of the consumption by sending signals to the appliances. Finally, the end-user interface gathers information concerning comfort patterns.

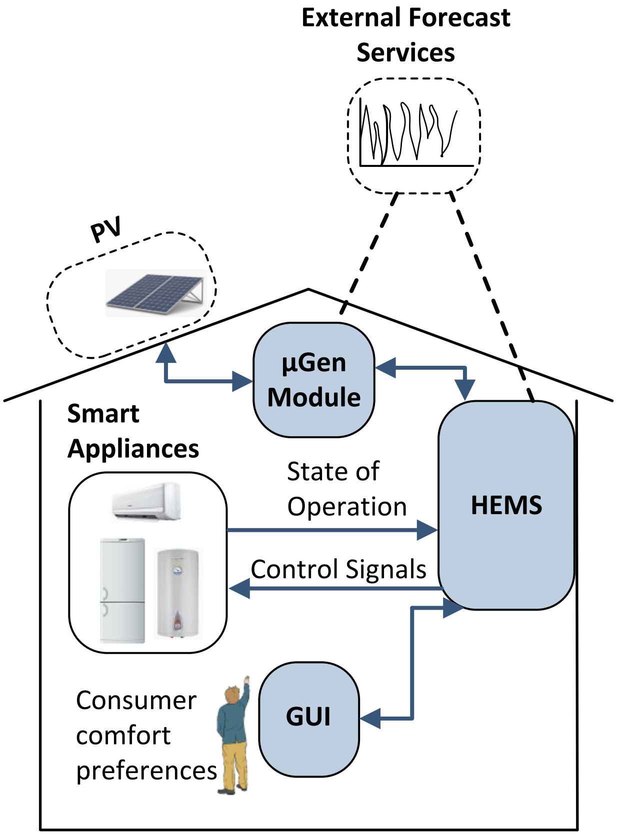


Figure 4-10. HEMS PV based self-consumption architecture.

Furthermore, HEMS also receives information regarding electricity costs (λ_E) and the remuneration costs for injecting PV into the grid (λ_{PV}). However, as stated above, due to the recent legislation in Portugal for self-consumption the remuneration of microgeneration energy delivered to the grid is lower than the energy price.

The optimal scheduling of the EWH for the day-ahead involves solving a multi-period optimization problem, similar to the one presented in (4-16)-(4-19). The objective function presented in (4-32) consists in maximizing the remuneration associated with PV based self-consumption for the day-ahead operation taking into account the expected PV generation and the domestic inflexible load.

According to the recent Portuguese legislation to promote self-consumption [180], if the sum of uncontrollable residential load (P_{UL}) and the appliance modified consumption (P_{MCt}) is lower than the PV generation (P_{PV}), the end-user is remunerated by the energy that is injected into the grid (λ_{PV}). In contrast, if the load is higher than the PV, the end-user has to pay an energy price (λ_E) for the energy consumed that is not locally generated. Since the prices for producing energy from PV are lower than grid delivered the energy prices, self-consumption is always more profitable than injecting PV generation into the grid. The EWH on/off states in each time period (P_{MCt}) are the decision variables whereas the maximum and minimum temperatures limits are the constraints of the problem, such as in the availability model (4-16)-(4-19).

$$\max \sum_{t=1}^{n} R_t = \begin{cases} \lambda_{PVt}\left(P_{PVt} - P_{ULt} - P_{MCt}\right), if\, P_{PVt} > (P_{ULt} + P_{MCt}) \\ \lambda_{Et}\left(P_{PVt} - P_{ULt} - P_{MCt}\right), if\, P_{PVt} < (P_{ULt} + P_{MCt}) \end{cases} \tag{4-32}$$

Equations (4-33)-(4-36) show an equivalent formulation of the objective function (non-branched) in order to enable the application of linear programming techniques. Similarly to the availability formulation, decision variables Y_t^+ and Y_t^- were included in order to represent the situation when the PV is higher and lower than the residential consumption, respectively. The binary variable u_t is used to impose either/or constraints.

$$\max \lambda_{PVt} Y_t^+ - \lambda_{Et} Y_t^- \tag{4-33}$$

Subject to:

$$Y_t^+ - Y_t^- = P_{PVt} - P_{ULt} - P_{MCt} \tag{4-34}$$

$$Y_t^+ \le u_t M \tag{4-35}$$

$$Y_t^- \le (1 - u_t) M \tag{4-36}$$

4.3.2 Availability at the level of a multi-service HEMS

In this section a HEMS with the capability of providing availability services and, at the same time, maximizing the PV based self-consumption is considered. For the *k* smart appliances that are controlled by the HEMS with a total baseline of P_{HBL}, the remuneration function can be written in four branches as displayed in equation (4-37).

$$R_t = \begin{cases} \lambda_{PVt}\left(P_{PVt} - P_{ULt} - \sum_{i=1}^{k} P_{MCti}\right) + \lambda_{RUPt}\left(P_{HBLt} - \sum_{i=1}^{k} P_{MCti}\right), if\ P_{PVt} > (P_{ULt} + \sum_{i=1}^{k} P_{MCti}) \wedge P_{HBLt} > \sum_{i=1}^{k} P_{MCti} \\ \lambda_{PVt}\left(P_{PVt} - P_{ULt} - \sum_{i=1}^{k} P_{MCti}\right) + \lambda_{DWt}\left(P_{HBLt} - \sum_{i=1}^{k} P_{MCti}\right), if\ P_{PVt} > (P_{ULt} + \sum_{i=1}^{k} P_{MCti}) \wedge P_{HBLt} < \sum_{i=1}^{k} P_{MCti} \\ \lambda_{Et}\left(P_{PVt} - P_{ULt} - \sum_{i=1}^{k} P_{MCti}\right) + \lambda_{RUPt}\left(P_{HBLt} - \sum_{i=1}^{k} P_{MCti}\right), if\ P_{PVt} < (P_{ULt} + \sum_{i=1}^{k} P_{MCti}) \wedge P_{HBLt} > \sum_{i=1}^{k} P_{MCti} \\ \lambda_{Et}\left(P_{PVt} - P_{ULt} - \sum_{i=1}^{k} P_{MCti}\right) + \lambda_{DWt}\left(P_{HBLt} - \sum_{i=1}^{k} P_{MCti}\right), if\ P_{PVt} < (P_{ULt} + \sum_{i=1}^{k} P_{MCti}) \wedge P_{HBLt} < \sum_{i=1}^{k} P_{MCti} \end{cases} \tag{4-37}$$

The equations (4.38)-(4.42) represent the linear (non-branched) formulation, similar to the previous cases. However, a new constraint is added to the model – see equation (4-42) – which represents the limits imposed by the contracted power.

$$\max \lambda_{PVt} Y_t^+ - \lambda_{Et} Y_t^- + \lambda_{RUPt} X_t^+ + \lambda_{DWt} X_t^- \tag{4-38}$$

Subject to:

$$X_t^+ - X_t^- = P_{HBLt} - \sum_{i=1}^{k} P_{MCti} \tag{4-39}$$

$$Y_t^+ - Y_t^- = P_{PVt} - P_{ULt} - \sum_{i=1}^{k} P_{MCti} \tag{4-40}$$

$$X_t^+ \le y_t M \ ,\ X_t^- \le (1 - y_t) M \ ,\ Y_t^+ \le u_t M \ ,\ Y_t^- \le (1 - u_t) M \tag{4-41}$$

$$P_{ULt} + \sum_{i=1}^{k} P_{MCti} - P_{PVt} \ge P_{CP} \tag{4-42}$$

4.4 Case Study

4.4.1 Availability at the level of appliances

In this subsection, the availability services at the level of controllable appliances are quantified for the day ahead by calculating the availability curve of each type of TCL considered in this thesis: AC, EWH and refrigerator. A HEMS aiming at maximizing the remuneration due to the provision of availability services is considered.

The focus of this study relies on the evaluation of the power consumption and temperature behavior of these domestic appliances (given by the PBLM presented in section 4.1.1) in the provision of availability services. Furthermore, a sensitivity analysis is also performed in order to assess the impact of the appliances thermal parameters (thermal capacity and thermal resistance) on the amount of potential upward and downward availability services.

Table 4-2 presents the appliances' characteristics, the consumption patterns and the comfort requirements used in the study. Parameters of typical commercial appliances were considered. Since this subsection is focused on the appliances behavior, the ambient and house temperatures as well as water inlet temperature were assumed constant during the day. A 15 minutes time step was considered in the calculations. Realistic comfort temperatures as well as consumption patterns of the end-user were included. The EWH analysis comprised three hot water usages (38^{o}C): 60, 40 and 50 liters at 11:45 am, 8:30 pm and 10:00 pm, respectively.

		Appliances Characteristics					**Consump. Patt.**			**Conf. Req.**	
		C	*R*	*α*	Power	η	*v*	Set point	θd	θmin	θmax
		(kWh/ºC)	(ºC/kW)	(kW/ºC)	(kW)	3.6	Liters	(ºC)	(ºC)	(ºC)	(ºC)
Appliances data	AC	2.72	4.0	-	2.5			21		17.5	24.2
	EWH	0.117	-	9.42x10^{-4}	2		3 uses	64.3	38	~45	80
	Refrigerator	0.05	286	-	0.09	3.7	-	5		3.6	7
Case Study data	House temperature(ºC)							20			
	Ambient Temperature (ºC)							30			
	Water Inlet Temperature (ºC)							17			
	Time Step (min)							15			
	Duration (hours)							24			
	Electricity Prices (€/kWh)							0.15			

Table 4-2. Case Study: single appliance availability

Constant energy prices (0.15 €/kWh) were assumed and the hourly remuneration for upward and downward availability service considered in this study is presented in Figure 4-11. These values are close to the typical tertiary reserve market prices [185]. They are chosen with the objective of demonstrating of the appliances behavior throughout the day in the provision of availability services.

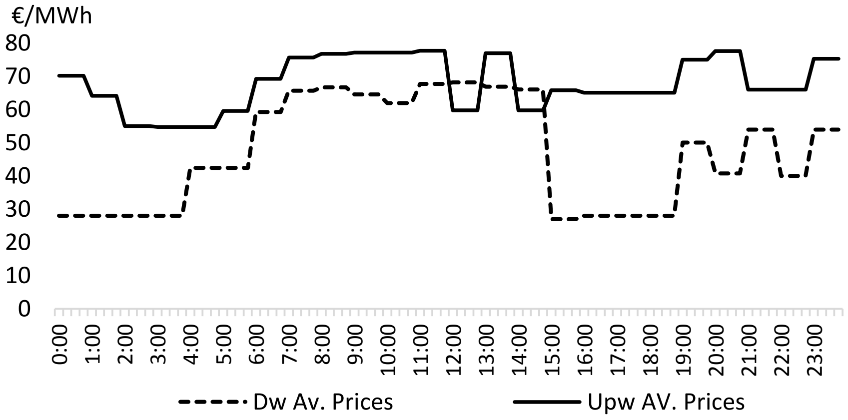


Figure 4-11. Upward and downward availability prices: single appliance case study.

Availability of the appliances

Figure 4-12 illustrates the comparison between the baseline demand and the modified consumption of the EWH device. As discussed in section 4.2.2, the baseline consists in simulating the thermostat control and keeping the temperature at the set point level (64.3 °C). In the figure, the grey line shows the temperature variation inside the water tank considering a normal consumption behavior, *i.e.*, without provision of availability services. The hot water usages (at 11:45 am, 8:30 pm and 10:00 pm) can be identified by a sudden decrease in the temperature caused by the cold water entering in the tank. Nevertheless, after the hot water consumption, the temperature goes back to the thermostat levels by increasing electric power demand (grey bars).

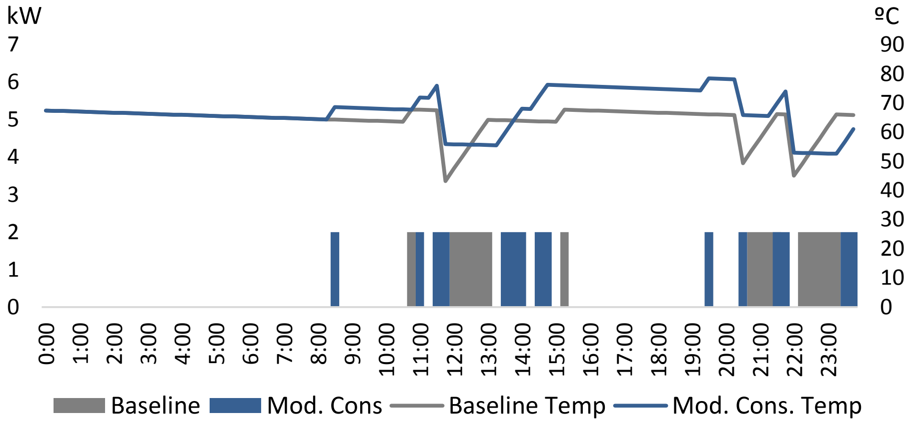


Figure 4-12. EWH baseline vs modified consumption.

In contrast, modified consumption works by accumulating thermal energy before and after the first hot water usage (11:45 am) keeping the temperature near the maximum (80°C) until the evening usages. As depicted in Figure 4-12, the modified electricity consumption (blue bars) in the evening periods is considerable lower than the baseline. However, before the evening hot water usages (8:30 pm and 10:00 pm) the modified water temperature is still above 64.3 °C, which shows that the end-user comfort is not violated. By comparing the baseline and the modified consumption behavior, it is possible to conclude that the thermal energy stored inside the water tank allows a load shifting from the evening to the morning periods.

In fact, this anticipation of the electricity demand occurs due to the variation of the availability remuneration throughout the day. As illustrated in Figure 4-13, the downward availability prices are higher in the morning, which leads the HEMS to increase the consumption in relation to the baseline during these periods. Therefore, a significant part of the appliance downward availability is provided in the morning. On the other hand, the upward availability depends more on the baseline consumption rather than on the upward prices variation. Indeed, the appliance can provide upward availability only in those periods when it is "switched on" in the baseline consumption. Thus, the upward availability services provided by EWH devices are strongly correlated with the hot water usages, when the baseline consumption is typically higher.

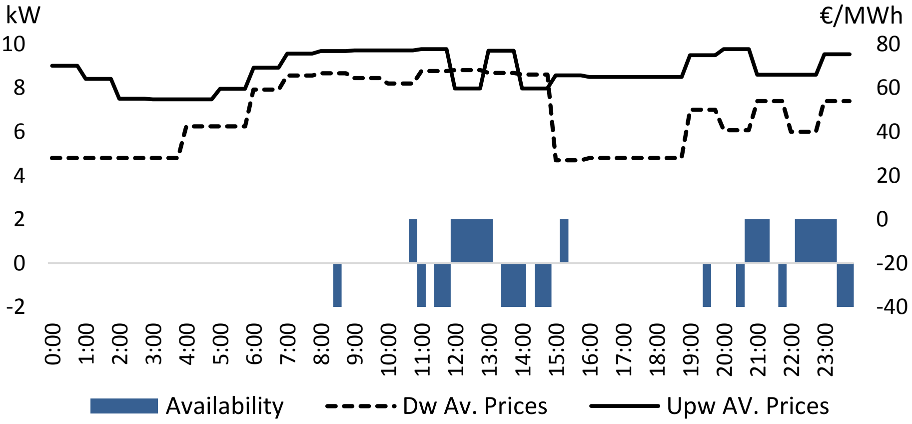


Figure 4-13. EWH availability.

Figure 4-14 presents a comparison between baseline and the modified consumption of an AC appliance used to cool a room during 24 hours. In the baseline mode, the room temperature is kept around the setpoint value of the thermostat (21°C). However, since the end-user allows a temperature variation between 17.5 and 24°C, the HEMS optimizes the consumption of the appliance in order to take advantages of the availability remuneration. Hence, in this mode, the AC is rarely switched off in the night periods until it reaches the maximum temperature. Afterwards, it is switched on more often during the morning. When the minimum temperature is achieved at 2:30 pm, the appliance remains in the off state until the evening.

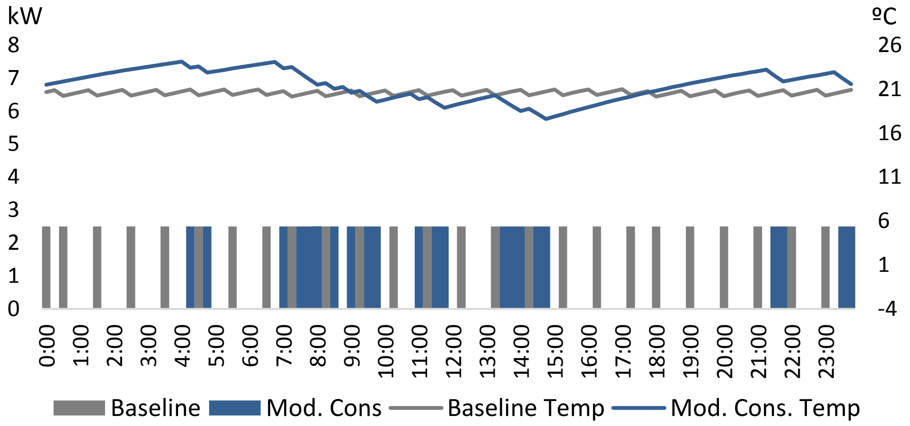


Figure 4-14. AC baseline vs modified consumption.

Similarly to the EWH, the behavior of the AC appliance can be explained by the variation of the availability remuneration. In fact, as illustrated in Figure 4-15, the AC device switches on more often during the morning in order to provide downward availability services. In fact, the HEMS schedules the consumption of the appliance to this period since the downward availability prices are higher. Instead, the upward availability provided by the AC is shared almost uniformly throughout the day.

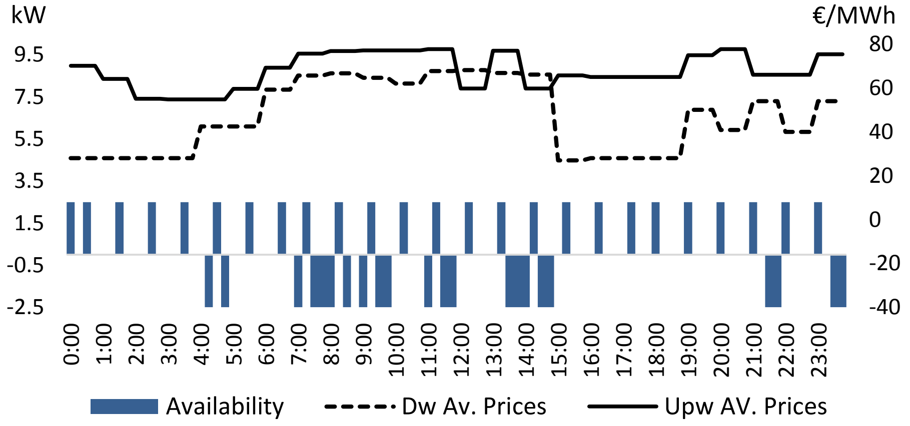


Figure 4-15. AC availability.

The example of the AC operation shows clearly the dependence between the downward and upward availability services. In fact, the provision of upward availability during the night raised the temperature inside the room, which increased the margin for the provision of downward availability. Analogously, this increase of AC consumption relative to the baseline in the morning enabled the possibility to decrease the consumption during the afternoon. Thus, large upward availability leads to large downward availability and vice-versa. Further on this thesis, the discussion on the dependence between upward and downward availability throughout the time will be detailed.

Figure 4-16 presents the temperatures and the power consumption of the refrigeration unit considered in this case study. The baseline temperature is kept bellow the setpoint (5ºC) whereas the average temperature of the modified consumption is often above this value during the day. However, either in baseline or in modified consumption profiles the periods when the appliance is "on" are dispersed throughout the day. This is observable in the availability curve of the refrigerator presented in Figure 4-17, where the upward and downward services remain uniformly distributed rather than changing with the service remuneration.

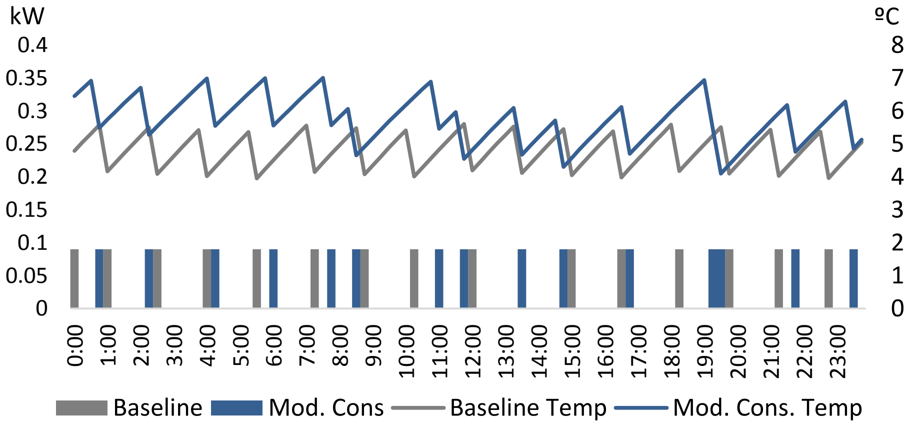


Figure 4-16. Refrigerator baseline vs modified consumption.

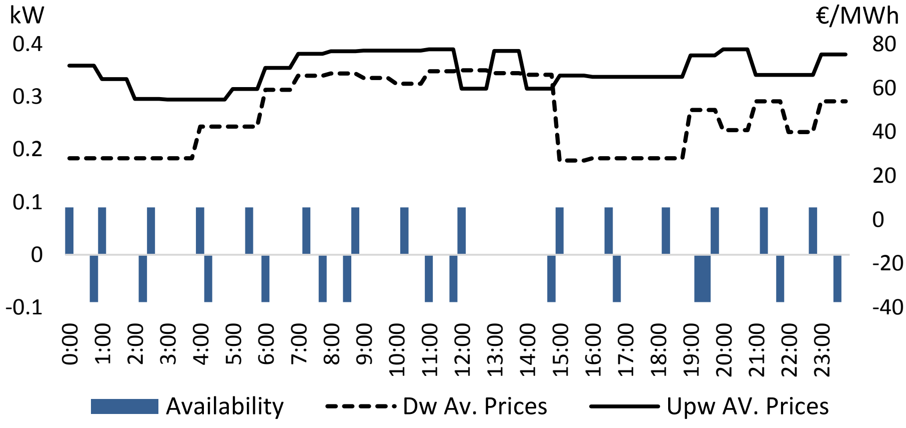
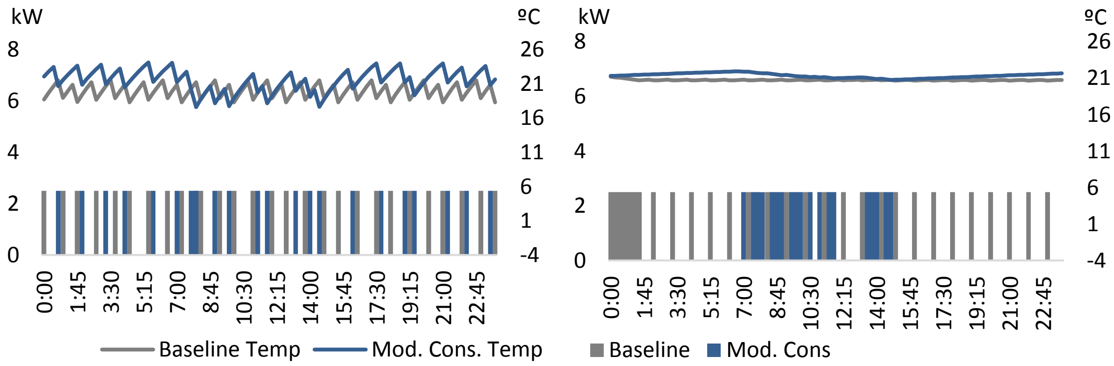


Figure 4-17. Refrigerator availability.

By comparing the availability curves of the AC and the refrigerator, it is possible to conclude that refrigerators have a limited capability to shift consumption to the periods when the downward availability prices are higher. Although the same PBLM was used to AC and refrigerators (see section 4.1.1), the AC devices have a stronger potential to take advantage of the availability prices variation. Hence, besides the consumption patterns and comfort requirements of the end-user, the potential to provide availability services also depends on the appliances' parameters, *i.e.*, thermal capacity and thermal resistance. Therefore, in the following paragraphs a sensitivity analysis is performed in order to assess the impact of the appliances thermal parameters on the potential for the provision of upward and downward availability services.

Sensitivity Analysis

The AC device described in Table 4-2 is used to evaluate the effect of thermal capacity and thermal resistance on the availability curve. The original thermal capacity (*C*) of the room where the AC unit is installed was varied between *C/4* and *8C* and the availability curve was calculated. Figure 4-18 presents the comparison between the baseline and the modified consumption behaviors in these two extreme situations.



Thermal Capacity = C/4

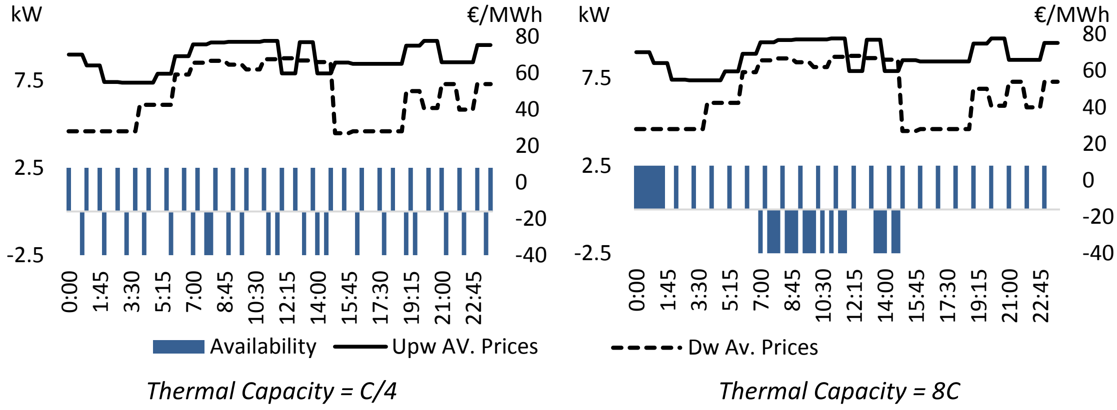
Thermal Capacity = 8C

Figure 4-18. AC baseline and modified consumption considering extreme thermal capacities.

As illustrated in Figure 4-18, when the thermal capacity is low, a low energy consumption is enough to provoke a considerable increase of the room temperature. Analogously, when the appliance is "off" the temperature also increases dramatically. In contrast, when the thermal capacity is larger, the "on" and "off" states of the appliance does not have such significant impact on the room temperature. In other words, the increase of thermal capacity means that more time is needed to cool the room when the AC is "on" and to heat the room when the AC is "off". Therefore, in the baseline mode, the temperature control is more accurate whereas in case of low thermal capacity a higher variation in room temperature is observable.

In modified consumption mode, the consumption must be distributed throughout the day in order to keep the temperature within the maximum and minimum limits in case of a small thermal capacity. On the other hand, if the thermal capacity is higher, the consumption can be shifted in time without violation the end-user comfort. Thus, when the thermal capacity increases the potential for thermal storage also increases, which allows the HEMS to shift consumption to the more profitable periods.

Figure 4-19 presents the difference between the AC availability curves considering extreme thermal capacities. As depicted in the figure, in the *8C* case the downward availability service is concentrated in those periods where the downward remuneration is higher, while in *C/4* case this service is distributed throughout the day.



Thermal Capacity = C/4 *Thermal Capacity = 8C*

Figure 4-19. AC availability considering extreme thermal capacities.

The number upward and downward deviations in Figure 4-19 are similar for both cases (*C/4* and *8C*), which means that thermal capacity does not affect the amount of availability service. Nevertheless, it has a significant impact on the time when the availability service is delivered.

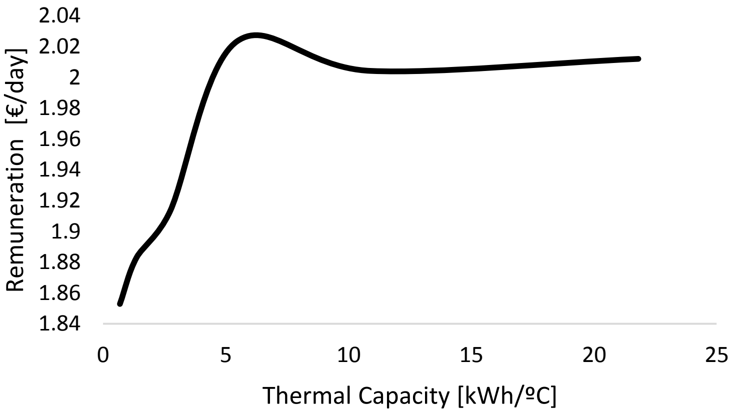


Figure 4-20. Impact of thermal capacities in AC availability remuneration.

Figure 4-20 illustrates the impact of thermal capacity on the daily remuneration of the upward and downward availability service (for a better understanding of the impact, the constant electricity prices were not considered). As shown in the figure, the availability remuneration increases with the thermal capacity. However, for thermal capacities larger than 5kW/ºC the remuneration stabilizes. This means that at 5 kW/ºC the capability of thermal storage is enough to enable the consumption shifting to periods of highest downward availability prices.

The second sensibility analysis regarding AC device consist in varying the thermal resistance (*R*) of the room walls where the appliance is installed. Values between *R/2* and *4R* were considered in this analysis. The objective is to assess the impact of the thermal resistance parameter on the AC availability services.

Figure 4-21 presents the baseline and the modified consumption in the situations involving the extreme thermal resistance values (*R/2* and *4R*). As illustrated in the figure, a small thermal resistance provokes significant thermal energy losses which leads to a dramatic increase of the load demand during the day both in the baseline and in the modified consumption profiles. In contrast, a large thermal resistance improves the thermal efficiency of the room and the AC consumption is considerably lower.

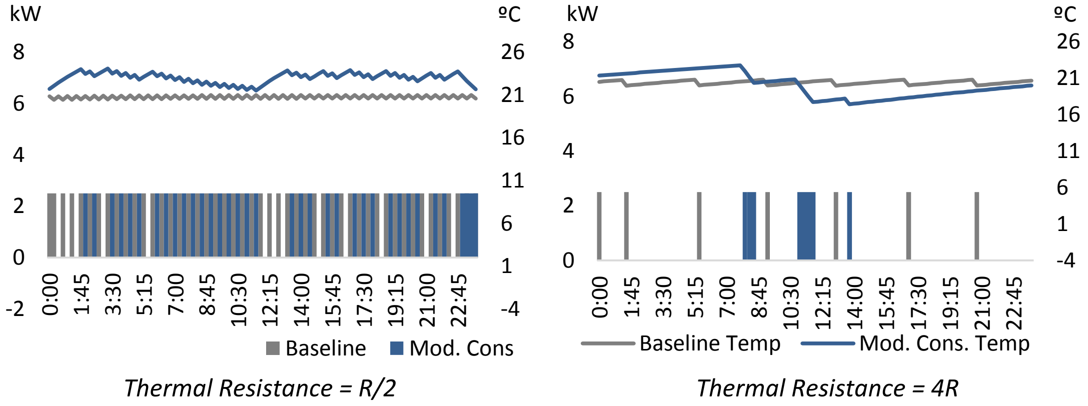
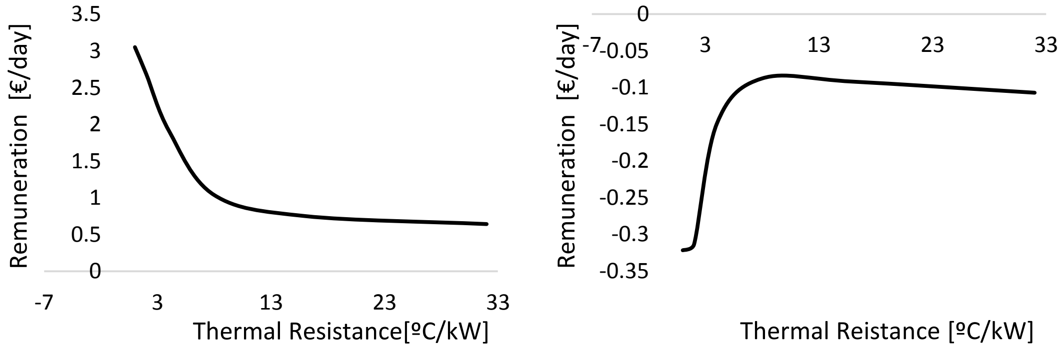


Figure 4-21. AC baseline and modified consumption considering extreme thermal resistances.

Figure 4-21 clearly demonstrated that resistance of the walls has a considerable impact on the provision of upward and downward availability services. As the thermal resistance increases, the baseline electricity consumption decreases which reduces the margin for availability services.



Availability remuneration *Remuneration considering electricity prices*

Figure 4-22. Impact of thermal resistance on availability remuneration.

Figure 4-22 presents the impact of the thermal resistance on the availability remuneration. By analyzing the curves presented on the left, if the electricity prices are ignored, it is possible to conclude that lower thermal resistances lead to higher remunerations since the amount of upward and downward availability services in this case is larger. However, as already mentioned, the small thermal resistances also encompass a considerable amount of consumption. Hence, if the price paid for electricity is considered – see equation (4-16) – the remuneration are higher in case of larger resistance values.

4.4.2 Controllable loads providing PV based self-consumption: Laboratory test

In this subsection, the provision of home domain internal services using appliances control is analyzed. Therefore, a HEMS aiming at maximizing day-ahead PV based self-consumption is considered.

This section is divided in two parts:

(1) The first part is focused on the appliances smart appliances scheduling and control in real conditions. A laboratory test is conducted to validate the methodology proposed in section 4.1.3 regarding the automatic learning of appliances' thermal parameters. Although the control is performed in the context of PV self- consumption, this validation is applicable to other type of control (*e.g.* the provision of availability services).

(2) The second part aims at validating the PV based self-consumption model, presented in equations (4-32)-(4-36). Therefore, besides the laboratory test that includes a single appliance, this section also presents a simulation study where a group of appliances is used to maximize the PV based self-consumption considering uncontrollable load.

The laboratory test was conducted at INESC Porto laboratorial facilities [184], where a 1.5 kW EWH smart appliance, a prototype developed by *Bosch*, is connected to a 230 V bus as well as a 3 kW PV inverter prototype developed in-house.

The particular characteristic of the device is that it allows the report of the temperature inside the tank in a periodic basis using wireless communications. In order to emulate a Home Area Network (HAN), a Gateway node associated with the HEMS was used to remotely exchange data with the EWH controller (namely real time temperature reports) using a proprietary *Bosch* wireless module. Besides this HAN, the laboratory also includes a certified data acquisition and control system responsible for the automatic metering and logging of data that allows a detailed analysis of the experimental results.

The ambient temperature in the laboratory was kept around the 20°C and the measured water inlet temperature was 16.9°C.

Three hot water uses for shower (35 liters per use at 38 °C) were considered: at 7:45, 17:45 and 21:15. These hot water consumption were simulated in real conditions, using a tank to measure the hot water volume exiting the EWH at the set point temperature value (55°C). Since the shower use includes both cold and hot water mix, the 35 liters at 38°C corresponds to 19 liters at 55°C, taking into account the water inlet temperature 16.9.

Figure 4-23 presents the EWH experimental setup.

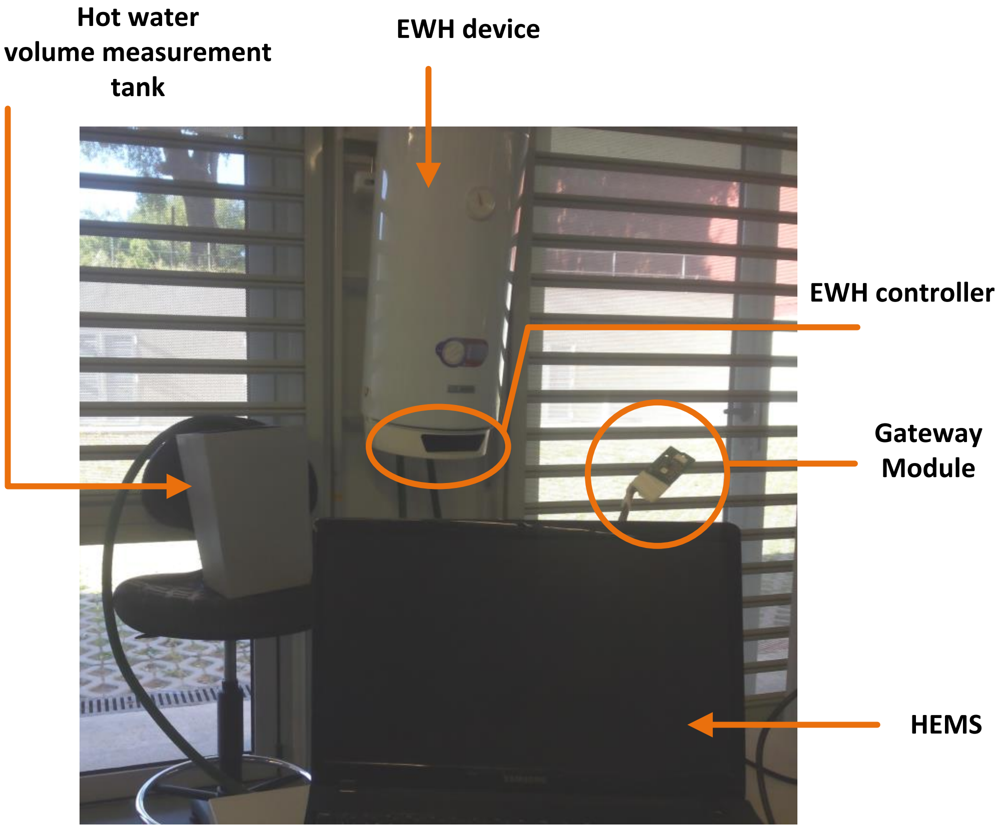


Figure 4-23. Experimental setup.

The laboratory tests were divided into three phases:

- Automatic learning of EWH thermal parameters, using the methodology presented in section 4.1.3;
- Calculation of the EWH day-ahead modified consumption – using the optimization model presented in (4-32)-(4-36) – taking into account the local forecasts of PV generation, the hot water consumption and the thermal parameters obtained in the first phase;
- Evaluation of the real temperature inside the tank that results from the on/off control profile suggested by the scheduling module.

Automatic learning of thermal parameters

Thermal parameters of the EWH were calculated considering the temperature readings obtained during the regular operation of the appliance. As described in section 4.1.3, the methodology consists in performing two tests in order to obtain the thermal admittance (α) and the thermal capacity (C) of the water tank: a heating test and a thermal loss test.

During the heating test (73 minutes), the temperature increased from 23.5ºC to 46.6ºC. As illustrated in Figure 4-24, the measured consumption of the EWH was lower than 1.5 kW due to the network voltage fluctuation. Afterwards, the EWH remained disconnected during almost 17 hours. The temperature decreased from 46.6ºC to 37.7ºC.

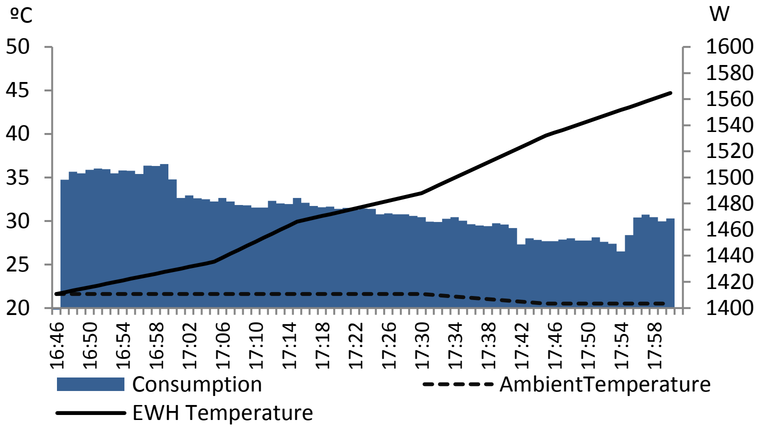


Figure 4-24. Heating Test.

Table 4-3 summarizes the heating as well as thermal loss tests and presents the EWH thermal capacity and thermal loss coefficient obtained by applying the equations (4-7) and (4-8) shown in section 4.1.3.

Heating test				Thermal loss test		
ΔΘ up (°C)	ΔT up (h)	PEWH	ΔΘe up (°C)	ΔΘ dw (°C)	ΔT dw (h)	ΔΘe dw (°C)
23.10	1.22	1.48	11.89	-8.90	16.62	22.15

Automatic learnt Thermal Capacity – *C* (kwh/ºC)	0.0766
Automatic learnt Thermal Loss Coefficient – α (kW/ºC)	1.85E-03

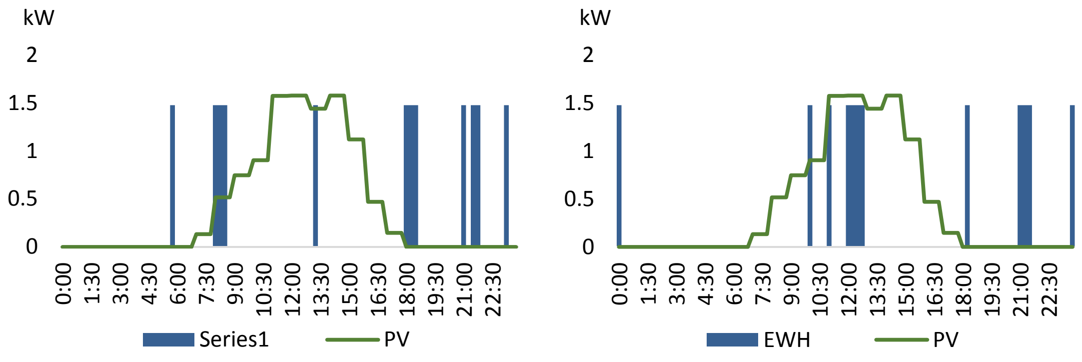
Table 4-3. Heating and thermal loss laboratory tests

Modified consumption calculation

The EWH modified consumption was calculated considering the day-ahead forecasts regarding the PV unit installed at INESC Porto's laboratory. Power forecasts for the 4th October 2014 were considered.

The model presented in 4.3.1 was used in order to identify the optimal modified consumption profile of the Bosch EWH for the day ahead, considering 15 minutes time step. Constant energy prices (0.15€/kWh) and PV injection remuneration (0.06€/kWh, close to the average wholesale electricity market price) were assumed. Since the main objective of this laboratory test is focused on the behavior of EWH device, no additional uncontrollable load was considered.

Figure 4-25 presents a comparison between the EWH baseline and the modified consumption. The forecasted PV generation is also included in the chart to facilitate the analysis of the results. As shown in the figure, in the baseline mode, the appliance switches on after the hot water usage periods (7:45, 17:30 and 21:15). In contrast, in the modified consumption mode the baseline early morning consumption is shifted to the hours when the PV generation is higher (i.e., between 11:00 and 13:00).



baseline *Modified Consumption*

Figure 4-25. EWH baseline and modified consumption: laboratory test.

Figure 4-26 illustrates the difference between the temperatures associated with the baseline and modified consumption. In the baseline mode the temperature is kept around the regular set point value of 60ºC. However, in the modified consumption mode, the EWH preserves a low temperature after the first hot water usage, "waiting" for the local PV generation. When the PV installation starts to inject power in the grid, the EWH device switches on until it reaches the upper bound temperature limit. The thermal energy stored in the tank during the PV injection time avoids significant additional consumption to accomplish with the hot water usages in the evening.

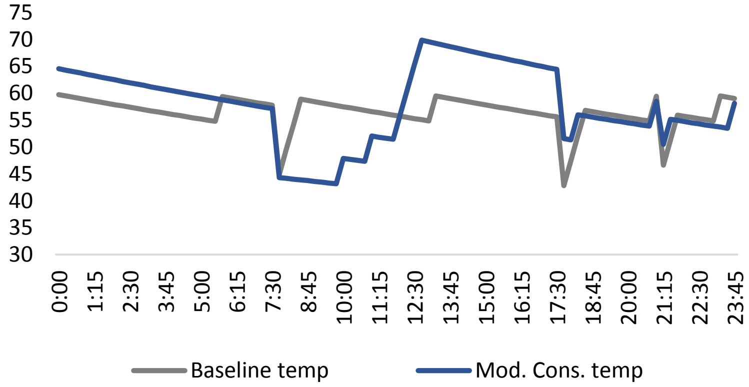


Figure 4-26. EWH baseline and modified temperatures: laboratory test.

Temperature Evaluation

In order to validate the methodology that enables the automatic learning of thermal parameters, the real temperature inside the water tank was evaluated. On/off signals were sent to the Bosch smart appliance during the day in order to accomplish with the modified consumption profile suggested by the HEMS (Figure 4-25). Simultaneously, real temperature measurements were frequently collected, namely in the critical periods (*e.g.*, after and before a hot water usage).

Figure 4-27 presents the comparison between the estimated temperature associated with the modified consumption profile and the real temperature obtained.

The laboratory tests showed that the methodology proposed in section 4.1.3 can estimate the EWH temperature given a consumption profile scheduled by the HEMS. Nevertheless, the real temperature losses inside the water tank are slightly above than the estimated. This means that the thermal loss coefficient learnt by the HEMS was a little higher than the real parameter of the appliance. In fact, in EWH devices this coefficient is very low and the accuracy of the temperature acquisition does not allow a precise estimation. As shown in Table 4-3, the duration of the thermal loss test was more 16 hours and the temperature decreased less than 9ºC in this period. Thus, an imprecision of the temperature measurements have a considerable effect in the parameter estimation, taking into account its small value. However, this had no impact on the comfort of the end-user.

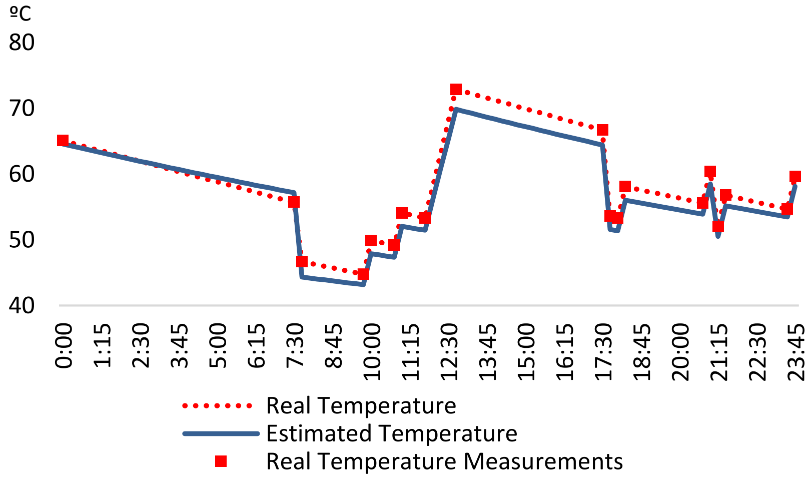


Figure 4-27. Modified Consumption: real temperature behavior.

Provision of PV based self-consumption considering uncontrollable load

The laboratory test presented above demonstrated a single appliance providing self-consumption services within the Home Domain. The tests were focused on controllability aspects, namely the capability of HEMS to learn automatically the thermal parameters of a EWH device. In the following paragraphs, a simulation study is performed in order to expand the single appliance self-consumption services to a group of EWH devices. The objective of this simulation is to demonstrate the results of the optimization model presented in (4-32)-(4-36). Hence, this model is used to calculate the modified consumption of a population of 100 EWH appliances (comprising different thermal parameters) in the provision of self-consumption services. In this simulation, uncontrollable load was considered.

Table 4-4 summarizes the minimum and maximum values of the thermal and electric characteristics of the EWH population, the ambient and water inlet temperatures assumed as well as the set point and comfort temperatures.

	C (kWh/ºC)	α (kW/ºC)	P_{EWH} (kW)	θ_e (ºC)	θ_i (ºC)	θ_d (ºC)	*Set point* (ºC)	θ_{min} (ºC)	θ_{max} (ºC)
Min	0.059	1E-04	1.5	25	13.5	38	60ºC	~40	80
Max	0.234	2E-03	2.6						

Table 4-4. Case Study: 100 EWH

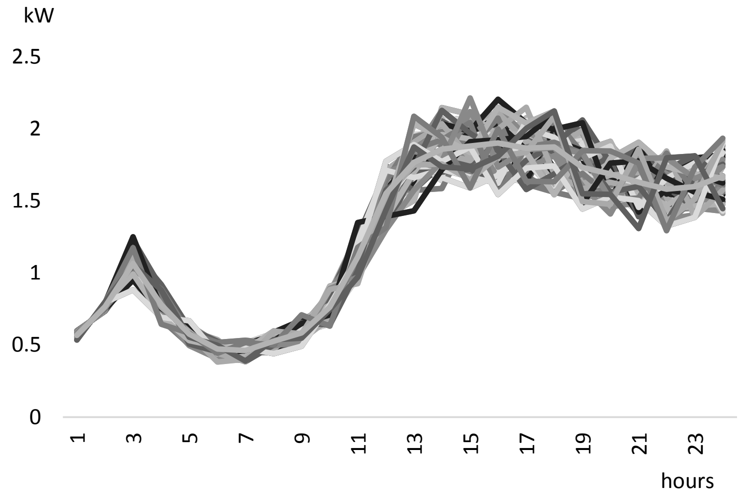


Figure 4-28. 100 uncontrollable load profiles.

Figure 4-28 depicts the uncontrollable load diagrams forecasted by each HEMS of the 100 residential consumers. The total hot water usage (in liters) of the consumers are shown in Figure 4-29. As illustrated in the figure, the hot water demand is concentrated in the morning and evening periods. The electricity price (0.15 €/kWh) and the feed-in remuneration for the PV (0.06 €/kWh) used in the laboratory tests were considered in this simulation. The same PV profile was assumed, however, in this case a 6 kW PV installation was considered.

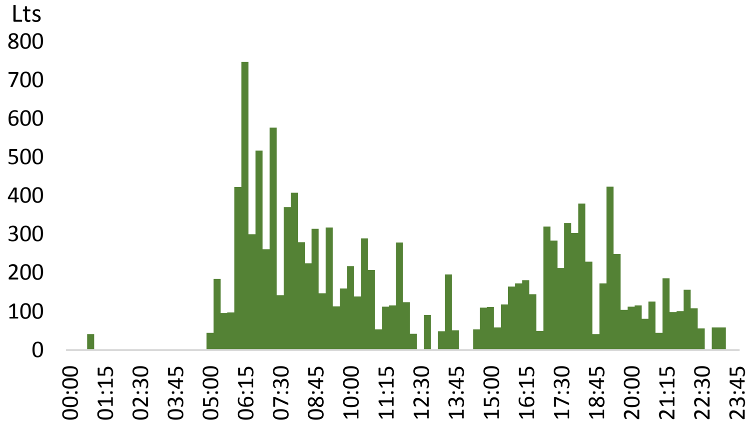


Figure 4-29. 100 end-users total hot water consumption.

Figure 4-30 presents the comparison between the baseline consumption of the appliances and the modified consumption profile obtained by the self-consumption optimization method considering a time step of 15 minutes. The normal consumption follows the hot water usages of the consumers, *i.e.*, the electric consumption of EWH population increases in the morning and evening periods. In fact, immediately after a the temperature decrease due to a hot water usage, the heating devices switch on in order to keep the temperature at the set point levels.

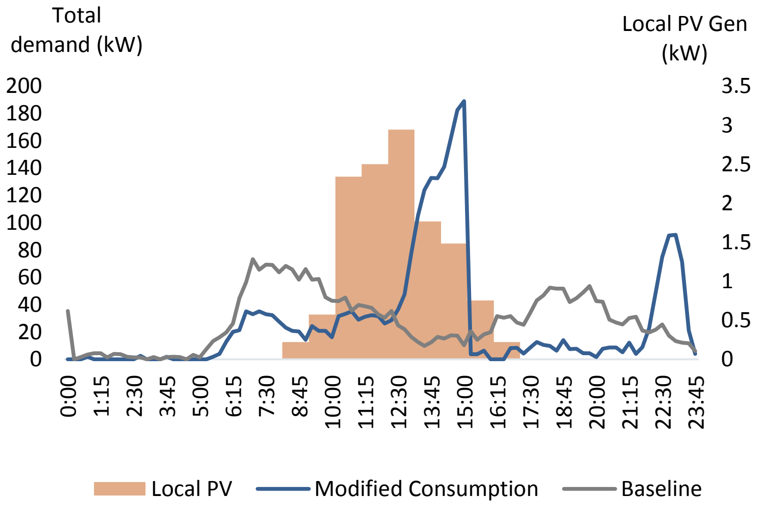


Figure 4-30. PV based self-consumption: EWH baseline and modified consumption.

In the modified consumption of the appliances, the electricity demand is lower in the early morning and evening periods. Similarly to the laboratory test case, the consumption is “moved” to the PV injection periods. At the end of the day a lower peak consumption brings the temperature of the hot water tank back to the set value (it was imposed that temperature at the end of the day near the initial conditions).

However, the peak of the consumption and the peak of solar irradiance do not happen at the same time. This can be explained due to the uncontrollable load. At 13:00, a peak in most uncontrollable load profiles also occurs (see Figure 4-28), which decreases the difference between the generation and demand at the local level. Indeed, a peak of local PV generation does not mean an increase of the need for self-consumption through controllable devices. Therefore, the EWH consumption is moved to the subsequent periods, when a small decrease of uncontrollable load occurs in the majority of residential buildings. Furthermore, by postponing the consumption to the afternoon hours, the EWH can store significant thermal energy to accomplish the hot water needs in the evening with less thermal losses. Even so, smaller peak consumption occurs at the end of the day in order to bring the temperatures back to the set point levels.

The consumption peak shown in Figure 4-30 happen at 15:30 because the same PV generation profile was used for all the residential buildings. Moreover, the scheduling of the appliances was not performed at the system level. In fact, self-consumption relies on local HEMS optimization, which may lead to similarities regarding modified consumption. Finally, it is important to stress that these peaks in EWH consumption do correspond to actual peak in the system demand, since they occur to compensate the local generation.

4.4.3 Availability at the HEMS level

In this section, the availability curve at the residential level HEMS is estimated. The controllability of appliances in the home domain – EWH, AC and refrigerator – is used to provide availability in three different scenarios, each one representing a different strategy regarding the modified consumption:

- **Availability strategy**: in this strategy, it is assumed that the HEMS aims at maximizing the remuneration of availability services provided by the controllability of loads. Although a PV installation is considered at the residential facilities, the HEMS does not include the self-consumption functions in the modified consumption calculations.
- **Self-consumption strategy**: in this strategy, a PV installation is considered at the residential building and the HEMS aims at maximizing the PV based self-consumption. In the modified consumption profile suggested by the HEMS, the remuneration paid for the availability services is ignored.
- **Multi-service strategy:** in this strategy, a PV installation is considered at the residential building. However, HEMS aims at maximizing the total household remuneration, *i.e.*, it takes into account not only availability services remuneration but also the electricity costs savings with the PV based self-consumption on the calculation of the modified consumption.

This section aims at comparing the residential availability services (*i.e.*, consumption changes regarding the baseline demand) for the day ahead in these three different situations.

Table 4-5 presents the appliances characteristics, the consumption patterns and the comfort requirements used in the study. End-user comfort and consumption patterns are similar to those assumed in section 4.4.1. For example, regarding EWH the same three hot water usages (at 38^{o}C) were considered: 60, 40 and 50 litres at 11:45 am, 8:30 pm and 10:00 pm, respectively. The ambient, house and water inlet temperatures were assumed constant during the day. A 15 min time-step was used in the discrete calculations of the baseline and modified consumption in each strategy.

		Appliances Characteristics					**Consump. Patt.**			**Conf. Req.**	
		C	*R*	*A*	Power	η	*v*	Set point	θd	θmin	θmax
		(kWh/ºC)	(ºC/kW)	(kW/ºC)	(kW)	3.6	Liters	(ºC)	(ºC)	(ºC)	(ºC)
Appliances data	AC	2.04	5.2	-	2.5			21		17.5	24.2
	EWH	0.117	-	$9.42x10^{-4}$	2		3 uses	64.3	38	~45	80
	Refrigerator	0.05	542	-	0.09	3.7	-	5		3.6	7
Case Study data	House temperature(ºC)							20			
	Ambient Temperature (ºC)							30			
	Water Inlet Temperature (ºC)							17			
	Time Step (min)							15			
	Duration (hours)							24			
	Electricity Prices (€/kWh)							0.15			
	PV feed-in remuneration (€/kWh)							0.06			

Table 4-5. Case Study: availability at the HEMS level

Since the analysis is focused on the comparison of the availability services in the three strategies previously presented, the residential uncontrollable load was not included in this study.

The electricity prices were also assumed constant during the day (0.15€/kWh) and a near gross market value was used for the feed-in remuneration regarding local PV (0.06 €/kWh). Since the discussion on the remuneration schemes will occur further on this thesis, realistic ancillary services market prices were used at this phase to represent the remuneration that an aggregator is willing to pay for the residential availability services. The November 2013 hourly average prices of the Portuguese tertiary reserve markets [185], presented in Figure 4-31 were assumed. A PV installation of 12kW was taken into account. Such significant dimension of the PV was used in order to improve the comparative analysis, *i.e.*, widening the gap between strategies that include PV and those that do not include any local generation.

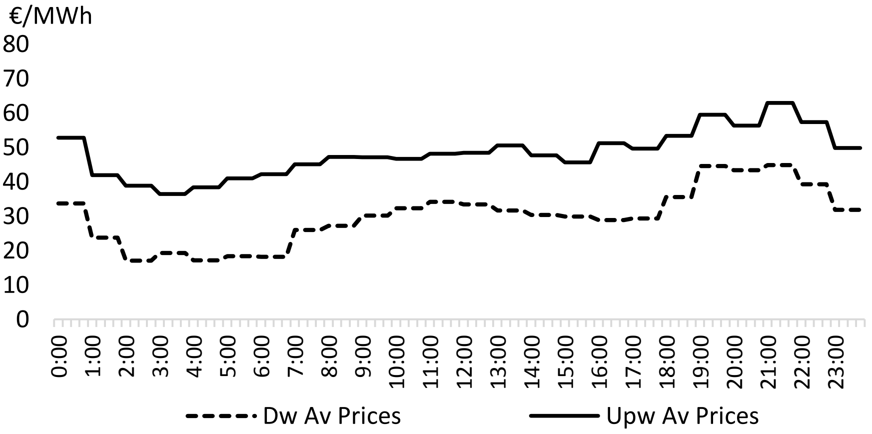
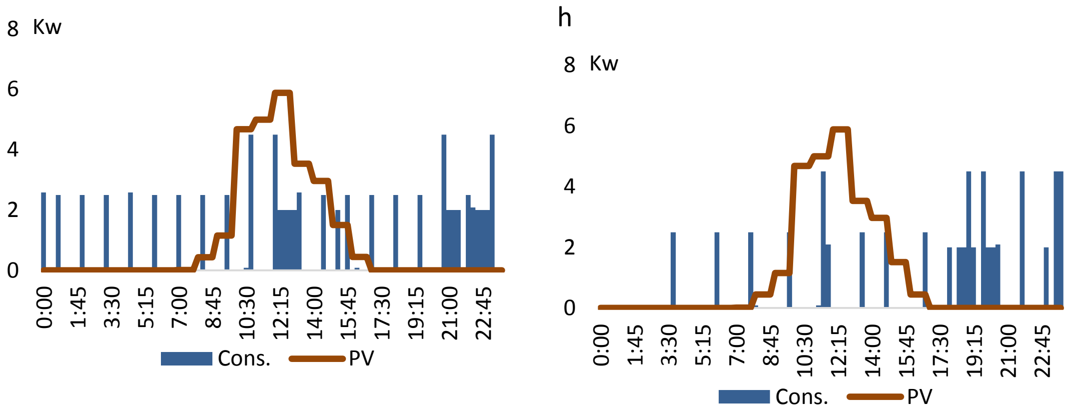


Figure 4-31. Availability Remuneration (tertiary reserve market prices).

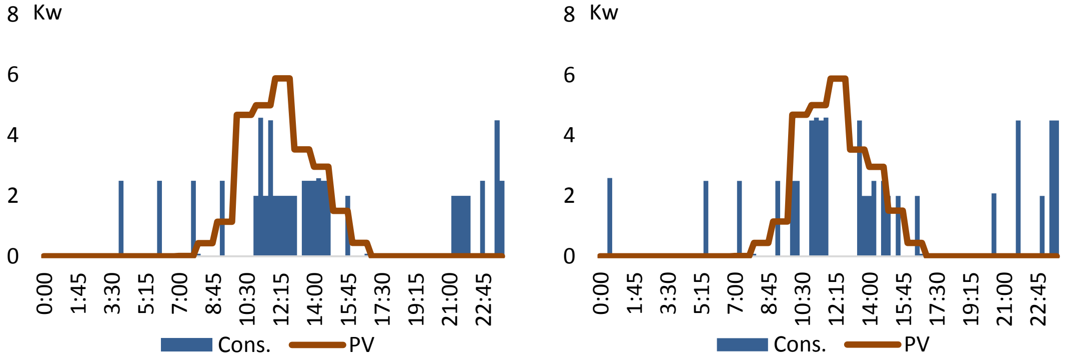
Figure 4-32 presents the baseline demand as well as the modified consumption of the appliances in each HEMS strategy considered in this study (availability strategy, self-consumption strategy and multi-service strategy) as well as the day-ahead forecasted PV curve.

In availability strategy a shift of the consumption to the evening hours can be identified. In fact, since the objective relies on maximizing the remuneration from the provision of availability services, the HEMS moved the appliances demand to the hours when the downward availability prices are higher. In contrast, in self-consumption mode, the residential demand is transferred to the morning and afternoon hours, when a significant local PV generation exists. The HEMS uses the thermal storage capability of TCL to concentrate the consumption in order to maximize the self-consumption of local energy resources. Finally, in the multi-service strategy, a part of the appliances' electricity demand is shifted to the PV injection periods and another part of the consumption is modified so that the HEMS can benefit from the remuneration of upward and downward availability service.



Baseline

Modified consumption Availability strategy



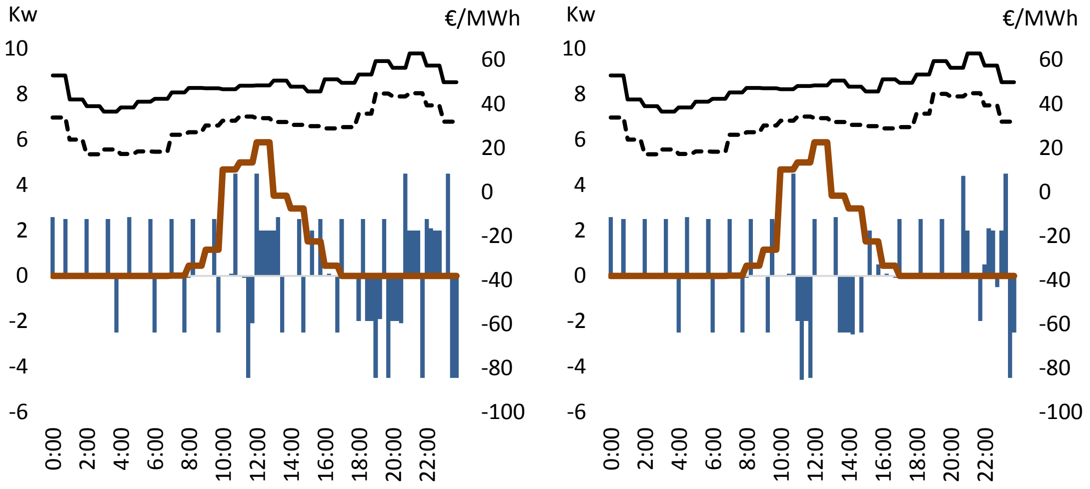
Modified consumption Self-consumption strategy

Modified consumption Multi-service strategy

Figure 4-32. Baseline and modified consumption at the HEMS level.

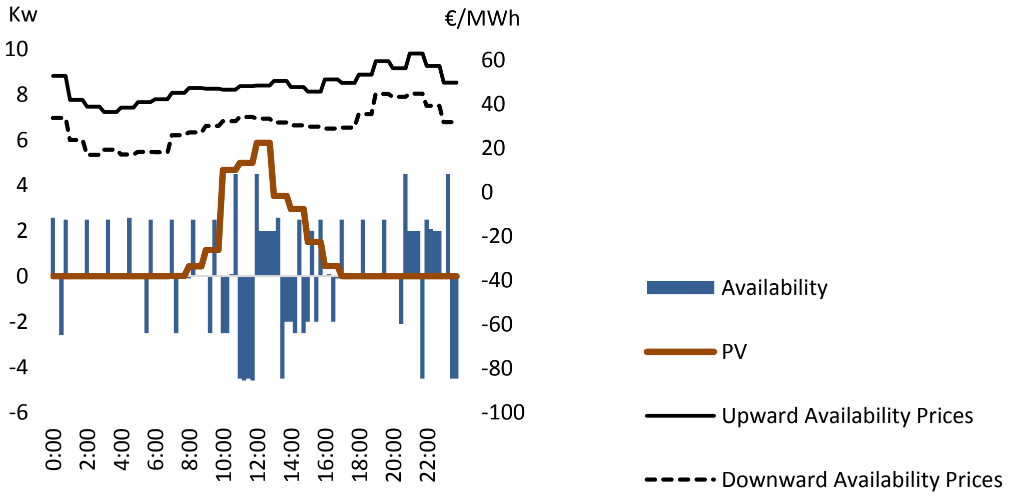
Figure 4-33 presents the day-ahead availability curve in each strategy. As displayed in figure, in the availability strategy the provision of day-ahead availability services follows the upward and downward remuneration and no relation exists with the local generation. Indeed, during the forecasted PV injection, the HEMS is often avoiding consumption in order to provide upward availability services. The opposite behavior happens in the self-consumption strategy, where the downward availability is concentrated at the PV generation hours, regardless of the remuneration that is paid for this service. The shift in the appliances demand to maximize self-consumption provokes upward deviations related to the baseline. However, these deviations are distributed throughout the day and they are not related with the upward availability prices. In contrast, they occur to allow the provision of downward in the daylight periods.

The availability of the multi-services strategy shows the dual objective of the HEMS modified consumption. In fact, at the evening periods the curve is similar to the first strategy. However, a significant part of the downward availability service is moved to the periods when local generation exists. In fact, during this period, the residential HEMS provides subsequently downward and upward availability in order to take advantage of low energy costs due to self-consumption and, at the same time, benefit from the upward availability remuneration.



Availability Curve
Availability strategy

Availability Curve
Self-consumption strategy



Availability Curve
Multi-service strategy

Legend

Figure 4-33. Availability at the HEMS level.

Figure 4-34 presents the total upward and downward availability services provided in each strategy. As displayed in the figure, in the self-consumption strategy the total availability services are lower. Actually, in this case, the HEMS is only encouraged to perform a shift of appliances demand to the periods when local PV generation exists. In the other strategies, a similar amount of availability is identified. However, in multi-service strategy, the downward availability is higher since the consumption occurs both in periods of PV generation and of advantageous downward remuneration.

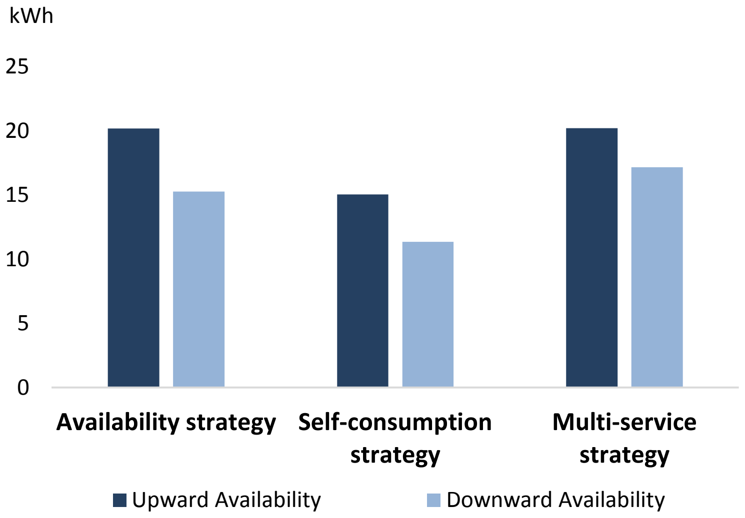


Figure 4-34. Total upward and downward availability.

Figure 4-35 shows the daily income in each strategy considering the remuneration that the end-user receives from the aggregator. The values were obtained by applying the equation (4-16), *i.e.*, they only include the electricity consumption costs and the remuneration for the upward and downward services.

Since the remuneration associated with the PV injection is not considered in this chart, the availability strategy yields better economic benefits to the end-user. Although multi-service strategy comprises higher amount of downward availability (as seen in Figure 4-34), some of these services are provided in low remunerated periods.

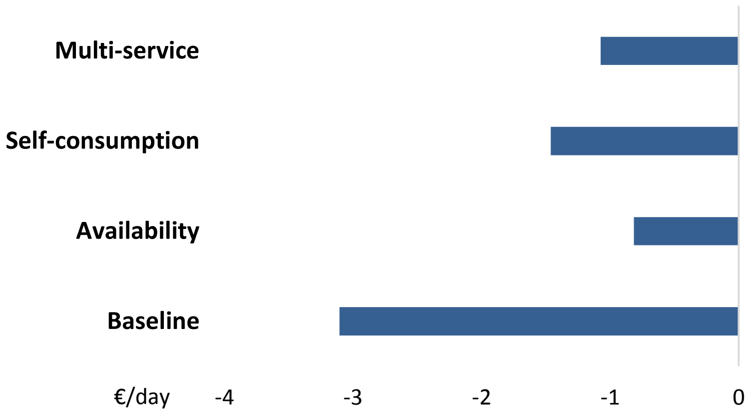


Figure 4-35. Income considering availability remuneration and electricity costs.

Figure 4-36 presents the opposite analysis. In other words, the electricity costs presented in this figure take into account the remuneration from the PV injection but the availability remuneration is neglected. In this case, the self-consumption strategy is the one that has more impact on the electricity costs reduction.

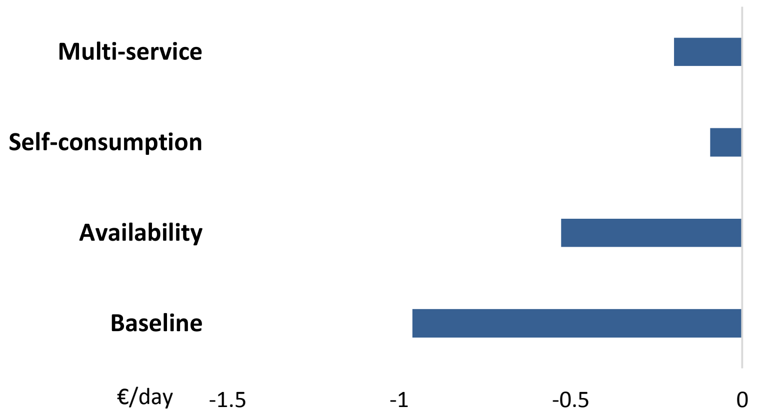


Figure 4-36. Income considering PV remuneration and electricity costs.

Finally, Figure 4-37 presents the total income of the end-user considering the remuneration not only due to the PV injection but also due to the availability services. In this case, the three strategies lead to a positive income, which means that the remuneration for services is higher than the energy costs. These unrealistic incomes occur due to the significant size of the PV installation used in this case study (12 kW). However, it is important to stress that this section aims at focusing on the comparative analysis between the three strategies.

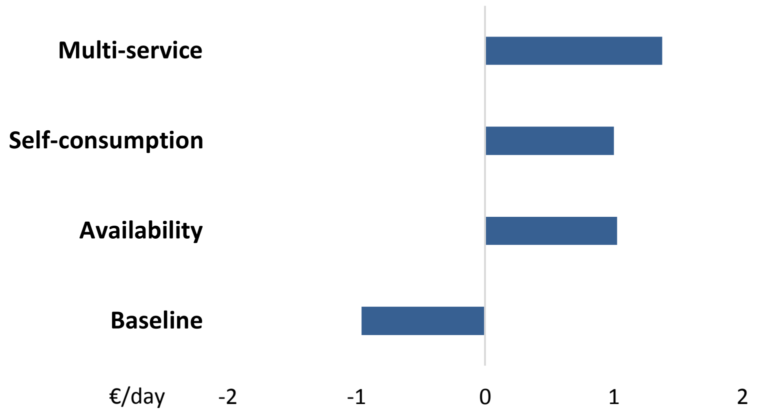


Figure 4-37. Total income.

As shown in Figure 4-37, the higher income was achieved through the multi-service strategy. In this strategy, the HEMS is considering the total remuneration of the end-user in the calculation of the modified consumption.

4.4.4 Availability at multi-HEMS level

In this subsection the comparison of the three strategies performed in 4.4.3 is extended to 1500 residential consumers. The main objective is to evaluate the changes in availability curve in situations where the controllable resources are shared in order to provide more than a single service.

The analysis data used in this case study is similar to the one presented in Table 4-5. The availability upward and downward remuneration assumptions are also equal to those considered in 4.4.3. However, the consumption patterns and the comfort requirements of the 1500 end-users as well as the appliances characteristics were considered to vary randomly within realistic boundary values. Table 4-6 displays the maximum and minimum limits, within which 1500 consumption scenarios were derived through uniform distribution.

In this case study, the AC and refrigerators devices were assumed to be running during the 24 hours of the day ahead. The total hot water demand throughout the day estimated for the 1500 end-users is displayed in Figure 4-38. As shown in the figure, the hot water consumption using EWH devices is concentrated mainly in morning and evening hours.

		Appliances Characteristics					**Consump. Patt.**			**Conf. Req.**	
		C	R	α	Power	η	v	Set point	θd	$\Delta\theta min$	$\Delta\theta max$
		(kWh/ºC)	(ºC/kW)	(kW/ºC)	(kW)	3.6	Liters	(ºC)	(ºC)	(ºC)	(ºC)
Appliances data	AC	0.7-4.2	4-15	-	1.5-3.5		-	20-21		2	4
	EWH	0.06-0.24		5.5×10^{-4}- $11. 5\times10^{-4}$	1.5-2.6		Fig4-38	60-65	38	*	**
	Refrigerator	0.03-0.07	434-760	-	0.07-0.12	3-4	-	4-6		1	2
Case Study data	House temperature(ºC)						20				
	Ambient Temperature (ºC)						30				
	Water Inlet Temperature (ºC)						17				
	Time Step (min)						15				
	Duration (hours)						24				
	Electricity Prices (€/kWh)						0.15				
	PV feed-in remuneration (€/kWh)						0.06				

*The min temperature of the EWH was assumed to be at least equal to the set point before the water usages

**The maximum temperature was defined by to be 80ºC for all the EWH devices

Table 4-6. Case Study: 1500 HEMS

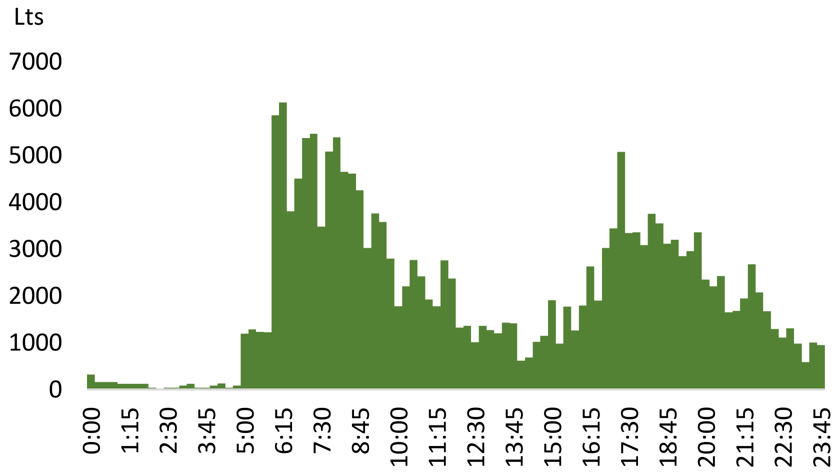
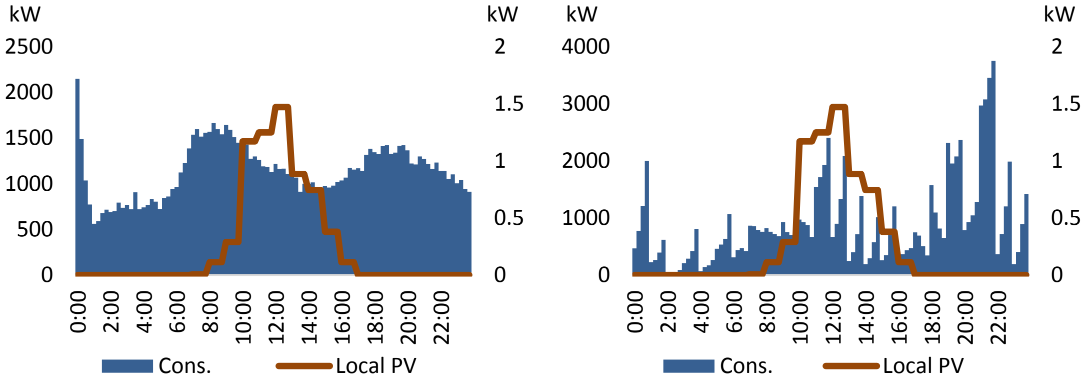


Figure 4-38. 1500 end-users total hot water consumption.

Figure 4-39 presents the appliances baseline as well as the modified consumption in each of the three strategies described in section 4.4.3: availability strategy; self-consumption strategy and multi-service strategy. By analyzing the baseline consumption curve, it is possible to distinguish the consumption of AC and refrigerators (nearly constant around 50 kW) from the consumption of EWH appliances, which increases dramatically in periods of high hot water demand.

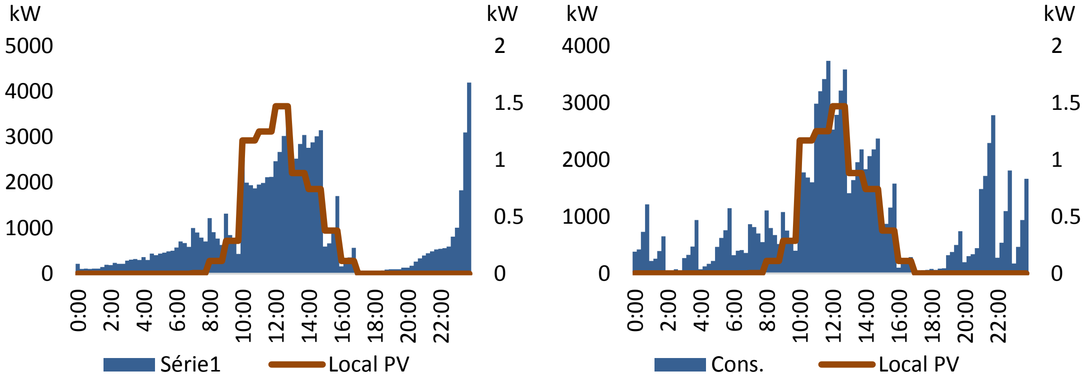
The modified consumption curve in availability strategy presents frequent fluctuations during the day driven by the upward and downward remuneration values. In contrast, in self-consumption strategy, the electricity demand increases in sunshine hours and decreases in off-sun hours. This is visible in the period between 16h and 22h where the electricity demand is insignificant due to the anticipation of appliances consumption to the sunshine hours. In this study, the temperatures at the end of the day were required to be near the initial temperatures so that the actual availability during the day could be consistently evaluated. Therefore, after 22h, the appliances demand increases again in order to bring back the temperatures to the initial levels.

The multi-service modified consumption is similar to the availability strategy during the off-sun periods and it is similar to the self-consumption strategy during the sunshine periods. Nevertheless, in multi-service strategy the appliances demand during the PV generation stage is higher than in the self-consumption strategy. Indeed, in multi-service strategy, this additional consumption during the sunshine periods enables the provision of upward availability services, which is a functionality that is not included in self-consumption strategy.



Baseline

Modified consumption Availability strategy



Modified consumption Self-consumption strategy

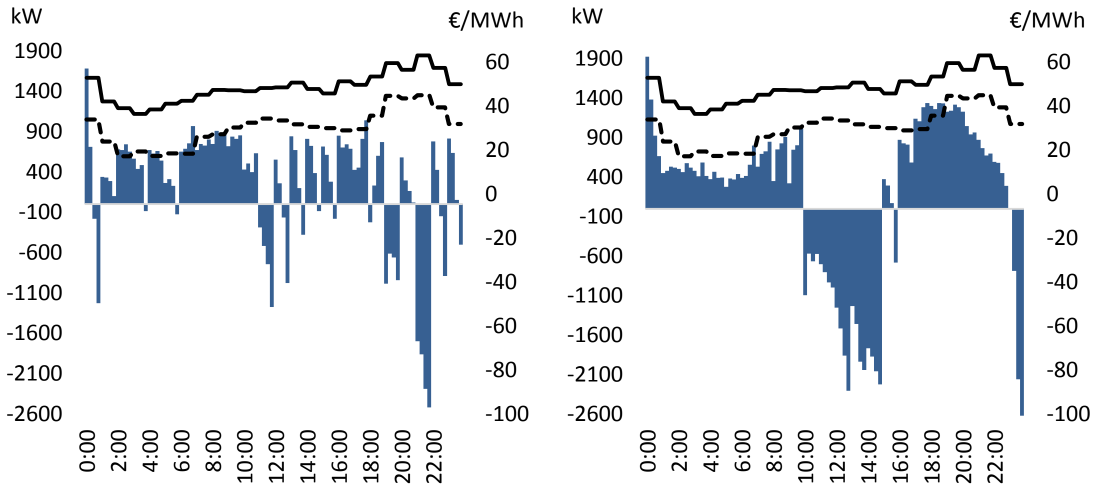
Modified consumption Multi-service strategy

Figure 4-39. Baseline and modified consumption: 1500 HEMS.

Figure 4-40 presents the availability curve in each strategy as well as the upward and downward prices assumed to be paid by the aggregator.

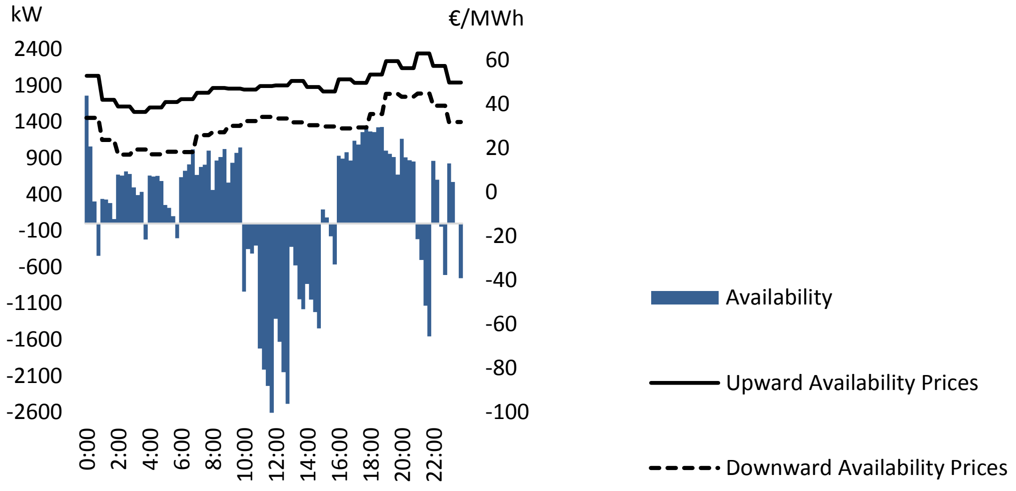
In the first strategy, the downward availability services are concentrated at the end of day (when the downward remuneration is higher) and the upward availability service is dispersed throughout the 24 hours. In contrast, in self-consumption and multi-service strategies, the provision of downward availability services occurs in the morning and afternoon periods while the upward availability services occur in the off-sun periods.

The similarity between the availability curve of multi-service and self-consumption strategies can be explained by the difference between the electricity prices and the other remuneration values. A cost of 0.15€/kWh is considerably higher in comparison with the PV feed-in tariff (0.06€/kW) and with the upward and downward availability remunerations considered in this study. Hence, if the HEMS schedules the consumption for the periods when local generation exists, the electricity costs reduce significantly. In fact, the energy price becomes the dominant factor in the calculations of the availability curve in the Home Domain, as will be discussed in detail in Chapter 6.



Availability Curve
Availability strategy

Availability Curve
Self-consumption strategy



Availability Curve
Multi-service strategy

Legend

Figure 4-40. Availability: 1500 HEMS.

4.5 Summary and Main Conclusions

This chapter presented a methodology to quantify the availability services that residential consumers can provide to the aggregators, considering the control of smart appliances. The methods capable of maximizing the provision of this services for the day ahead, considering diverse end-users' consumption patterns, and different characteristics of the appliances, developed. A particular attention was paid to the situations where the appliances control is used to provide other type of services within the home domain.

The calculation of the availability services at the level of TCL devices demonstrated that physical parameters of the appliances have a significant impact on the capability of providing these services. It can be concluded that thermal capacity increases the thermal storage potential. This means that, with a higher thermal capacity, the HEMS can shift the appliances for longer periods taking advantage from the intra-day variations of the availability remuneration. High thermal resistances improve the energy efficiency of appliances by decreasing the consumption, which leads to a low remuneration from availability services but high electricity savings.

Thus, an accurate estimation of the physical parameters of the appliances is needed. In this chapter a methodology enabling the HEMS to perform this estimation based on temperature measurements during the normal operation of the appliances was proposed. This methodology was validated in a laboratory demonstration, using a EWH device capable of reporting the temperature to the HEMS.

The evaluation of the availability curve at the HEMS level, in the situations where no external services were considered, allowed the identification of the main factors affecting the provision of availability services to the aggregator:

- The thermal parameters of the appliances and, hence, the external temperatures that have an impact on their electricity consumption (ambient temperature, in case of AC, and indoor temperature, in case of EWH and refrigerator).
- The end-users' consumption patterns, for example the periods when AC is running or the typical end-users' hot water usages. This have a higher impact on the upward availability in comparison with the downward availability services. In fact, the upward availability only occurs if the appliances are connected in the baseline mode.
- The end-users' comfort relaxation, *i.e.*, wider comfort rages increase the margin for load control and the capability to take advantage of the higher upward and downward availability remunerations during the day.
- In general, the provision of downward services increase the potential for the provision of upward services and vice-versa. Indeed, the downward services increases the thermal energy stored in the appliances that can be used during the downward availability services.

From the evaluation of the availability curve at the residential level taking into account the use of appliances control to other objectives it is possible to draw the following conclusions:

- If local PV is installed in the home domain, the HEMS tends to shift the appliances consumption for those periods when the need for self-consumption is higher, *i.e.*, when a significant difference exist between the local generation and the total residential load.
- The use of appliances control does not necessarily decrease the amount of upward and downward availability that is provided during the day. However, it has the effect of reducing the remuneration form these services.

Chapter 5 – Aggregators Providing Flexibility Services

Generators can participate in tertiary reserve service markets by offering their capacity to increase or decrease the power output in each hour of the day ahead. Similarly, the provision of these services from the demand side requires that aggregators offer the potential capacity to increase or decrease the consumption in relation to a predefined baseline power demand already contracted in the electricity market. Thus, aggregators should be capable of estimating the day-ahead flexibility profiles regarding each residential building and transform them into hourly bids for the day ahead tertiary reserve market.

As described in the structured approach presented in Chapter 3, aggregators are treated in this thesis as structures of resources, services and methods. Figure 5-1 summarizes the resources and services of the aggregator according to the conceptual approach proposed in this thesis.

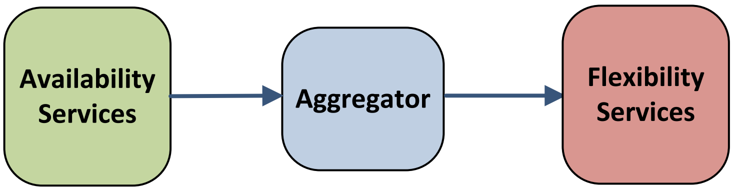


Figure 5-1. Aggregator resources and services.

The aggregators' resources include the day ahead availability that is provided by the end-users and communicated by the Home Energy Management System (HEMS) in the previous day. Although the availability curves correspond to services offered by the end-users and obtained by the optimization tools within the Home Domain, from the aggregators' perspective they are viewed as unchangeable resources that can be used to provide flexibility services. These services can be traded in the reserve markets or they can be directly offered to the system operators through bilateral contracts.

This section aims to present a method to maximize the aggregator's remuneration in the participation in day-ahead tertiary reserve market. Subsections 5.1.1 and 5.1.2 are focused on the aggregator's resources characterization as well as on the clarification of the difference between "availability" and "flexibility" concepts whereas 5.2 discusses the problem of demand side bidding in the day ahead tertiary reserve markets and 5.2 presents a method to enable the participation of residential households' aggregators in the day ahead tertiary reserve markets.

5.1 The Aggregator Resources

5.1.1 The bottom-up approach: from availability to flexibility

The role of demand side aggregators consists in representing a significant number of end-users that, due to their low levels of electricity demand, cannot participate in the electricity and ancillary services markets by their own. In the provision of tertiary reserve, the aggregators should be capable of estimating the flexibility that a group of end-users is willing to provide in each hour of the day. A variety of methodologies to estimate the flexibility in an aggregated scale have been proposed in the literature. For example, Gorria et *al.* [186] presented a mathematical model to forecast the aggregated flexibility of residential consumers under incentive-based contracts. In [187], the potential flexibility of the residential consumption involving typical Italian consumers was assessed and in [188] the flexibility of domestic electric floor heating installations was estimated. The common ground between these methods is that they aim at estimating the flexibility of a group of appliances without information regarding the specific characteristics of each appliance. In fact, these methods assume some generic characteristics of the consumption habits and infer about the behavior of particular appliances and end-users. This top-down approach for the flexibility estimation is reasonable in situations when the information regarding appliances and consumption is not available or a generic characterization of the flexibility profile is enough. Network planning studies or regulatory and policy reports are examples in which a top-down flexibility estimation is acceptable.

However, for the participation of residential end-users in ancillary services markets through an aggregator, these top-down flexibility estimation is not adequate, namely due to two main aspects: first, the aggregator must know who are the end-users that provide flexibility in each moment so that they can be remunerated for this service; second, because flexibility results from the capability of controlling smart appliances. Since this control is performed within the home domain, *i.e.*, at the HEMS level (in order to ensure the end-user privacy and comfort, as described in Chapter 4), then the flexibility should be calculated inside the house and afterwards communicated to the aggregation agent. Thus, taking into account the consumption patterns of the end-user as well as the specific characteristics of the appliances, HEMS should be capable of estimating the availability for the day-ahead by assessing the possibility to increase/decrease the appliances consumption in each period of the day. Afterwards, a 24 hours availability curve is provided to the aggregator so that bids can be prepared to the day ahead reserve markets.

In fact, considering a residential aggregator offering flexibility services in the reserve services markets, the bottom-up approach presented in this thesis (see Chapter 3) is a more adequate alternative to estimate that flexibility. According to the services/resources chain towards ancillary services presented in section 3.2.5, the quantification of the amount of flexibility services in each period involves two stages: (1) the quantification of the availability provided by each HEMS; (2) the quantification of the aggregated flexibility services.

As already mentioned, the quantification of the availability services is performed at the HEMS level according to the preferences of the end-users and with the objective of maximizing their remuneration, since this is a service that the end-users provide to the aggregators. Chapter 4 presented a method where the availability services were quantified in different scenarios comprising diverse characteristics of the electric devices, consumption patterns and the possibility of using appliances controllability for other flexibility services (such as for PV based self-consumption at the house level). However, for example, the availability curves presented in Figure 4-40 cannot be directly offered to the system operator in the form of bilateral contracts neither as bids to tertiary reserve markets. These curves only contain the possible upward and downward consumption modifications strategies of the 24 hours of the day, corresponding to a daily strategy that maximizes the remuneration of the end-user. Convert such curves into market bids is the responsibility of the flexibility aggregators.

5.1.2 Uncertain and sequential characteristic of residential availability

In the previous subsection, the conceptual difference between availability and flexibility under the approach of this thesis was clarified. It was also explained that the role of the aggregators consists in the transformation of availability into flexibility services. However, this transformation is not trivial and two important aspects of the availability should be taken into account: the uncertainty and the sequential characteristic.

Uncertainty aspects of the availability coming from specific appliances are nowadays starting to be discussed. Recently, Mathieu *et al.* [189] addressed some of the factors that influence the uncertainty in the available capacity, such as human behavior and ambient temperature. Unexpected changes in the daily households' consumption behavior (*e.g.*, take a shower half an hour later) may limit the possibilities of appliances control in certain periods and provoke modifications in HEMS availability curve. However, if these small changes in the consumption occur randomly and simultaneously in thousands of households at the same time, the resultant error is mitigated. Such effect can be observed in [190], where the authors used an example of 844 electric vehicles to demonstrate that the error in the availability forecast decrease dramatically with the aggregation size. Hence, in general, from the point of view of an aggregator, sudden changes in the end-users' behavior do not have an impact on the estimation of the total availability in each hour.

In contrast, common source events – such as a variation in the ambient temperature – have an aggravated impact on the flexibility uncertainty after the aggregation. Indeed, when the ambient temperature increases, the effect in the consumption profile of all heating/cooling appliances in the same region is similar, which changes the total availability curve that was estimated the previous day. Although the uncertainty associated with the common source events is not addressed in this thesis, it is important to stress its potential impact on the flexible resources available to the residential aggregators. In this chapter, it is assumed that these aggregators have access to accurate meteorological forecasts for the day ahead in order to compensate this effect.

Besides the uncertainty, residential availability also contains a time-dependent characteristic that can bring more severe problems for the aggregators' bidding activity. This characteristic is associated with comfort required by the end-user as well as with the sequential constraints involved in the domestic appliances operation. For instance, if a washing machine is turned on in a period *t*, it starts running a washing program. Later, in period *t+1* one can assume that this appliance is available to be interrupted, providing an upward availability service to the aggregator. In contrast, if the washing machine does not start in period *t*, the upward availability in the period *t+1* does not exist. In other words, each residential availability curve, such as the one presented in Figure 4-33, results from a specific strategy of the HEMS regarding appliances' consumption scheduling for the 24 hours of the day. If this schedule is modified during the day, it will have an impact on the subsequent consumption and the availability curve may change until the end of the day.

In order to demonstrate the effect of flexibility sequential characteristic, a more detailed example involving the availability profile of an Air Conditioner (AC) device is depicted in Figure 5-2 and in Figure 5-3. Figure 5-2 presents the evolution of the appliance temperature during the day while it is being used to provide availability services according to the profile that was sent to the aggregator in the previous day. The availability curve showed in the figures is a simplified example of those calculated in Chapter 4. During the first part of the day, the AC is being interrupted in order to provide upward reserve services. Afterwards, during the second part of the day, it starts being switched on more often than its normal consumption in order to provide downward flexibility services while the temperature increases. Finally, in the third part of the day the AC starts to be interrupted again for upward availability services.

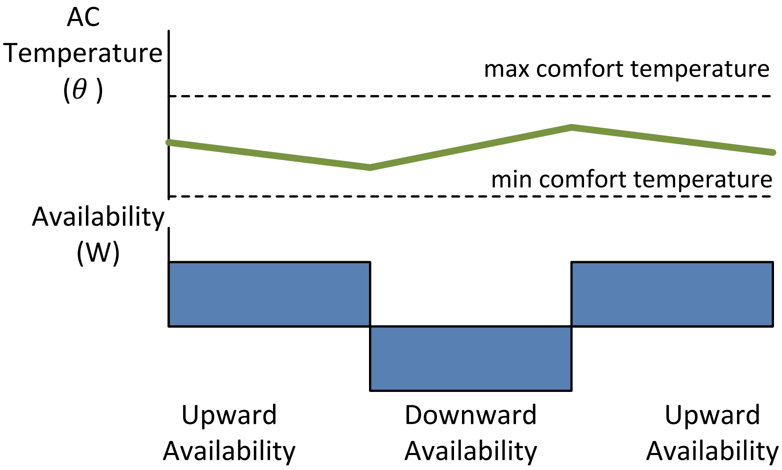


Figure 5-2. AC availability.

A similar situation is illustrated in Figure 5-3. However, in this case it is assumed that the downward availability service offered in the second period of the day is not accepted by the aggregator. Thus, as this decision is communicated to the HEMS, the AC is not switched on and the temperature continues decreasing in the second part of the day. However, this has an impact on the availability in the following periods of the day. For example, if the AC starts to be interrupted in the third part of the day for the provision of upward availability, the minimum temperature comfort of the end-user is violated. The comfort violation indicates that the provision of upward availability in the third part of the day is not possible to occur because the AC must be consuming electricity to keep the comfort levels of the end-user.

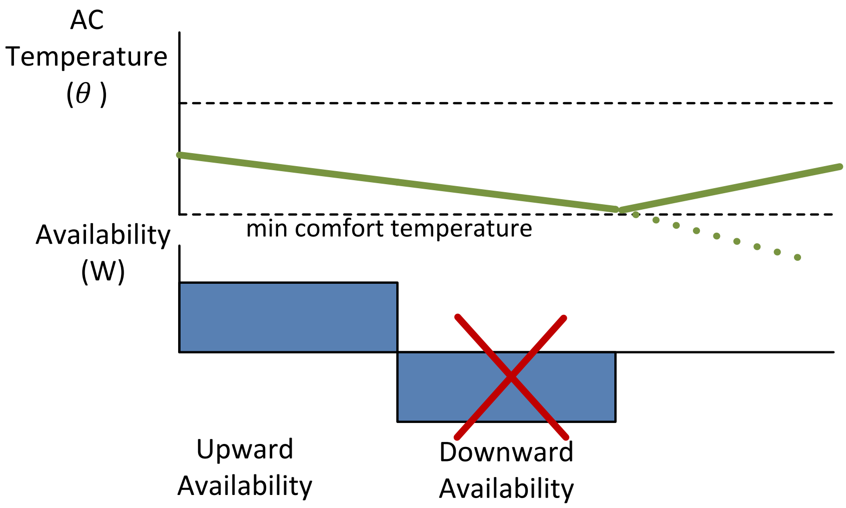


Figure 5-3. AC non-accepted availability: comfort violation.

Thus, a decision of the aggregator in a certain period of the day changes the household availability in the future. This sequential characteristic of demand side availability, namely in residential sector, raises a new challenge for the aggregators' participation in the day ahead ancillary services markets, namely for the provision of tertiary reserve. In fact, the day ahead capacities offered in the tertiary reserve markets are often not dispatched since the system does not need such reserve. Ideally, in these periods, aggregators should be capable to postpone their own available resources and offer them later. However, as demonstrated in Figure 5-3, these flexible capacities are potential changes on the consumption of the end-users that depend on the decisions taken at the HEMS level. They cannot be postponed and, if they are simply not accepted, the subsequent availability is affected, which may cause failures in delivering the total flexibility services that were bid in the previous day.

Furthermore, it is important to stress that the aggregators do not have access to the comfort of the end-users neither to the temperature of the houses. Hence, they cannot predict the effect of a sudden change of the day ahead bidding capacities.

Therefore, the sequential characteristic of the demand side availability increases the complexity of the aggregators' bidding activity. Undoubtedly, the volatility of the flexible resources is one of the most significant barrier for the participation of the demand side in the day ahead ancillary services markets. In fact, such degree of complexity does not exist in the generation side, where the resources can be easily manageable predictable and even stored.

5.2 The day ahead bidding problem

This section aims at describing the bidding problem regarding the participation of demand side aggregators in the day ahead tertiary reserve services markets. The sequential characteristic of the availability resources coming for direct control of appliances within the home domain are incorporated in the problem. As mentioned in the previous section, the uncertainty of the availability are not addressed in the problem formulation. However, the uncertainty regarding the dispatch of the aggregators' bids, *i.e.*, the probability of the bids being accepted in the market, is taken into account.

As mentioned in the beginning of this chapter, it is assumed that the aggregator receives the day ahead availability profiles from the residential households with whom they have such type of availability service contracts. During the last hour of the day, the aggregator should offer flexibility bids to the markets for each hour of the day ahead. These bids can be dispatched or not dispatched in the markets depending on the system needs. Therefore, the participation of residential aggregator in tertiary reserve markets will face two main challenges that are obviously related:

1) **Present independent flexibility market bids from resources that have a sequential characteristic.**
   As discussed above, it is not expected that the aggregators are responsible for the appliances control located at the household level. This responsibility is assigned to the HEMS. Thus, in the situations where the flexibility offered by the aggregator is not dispatched, all HEMS that were committed in the previous day to provide availability services keep their normal daily control strategy, *i.e.*, remain acting in order to keep the availability profile that was previously communicated to the aggregator. Indeed, there is no reason to change the consumption strategy that was established in the previous day, since it ensures the comfort of the end-user and guarantees the availability service that was settled with the aggregator.

   Due to the sequential characteristic, the availability profiles should be seen as conditional proposals for the 24 hours of the day when they are being considered by the aggregator to integrate the final bids. If a HEMS availability is included in a market bid for a certain hour, then it should also be included the bids for the other hours of the day. This means that the availability should be viewed as a "profile" and not as independent hourly service. Hence, the aggregator must choose which HEMS availability curves are accepted to integrate the 24 hours bids for the day ahead.

   This decision is taken during the final hour of day and communicated to the HEMS devices. Two situations can occur: (1) If the HEMS receives the information that its day ahead availability is committed to the flexibility offers of the aggregator, then it starts controlling the domestic appliances in order to achieve the profile that was settled with the aggregator; (2) if the HEMS is notified that its availability profiles is not accepted by the aggregator, then it does not activate any control for availability services and the household consumption is near the baseline.

2) **Deal with the uncertainty of the market and manage the risk**
   The dispatch of the bids placed in the day ahead tertiary reserve market is not fully predictable since it depends on the reserve needs of the system in each hour of the day ahead. In a certain hour, if the reserve bid is dispatched, the generation units currently providing this service receive a remuneration (established by the hourly market auction) according to the flexibility that these units actually delivered to the system. This means that they are paid to generate above or below the energy that was sold in the electricity

market. If the bid is not dispatched in the tertiary reserve markets, the generation units will generate the power output that was settled in the electricity market for that hour.

In case of DR aggregators, the procedure cannot be as simple as in the generation side, due to the reasons mentioned before. In fact, if the bid is not accepted in a certain hour, the HEMS that were committed to provide flexibility will continue behaving in order to accomplish with the consumption profile that ensures the provision of availability during the 24 hours. In such periods when the system does not require any reserve, the upward or downward availability provided by the HEMS is seen as a deviation in the consumption. Usually these deviations entails significant costs to the aggregators in the electricity markets. Figure 5-4 shows an example of the impact of the tertiary reserve market dispatch on the aggregators' services. Basically, the market dispatch determines whether the households' availability is considered a reserve service or a consumption deviation. Hence, the uncertainty regarding the hourly dispatch of tertiary reserve bids should be taken into account in the flexibility services offered by the aggregators and risk of paying significant deviations costs should be quantified.

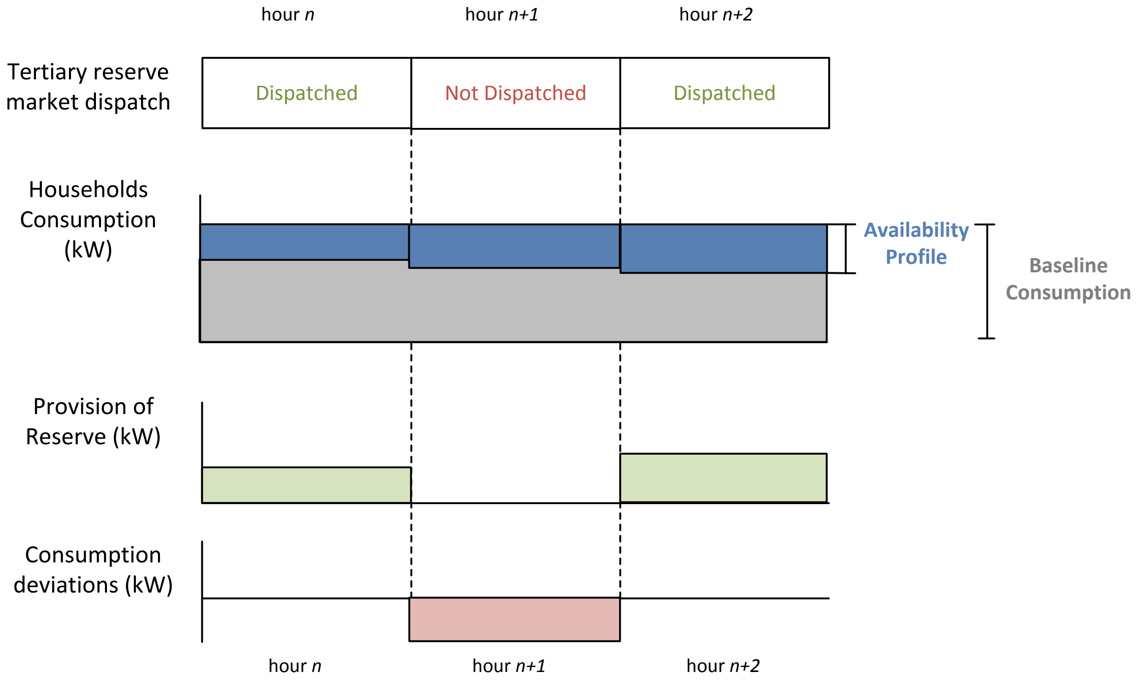


Figure 5-4. Impact of tertiary reserve market dispatch on the aggregators' service.

The aggregators aim at maximizing the remuneration coming from their bidding activity in tertiary reserve markets. However, as shown in the Figure 5-4, the sequential characteristic of the availability may lead to power deviations that entail significant cost for the aggregator. It is important to stress that these deviations and the costs will increase with the number of HEMS committed to provide flexibility services as well as with the number of periods when the reserve is not dispatched. Thus, taking into account the availability profiles provided by their residential end-users (communicated by a group of HEMS), the aggregators have to select the adequate size of their bids for each hour in order to maximize their profit and avoid the risk associated with penalty costs resulting from the consumption deviations in relation to their bids in the electricity market. Figure 5-5 describes the bidding problem. It is assumed that the aggregator has access to the forecasts of hourly reserve prices as well as the penalty costs regarding possible deviation. Furthermore, based on the historical data of the tertiary reserve markets, it can estimate the probability of reserve dispatch (upward and downward) for each hour, as performed in [160]. Considering this information, the aggregator should be capable of selecting the end-users' residential availability profiles that will integrate the final hourly bids.

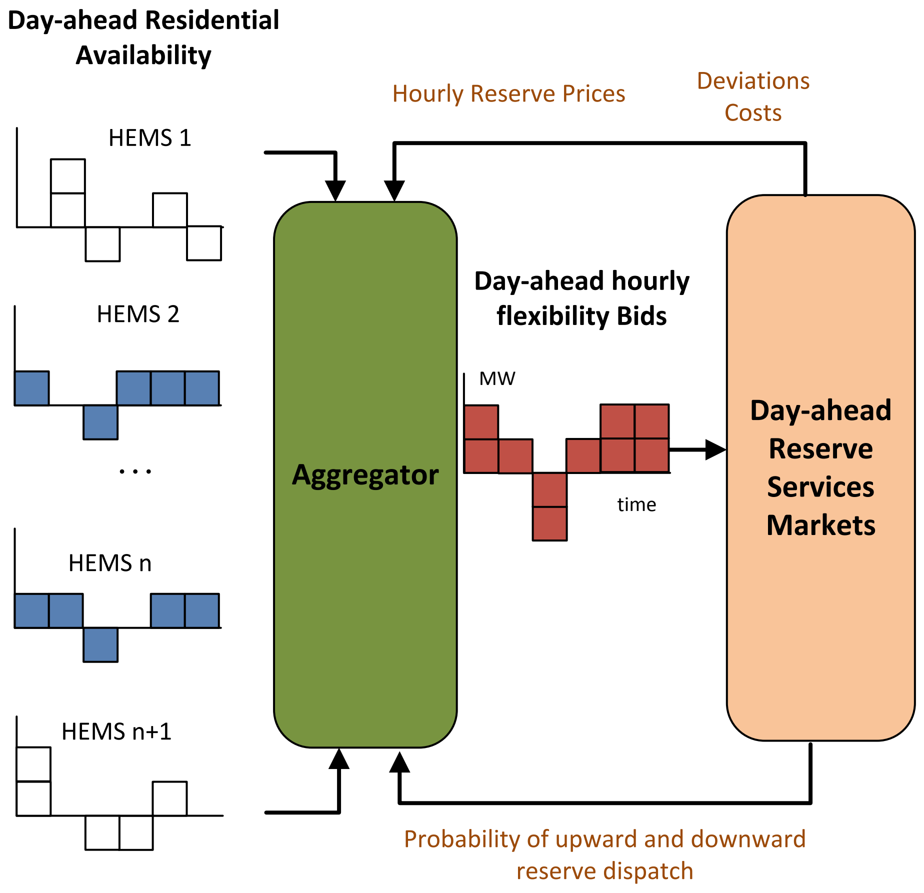


Figure 5-5. Aggregator's bidding problem.

The example of Figure 5-5 shows that the availability profiles coming from HEMS *2* and HEM *n* compose the day-ahead bid. These residential customers will be remunerated by their availability and their HEMS will act in order to comply with the profile that was proposed to the aggregator. In contrast, HEMS *1* and HEMS *n+1* were rejected and they will not participate in the flexibility offers of the aggregator in the day ahead tertiary reserve markets. Hence, they are free to perform their regular consumption without any specific appliances control actions regarding the provision of replacement reserve.

5.3 A methodology for aggregators’ bidding in day ahead tertiary reserve markets

This section presents a methodology to build tertiary reserve bids so that a residential demand side aggregator can participate in the day ahead tertiary reserve services markets. The formulation takes into account the upward and downward flexibilities coming from the HEMS that have a contract with the aggregator for the provision of availability services. Furthermore, the formulation also considers the uncertainty regarding the dispatch of tertiary reserve in each hour of the market.

Thus, as discussed in the previous section, the methodology aims at selecting the best combinations of HEMS availability profiles in order to maximize the aggregator remuneration and reduce the risk coming from the deviation costs that are paid in the electricity market in case of the flexibility bids offered by the aggregator are not dispatched. This methodology is divided in two steps:

- The first step of the method consists in performing an evaluation of each HEMS availability profiles for the day ahead considering the uncertainty associated with tertiary reserve dispatch. The objective is to assess the market value of each end-users’ availability profile in an uncertain dispatch scenarios. The expected value and the value at risk of each availability curve for the day ahead that is sent by the HEMS is calculated.
- The second step aims to maximize the remuneration of the aggregator by selecting the most appropriate combination of availability profiles to integrate the flexibility offers for the day ahead, as discussed in section 5.2. Based on the expected value and the value at risk of each availability profile (calculated in the first step), a heuristic method is proposed in order to find the combined solutions that lead to high expected values and low risk for the aggregator. Thus, a Pareto frontier is built enabling the aggregator to choose – according to its risk acceptance policy – which HEMS availability should be committed for the day ahead flexibility bids.

5.3.1 The value of HEMS availability considering reserve dispatch scenarios

Inputs of the problem

Based on the historical data of the tertiary reserve service markets activity, the aggregator can forecast the probability of reserve to be dispatched (upward and downward) in each hour of the day. As discussed in section 5.2, the inputs for the bidding problem also includes, for each hour of the day ahead, the availability that is communicated by the HEMS, the hourly day-ahead tertiary forecasted reserve prices (upward and downward) and the deviation costs in the wholesale electricity market that are paid in the scenarios where the reserve is not dispatched.

In order to evaluate the HEMS availability profiles, it is possible to build 24 hours dispatch scenarios for the day ahead. In the thesis it is assumed that two situations may occur in each hour: either the HEMS availability is dispatched or it is not dispatched. Hence, the total number of dispatch scenarios considering the 24 hours of the day ahead is 2^{24}=16 777 216. The dispatch scenarios (*S*) can be included in a Boolean matrix (24 x 2^{24}), where S_{ih} indicates the dispatch value (0, 1) in the scenario *i* regarding hour *h*.

Figure 5-6 summarizes the inputs of the aggregator bidding problem.

1 – dispatched in hour h   0 – not dispatched in hour h

2^{24} reserve dispatch scenarios	0	0	0	0	0	...	S_{ih}	...	0
	0	0	0	0	0	...	S_{ih}	...	1
					•••				
	0	1	0	1	0	...	S_{ih}	...	0

Availability of HEMS n	Av_{n1}	Av_{n2}	Av_{n3}	Av_{n4}	Av_{n5}	...	Av_{nh}	...	Av_{n24}
Hourly day-ahead upward reserve market prices	λ_1^{Rup}	λ_2^{Rup}	λ_3^{Rup}	λ_4^{Rup}	λ_5^{Rup}	...	λ_h^{Rup}	...	λ_{24}^{Rup}
Hourly day-ahead downward reserve market prices	λ_1^{Rdw}	λ_2^{Rdw}	λ_3^{Rdw}	λ_4^{Rdw}	λ_5^{Rdw}	...	λ_h^{Rdw}	...	λ_{24}^{Rdw}
Hourly downward deviation costs	ψ_1^{Dup}	ψ_2^{Dup}	ψ_3^{Dup}	ψ_4^{Dup}	ψ_5^{Dup}	...	ψ_h^{Dup}	...	ψ_{24}^{Dup}
Hourly upward deviation costs	ψ_1^{Ddw}	ψ_2^{Ddw}	ψ_3^{Ddw}	ψ_4^{Ddw}	ψ_5^{Ddw}	...	ψ_h^{Ddw}	...	ψ_{24}^{Ddw}
Probability of upward reserve dispatch in each hour	P_1^{Rup}	P_2^{Rup}	P_3^{Rup}	P_4^{Rup}	P_5^{Rup}	...	P_h^{Rup}	...	P_{24}^{Rup}
Probability of downward reserve dispatch in each hour	P_1^{Rdw}	P_2^{Rdw}	P_3^{Rdw}	P_4^{Rdw}	P_5^{Rdw}	...	P_h^{Rdw}	...	P_{24}^{Rdw}

Day ahead hour

Figure 5-6. Inputs of the aggregator bidding problem.

The value of each availability profile considering dispatch scenarios

The market value of the availability profile communicated by the HEMS can be calculated considering the forecasted remuneration for the hourly tertiary reserve as well as the penalty costs due to the non-dispatch events. These prices and costs (upward and downward) are included in the value function according to the dispatch (S_{ih}) and to the algebraic sign of the HEMS availability in each hour. If the availability is positive in the hour *h*, its market value is equal to the remuneration for an upward reserve service (λ_h^{Dup}). In contrast, if the HEMS availability is negative in the hour *h*, the value corresponds to the remuneration for a downward service in the market (λ_h^{Ddw}). Furthermore, when a positive HEMS availability is not dispatched, it provokes a downward deviation cost (ψ_h^{Ddw}), since it encompass a consumption increase. Similarly, when a negative availability is not dispatched, the aggregator must pay the costs associated with an upward deviation (λ_h^{Dup}).

Figure 5-7 presents a flowchart that describes the process of obtaining the aggregator revenue for each availability profile considering the dispatch scenarios for each hour.

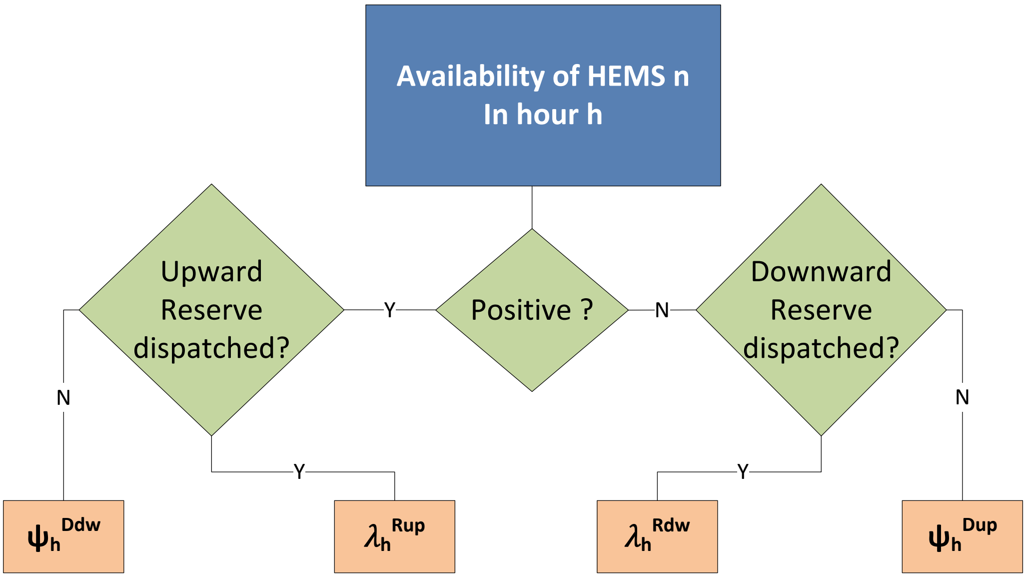


Figure 5-7. Aggregator's remuneration according to the dispatch scenario.

Thus, the value of the aggregator income in the scenario *i* regarding availability profile of the HEMS *n* can be calculated using the equation (5-1). The value depends on the dispatch scenario for the hour *h* (Boolean variable S_{ih}), on the availability of the HEMS (A_{nh}), on the upward and downward reserve remuneration (λ_h^{Rup}, λ_h^{Rdw}) as well as on the deviation costs (ψ_h^{Ddw} and ψ_h^{Dup}).

$$V_{ni} = \sum_{h=1}^{24} S_{ih} \left[\frac{Av_{nh} + \left| Av_{nh} \right|}{2} \lambda_h^{Rup} - \frac{Av_{nh} - \left| Av_{nh} \right|}{2} \lambda_h^{Rdw} \right] - \left(1 - S_{ih}\right) \left[\frac{Av_{nh} + \left| Av_{nh} \right|}{2} \psi_h^{Ddw} - \frac{Av_{nh} - \left| Av_{nh} \right|}{2} \psi_h^{Dup} \right] \tag{5-1}$$

As shown in the equation, when the availability is positive the value is equal to ($A_{nh}x\lambda_h^{Rup}$) if the reserve is dispatched and ($A_{nh}x\ \psi_h^{Ddw}$) if it is not dispatched. Analogously, when the availability is negative, the function value is ($-A_{nh}x\lambda_h^{Rdw}$) in the dispatch events and ($-A_{nh}x\psi_h^{Ddw}$) in the non-dispatch events. The total value for the daily dispatch scenario corresponds to the sum of the hourly remuneration values.

The probability of the scenario *i* regarding availability profile of the HEMS *n* also depends on the algebraic sign of the availability profile as well as on the probability of upward and downward tertiary reserve dispatch (P_h^{Rup} and P_h^{Ddw}, respectively). Equation (5-2) presents the formulation of the probability value for each scenario.

$$Prob_{ni} = \prod_{h=1}^{24} \left(\begin{array}{l} S_{ih} \left[\dfrac{Av_{nh} + \left|Av_{nh}\right|}{2Av_{nh}} P_h^{Rup} + \dfrac{Av_{nh} - \left|Av_{nh}\right|}{2Av_{nh}} P_h^{Rdw} \right] + \\ \left(1 - S_{ih}\right) \left[\begin{array}{l} \dfrac{Av_{nh} + \left|Av_{nh}\right|}{2Av_{nh}} \left(1 - P_h^{Rup}\right) + \\ \dfrac{Av_{nh} - \left|Av_{nh}\right|}{2Av_{nh}} \left(1 - P_h^{Rdw}\right) \end{array} \right] \end{array} \right) \tag{5-2}$$

According this formulation, if the HEMS availability in the hour *h* (A_{nh}) is positive, the probability of upward reserve dispatch (P_h^{Rup}) is considered in this hour. In contrast, if it is negative, the probability of downward reserve (P_h^{Ddw}) is taken into account. The probability of occurring a certain dispatch scenario (for the 24 hours) corresponds to the product of the probabilities for each hour of the day.

Taking into account the market value and the probability for the scenario *i* regarding the HEMS *n*, the expected value in the tertiary reserve market of each availability profile communicated by the end-user *n* can be calculated according to equation (5-3) after running the 2^{24} scenarios, *i.e.*, finding all possible combinations of S_{ih} throughout the day.

$$EV_n = \sum_{i=1}^{2^{24}} \left[V_{ni} \times Prob_{ni} \right] \tag{5-3}$$

The probability and the market value in each scenario can be represented in the form of a discrete probability distribution function, as illustrated in Figure 5-8. This representation gives an important information to the aggregators, since it describes the aggregators' market revenue of bidding a single availability profile (communicated by the HEMS *n*) in the day ahead tertiary reserve market. Besides the expected value, which is given by equation (5-3), the discrete probability distribution also contains the maximum and minimum market values associated with the availability profile as well as some information regarding the risk, such as the value at risk.

The value at risk (VaR), is a typical measurement of the risk losses. It aims at defining a threshold loss value that is associated with a certain probability. Thus, for example, if VaR =*X*, with a probability of 0.05, means that in 5% of the situations the value of the losses is higher than *X*.

Figure 5-8 illustrates the example of the $VaR_{0.05}$ taken from the probability distribution function of the market value of a certain availability profile.

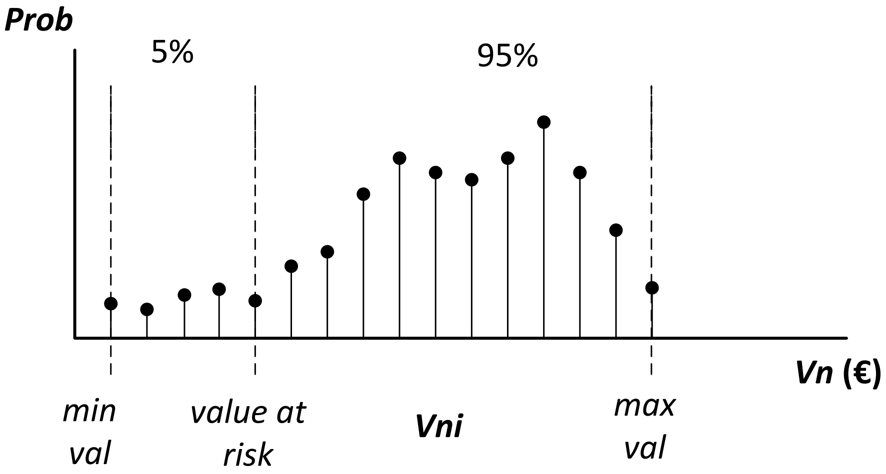
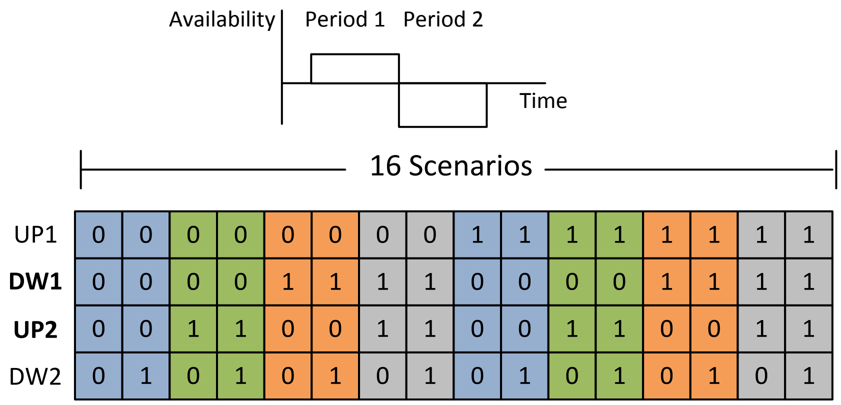


Figure 5-8. Discrete probability distribution of the availability profile value.

Computational aspects of the evaluation approach

As shown in the formulation of the problem above, the scenarios are created taking into account each HEMS availability profile. Thus, for each hour of the day ahead two situations may happen: either the availability is accepted or it is not accepted. This leads to a significant amount of scenarios (2^{24}), but still a reasonable number in computational terms, *i.e.*, the evaluation of each profile can be performed within few seconds in a normal computer.

Looking at the problem from the perspective of the availability profile appears an intuitive approach. Formally, it consists in grouping a vast majority of the scenarios of the original problem, which makes the evaluation feasible by decreasing dramatically the computational burden. As a matter of fact, in each hour of the day ahead market, 4 situations may happen: (1) both upward and downward availability are dispatched; (2) the upward availability is dispatched and downward availability is not; (3) the downward availability is dispatched and the upward availability is not; (4) both are not dispatched. However, considering 2 hours of the day ahead market, the number of dispatch combinations increases to 16. If 3 hours are considered, they number of dispatch combinations is to 64. Thus, the number of scenarios is the real problem is $2^{2xhours}$.



UP1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
DW1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1
UP2	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1
DW2	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

Figure 5-9. Scenarios of the original problem.

Figure 5-9 presents the 16 scenarios associated with 2 hours of the day ahead tertiary reserve market. In each scenario, 1 means that the reserve is dispatched and 0 means that it is not dispatched. The number of scenarios can be reduced to 4 if one considers the availability profile presented in the top of the figure, which comprises a downward capacity in the first hour and an upward capacity in the second hour.

Each scenario evaluated (marked with a color) includes 4 scenarios of the real problem. For example, the blue scenario corresponds to the case where neither the downward availability in the first hour (DW1) nor the upward availability in the second hour (UP2) are dispatched, no matter what happens with the dispatch of the upward reserve in the first hour (UP1) and the downward reserve in the second hour (DW2).

By extending this approach to the other group of scenarios and to the 24 hours of the day, the number of scenarios evaluated decrease from an unfeasible amount of (2^{2x24}=2.81x10^{14}) to a reasonable number (2^{24}=16 777 216) allowing the computation of the availability profiles' market value evaluation.

5.3.2 A heuristic method to build bidding solutions

In a bottom-up approach of aggregation, bids are composed by combinations of the HEMS availability profiles, as discussed in section 5.2. However, the size of the problem increase substantially with the number of end-users associated to an aggregator. For instance, for 10 end-users, 1024 possibilities of combining availability profiles to compose a bid exist. If the aggregator has contracts with 100 customers the number of combinations increase to 1.27x10^{30}. Taking into account that aggregators will represent thousands of residential consumers in the tertiary reserve markets, running such number of combinatorial problem would become impossible due to the computational burden. Therefore, in this subsection a heuristic method aiming at finding a set of non-dominated combinatorial solutions is presented in order to allow the aggregator to choose the adequate bid to be offered in tertiary reserve market. In the heuristic method for selecting the solutions, two parameters are considered: *the expected value of the aggregators' remuneration* and the *Value at Risk (VaR) of the solution*.

This heuristic approach consists in a merit order of the HEMS flexibility based on the expected value (EV). The method consists in 3 steps:

a) HEMS availability profiles are sorted according to their expected value (from the highest to the lower) calculated as shown in equation (5-3);

The first bidding solution corresponds to a selection of a single HEMS profile, *i.e.*, the one with highest expected value. The subsequent solutions are obtained through the combination of the existing solution with the next HEMS availability profile of the merit order. Thus, the second solution corresponds to the combination of the 2 HEMS profiles with higher expected value, the third solution is the combination of three 3 flexibility profiles with higher expected value and so forth. At the end, the number of solutions to be considered is equal to number of HEMS flexibility profiles received by the aggregator. Figure 5-10 illustrates the process of obtaining bidding solutions according to the merit order.

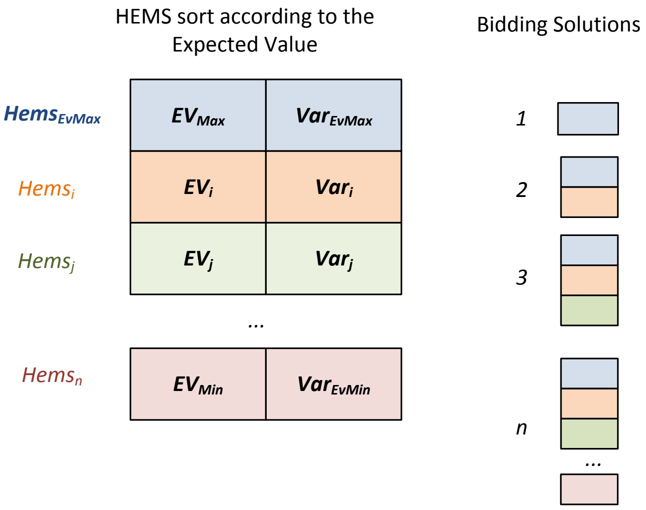


Figure 5-10. Bidding Solutions based on the HEMS merit order.

b) The value at risk and the final expected value of each solution that result from the combination of the HEMS availability profile functions is calculated. The details regarding the combination of the probability distribution functions are described in the following subsection.

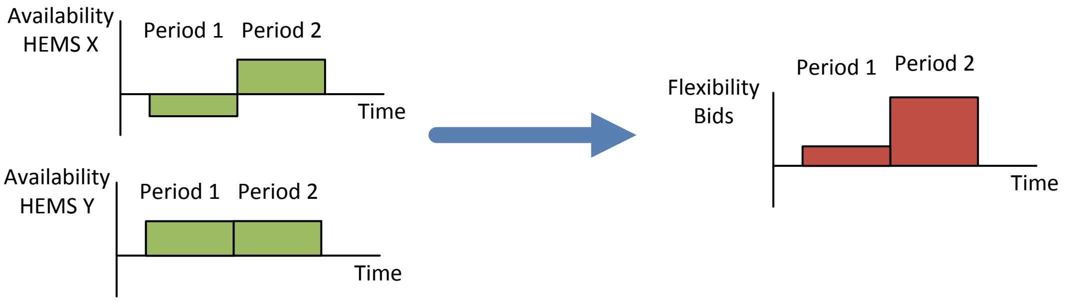
c) The non-dominated solutions considering the higher expected value and the lower value at risk are selected to be presented to the aggregator decision-maker.

5.3.3 Combining availability profiles towards bidding solutions

In the step *(b)*, the bidding solutions are obtained by combining the HEMS availability profiles received by the aggregator. In order to calculate the expected value and the VaR of the bidding aggregator solutions, the probability distribution function that results from each combination must be obtained.

The first aspect regarding the combination of availability profiles is related to the potential design of tertiary reserve markets to accommodate bids from demand side residential aggregators. In this thesis, two possibilities of bidding were identified: a single bid per hour and a double bid per hour. Although only the first possibility is addressed in this document, it is important to emphasize the difference between these two bidding alternatives.

Single Bid



Double Bid

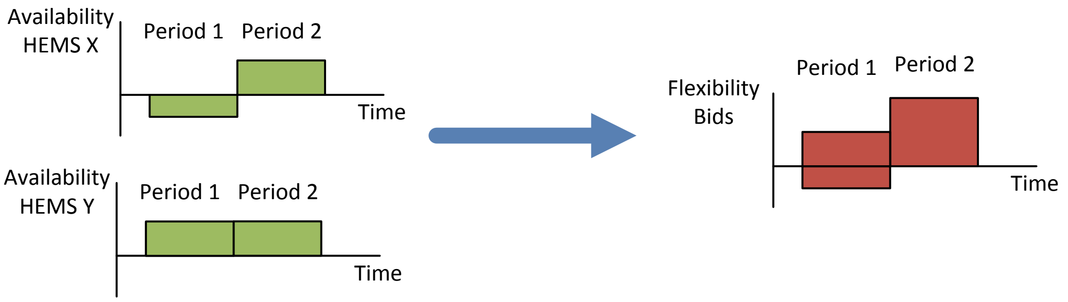


Figure 5-11. Single and Double bidding.

In a single bid market design it is assumed that, for each hour of the day ahead, the aggregator only can place one bid per hour, either upward or downward. In contrast, in a double bid scenario, the aggregator can offer both upward and downward reserve for the same hour of the day ahead. These two possibilities of bidding determine how the availability profiles are combined, as illustrated in the Figure 5-11. In the first case, the flexibility bids result from the sum of the availability profiles while in the second case the positive part of the curve are separated from the negative parts in order to form two bids per hour (upward and downward).

Considering the formulation of the aggregators' bidding problem, presented in section 5.2, where the time-dependent characteristics of the availability profile were considered, it is possible to conclude that in both bidding scenarios the result in terms of consumption deviations is the same. For example, in case of the profiles shown in Figure 5-11, HEMS X and HEMS Y activate the same appliances control strategy if they are committed to participate in the day ahead flexibility bids, no matter which type of bid they are. Hence, the difference relies on how these deviations are remunerated and penalized in the market, which has a significant impact on aggregators' remuneration.

The formulation of the aggregators' bidding problem and the methodology presented throughout this chapter assumes a single bid per hour. Thus, while combining availability profiles according to the merit order defined (expected value), the hourly availability of the HEMS is summed. Thus, assuming that A_{ih} is the availability for the hour *h* of the HEMS profile with the i^{th} higher expected value, *n* the total number of HEMS (and the total number of bidding solutions), the k^{th} flexibility bid for the hour *h* can be calculated by equation (5-4).

$$Flex_{kh} = \sum_{i=1}^{k} A_{ih} \tag{5-4}$$

$$\begin{aligned} V_{ki} = \sum_{h=1}^{24} S_{ih} \left[\frac{Flex_{kh} + \left| Flex_{kh} \right|}{2} \lambda_h^{Rup} - \frac{Flex_{kh} - \left| Flex_{kh} \right|}{2} \lambda_h^{Rdw} \right] - \\ \left(1 - S_{ih}\right) \left[\frac{Flex_{kh} + \left| Flex_{kh} \right|}{2} \psi_h^{Ddw} - \frac{Flex_{kh} - \left| Flex_{kh} \right|}{2} \psi_h^{Dup} \right] \end{aligned} \tag{5-5}$$

$$Prob_{ki} = \prod_{h=1}^{24} \left(\begin{aligned} & S_{ih} \left[\frac{Flex_{kh} + \left| Flex_{kh} \right|}{2Flex_{kh}} P_h^{Rup} + \frac{Flex_{kh} - \left| Flex_{kh} \right|}{2Flex_{kh}} P_h^{Rdw} \right] + \\ & \left(1 - S_{ih}\right) \left[\frac{Flex_{kh} + \left| Flex_{khnh} \right|}{2Flex_{kh}} \left(1 - P_h^{Rup}\right) + \frac{Flex_{kh} - \left| Flex_{kh} \right|}{2Flex_{kh}} \left(1 - P_h^{Rdw}\right) \right] \end{aligned} \right) \tag{5-6}$$

Afterwards, the value and the probability of each flexibility bid can be evaluated by a process similar to the one used in the availability profiles. Equations (5-5) and (5-7) result from the application of (5-1) and (5-2) to the flexibility profile. It is important to stress that this application is only possible since they are single bids. In fact, if double bids were considered the number of scenarios evaluated should be extended and the grouping technique already described would not be applicable.

5.4 Case Study

The previous sections discussed the bidding problem of the potential demand side aggregators participating in the provision of tertiary reserve services. The problem consisted in the transformation of the availability profiles (with a time-dependent characteristic) received by a group of HEMS into flexibility bids to be offered in the markets. A methodology enabling aggregators to select the best group of availability profiles to include in their bids was proposed.

5.4.1 Case Study description and assumptions

In this section, the proposed methodology is applied for illustrative purposes to a realistic case study. It is assumed that demand side aggregators are allowed to participate in the Portuguese day ahead tertiary reserve markets. An example of an aggregator with a portfolio of 1500 availability profiles is considered to illustrate the use of the bidding methodology in a realistic tertiary reserve market environment.

In order to simplify the analysis, the aggregator's portfolio assumed in this case study corresponds to the 1500 availability profiles that were calculated in Chapter 4. In that chapter three scenarios were evaluated: availability scenario, self-consumption scenario and a multi-service scenario. Only two of these scenarios (availability and multi-service) comprise the provision of availability services to an aggregator. Figure 4-40 presents their aggregated availability profiles for the 24 hours of the day that will be used in this section as an input of the aggregator's bidding method.

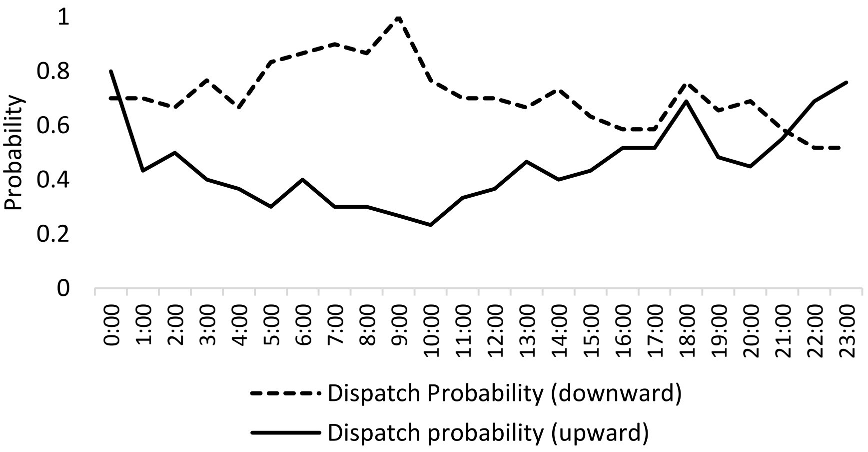


Figure 5-12. Probability of tertiary reserve dispatch in Portuguese market (Nov. 2013).

Similarly to the Chapter 4, the upward and downward market prices for the tertiary reserve were assumed to be equal to the result of the Portuguese reserve market in November 2013 [185], already presented in Figure 4-31. Furthermore, the dispatch of tertiary reserve that result from the activity of the market in this month was also considered in this case study. The probability of tertiary reserve dispatch (upward and downward) was calculated for each hour of the day. The results are depicted in the Figure 5-12. The deviation costs (upward and downward) that should be paid by the aggregator in case of a non-dispatch event were assumed to be 60€/MWh, *i.e.*, a value near the average wholesale electricity price.

The market prices and dispatch probabilities assumed in this section correspond to the real results of the Portuguese market. However, they may not be representative of the average market activity. Besides, nowadays residential demand side aggregators are not able to participate in these markets, neither to establish contracts with the end-users for the provision of availability services. No legislation exists regarding the price that should paid to the end-users by the aggregators for the provision of availability services. Hence, in this case study, the remuneration of the end-users was neglected in the aggregators bidding problem. It is important to stress that a discussion regarding the economic viability of residential flexibility aggregators, the prices and deviations costs that enable their participation in the market and remunerate the end-users will take place in Chapter 6. This section aims at illustrating the methodology taking into account the data that was collected within the current regulatory framework.

5.4.2 HEMS availability market value

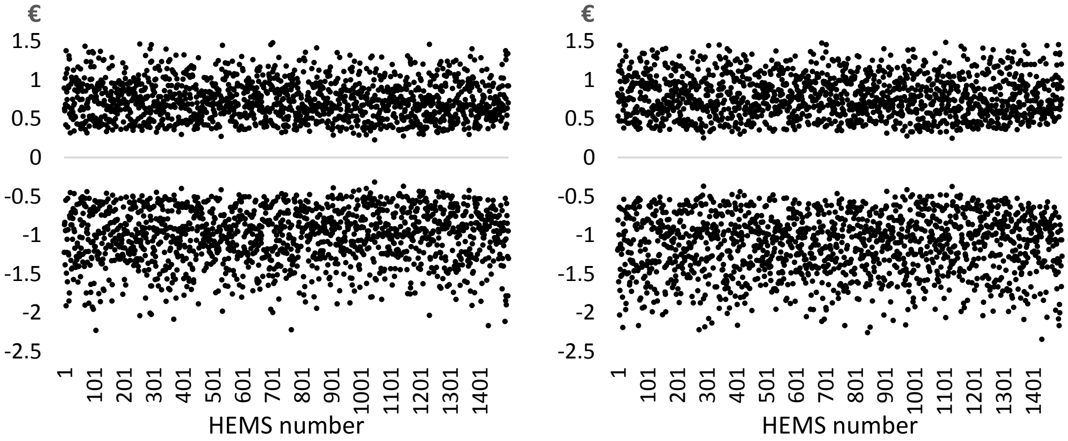
In this section the market values of the 1500 availability profiles that were presented in Chapter 4 are calculated through the application of the methodology presented in subsection 5.3.1, that takes into account the uncertainty of the tertiary reserve dispatch in the market. Two strategies of HEMS were considered: the availability strategy and the multi-service strategy. Additionally, two scenarios were considered regarding the penalization paid by the aggregator for the deviations in case of non-dispatch flexibility: a cost equal to the average wholesale electricity market (60€/MWh) and a cost equal to the tertiary reserve prices (see Figure 4-31).

Deviation costs equal to the wholesale electricity price

Figure 5-13 presents the market price of the 1500 availability and multi-service HEMS profiles that were received by the aggregator. In this case, the deviation cost was assumed to be equal to the electricity market price. The top charts of the figure present the extreme values of each HEMS availability services in the two strategies explored (availability and multi-service). These values correspond to the maximum and minimum potential remuneration of the aggregator if each availability profile was offered separately in the market. The minimum values comprise the extreme scenarios where all the availability that is offered by an individual HEMS is not dispatched and, on the contrary, the maximum values comprise the scenarios where the entire availability profile is dispatched.

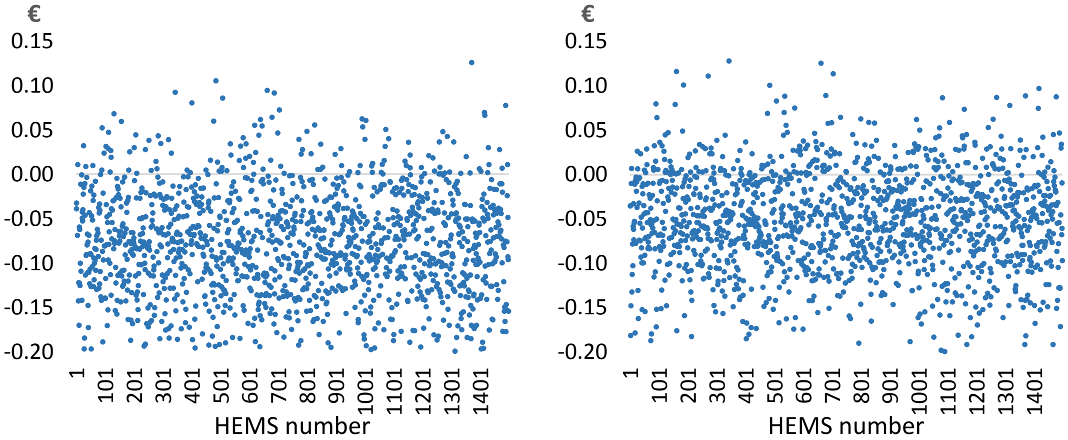
As shown in the figure, the maximum values are positive and the minimum values are negative in both cases, which means that all the HEMS profiles may lead to gains and losses of the aggregator with a certain probability.

Although the extreme values are similar in both strategies, the expected value of the HEMS availability profiles – shown in the bottom of the figure – are a little higher in the multi-service strategy. However, in both cases the majority of the expected values are negative, which means that aggregator tends to lose money if it includes these availability profiles in its flexibility offers for the day ahead tertiary reserve markets.



Maximum and Minimum Values
Availability strategy

Maximum and Minimum Values
Multi-service strategy



Expected Value
Availability strategy

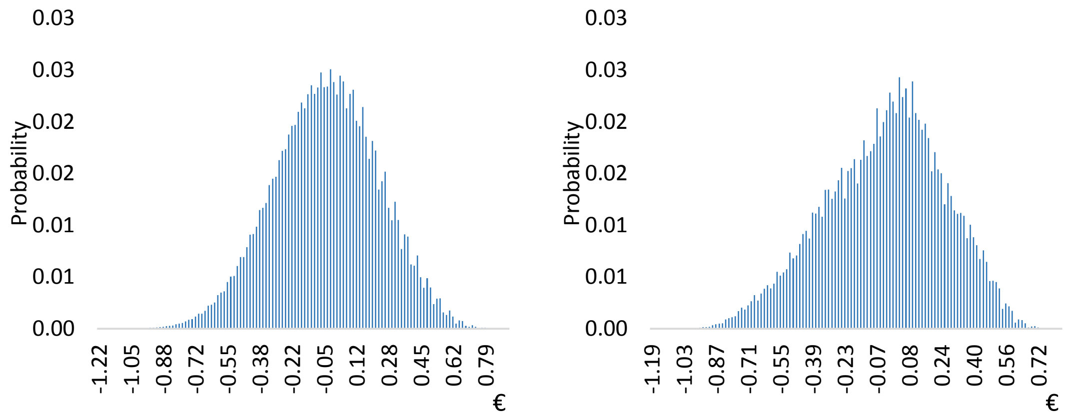
Expected Value
Multi-service strategy

Figure 5-13. Extreme and expected market: 1500 HEMS (deviation costs=electricity price).

The analysis of the expected values allows aggregator to identify those HEMS that can be potentially included in the flexibility bids. As shown in the Figure 5-13, the multi-service strategy comprises more positive values than the availability strategy. This can be explained by the quantity of downward availability service that is delivered in the multi-service strategy. In fact, as analyzed in Chapter 4, although the delivery of upward availability service is similar in these two strategies, the multi-service HEMS tends to increase the consumption during the daylight hours, hence providing higher downward availability services. Precisely, it is possible to observe in Figure 5-12 that the probability of the dispatch of the downward tertiary reserve is significantly higher than the dispatch of the upward reserve during almost every hour of the day.

A more detailed information about the market value of each specific HEMS availability profile can be obtained by observing the probability distribution function that is calculated during the evaluation of the dispatch scenarios.

Figure **5-14** presents the discrete probability distribution functions – plotted with 128 discretization points – regarding the availability market value of a single HEMS. This HEMS is the one already analyzed in the section 4.4.3. The shape of the probability distribution functions in the two strategies (availability and multi-service) are compared in the bottom of the figure.



Probability distribution function
Availability strategy

Probability distribution function
Multi-service strategy

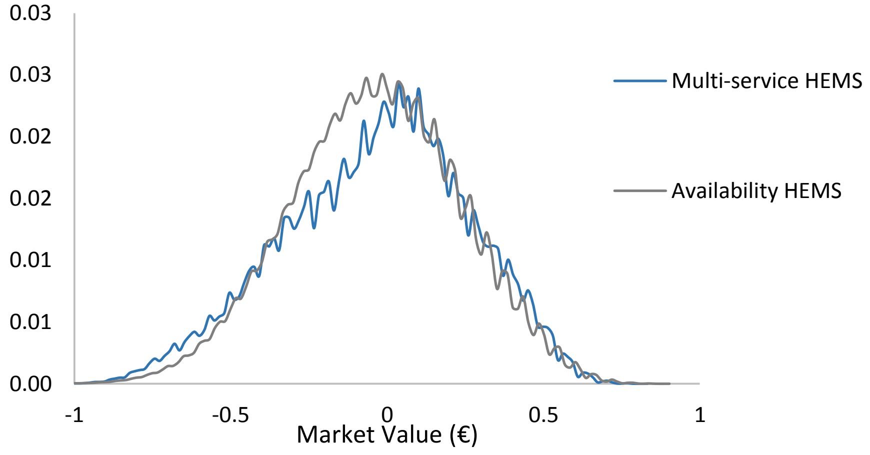


Figure 5-14. Probability distribution curves (deviation costs=electricity prices)

The results in the figure confirm that the availability profile of the multi-service HEMS lead to higher expected value in comparison with a single availability service HEMS. On the other hand, in the left-hand side of the probability distribution function it is possible to observe that the tail of the multi-service HEMS curve comprises larger probability values. This means that the value at risk ($VaR_{0.05}$) is also higher when compared to the single availability HEMS. In fact, as discussed in section 4.4.3, the multi-service HEMS provides higher downward flexibility service. This conducts to a higher remuneration in case of downward availability dispatch but also leads to higher losses in case of non-dispatch events.

	Expected value [€]	**$VaR_{0.05}$ [€]**	**Minimum value [€]**	**Maximum value [€]**
Availability strategy	-0.0383	0.5007	-1.2191	0.9025
Multi-service strategy	-0.0356	0.5683	-1.1891	0.8325

Table 5-1. Market value of a single HEMS (deviation costs=electricity price)

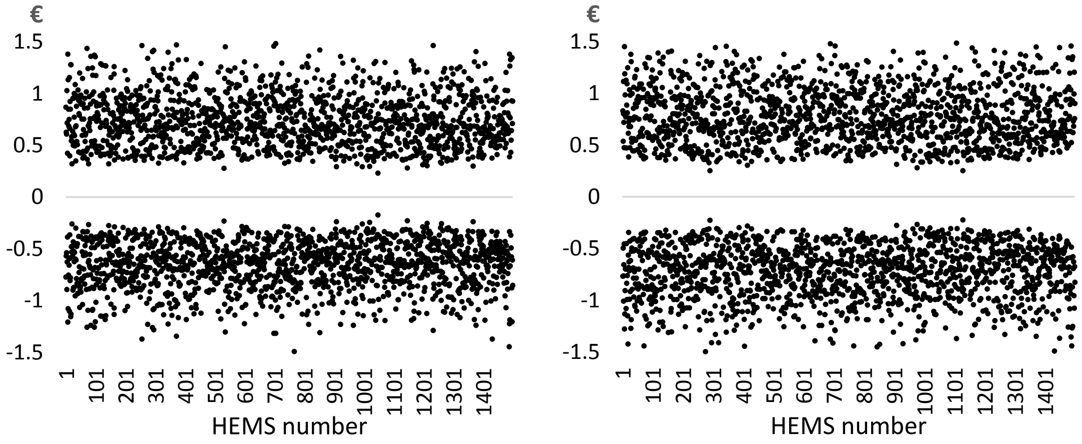
Table 5-1 presents the expected value and the value at risk in availability and multi-service situations as well as the maximum and minimum market value of this HEMS. Although the expected value of the multi-service strategy is higher, both situations lead to a mean negative remunerations in the market. The risk is higher in the multi-service strategy but the minimum and maximum remunerations occur in the availability strategy, -1.22€ and 0.90€ respectively. This means that by offering these availability profiles in the tertiary reserve market, the aggregator remuneration is 0.90€/day (approximately 228€/year) if the entire availability profile (Figure 4-33) is dispatched. In contrast it loses on average 0.04€/day (approximately 13€/year) and 1.22€/day (445€/year) if all the availability profile is never dispatched.

The same calculations can be done for all the 1500 end-users that have an availability contract with the aggregator. A variety of situations exist, as illustrated in the Figure 5-13. Some of the availability profiles may lead to average losses of 0.20€/day (73€/year) and others to an average income around 0.13€/day (48€/year). This average remuneration in the market depends on the amount of upward and downward availability that is offered for each hour of the day ahead, which is related with the characteristics of the controllable appliances and the comfort relaxation as discussed in Chapter 4. Obviously, a part of the aggregator income should be used to pay to the end-users in order to incentivize the provision of availability services. A discussion on the elasticity of the supply of these services will be held in Chapter 6. At this stage, it is important to keep in mind that a variety of availability profiles conducts to a variety of remunerations depending on the reserve prices, the dispatch and the penalty costs that are paid for the deviations.

Deviation costs equal to the reserve prices

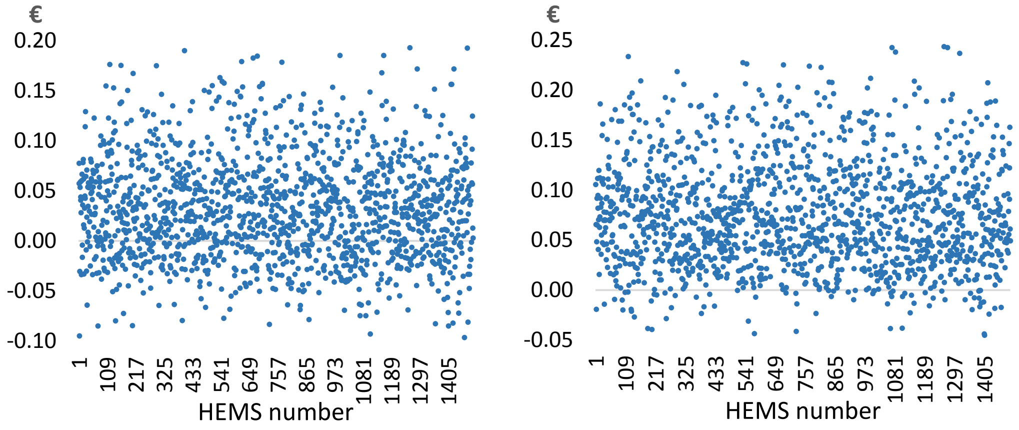
In order to understand the impact of the deviation costs in the market value of the HEMS availability profile a scenario where the deviation costs are equal to the reserve prices will be explored. As shown in the Figure 4-31, the tertiary reserve prices in Portuguese market (November 2013) were between 30€/MWh and 60€/MWh, *i.e.*, lower than the average wholesale electricity price. In this case study, the upward deviation costs were assumed to be equal to the downward reserve prices and vice-versa.

Figure 5-15 presents the extreme and expected market values of the 1500 HEMS both in the availability and multi-service strategy, taking into account the new deviation costs. It is possible to observe that the maximum values are similar to the previous case. Indeed, the reserve prices remain the same, which means that the remuneration that is received in case of the dispatch of the full availability profiles does not change. In contrast, although the minimum value are still negative, they are significantly larger in comparison with previous case study. The expected value also increased in both strategies. Now the majority of market values of the 1500 profiles are positive, which means that the aggregator can include a larger quantity of HEMS availability profiles in its flexibility bids. Finally, the expected value of the multi-service HEMS continue to be larger than the single availability service ones. In fact, the probability of dispatch of the downward reserve remain higher than the upward reserve.



Maximum and Minimum Values
Availability strategy

Maximum and Minimum Values
Multi-service strategy

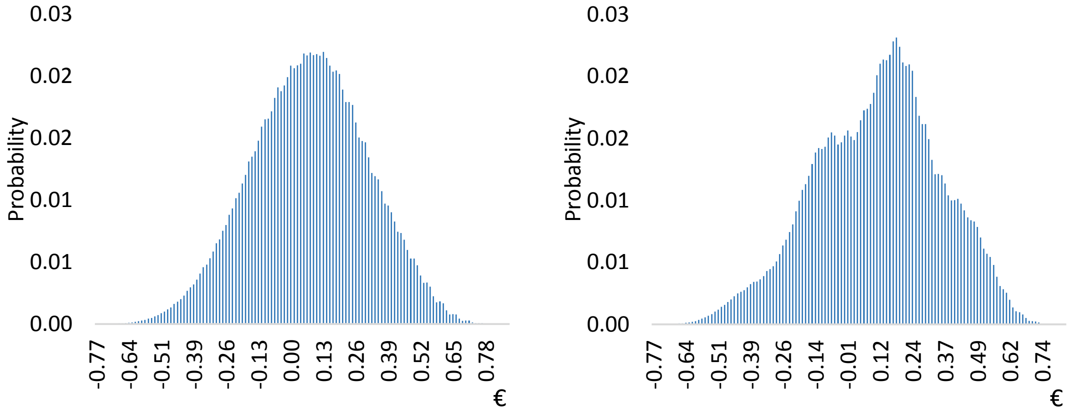


Expected Value
Availability strategy

Expected Value
Multi-service strategy

Figure 5-15. Extreme and expected market: 1500 HEMS (deviation costs=reserve prices)

The discrete probability distribution functions (plotted with 128 points) regarding the market value of the single HEMS that was previously analyzed are depicted in the Figure 5-16. The minimum value increased in both strategies and the HEMS has now a higher probability of generating a positive income to the aggregator.



Probability distribution function
Availability strategy

Probability distribution function
Multi-service strategy

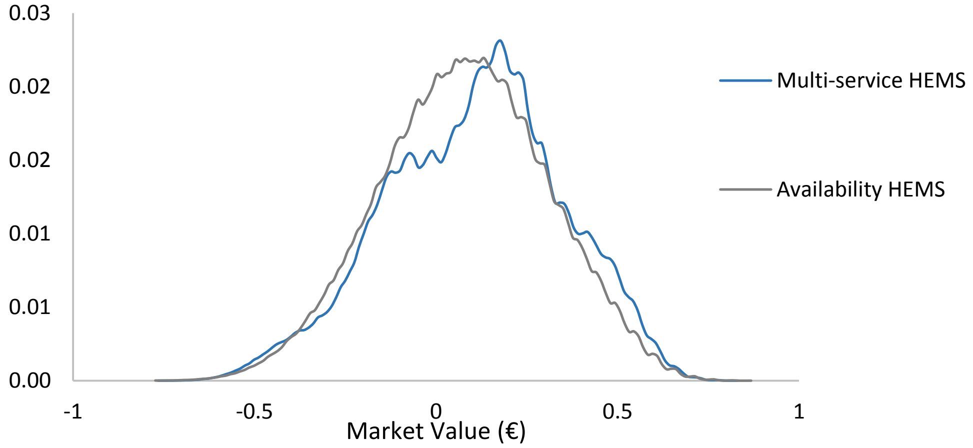


Figure 5-16. Probability distribution curves (deviation costs=reserve prices)

	Expected value [€]	$\mathrm{VaR}_{0.05}$ [€]	Minimum value [€]	Maximum value [€]
Availability strategy	0.0773	0.3209	-0.7733	0.9025
Multi-service strategy	0.1055	0.3255	-0.7660	0.8325

Table 5-2. Market value of a single HEMS (deviation costs=reserve price)

Table 5-2 presents the expected value, the $VaR_{0.05}$ and the extreme values of the distribution functions. The expected value is now positive in the two strategies due to the decrease of the deviation costs. In fact, considering these costs equal to the tertiary reserve prices, the aggregator can receive an average remuneration of 0.08€/day (29€/year) in case of a single availability HEMS and 0.10€/day (35€/year) in case of a multi-service HEMS. However, the $VaR_{0.05}$ in both cases is 0.32€/day, which means that in 0.05% of the cases the availability profile of this end-user leads to losses higher than this value.

The analysis of the availability market value showed that the potential remuneration achieved by the aggregator with each HEMS strongly depends on the market conditions. The impact of the dispatch probability on the availability market value was demonstrated through the difference between values observed in the single availability strategy and in the multi-service strategy. On the other hand, a small change in the deviation costs (or in the reserve remuneration) may increase or decrease substantially the number of availability profiles that become economically viable to be included in the aggregator flexibility bids for the day ahead. However, due to the diversity of consumption patterns and availability profiles, even in situations of high deviations costs is still possible to find some economic viable profiles that lead to positive average remuneration. Analogously, even under favorable price conditions, some HEMS are not able to participate in the aggregator flexibility bids.

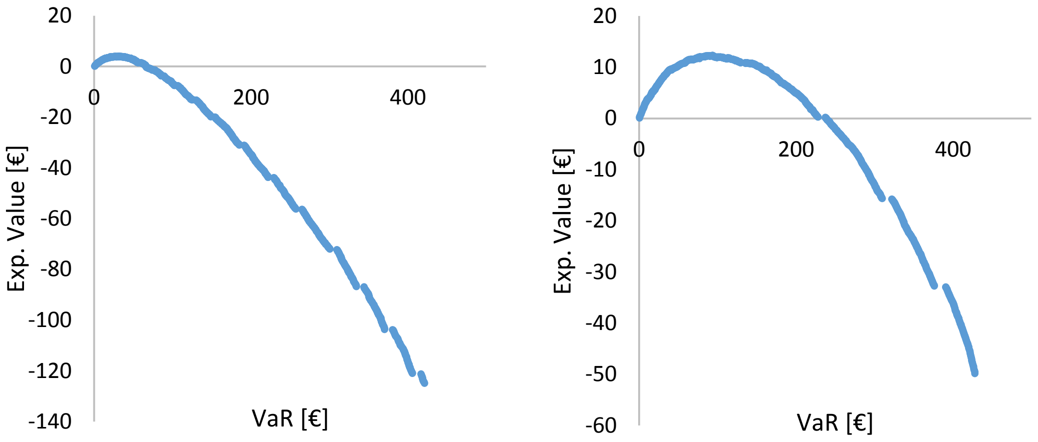
5.4.3 Bidding solutions

The hourly flexibility bids presented by a residential aggregator in the day ahead tertiary reserve market take into account the availability profiles that are communicated by a group of HEMS in the previous day. In this subsection the 1500 availability profiles that corresponds to the daily upward and downward deviations of the end-users consumption are organized to compose the aggregator day ahead bids in the market. The potential market value of each availability profile was previously evaluated, considering two different scenarios of deviation costs that are paid by the aggregator in case of non-dispatched reserve.

The method presented in section 5.3 is used to select the most appropriate combination of end-users availability curves to be included in the aggregator flexibility bids, based on the expected value as well as the value at risk of each profile. The probability distribution functions associated with each HEMS are combined in a descendent order of the expected and 1500 solutions are obtained. Afterwards, the non-dominated day ahead bidding solutions are selected and presented to the aggregator so that it can choose the one that fulfils its remuneration and risk expectations.

Deviation costs equal to the wholesale electricity price

Figure 5-17 presents the expected value and the $VaR_{0.05}$ of the 1500 bidding solutions obtained for the availability and multi-service HEMS, assuming that the deviation costs are equal to the electricity price. Thus, the distribution probability functions, whose extreme and expected values are presented in the Figure 5-13, were combined in order to build the bidding solutions.



1500 bidding solution
Availability strategy

1500 bidding solutions
Multi-service strategy

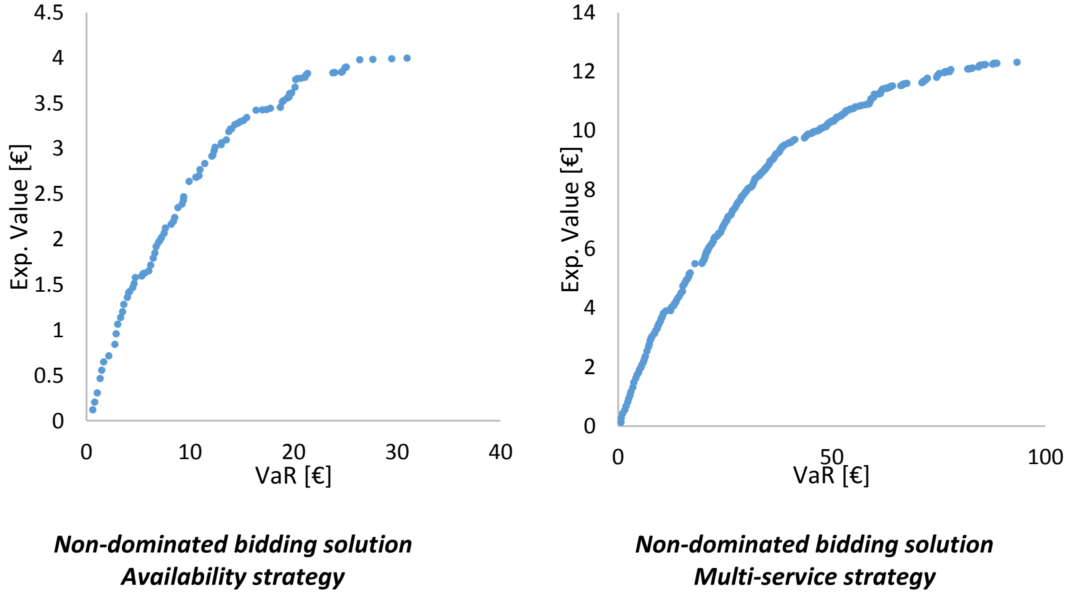
Figure 5-17. Bidding Solutions (deviation costs=electricity prices)

In both cases (availability and multi-service HEMS) the majority of bidding solutions obtained have a negative expected value and a significant risk. In the initial phase of the method, where the availability profiles with higher expected value were combined, the solutions obtained result in a positive expected remuneration and a relatively low risk. However, as the number of HEMS participating in the solution increases, the availability profiles with negative expected value start to be included in the bids and the overall economic viability of the solutions decreases dramatically. However, due to the reasons mentioned before, a higher remuneration is observed in the multi-service HEMS.

Thus, the non-dominated solutions occurred in the beginning of the combination process and incorporated a small number of HEMS availability profiles. In the single availability strategy, 88 non-dominated solutions were found and they include 1 up to 156 availability profiles, *i.e.*, around 10% of the aggregator portfolio in the best case. The solution that includes 156 HEMS profile lead to an expected income of 4€/day (1.460€/year) and a value at risk of 30€/day. However, a solution comprising 34 HEMS leads to an expected income of 2€/day and a value at risk significantly lower (7€/day). Thus, by reducing the expected values to half, the solution risk decreases considerably.

In the multi-service strategy 269 non-dominated solutions were found, including from 1 up to 381 availability profiles. The maximum possible expected remuneration is 12.3 €/day. However, for the value at risk in that case is 93.35€/day, which indicates that in 5% of the times the aggregator will have losses higher than this value.

Figure 5-18 present the Pareto frontier of the bidding solutions for availability and multi-service strategies.

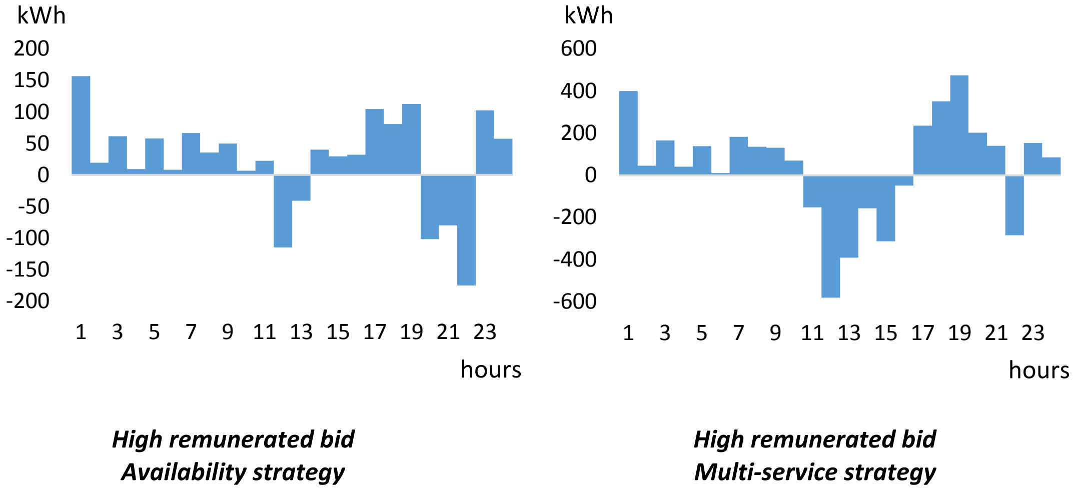


Non-dominated bidding solution Availability strategy

Non-dominated bidding solution Multi-service strategy

Figure 5-18. Non-dominated bidding Solutions (deviation costs=electricity prices)

In fact, the significant costs that are associated with the deviations (60€/MWh) limits the number of solutions and the magnitude of the profitable aggregators' flexibility offers. Figure 5-19 presents the flexibility bids that correspond to the integration of a highest number of HEMS availability profiles in both strategies, *i.e.*, 156 availability HEMS and 381 multi-service HEMS.



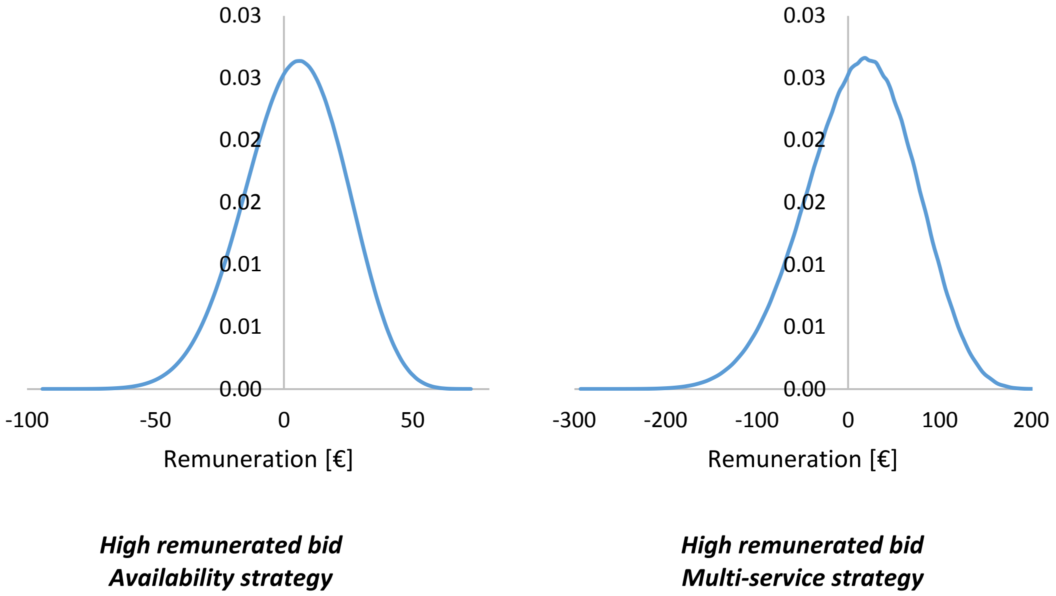
High remunerated bid Availability strategy

High remunerated bid Multi-service strategy

Figure 5-19. High remunerated bids (deviation costs=electricity prices)

Figure 5-19 shows that the aggregator can offer higher flexibility capacities in the multi-service strategy in comparison with the availability strategy. As expected, the downward flexibility is higher in the HEMS multi-service strategy which allows a higher expected remuneration of the aggregator due to the probability of downward reserve dispatch. The maximum flexibility bid in the availability case is around 150kWh while in the multi-service strategies it is near 600kWh.

Figure 5-20 presents the probability distribution function of the remuneration that an aggregator can obtain in the market by offering the bids presented above. Table 5-3 summarizes the maximum and minimum remuneration as well as the expected value and the $VaR_{0.05}$ of the maximum remunerated bids in both strategies.



High remunerated bid
Availability strategy

High remunerated bid
Multi-service strategy

Figure 5-20. Probability distribution function of the bids remuneration (deviation costs=electricity prices)

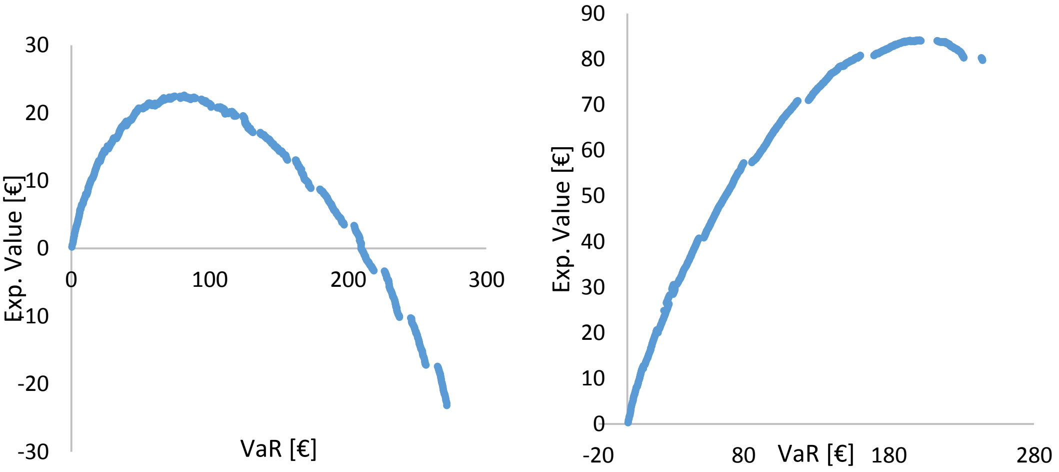
	Availability	Multi-service
Min Remuneration (€/day)	-93.99	-293.12
Max Remuneration (€/day)	72.77	214.30
$VaR_{0.05}$ (€/day)	30.97	93.35
EV (€/day)	4.00	12.32
% of the HEMS committed	10.4	25.4
EV/ HEMS committed (€/day)	0.026	0.032

Table 5-3. Bids summary (deviation costs=electricity price)

As shown in the table, only 10% of the availability HEMS and 25% of the multi-service HEMS can participate in the provision of the tertiary reserve, taking into account the market conditions assumed in this case study. The average contribution of each of these HEMS to the final expected value of the aggregator is 0.026€/HEMS and 0.032€/HEMS per day, respectively.

Deviation costs equal to the reserve prices

Figure 5-21 presents the expected value and the $VaR_{0.05}$ of the 1500 bidding solutions obtained for the availability and multi-service HEMS, assuming that the deviation costs are equal to the reserve prices. This means a decrease in the deviation costs and a more favorable market conditions in comparison with the previous case study. In fact, as presented in the Figure 5-15, within this new conditions of the market the majority of availability profiles lead to a positive expected. Thus, when the HEMS profiles with higher expected values start to be convolved the overall expected value of the bidding solutions obtained increases for during a large number of iterations. Afterwards, when the availability profiles with negative expected value are integrated in the solution, a decreasing in the overall value is observed. In the availability strategy, this effect leads to negative expected value in the final solutions that are obtained. In contrast, in the multi-service strategy, such effect is visible but it does not provoke a significant decrease, since the number of HEMS profiles with negative expected value is lower.



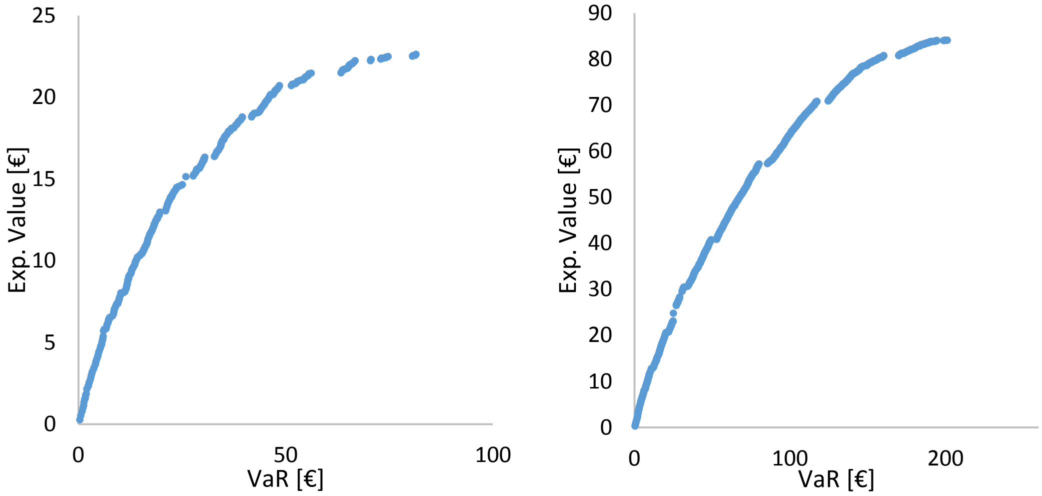
1500 bidding solution
Availability strategy

1500 bidding solutions
Multi-service strategy

Figure 5-21. Bidding Solutions (deviation costs=reserve prices)

Thus, a large number of non-dominated solutions were identified. In the single availability strategy, 318 non-dominated solutions were found and they include 1 up to 548 availability profiles, *i.e.*, more than one third of the aggregator portfolio in the best case. The solution that includes 548 HEMS profile lead to an expected income of 22.66€/day (8.271€/year) and a value at risk of 81.48€/day. However, a solution comprising 100 HEMS leads to an expected income of 10.32€/day and a value at risk significantly lower (14.72€/day). Thus, halving the expected value leads to solutions with a considerable lower risk.

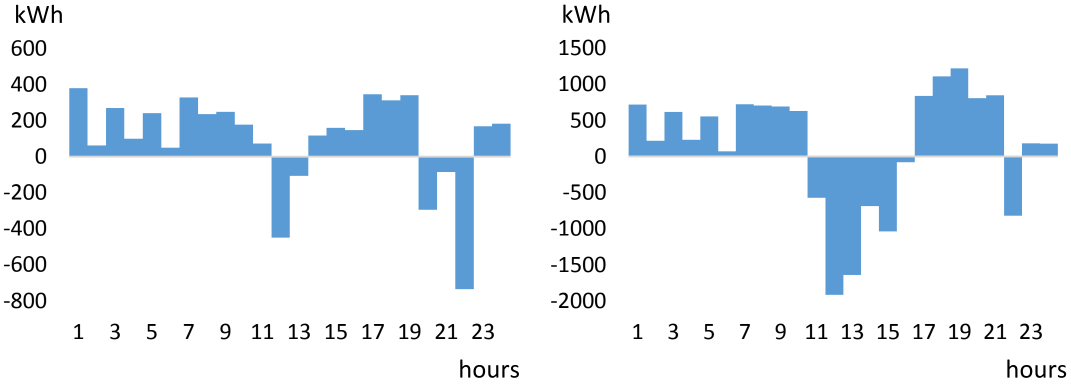
In the multi-service strategy 1049 non-dominated solution were found, including 1 up to 1315 availability profiles. In fact, almost all the solutions originated by combinations of non-negative availability profiles are non-dominated. The maximum possible expected remuneration is 84.16 €/day. However, for the value at risk in that case is 201.10€/day, which indicates that in 5% of the times the aggregator will have losses higher than this value. Figure 5-22 presents the Pareto frontier of the bidding solutions for availability and multi-service strategies.



Non-dominated bidding solution
Availability strategy

Non-dominated bidding solution
Multi-service strategy

Figure 5-22. Non-dominated bidding Solutions (deviation costs=reserve prices)



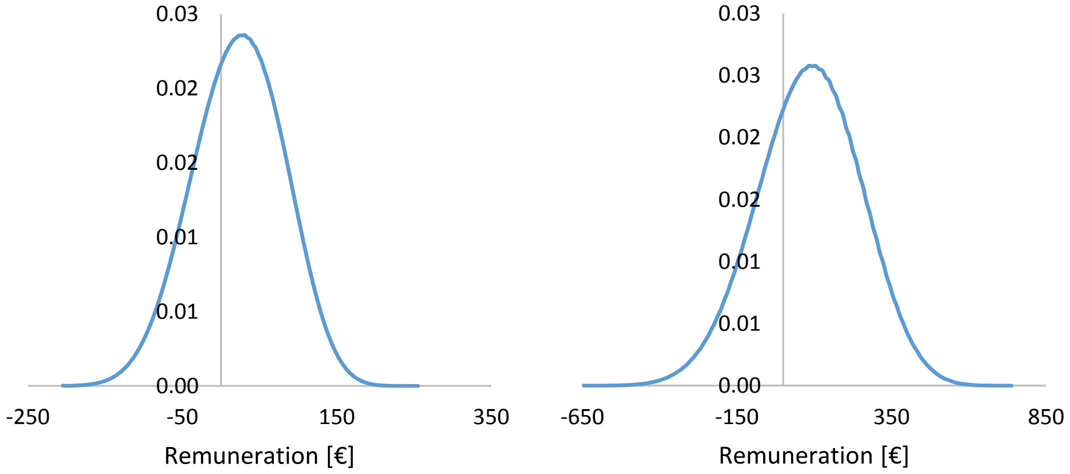
High remunerated bid
Availability strategy

High remunerated bid
Multi-service strategy

Figure 5-23. High remunerated bids (deviation costs=reserve prices)

Figure 5-23 presents high remunerated flexibility bids in availability and multi-service strategy. In both cases, the amount flexibility service that is delivered by the aggregator is significantly higher than in the previous case study, where the deviation costs were equal to the electricity prices. In the availability strategy the maximum upward and downward flexibility offered is 380 kWh and 734 kWh, respectively while in the multi-service strategy, the maximum upward reserve bid is 1.21 MWh and the maximum downward flexibility is 1.92 MWh. In fact, due to the higher dispatch probability of the downward reserve, the aggregator bidding solutions tend to commit the HEMS profiles with a predominant presence of downward availability services.

Figure 5-24 presents the probability distribution function of the remuneration that an aggregator can obtain in the market by offering the bids presented above. Table 5-4 summarizes the maximum and minimum remuneration as well as the expected value and the $VaR_{0.05}$ of the maximum remunerated bids in both strategies.



High remunerated bid
Availability strategy

High remunerated bid
Multi-service strategy

Figure 5-24. Probability distribution function of the bids remuneration (deviation costs=reserve prices)

The results presented in the table demonstrate that the number of HEMS committed to participate in the aggregator flexibility bids increased in relation to the previous case study. In fact, since the conditions of the market are more favorable bids including a larger number of HEMS started to be economically viable. However, it is important to stress that the risk also increases with the size of the bids. Thus, the Pareto frontier presented in the Figure 5-22 is an important instrument to assist aggregators' in their decision making processes.

	Availability	Multi-service
Min Remuneration (€/day)	-204.62	-649.36
Max Remuneration (€/day)	255.33	739.30
$VaR_{0.05}$ (€/day)	81.48	201.05
EV (€/day)	22.67	84.17
% of the HEMS committed	36.53	87.67
EV/ HEMS committed (€/day)	0.041	0.064

Table 5-4. Bids summary (deviation costs=reserve price)

5.5 Summary and Main Conclusions

This chapter discussed the characteristics of the availability services and formulated the problem of the aggregators' participation in the day ahead tertiary reserve market representing a group of residential consumers. A bidding method to maximize the aggregators' remuneration in these markets was presented.

In order to participate in ancillary services markets, the demand side aggregators need to estimate the potential flexibility available in their portfolio of residential consumers. Thus, the availability profiles that are sent by the HEMS in the previous day consist in useful information to prepare the flexibility bids. However, the changes of residential consumption have a sequential characteristic, i.e., the variations in the consumption in a certain hour, have an impact on the potential changes in the subsequent hours. Thus, the availability services that are provided by the end-users to the aggregators should be seen as an "entire profile" and not as a group of independent flexibility.

This aspect of the residential availability raises new challenges to the aggregators in their participation in day ahead ancillary services markets. In fact, aggregators have to trade independent hourly flexibility services in the markets taking into account flexible resources that have a time-dependent characteristic. This increases the complexity of the aggregators' bidding problem, especially if the uncertainty regarding the reserve dispatch in the markets is considered. When the reserve is not dispatched, the availability services selected to compose the aggregators' bid are interpreted as consumption deviations in the wholesale electricity market, which entails penalization costs to be paid by the aggregator. These costs are proportional to the deviations. Hence, the higher the flexibility bid, the higher the risk of paying deviation costs. Therefore, in the definition of the day ahead bids, the aggregators' problem consists in selecting the adequate size of the bids (*i.e.*, the adequate number of availability profiles participating the bid) that maximizes the remuneration and minimizes the risk.

A methodology to deal with the aggregators' bidding problem was proposed in this chapter. This methodology includes: (1) an analytical method to calculate the market expected value of each individual availability profile; (2) a heuristic method, based on a merit order, in order to find the high valuable and less risky bids from the combinations of availability profiles in the aggregator portfolio.

The following conclusions can be drawn from the application of this methodology to an aggregator representing 1500 end-users in the tertiary reserve market:

- The value of deviation costs associated with the probability of the reserve dispatch has a dramatic impact on the market value of the availability profiles as well as the expected remuneration and risk of the aggregators' bidding solutions.
- The market value of the individual availability profiles as well as the remuneration of the aggregated bids are described by a wide range of values. However, the extreme values (maximum and minimum) correspond to scenarios with very low probability, for example, the reserve is never dispatched during the day. Hence, the probability distribution of these values is similar to the normal distribution.
- The diversity of availability profiles in the aggregator portfolio lead to different expected market values. This means that, even in disadvantageous conditions of deviation costs, it is possible to find some profiles with positive expected value. Similarly, even in favorable situations, some availability profiles have negative expected values.
- The maximum upward and downward flexibility in the availability strategy was 380 kWh and 734 kWh, respectively. Considering that the 1500 consumers have an average installed power around 10kW, it is possible to conclude that per each 100 MW of residential installed power, the maximum upward and downward flexibility is 2.5 MW and 4.9 MW, respectively.

Chapter 6 – Economic, Social and Regulatory aspects of Demand Side Flexibility

In the previous chapters, the services/resources chain towards the provision of ancillary services from the demand side was addressed from a technical perspective. Chapter 4 presented a methodology to quantify the availability services that can be provided by the home domain to the aggregators as well as a set of methods capable of maximizing the end-users' remuneration. Chapter 5 focused on the perspective of the aggregators considering their participation in ancillary services markets representing a group of residential consumers.

This chapter aims at discussing some economic, social and regulatory aspects related to the provision of ancillary services through demand response (DR). For that purpose, the methodologies and methods developed in the previous chapters will be used to perform a set of sensitivity analysis to support the discussion.

This chapter is divided as follows: section 6.1 aims at identifying the main barriers and drivers within the home domain regarding the provision of ancillary services from residential consumers; section 6.2 evaluates the elasticity of the availability services supply taking into account the remunerations that are paid by the aggregator to the end-users; section 6.3 discusses the economic viability of the demand side participation in the day ahead tertiary reserve markets.

6.1 From controllability to availability: drivers and barriers within the Home Domain

This section aims at identifying the main drivers and barriers within the home domain that may affect or enable the supply of upward and downward availability services by the residential electricity consumers. Although this thesis is focused on the provision of tertiary reserve services, it is important to stress that the discussion on availability drivers and barriers can be extended to other type of flexibility services, since it is expected that the residential availability (*i.e.,* the potential capability to increase and decrease the consumption in relation to a baseline) can be used by the aggregators to different objectives that were not addressed in this thesis.

Two factors that may affect or enable the provision of availability services were identified: the effect of peak power constraint (imposed by the contracted power that is included in the regulation of the majority of the countries) – discussed in 6.1.1 – and the attitudes of the end-users regarding the provision of these services, that will be addressed in 6.1.2.

6.1.1 The effect of residential contracted power

Charging the maximum peak power of each consumer installation was one of the main topics of the debate over the electricity tariffs schemes during the 80's of the XX century, which was presented in 2.2.2. The main argument against this charge applied to the maximum demand was that it has the effect of discouraging individual peaks but it gives no incentive to reduce the consumption coincidental with the system peak. The following paragraphs aim to contribute to this debate, now assuming that residential consumers have the capability of providing availability services. Thus, the effect of the electricity contracted power, which means a peak power constraint to the HEMS, is evaluated. This constrain was described within the HEMS model in Chapter 4 equation (4-42).

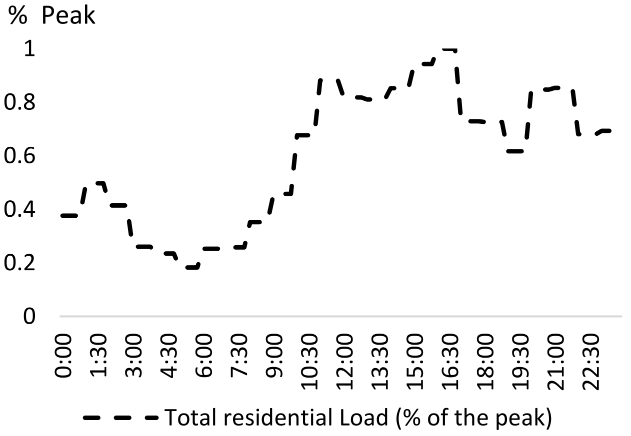
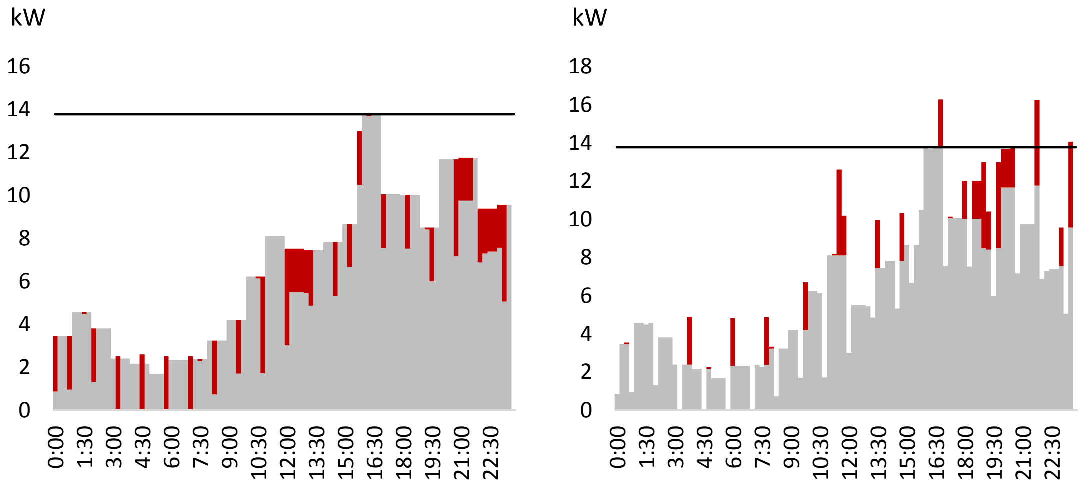


Figure 6-1.Residential load diagram.

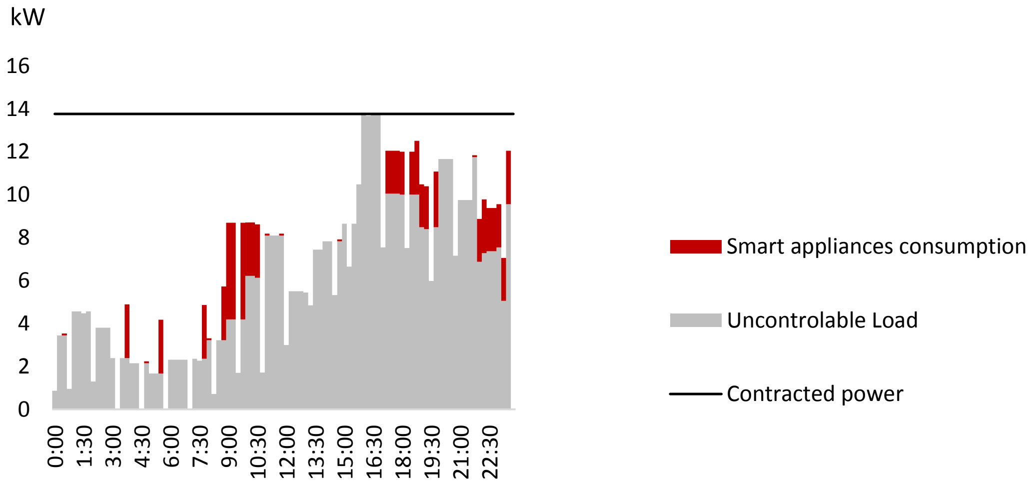
In order to illustrate the effect of the contracted power, an uncontrollable load should be considered. For that purpose the load diagram of the residential households, presented in Figure 6-1, was assumed. The peak power was assumed to be 3 times the maximum controllable capacity, *i.e.*, the total power of the 3 smart appliances that were studied in this thesis: EWH, AC and refrigerator. Thus, the uncontrollable load corresponds to the difference between the load diagram and the baseline of these appliances. Finally, the contracted power was assumed to be equal to the peak load, which ensures that, in the baseline consumption mode, the total demand is below the contracted power but near this limit in the peak periods.

Figure 6-2 illustrates the application of these assumptions to the single household consumption ("Availability Strategy") evaluated in subsection 4.4.3. As shown in the figure, the total demand considering the baseline consumption of the smart appliances reaches the contracted power (14kW) at 16:30 without overcoming it. However, the modified consumption enabling the provision of availability services – already calculated in Chapter 4 and presented in Figure 4-32 – violates the peak power limit. Therefore, due to this new constraint, the HEMS needs to calculate a different modified consumption for the smart appliances that keeps the demand bellow the contracted power, as shown in Figure 6-2. Under the new conditions, a considerable amount of the appliances consumption during the evening periods had to be scheduled back to their original positions, decreasing the capability of delivering availability services.



Baseline

Modified Consumption without peak power constraint



Modified Consumption with peak power constraint

Legend

Figure 6-2. Consumption with peak power constraint (single household).

Figure 6-3 illustrates this effect applied 100 HEMS, taken from the case study presented in the subsection 4.4.4. Similarly, these residential consumptions were assumed to be near its contracted power during the peak hours.

The example presented in the figure demonstrates that the existence of a peak power constraint may cause a dramatic decrease of the availability services, especially in those cases where the residential consumption peak is close to the power that is contracted. In fact, this constraint may impose severe limits to the smart appliances controllability during the individual peak periods. However, it is important to stress that the impact on the availability services goes beyond these periods. As shown in the figure, the incapacity of delivering downward services (increase the consumption) in the evening forced a decrease of the upward availability throughout the day, since the evening consumption was used as a payback to meet the end-user comfort requirements.

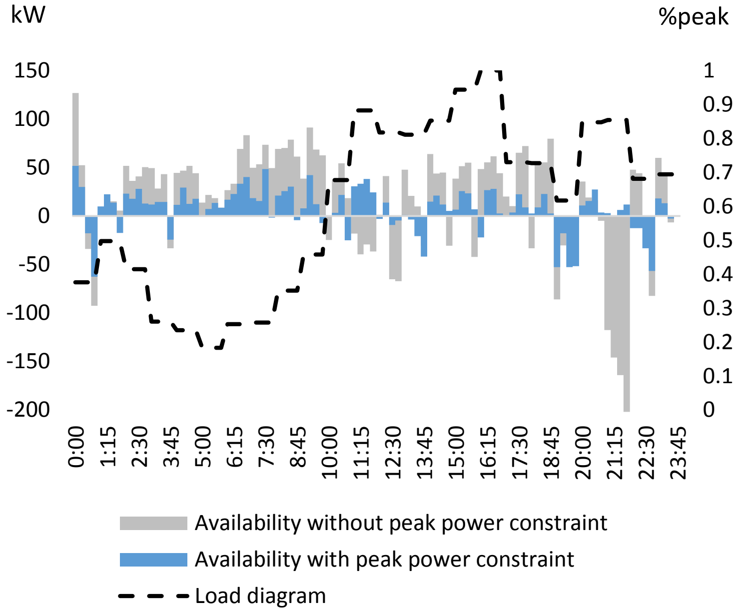


Figure 6-3. The effect of peak power constraints in availability services supply (100 HEMS).

Thus, the direct effect of the contracted power becomes a limitation of smart appliances scheduling to the individual peak periods. If this residential consumption peak and system peak occur at the same time, the contracted power accomplish its objective. In contrast, if the individual peak is not coincidental with the system peak, the contracted power has the direct effect of disabling the provision of downward availability services (consumption above the baseline). Furthermore, due to the relationship between downward and upward consumption changes, in both cases the contracted power limitation may lead to the perverse effect of reducing the total upward availability supply during the day.

In order to ensure a maximum degree of appliances controllability, it is expected that the end-users tend to increase their contracted power. From the economic point of view, this represents a fixed cost that will certainly be reflected on the price of the availability services (upward and downward). Therefore, it is possible to conclude that the contracted power may be a barrier to the provision of demand side flexibility services.

6.1.2 The role of the end-users in smart appliances controllability

As discussed in Chapter 4, the provision of availability services requires smart appliances' control, which means the existence of a controlling platform that comprises sensing and communication infrastructure as well as a HEMS that processes the information and communicates with the aggregators.

On the other hand, the availability services also depend on two dimensions of the end-users engagement: acceptance and participation. The acceptance is associated with the predisposition of the end-users to allow appliances control by the HEMS without any active engagement. In contrast, the participation encompasses the willingness of end-users to interact with the HEMS and to be available to relax their comfort requirements in order to increase the control range and maximize the provision of availability services.

Usually, the promotion of end-users' acceptance may typically include subsidy mechanisms for the acquisition of the technology platform. As done in the direct load control programs of the past (see section 2.3), these economic incentives can be introduced by public programs or by the private sector, for example companies that have a direct interest in the availability services may share the investments with the end-users. In contrast, the promotion of end-users' participation encompasses, for example, the design of the human machine interfaces and the information to the end-users so that they can be aware of the economic benefits that result from a permanent interaction with the HEMS by setting the comfort requirements.

From the point of view of regulators and policy makers aiming to design a new regulatory framework capable of including the provision of flexibility services coming from residential demand side it is important to understand the relative importance of these two dimensions of the end-users attitude in the supply of these services. In other words, in order to define the public investments, the economic incentives, the promotion mechanisms and the new regulatory framework that will enable residential demand response, it is necessary to differentiate the amount of availability services that is directly related to the existence of the control platform and its acceptance from the amount of availability that comes from the end-users' active participation.

For that purpose, a sensitivity analysis was performed. Four types of end-users attitudes regarding appliances control were considered: one "acceptance" attitude, meaning that the control is accepted but the end-user does not have a predisposition to relax the comfort; and three participation attitudes where it is assumed that end-users accept and they are willing to change their comfort preferences with different levels of relaxation: "low", "medium" and "high". In the "acceptance" attitude the control is performed with no impact on the end-users' comfort, *i.e.*, the temperature is kept close to the normal set point dead band of each appliance (+/- 0.05 °C was considered) while in the other cases the comfort relaxation was determined by the level of participation of the end-users. The exception is the maximum temperature of the EWH, which has no influence in the end-user comfort, since it is normally mixed with cold water to obtain the desired temperature. Hence, the maximum control temperature of this appliance was defined by the technical temperature limit of the hot water tank (a value of 80°C was assumed for all scenarios of end-users' attitudes). Table 6-1 presents the upper and lower temperature bounds in relation to the normal set point that were used in each scenario.

Upper and lower temperature bounds in relation to the set point (°C)	**AC**		**EWH**		**Refrigerator**	
	Min	**Max**	**Min**	**Max**	**Min**	**Max**
High comfort relaxation	-3	3	-3	App. Limit temperature (80°C)	-2	2
Medium comfort relaxation	-2	2	-2		-1	1
Low comfort relaxation	-1	1	-1		-0.5	0.5
Acceptance	-0.05	0.05	-0.05		-0.05	0.05

Table 6-1. Comfort limits range in the 4 types of end-users' attitudes

The availability curve of 100 households (with the same characteristics of the case study presented in 4.4.4) was calculated for each end-users engagement scenario. Figure 6-4 shows the comparison between the different availability curves. It is clear that higher comfort relaxations have higher potential for the provision of availability services (upward and downward) throughout the day. Indeed, wide temperature ranges increase the control capability and the potential for thermal storage, enabling longer periods of load shifting. When the control is accepted but without any type of participation through comfort relaxation, the availability is restricted. However, some availability potential still exists in this situation, mainly due to the possibility of shifting EWH devices without affecting the end-users' comfort.

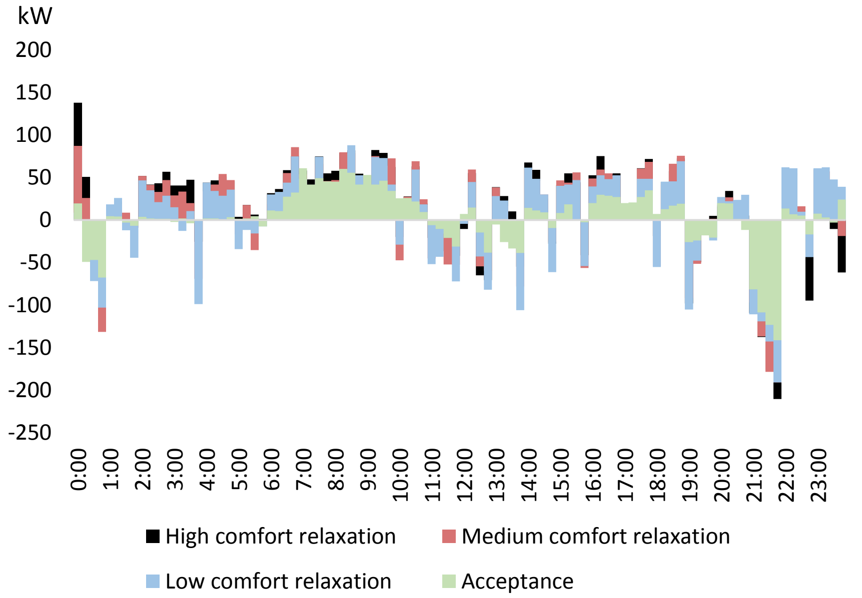


Figure 6-4. Availability considering different types of end-users' engagement (100 HEMS).

Table 6-2 summarizes the amount of availability services delivered as well as the remuneration received (in case of availability dispatch) in each scenario of end-user engagement. As shown in this table, if the end-user only accepts the control without participating he/she provides low upward and downward availability. The higher upward availability services and remuneration occur when the end-users relax the comfort limits while the higher downward services occur in case of low comfort relaxation. In fact, when the comfort range is narrower, the thermal storage capacity is lower, which means that electric consumption is required more often to keep the temperature within the comfort zone. Hence, although the downward availability is higher in this case, it conducts to lower remuneration in comparison with the other scenarios, because it is driven by comfort reasons and not by the price fluctuations throughout the day.

	Availability		**Availability Remuneration**		
Values per end-user	**Upward (kWh)**	**Downward (kWh)**	**Upward (€)**	**Downward (€)**	**Total (€)**
High comfort relaxation	7.87	3.86	0.37	0.35	**0.72**
Medium comfort relaxation	7.16	4.28	0.34	0.33	**0.66**
Low comfort relaxation	6.35	4.58	0.30	0.30	**0.60**
Acceptance	0.31	0.25	0.15	0.15	**0.30**

Table 6-2. Availability service and remuneration considering different levels of end-users engagement

	Participation	**Acceptance**
High comfort relaxation	59%	41%
Medium comfort relaxation	56%	44%
Low comfort relaxation	51%	49%

Table 6-3. Remuneration share for different levels of participation

For the end-users that participate in the provision of availability through comfort relaxation it is possible to assess the share of remuneration that comes from their participation in comparison with a situation where they just accept the control infrastructure. Table 6-3 shows that the participation of end-users may represent 51% up to 59% of the total remuneration that is received for the provision of availability services.

Thus, it is possible to conclude that the end-users' attitude has an important role in leveraging the value of the control infrastructure. Promoting end-users participation, for example through the integration of human machine interface devices and data mining algorithms, is essential to increase the availability services that are provided to the aggregators.

6.2 Elasticity and cross elasticity of availability services supply

The objective of this section is to evaluate the variation of the availability services supply with the prices that are offered by the aggregators. It is expected that this type of analysis can contribute to the discussion on the future regulatory framework as well to the definition of availability pricing strategies of demand side aggregators.

For the evaluation of elasticity and cross-elasticity of availability services supply, the daily upward and downward prices used Chapter 4 and Chapter 5 will be considered as a reference price. However, it is important to stress that the conclusions of this section can be applicable to all pricing conditions, since the elasticity and cross elasticity analysis is focused on the variation and not on the magnitude of the prices.

Finally, in this analysis, the concept of elasticity of the supply was considered. This means that it does not consider the impact of the prices in the behavior of the end-users (which is typically studied in the elasticity of the demand). Instead, it takes into account the costs for the provision of the service (electricity price).

6.2.1 Elasticity of availability services supply

In order to estimate the elasticity of availability services supply, the upward and downward average prices were variated from 1/10 up to 20 times the reference price and the availability curve of 100 HEMS was evaluated. Figure 6-5 presents the upward and downward availability services obtained during the price variation. As shown in the figure, the initial variations of the price had an insignificant impact on the total amount of upward and downward services delivered by the residential end-users. However, for higher prices (between 2 and 5 times the reference price) the supply of availability services become very elastic, especially the downward availability services. Finally, when the prices increase from 10 up to 20 times the reference, the availability services tend to be inelastic again. Thus, the observation of the availability elasticity curve allows the identification of three price regions that correspond to three different behaviors of the service supply. For a comprehensive interpretation of these regions, the electricity price should be taken into account.

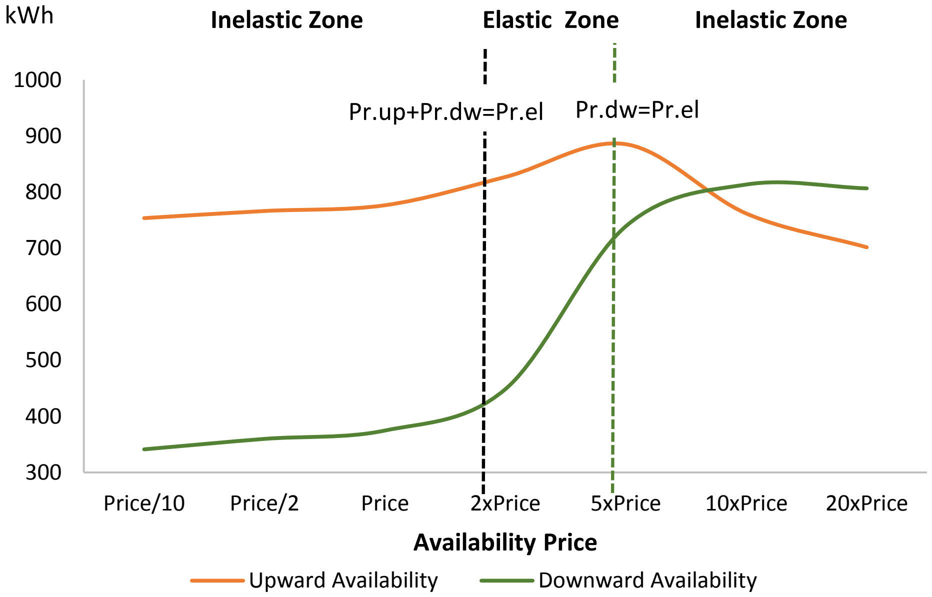


Figure 6-5. Availability services elasticity

In first region, encompassing small prices, the upward availability is high while the downward availability is low. This means that the electricity price plays a dominant role in the availability services supply. In this situation, the remuneration of downward availability does not cover the costs regarding this consumption above the baseline. For the same reason the electricity prices represent an incentive to the upward availability services, *i.e.*, the consumption decrease lead to significant energy savings.

When the sum of upward and downward availability prices is higher than the electricity price, it becomes viable to use all the thermal storage capacity of the appliances. Hence, a consumption above the baseline in some periods allows a consumption decrease in subsequent periods. Since each pair of downward and upward deviations represent a remuneration higher than the electricity cost, the load shifting is encouraged. Consequently, both upward and downward service increase.

When the downward price become higher than the electricity price, there is an incentive to consume above the baseline (downward). Although the upward services are also promoted in this case, the downward availability is higher. Indeed, the upward deviations only occur if the appliances are switched on, while the downward services are provided when the appliances are switched off. Since the majority of the appliances are more time disconnected that connected, in situations where both services are highly remunerated the downward availability tends to be higher.

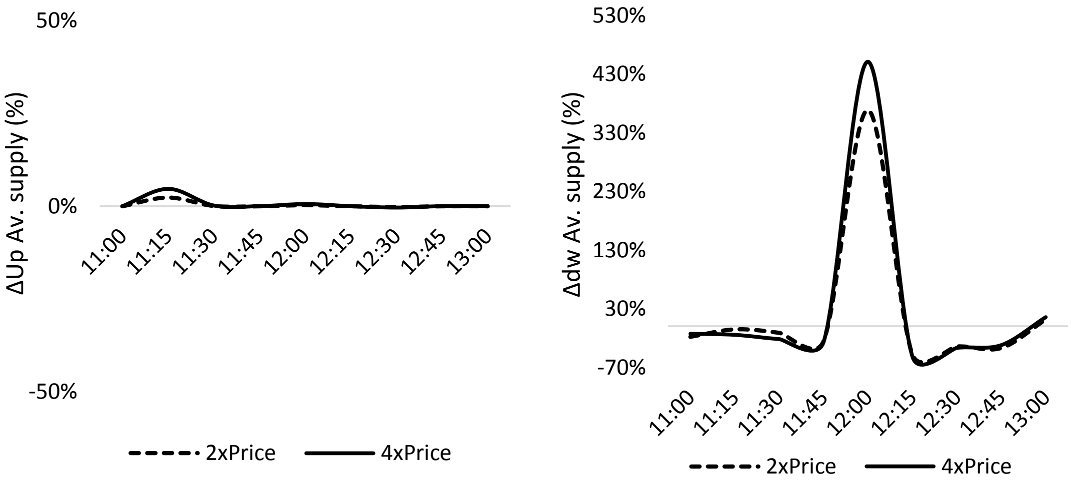
Thus, the supply of availability services is defined by the relation between their prices and the electricity costs. However, in the real world, the cost of electricity that is paid by the final end-user (around 150€/MWh) is very high in comparison with the market upward and downward reserve prices (around 40€/MWh). Thus, from the analysis of the elasticity curve two conclusions can be drawn:

1) The availability services are inelastic, *i.e.*, due difference between the electricity and the reserve prices, in real situations the elasticity of the availability services corresponds to the first region of the curve. Therefore, it is not expected that the availability curve communicated by the HEMS can change with the upward and downward remuneration offered by the aggregator.
2) The electricity costs are dominant in the provision of availability services. This means a natural incentive to the upward services and a limitation to the downward services. In fact, in order to provide a downward services (whose maximum remuneration may achieve 60€/MWh in the reserve market), the end-user must pay the electricity costs, which are 2 or 3 times higher. Thus, the provision of downward availability services is economic viable only if it is associated with an upward service in the previous or subsequent hours.

6.2.2 Intra-day cross elasticity of availability services supply

In the previous subsection, it was concluded that the total amount of upward and downward availability services do not change with the average variation of prices. However, due to the sequential characteristic of the availability – and assuming intra-day price variations – it is important to evaluate the cross elasticities of the availability services, *i.e.*, how the supply of availability services in the hour X varies with the price in hour *Y*.

For the evaluation of the cross elasticities, the availability price at 12:00 was increased while in the other periods the remuneration remained equal to the reference price. Afterward the availability services during the previous and subsequent hour were quantified for a group of 100 HEMS. Figure 6-6 present the cross elasticities of upward and downward services.



Upward cross elasticity

Downward cross elasticity

Figure 6-6. Availability services intra-day cross elasticity

The variation of upward availability prices did not affect the supply of this services neither in the period when the price was modified nor during the previous and following hours, as shown in Figure 6-6. In contrast, in the provision of downward availability, a price 2 times and four times higher at 12:00 caused a service increase of 380% and 450%, respectively, in this period. Furthermore, a decrease in the downward service during the preceding and subsequent periods was observed.

The difference between upward and downward availability cross elasticities can also be explained by the relation with the electricity price. As a matter of fact, the electricity price represents a natural incentive to the provision of upward availability services. Hence, the appliances that can be switched off without violating the comfort of the end-user are disconnected by the HEMS, regardless the price that is paid for the upward availability. On the other hand, the increase of downward availability price in a certain period represents an incentive to the consumption, which causes a shift of the appliances demand that were scheduled for the previous and following periods.

Thus, it is possible to conclude that the upward availability is inelastic even in the intra-day price variation while the downward can change significantly with the price fluctuations throughout the day.

6.3 Economic viability of the provision of tertiary by the demand side

The section aims to assess the economic viability of the provision of tertiary reserve services through the flexibility of the residential appliances. The objective is to identify the remuneration and penalization costs that can create business opportunities to demand side aggregators for the participation in the day ahead tertiary reserve market.

Thus, real conditions of the tertiary reserve markets were taken into account. The average probability of dispatch in each hour as well as the average remuneration prices of the downward and upward tertiary reserve in the Portuguese market in 2013 were considered in this analysis. As shown in Figure 6-7, the annual average price of upward reserve is higher than the downward. In contrast, the downward reserve was dispatched more often in comparison with the upward reserve.

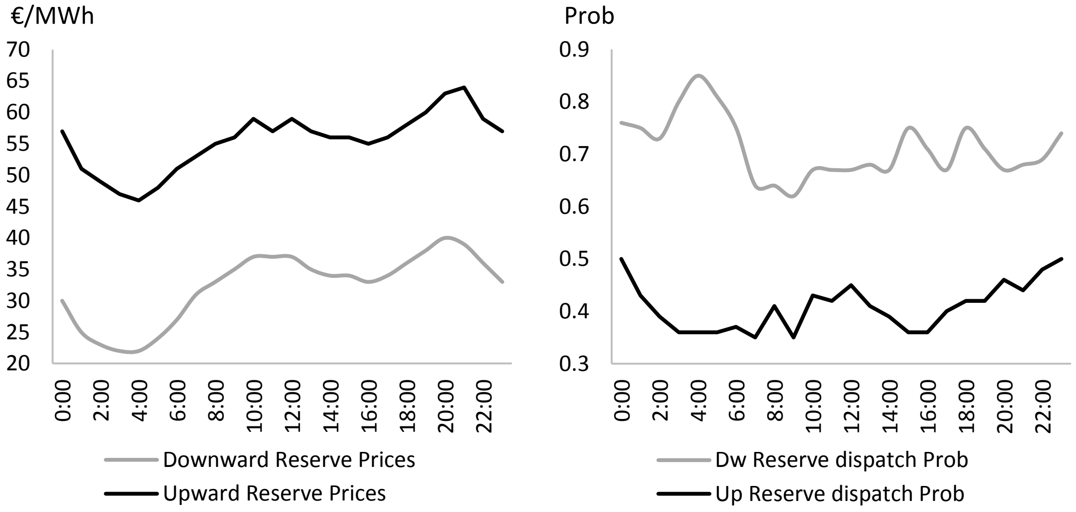


Figure 6-7.Hourly Average prices and probability of dispatch of tertiary reserve market: Portugal 2013

6.3.1 Deviation costs enabling the provision of demand side tertiary reserve

As previously discussed, the remuneration of the aggregators' participation in tertiary reserve markets depends on the upward and downward reserve prices as well as on the penalization that are paid, in case of non-dispatched reserve, for the unbalance provoked in the system. Usually, in the current regulatory framework, the downward and upward reserve prices are determined by the market, while the deviation costs are fixed by the regulatory entities of each country. For example, in Portugal, this costs are calculated based on the prices for balancing the supply and demand in each hour plus an additional cost related to the activation of this service [191].

Thus, the deviation costs are a regulatory instrument to discourage energy deviations and ensure that the generation and retailing bids in the electricity market are actually accomplished in real situations. However, they also limit the participation of the aggregators, in providing ancillary services, by decreasing the total remuneration and increasing the value at risk (VaR), as discussed in Chapter 5. Therefore, it is important to identify the range of values of penalization costs that guarantee the economic viability of the aggregators' business in real conditions regarding their participation in day ahead tertiary reserve markets.

Considering the dispatch probabilities and the remunerations of the Portuguese market in 2013, the expected remuneration and the $VaR_{0.05}$ of an aggregator representing 1500 HEMS were calculated. The availability profiles of each end-user were determined taking into account the appliances' characteristics used in section 4.4.3. The hourly remuneration of the end-users availability was assumed to be proportional to the average annual reserve prices. The magnitude of this proportion is irrelevant in this study, since it does not change the availability profiles due to the inelasticity of these services (see section 6.2).

Figure 6-8 presents the expected remuneration and the value at risk of the non-dominated bidding solutions of the aggregator considering 3 scenarios of deviation costs: (1) deviation penalties are equal to the reserve prices; (2) deviation costs are 75% of the reserve prices; (3) deviation costs are 50% of the reserve prices.

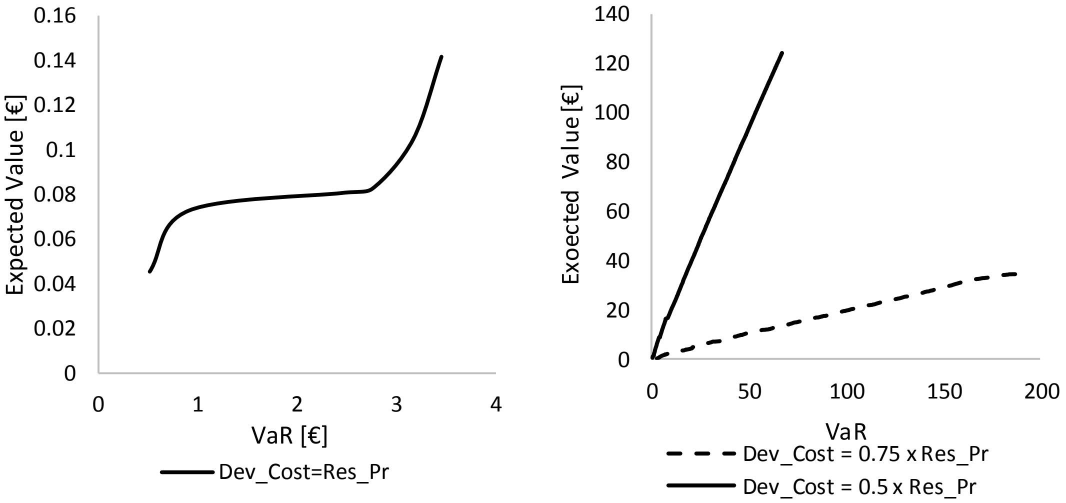


Figure 6-8. Non-dominated bidding solutions considering different deviation costs

Considering the Portuguese tertiary reserve market average conditions in 2013, if the deviation costs are equal to the reserve prices the participation of the demand side is very limited, as shown in the chart presented in the left-hand side. In fact, less than 1% of the availability profiles in aggregator portfolio has a positive expected value, which conducts to low flexibility bids. However, if the penalizations value is 75% of the hourly reserve price, 99% of the availability profiles have positive expected value. However, the aggregators $VaR_{0.05}$ of the aggregator in this scenario is 4 times higher than the expected remuneration. In other words, in 5% of the days, the aggregator loses 4 times the average daily remuneration, if it includes all the viable availability profiles in its bids. Finally, in the scenario where the value of deviation costs is 50% of the reserve price, the remuneration of the aggregator increases and the risk decreases dramatically, allowing a massive participation of residential end-users in the provision of tertiary reserve.

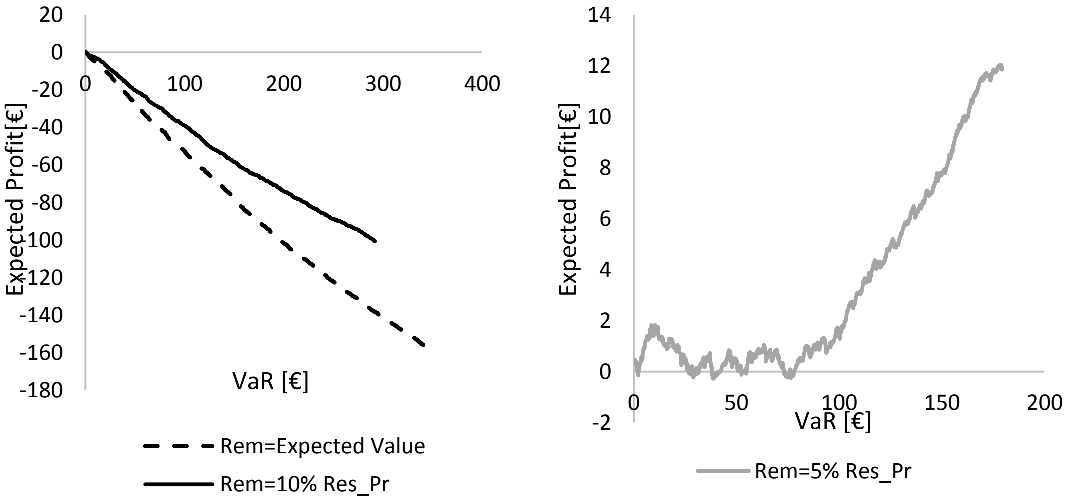
By analyzing the aggregators bidding solutions in real markets average annual conditions, it is possible to conclude that the value of the deviations costs is a determinant factor to ensure the economic viability of the provision of tertiary reserve services through the demand side. High penalization of energy deviations are a barrier to the demand side participation whereas low deviation costs may represent an opportunity for the provision of tertiary reserve by aggregators and residential consumers. This conclusion should be taken into account in the future by the regulatory entities aiming at promoting demand side bidding in ancillary services markets. However, it is important to stress that the value of deviation costs also encompass other objectives, namely in the regulation of the wholesale electricity market.

6.3.2 The impact of end-users remunerations on the aggregator's profit

In section 6.2 it was concluded that, from an economic point of view, the supply of residential availability services is inelastic due to the effect of the electricity costs. Nevertheless, as discussed in 6.1.2, the participation of the end-users is a key factor to increase the provision of these services. Therefore, although for a given participation the residential availability profiles do not change with the value of the remuneration that is paid by the aggregator, this value can be an additional incentive to the participation of the end-users and, in that case, it has an impact on the volume of downward and upward availability services supply.

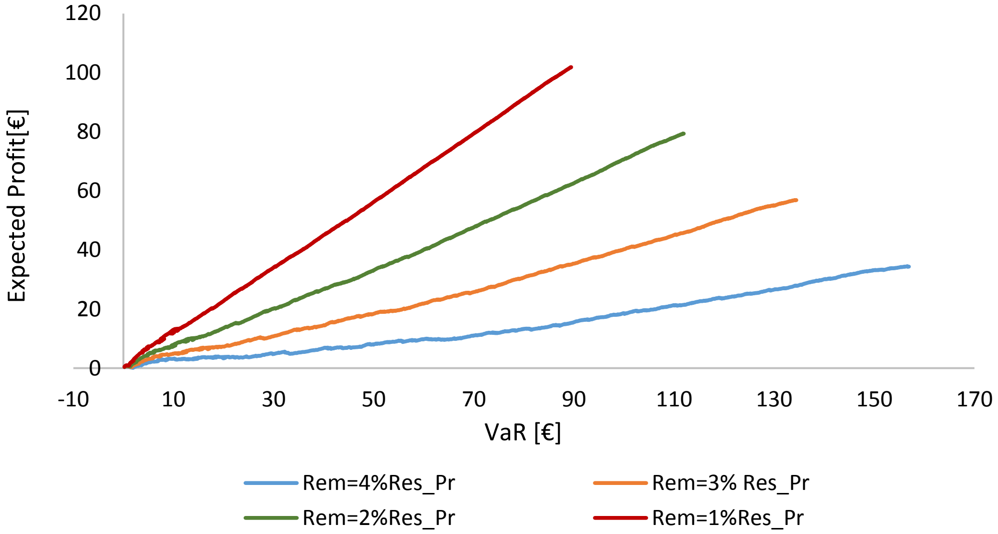
The remuneration of availability services can be defined either by the regulatory entities or by the aggregators in their commercial products, depending on the future legislation model adopted. However, despite this aspect, it is clear that higher availability remunerations conducts to lower aggregator profits and vice-versa.

In this section the impact of the availability remuneration on the aggregators' profit is quantified. For illustration purposes, the Portuguese market conditions were assumed considering deviation costs equal to 50% of the reserve prices. Seven availability remuneration scenarios were considered: 1 scenario where the end-users remuneration was equal to the market expected value of their availability profiles; 6 scenarios where the availability profiles were remunerated according a percentage of the hourly reserve prices, 10%, 5%, 4%, 3%, 2%, 1%, respectively. Figure 6-9 presents the aggregator expected profit and the $VaR_{0.05}$, considering the different remuneration scenarios, for different bidding solutions.



End-users remunerations leading to aggregator losses

End-users remunerations partially leading to aggregator losses



End-users remunerations leading to aggregator profits

Figure 6-9. Bidding solutions expected profit and risk

The impact analysis showed that remunerating end-users by the expected market value of their availability profiles conducts to significant losses for the aggregators. This occurs because, in most cases, the expected value of a combination of availability profiles is lower than the sum of expected value of the individual profiles. The main reason for this effect is related with the bidding design and the single hourly bid option, discussed in 5.3.2. In fact, in the single bid approach, the downward services cancel the upward services for the same hour (and vice-versa), which decreases the total amount of flexibility. Therefore, remunerating availability services based on the expected value of each individual profile is not a suitable solution.

Remunerating end-users based on the reserve price lead to different aggregator's profits according to the percentage used. Values higher than 10% are not viable in 2013 Portuguese market conditions. Indeed, the low probability of tertiary reserve dispatch, mainly the upward reserve, reduces the remuneration of the aggregator, which is not capable of paying high costs for the availability of end-users.

A remuneration of 5% of the reserve price is partially viable, *i.e.*, it conducts to profits only if the aggregator includes a significant number of HEMS profiles in its flexibility bids, as illustrated in the top left corner of the Figure 6-9. Surprisingly, the profit of the aggregator increases when the last HEMS profiles – those with lower expected market remuneration – start to be included in the bids. In fact, these profiles have lower expected value since they deliver small amount of availability services in low remuneration periods. By adding these profiles to the bids, the aggregator is paying lower remunerations and increasing the diversity, which leads to lower risk. Therefore, although the market expected value of this profiles is lower, they represent a significant added value in the combination with other profiles.

The remuneration levels that ensure the fully economic viability of the aggregator in the conditions verified in the Portuguese market in 2013 are those below 4% of the reserve price, as shown in the bottom of the Figure 6-9. Within this range, the profit of the aggregator increases as the end-users remuneration decreases. Table 6-4 presents the aggregator profit for different levels of end-users remuneration, considering the flexibility bid where the 1500 HEMS profiles were included. In order to allow the estimation of these values for aggregations higher than 1500 residential consumers, the annual profit and remunerations are presented in €/household and the risk is presented in $VaR_{0.05}$/daily profit.

Availability Remuneration [% Res. Price]	**Aggregator Profit and Risk**		**End-users annual Remuneration**		
	Annual Expected Profit [€/household]	$VaR_{0.05}$/ daily Profit	Min [€/household]	Max [€/household]	Average [€/household]
5%	2.89	15.12	9.69	55.39	27.37
4%	8.36	4.57	7.76	44.31	21.89
3%	13.84	2.36	5.82	33.24	16.42
2%	19.31	1.41	3.88	22.16	10.95
1%	24.78	0.88	1.94	11.08	5.47

Table 6-4. Aggregator's profit vs end-users' remuneration

A remuneration of 1% of the reserve price lead to an annual aggregator profit of 24.78€ per each availability profile that is included in the bid and the end-users receive an average remuneration of 5.47€. In contrast, a remuneration level of 5% of the reserve price allows end-user to profit 2.89€/year per each availability contract that is established with the consumers. In this case, the end-users average remuneration is 27.37€, which represents a significant incentive to the end-users engagement in the provision of availability services. However, the end-users that deliver high amount of availability services may receive up to 55.39€/year whereas those who provide low availability services will only receive 9.69€/year. This difference depends on the end-users participation through comfort relaxation and also on the appliances characteristics, as discussed in Chapter 4.

In a scenario where ancillary services markets are open to demand side bidding, the decision regarding the remuneration that is offered to the end-users for the availability services should be studied in the context of the business plan of the companies potentially interested in playing the role of an aggregator. This section contributed to this topic by identifying a range of possible remuneration values that become this business viable. However, it is important to emphasize that, even within this range, different remuneration values may lead to different attitudes of the end-users. In fact, if a low remuneration is paid, it is expected that the number of end-users participating in the provision of these services is insignificant. Thus, although the aggregator earns the higher share of flexibility services' value, the number of availability profiles in the portfolio is low, which decreases the global profit.

In the formulation of the aggregators' bidding problem, presented in this thesis (Chapter 5), the possibility of risk sharing between the aggregator and the end-users was not considered. In the perspective of this work, since the aggregator is the responsible for preparing the bids and making all the decisions regarding the participation in the market, it is expected that it also assumes the risk. Indeed, nowadays this is a common practice in the wholesale electricity markets' demand side bidding, where the retailers offer consumption bids and are responsible for paying the deviation costs. However, it is possible that in the future remuneration schemes including some kind of risk sharing can be proposed by the aggregators.

6.4 Summary and Main Conclusions

This chapter discussed some economic, social and regulatory aspects related to the provision of ancillary services through DR. The different sensitivity analysis performed allow us to derive the following conclusions:

- The contracted power may be a barrier for the provision of demand side flexibility services. In fact, it has the effect of limiting the potential control of the appliances. The impact of this limitation goes beyond the local peak periods, since the entire availability profile is affected.
- The end-users' attitude has the potential of leveraging the value of the control infrastructures, since a relaxation in the comfort can increase significantly the volume of upward and downward availability services.
- The electricity costs are dominant in the provision of availability services and it is a natural incentive to the upward services and a limitation to the downward services. In fact, in order to provide a downward services, the end-user must pay the electricity costs, which are 2 or 3 times higher.
- The supply of availability services is predominantly inelastic, *i.e.*, it almost do not change with the homothetic variations in the price of the aggregator.
- Regarding the cross elasticities of the availability services, the upward availability is inelastic even in the intra-day price variation while the downward can change significantly with the price fluctuations throughout the day.

- High penalization of electricity deviations can be a barrier to the demand side participation. In fact, these costs have the effect of decreasing the expected value of the flexibility bids and increasing the risk.
- The remuneration values paid to the availability of end-users that ensure the fully economic viability of the aggregator, in the conditions verified in the Portuguese tertiary reserve market in 2013, are those below 4% of the reserve price.
- As already mentioned, the electricity prices are a limitation for the provision of downward services and an incentive for upward services. However, in the Portuguese tertiary reserve market, the probability of dispatch of upward reserve is significantly lower than the downward reserve, which increases the overall risk and decreases the remuneration of the demand side participation in this markets. This means, taking into account the current regulatory framework and the historical data of the reserve dispatch, it is possible to conclude that the conditions of tertiary reserve market are not favorable for demand side bidding and may lead to low remunerations.

Chapter 7 – Conclusions

This chapter summarizes the main contributions and findings from this thesis towards the technical framework for the provision of ancillary services through demand response. Furthermore, the topics for future work are also identified, covering possible improvements to the methods presented in this research as well as new developments compatible with the structured approach and the conceptual vision of DR that drove this thesis.

7.1 Contributions and main findings

7.1.1 Contributions

The first contribution of this thesis was the conceptualization of a technical framework for the provision of ancillary services through demand response within the smart grid paradigm. This concept guided all the developments of this work and resulted directly in two theoretical contributions:

- A structured approach to DR applications enabling the participation of loads in ancillary services. It consists in looking at the provision of ancillary services as services/resources chain, starting in the appliances control and ending in market flexibility products.
- An architecture that identifies the entities participating in the provision of ancillary services through residential consumers and establishes, from a technical point of view, the main interactions among them.

The second general contribution of this thesis was a set of methods and tools – that can run in a Home Energy Management System – to facilitate demand response services in the home domain. This can be divided in four main contributions:

- A methodology to enable automatic learning of appliances' thermal parameters by the HEMS in real environment. This methodology, validated in a laboratory experimentation, allows the identification of appliances' physical parameters that are essential to load control.
- A sensitivity analysis regarding the impact of the appliances' thermal characteristic in their potential to provide availability services.
- An optimization method and a HEMS tool capable of quantifying and maximizing the availability services that can be provided by a residential consumer for the day ahead. These functionalities are essential to ensure that the end-users can participate in the provision of ancillary services via an aggregator.
- An optimization method and a HEMS tool capable of scheduling the appliances' consumption in order to supply different services in the home domain. The advantage of this method is that it can combine different prices and services and optimize the global remuneration of the end-user.

The third general contribution of this thesis was a comprehensive methodology for the provision of flexibility services by demand side aggregators. This can be divided in four main contributions:

- A characterization of the availability services under the perspective of the aggregators aiming at providing flexibility services. This contribution is essential, since it points out the main difference between the flexible resources in the demand side in comparison with the generation side, *i.e.*, the sequential characteristic of the demand side availability.
- A formulation of the aggregators' bidding problem regarding their participation in the day ahead tertiary reserve markets. This formulation takes into account the uncertainty of the reserve dispatch as well as the reserve remuneration and the deviation costs of electricity consumption.
- A methodology to evaluate the market value of the availability profiles. Besides their application in the aggregators' bidding activity, this methodology allowed to quantify the economic value of single availability profiles, considering the uncertainties of the market.
- A bidding method capable of identifying a set of non-dominated bidding solutions so that aggregators can trade flexibility services in the tertiary reserve markets, being aware of the expected remuneration and the risk.

The fourth general contribution of this thesis was a discussion about economic, social and regulatory aspects related to the provision of ancillary services through demand response. This can be divided in three main contributions:

- An identification of the main drivers and barriers within the home domain that can enable or limit the potential control of the appliances. This contribution allowed to quantify and discuss the impact of the end-users' attitude on the volume of demand side flexibility services delivered in residential sector.
- An evaluation of the elasticity of the availability services supply, which permitted to understand the impact of the availability remuneration and the electricity on the volume of flexible services that can be delivered by the residential consumers.
- A discussion about the economic viability of the provision of tertiary reserve services by demand side aggregators. This contribution was essential to assess, under real market conditions, the impact of the electricity deviation costs defined by the regulators on the economic viability of the provision of balancing services through the demand side.

With the exception of the formulation of the aggregators' bidding problem, all the contributions of this thesis can be adapted to any type of ancillary service, despite they were developed and presented in the context of the provision of tertiary reserve.

7.1.2 Main findings

From the development of the methods and tools within the Home Domain and from the case studies and the laboratory experimentation, the following conclusions can be drawn:

- The availability services of residential consumers depend on: the thermal parameters of the appliances and, hence, the external temperatures that have an impact on their electricity consumption (ambient temperature, in case of AC, and indoor temperature, in case of EWH and refrigerator); the end-users consumption patterns and their willingness to relax the comfort.
- In general, the provision of downward availability services increases the potential for upward availability services (and vice-versa), since the downward services increases the thermal energy stored in the thermal appliances that can be used for supplying upward availability services.
- The use of appliances control for other services within the home domain does not necessarily decreases the amount of upward and downward availability that is provided during the day. However, it has the effect of reducing the remuneration of the end-users coming from this service.

The development of the aggregators' bidding method to participate in tertiary reserve services as well as the case study used to illustrate it allowed to derive the following conclusions:

- The demand side availability has a sequential characteristic. This raises a new challenge to the demand side agents aiming at participating in ancillary services markets: to offer independent flexibility bids for resources entailing a time-dependent characteristic.
- By calculating the market value of the flexibility bids it is possible to estimate the expected remuneration and the risk of the aggregators in their participation in day ahead tertiary reserve markets.
- The diversity of availability profiles in the aggregator portfolio lead to different expected market values. This diversity can be useful to reduce the risk of the aggregator.

From the discussion and the sensitivity analysis regarding the economic, social and regulatory aspects of demand side flexibility the following conclusions can be drawn:

- The contracted power can limit the provision of demand side flexibility services and this effect is observed not only in the local peak periods but throughout the day. In contrast, the end-users participation has the potential of leveraging the value of the load control and increasing the flexibility services both upward and downward.
- The electricity costs are dominant in the provision of availability services and they a natural incentive to the upward services and a limitation to the downward services.

- The penalization costs of the electricity deviations can be a barrier to the demand side participation whereas low deviation costs may represent an opportunity for the provision of tertiary reserve by aggregators and residential consumers.
- The remuneration values paid to the availability of end-users that ensure the fully economic viability of the aggregator, in the conditions verified in the Portuguese tertiary reserve market in 2013, are those below 4% of the reserve price.
- In the Portuguese tertiary reserve market, the probability of downward reserve dispatch is higher than the probability of upward dispatch. However, in order to provide downward services, the end-users have to pay the electricity costs, which are significantly higher than the potential availability remuneration. Taking into account the current regulatory framework and the historical data of the reserve dispatch, it is possible to conclude that the conditions of tertiary reserve market are not favorable for demand side bidding and may lead to low remunerations. Therefore, provision of alternative ancillary services by the demand side should be explored in order to increase the value of the consumption flexibility.

7.2 Future Work

Regarding potential improvements to the methods developed in this thesis, the following topics were identified for future work:

- **Intraday flexibility services and optimization**: using the HEMS optimization tools developed in this thesis to quantify the availability services for the next hours ahead in order to allow aggregators to participate in intraday reserve markets. This would increase the value of demand side flexibility in the markets, since the accuracy of the aggregators' forecasts regarding reserve dispatch and prices is higher in intraday time periods in comparison with the day ahead.
- **Considering the uncertainty of the availability services in the aggregators' bidding method**: this includes modeling the uncertainty of the parameters affecting the availability, such as the ambient temperature and the end-user behavior. Furthermore, this comprises an improvement to the methodology for the calculation of availability market value. Besides the probability of reserve dispatch, this methodology should also take into account the probability of the supply of the availability services communicated by the HEMS.
- **A meta-heuristic approach for the bidding method:** the aggregators' bidding method proposed in this thesis consisted in a heuristic approach, based on a merit order, to combine the consumers' availability profiles. Alternative approaches based on meta-heuristic algorithms, can be used to obtain the Pareto frontier of the bidding solutions and compared with the heuristic approach of this thesis.

The following topics, not addressed in this theses but still under the concept proposed, were identified for future work:

- **Exploring the additional ancillary services**: as concluded in the previous section, considering the current deviation costs and the probability of reserve dispatch, the demand side participation in tertiary reserve services lead to low remunerations. Thus, the services/resources chain concept developed in this thesis can be used to explore alternative ancillary services. This means that, by using the availability profiles of residential consumers, methods allowing the provision of other flexibility services can be proposed, namely those provided directly to the system operator through bilateral contracts.
- **Expanding the bidding method to the wholesale electricity market:** With the purpose of increasing the value of demand side flexibility, the bidding method presented in this thesis can be adapted so that the aggregators can participate in the wholesale electricity markets. In fact, the possibility of optimizing the day ahead participation in both tertiary reserve and wholesale electricity markets allows the combination of bidding strategies that reduce the risk of the aggregator.

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