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Study and assessment of energy policies to achieve consumer centered power systems

by

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A mi abuelo, a quien más ilusión le hubiese hecho esta tesis.

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Abstract

The climate crisis requires an energy transition to reduce primary energy consumption and replace fossil fuels with renewable energies while electrifying energy consumption. This energy transition is changing the paradigm of the electricity sector from a system with centralised generation, passive demand, and almost no storage capacity, to a system that will have to adapt to the variability in the use of renewable energy flows. The development of new technologies and the greater flexibility needs that arise from this change imply a new context of decentralized generation, active demand, and the development of storage as an essential system tool. And in this new situation, consumers acquire a central role in the present and future electricity systems.

This doctoral thesis aims to analyse the public policies and regulations that will promote the energy transition within the electricity system where the consumer will play an essential role being at the center of it. The thesis employs a series of transdisciplinary methodologies and tools to address and analyse the three stages of the public policy process: formulation, design, and evaluation.

The main body of the thesis contains four contributions organised in three blocks. The first block, formulation, responds to the first two specific objectives that focus on analysing demand response programs at the international level in a standardised way and quantifying the potential for flexibility in the residential sector. The second, design, responds to the third specific objective, which focuses on analysing the impacts that the regulation to promote self-consumption would have on the electricity system. And the third, evaluation, responds to the fourth specific objective of extracting good practices and improvements on an already implemented public policy that uses industrial demand to provide complementary services to the system. Each of the contributions contains case studies and real policies that have been implemented or are under study. In this way, the thesis addresses the current regulatory issues focused on promoting a new regulatory framework for an energy transition where electricity demand increases its role in the system.

The four contributions presented in this thesis demonstrate the need to continue advancing in the formulation, design, and evaluation. Through a combination of techniques and methodologies, the document shows different ways of approaching the problem to improve public policies aimed at promoting the energy transition from the current energy system to a renewable system with greater participation of citizens and electricity consumers.

Resumen

La crisis climática hace necesaria una transición energética para reducir el consumo de energía primaria y sustituir los combustibles fósiles por el uso de energías renovables mientras se electrificacan consumos energéticos. Esta transición energética está cambiando el paradigma del sector eléctrico, que pasa de ser un sistema con generación centralizada, demanda pasiva y casi nula capacidad de almacenamiento, a un sistema que tendrá que adaptarse a la variabilidad en el aprovechamiento de los flujos energéticos renovables. El desarrollo de nuevas tecnologías y las mayores necesidades de flexibilidad que aparecen implican un nuevo contexto de generación descentralizada, demanda activa y el desarrollo del almacenamiento como herramienta imprescindible de sistema. Y en esta nueva situación, los agentes consumidores adquiere un rol central en los sistemas eléctricos presentes y futuros.

Esta tesis doctoral tiene como objetivo analizar las políticas públicas y la regulación que fomentarán la transición energética dentro del sistema eléctrico donde el consumidor jugará un papel imprescindible y se situará en el centro de mismo. La tesis emplea una serie de metodologías y herramientas transversales para abordar y analizar las tres etapas del proceso de las políticas públicas: formulación, diseño y evaluación.

El cuerpo principal de la tesis contiene cuatro aportaciones recogidas en tres bloques. El primer bloque, formulación, responde a los dos primeros objetivos específicos que se centran en analizar programas de respuesta de la demanda a nivel internacional de forma estandarizada y cuantificar el potencial de flexibilidad en el sector residencial. El segundo, diseño, responde al tercer objetivo específico que se centra analizar los impactos que la regulación de fomento del autoconsumo tendría sobre el sistema eléctrico. Y el tercero, evaluación, responde al cuarto objetivo específico de extraer buenas prácticas y mejoras sobre una política pública ya implementada que utiliza la demanda industrial para proporcionar servicios complementarios al sistema. Cada una de las aportaciones contiene casos de estudio y políticas reales que han sido aplicadas o están siendo estudiadas. De esta forma la tesis aborda la problemática regulatoria actual centrada en fomentar un nuevo marco normativo para una transición energética donde la demanda eléctrica incrementa su papel en el sistema.

Las cuatro aportaciones presentadas en esta tesis demuestran la necesidad de continuar avanzando en la formulación, diseño y evaluación de políticas con el

objetivo de situar a los consumidores en el centro del sistema eléctrico. Mediante una combinación de técnicas y metodologías se muestran diversas formas de abordar la problemática y así mejorar las políticas públicas encaminadas a fomentar la transición energética del sistema energético actual a un sistema renovable y con una mayor participación de la ciudadanía y los agentes consumidores de electricidad.

Resum

La crisi climàtica fa necessària una transició energètica per a reduir el consum d'energia primària i substituir els combustibles fòssils per l'ús d'energies renovables mentre s-electrifiquen els consums energètics. Aquesta transició energètica està canviant el paradigma del sector elèctric, que passa de ser un sistema amb generació centralitzada, demanda passiva i quasi nul·la capacitat d'emmagatzematge, a un sistema que haurà d'adaptar-se a la variabilitat en l'aprofitament dels fluxos energètics renovables. El desenvolupament de noves tecnologies i les majors necessitats de flexibilitat que sorgeixen impliquen un nou context de generació descentralitzada, demanda activa i el desenvolupament de l'emmagatzematge com a eina imprescindible del sistema. I en aquesta nova situació, els agents consumidors adquireix un rol central en els sistemes elèctrics presents i futurs.

Aquesta tesi doctoral té com a objectiu analitzar les polítiques públiques i la regulació que fomentaran la transició energètica dins del sistema elèctric on el consumidor jugarà un paper imprescindible i se situarà en el centre del mateix. La tesi empra una sèrie de metodologies i eines transversals per a abordar i analitzar les tres etapes del procés de les polítiques públiques: formulació, disseny i avaluació.

El cos principal de la tesi conté quatre aportacions recollides en tres blocs. El primer bloc, formulació, respon als dos primers objectius específics que se centren a analitzar programes de resposta de la demanda elèctrica en l'àmbit internacional de forma estandarditzada i quantificar el potencial de flexibilitat en el sector residencial. El segon, disseny, respon al tercer objectiu específic que se centra analitzar els impactes que la regulació de foment de l'autoconsum tindria sobre el sistema elèctric. I el tercer, avaluació, respon al quart objectiu específic d'extraure bones pràctiques i millores sobre una política pública ja implementada que utilitza la demanda industrial per a proporcionar serveis complementaris al sistema. Cadascuna de les aportacions conté casos d'estudi i polítiques reals que han sigut aplicades o estan sent estudiades actualment. D'aquesta manera la tesi aborda la problemàtica reguladora actual centrada a fomentar un nou marc normatiu per a una transició energètica on la demanda elèctrica incrementa el seu paper en el sistema.

Les quatre aportacions presentades en aquesta tesi demostren la necessitat de continuar avançant en la formulació, disseny i avaluació de polítiques amb l'objectiu de situar als consumidors en el centre del sistema elèctric. Mitjançant una combinació de tècniques i metodologies es mostren diverses maneres d'abordar la

problemàtica i així millorar les polítiques públiques encaminades a fomentar la transició energètica del sistema energètic actual a un sistema renovable i amb una major participació de la ciutadania i els agents consumidors d'electricitat.

Contents

Chapter 1

Introduction

This thesis follows the journal compilation publishing modality. The document comprises three papers published in JCR journals and one paper submitted for publication under the first round of revision. The thesis has six chapters. It starts with an introduction that frames and explains its background, motivation, and structure. Then, it continues the three main chapters of the thesis, which include the journal articles. The fifth chapter presents the main conclusions and future work. The document ends with a chapter that summarises the publications and research project participation that occurred during the development of this thesis but was not included in the document for narrative and reasons of length (Chapter 5).

The structure of chapters in this thesis constructs a logical order of the policy cycle analysis, thus, following a timeline narrative of the different steps of the cycle. Therefore, the published papers do not follow a strict chronological order of publication. In this way, the document aims to help the readers understand the chronological order that policy analysis should follow.

1.1 General approach

The climate crisis is one of the most pressing challenges for humankind [1]. The accumulated emissions of Green House Gases (GHG) in the atmosphere results in an increased concentration of these, which become destabilising patterns of global and local climates. The impacts of Climate Change are vast and range from the increase of mean temperatures, sea levels, and extreme events to the reduction of precipitation patterns and available freshwater [2]. Scientific literature is clear: without clear and drastic actions, the effects will be devastating for humankind and ecosystems, and the cause of Climate Change has anthropogenic causes [3].

The industrial revolution meant a shift in the usage of energy. Humans used to rely upon organic sources of energy but the development of technology such as the steam engine and new forms of production started to extract energy from inorganic sources. Coal dominated the XVIII and XIX centuries. The start of the XX century saw the rise of oil, and at the end of that century, natural gas gained importance. Nowadays, the combustion of fossil fuels still represents more than 75 % of the annual emissions, being the principal source of such emissions. Figure 1.1.1 shows how industry, transport, and buildings (both residential and commercial) are the main energy consumers.

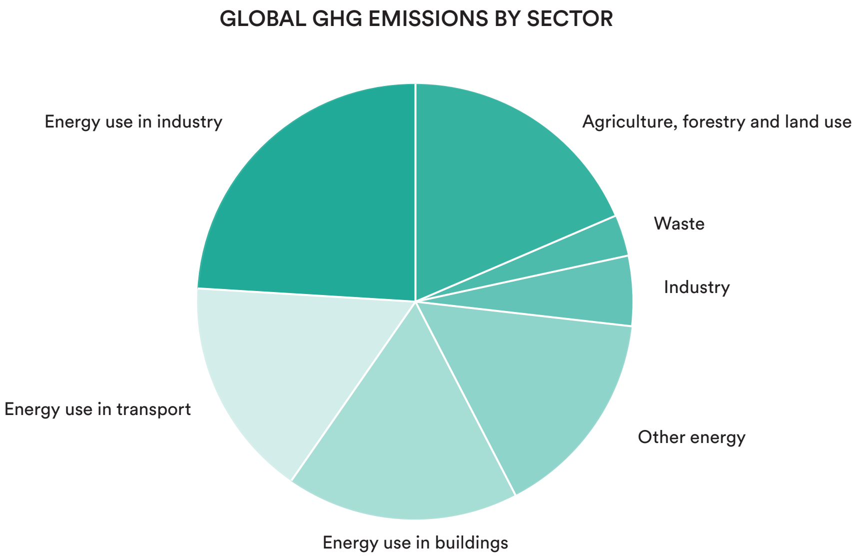

Figure 1.1.1: Global GHG emissions by sector 2016. Own elaboration based on [4]

Therefore, objectives and plans to mitigate climate change have as a central element the energy transition as the main tool to reduce emissions and achieve the 1.5ºC objective set by international agreements [5]. The energy transition focuses on the structural changes of energy systems. These changes deal with both aspects of the system: the supply and demand sides. On the one hand, regarding energy supply, energy transitions aim to replace the current fossil matrix with an energy matrix based on a combination of different Renewable Energy Sources (RES), especially the existing hydropower and the rapidly increasing technologies of wind power and solar PV that generate electricity with stochastic natural resources. On the other hand, energy demand is able to be reduced by efficiency improvements, but also, shifted from fossil consumption to new applications and technologies. These will rely on electricity as their main energy vector instead of the burning of fossil fuels [6], in a process known as the electrification of energy demand. Thus, the energy transition means a double shift that combines the increasing needs of electricity supplied by RES instead of fossil fuels.

In this sense, International Objectives and plans have been rolling out regarding the energy transition. At a global level, the Paris Agreement reached in the Conference of Parties (COP) 21 resulted in countries needing to present plans to reduce their GHG every five years [7]. The Net Determined Contributions (NDCs) have energy as one of the main plans among reforms and actions.

At a European level, the European Commission has set ambitious objectives regarding energy efficiency, GHG emission reductions, and RES penetration in both the electricity sector and as part of primary energy consumption. For 2030, the European Commission (EC) set a reduction (from 1990 levels) of at least 55 % of GHG, achieving 32 % of primary energy consumption coming from RES, and 32.5 % improvements in energy efficiency. These are intermediary objectives for achieving no net emissions in 2050 [8].

Rolling down, the EC demands that member states draft plans regarding their contributions, objectives, and actions to achieve the European objectives. In the case of Spain, this pathway is defined by the Spanish *Plan Integrado de Energía y Clima* (PNIEC), which aims to reduce 23.3 % of GHG and 10 % of energy dependence, while increasing the share of RES in the power sector from 40% to 74%, the electrification of transport from 10% to 22%, and improving energy efficiency by 39.5 % [9].

This means a shift and structural changes in the sector and its uses. Therefore, concerns about the justice and equity of the energy transition are arising at all levels of governance [10]. The United Nations set the Sustainable Development Goal 7: Affordable and Clean Energy for All that aims to solve the energy access problems in the Global South, tackle energy poverty regarding economic reasons and increase the share of RES in the mix [11]. Regarding developed countries, fair energy transition plans exist to deal with the populations that can become losers in this transition, bearing the burdens of it due to loss of jobs, lack of opportunities, and difficulties in energy access due to economic reasons [10].

One of the main solutions proposed by governments and policymakers to align the equity concerns and the needed energy transition is to position energy consumers in the centre of energy systems [12]. The new energy model appearing from this energy transition maintains radical differences with the fossil fuel based model. Technological, economic, and social changes make possible a system where citizens are not just passive consumers of energy, but active and key stakeholders of the system [13].

To align, frame, and catalyse these changes, policies and regulations must shift from an old paradigm of thought of a fossil fuel based model to a new paradigm. Policymakers must work considering all the advances regarding renewable technologies, scale and ownership of the energy infrastructure, advances in ICT that permit consumers to become more flexible and active, and the whole myriad of new possibilities that arise from this revolution.

This paradigm shift to achieve an economy fuelled by natural and renewable resources poses environmental, technical, economic, social, and regulatory questions. These issues will require new legal frameworks and regulations for each of the sectors and subsectors based on the analysis of the current and future contexts [14]. Due to the key role that power systems will have in the future of energy, specific policies have to address their particularities to boost the energy transition with efficiency and equity considerations.

1.2 Background

The XX Century saw the rise of power systems as we used to know them. Local companies developed small grids that after the New Deal and especially the post-Second World War era were centralised and interconnected. In these centralised systems without the capacity to store electricity, the demand side had a passive role. Utilities located big thermal generation plants away from the principal centres of consumption (cities and industrial districts) due to economies of scale. The electricity travelled from those points through transmission lines at high voltage, then was reduced to medium and low voltage at the distribution grid to be delivered to consumers [15]. Consumers used to see electricity as something given that they could consume whenever needed. Generation facilities adapted their output to the demand needs thanks to the dispatchability that stored fuel allows them.

However, as previously mentioned, the need to replace fossil generation with RES, the increase of electricity demand, and advances in both ICT and renewable energy technologies will profoundly modify the XX Century system [16]. These structural changes in power systems relate to a paradigm shift where electricity generation comes from non dispatchable and zero marginal cost RES, the need and deployment of storage technology, the viability of decentralised energy infrastructure, and an active demand side [13]. All of them have occurred under a shift from systems controlled by the state to liberalised systems, which have been framed for the past 20 years to have subsectors (generation and retail) that assume energy as a commodity and aim to structure it as a competitive market [17]. This transformation has not been fully completed and presents advantages but also many drawbacks.

The first shift comes from moving from a fossil fuel generation system to an RES generation system. The first technologies (coal, natural gas, and oil) have large economics of scale that favour centralised plants requiring relatively low capital costs and high operation costs related to fuel costs [18]. In contrast, RES demand high initial capital costs to pay the infrastructure and almost no operation costs as they use natural fluxes such as solar radiation and wind resources. Nevertheless, if the former are dispatchable in nature as fuel can be stored, the latter rely on stochastic and variable climatic patterns, resulting in the lower capacity to dispatch electricity upper bounded by the instantaneous natural resource. Therefore, the new characteristics of generation require new elements and roles in the system, both regarding the inclusion of firm generation (such as hydro, geothermal, or biomass), storage needs, and an active demand that can increase and reduce its needs to couple with instantaneous generation potentials.

Advances in renewable generation and storage technologies and the characteristics of their economics allow their deployment in a decentralised way. The economics of these new technologies may permit the installation of energy infrastructure in smaller capacities without losing competitiveness. Economics of scale still exist in large wind farms, solar PV projects, and storage. However, now these economies are less abrupt, allowing for smaller generation and storage at the low and mid voltage grids. This infrastructure can be owned by consumers, opening the door for the democratisation of the energy sector. Although these deployments have larger initial costs, the advantages they provide overcome this cost. Among other benefits, having generation facilities near the consumption points reduces electrical losses, increases the reliability of the whole system, reduces the need to expand the current grid infrastructure, and increases competition and efficiency in the sector by increasing the number of players and active agents in the system.

Storing electricity at a daily and seasonal scale used to be extremely costly and was only achieved by pumped hydro systems. In contrast, rapid learning curves in different storage technologies are making storage viable by absorbing cheap renewable generation peaks and delivering energy at expensive demand peak moments [19]. Technology advances go in parallel with the increasing need to manage RES's stochasticity and non dispatchability. Nowadays, several technologies are competitive at storing electricity in power systems [20]. They are a combination of already existing technologies such as pumped hydro, and new electrochemical technologies at system scale mainly represented by Lithium-Ion batteries.

Finally, electricity consumers are moving from a passive role in the system to an active role thanks to the advances in ICT technologies that allow monitoring, control, and program consumption. While some electricity demand is extremely inelastic due to its positive public characteristics, some loads have huge flexibility potentials. Demand can be moved from one moment to another in a concept known as load shifting. Demand has the potential to be instantaneously reduced to accommodate lower generation in a concept known as peak shaving. Moreover, the combination of the potential of demand flexibility, which will increase with new electrical demands such as Electric Vehicles, with new onsite generation and storage facilities multiplies the capacity of consumers to adapt and provide flexibility to the system [21]. Although traditionally not considered, demand flexibility is a valuable resource to the system by proving at least as reliable as generation sources with some resources having the capacity to provide the value at lower costs [22].

In this context of a shifting paradigm, new policies and regulations need to be developed to boost this transition while ensuring the efficiency and equity of the system. The role of demand, distributed energy infrastructure, and RES deployment are key present and future resources. Elements and questions arise on catalysing this energy transition, which aims to decarbonise power systems while putting consumers at the centre. How do we formulate policies that tap the potential of consumers and RES that come from the combination of decentralised demand and generation.

1.3 Motivation

Future power systems will encapsulate a structure where electricity consumers have a more active role. For instance, at the EU level, future energy policies will be framed following a consumer centred perspective [12]. The EU Directive on the internal market for electricity focuses on the potential that consumers have to provide flexibility to help the system to integrate more RES and increase its reliability. The directive focuses on empowering consumers to use their flexibility as a resource for the system, in both energy and operation markets.

Demand flexibility can be defined as the capability of electricity consumers to respond and modify their consumption patterns, adapt to system signals, and provide operation through demand changes and generation resources. The activation of demand provides several benefits, such as loss reductions [23], investments deferral on the distribution grid and operational savings at a system level [24], increased competition and efficiency in the system by providing these services at lower prices [22], and increasing reliability as it depends on lower and granular resources [25]. These benefits allow the increasing of the long term penetration of RES [26].

Nevertheless, policies have to overcome the barriers that demand faces in order to become active and use their flexibility potential. [27]. These barriers occur from a technical, social, regulatory, and economic perspective [28]. ICT advances allow rapid demand management, but System Operators have not fully integrated it. Operators are not used to demand resources, which are more granular and require more control than traditional sources of generation flexibility. Socially, demand flexibility is mistrusted by many consumers as it generates changes in consumption patterns to which they are not accustomed [29]. Finally, as regulatory frameworks are many times underdeveloped, demand has difficulties as regards participating in markets and recovering the investment needed to provide flexibility [28].

To tap decentralised demand resources and flexibility, there is a need to overcome the current barriers in order to obtain all their benefits. To do so, new policies and regulations need to be put into place [14, 30]. These new policies will have to facilitate the use of demand side flexibility at both residential, commercial and industrial levels. Policies and programs should promote the usage of demand resources and make consumers aware of their flexibility potential, which can deliver benefits for individuals, the system, and society as a whole.

New regulations will have impacts on the current market structure and performance of the system. Therefore, from a policy perspective, there is the need to consider all the stages of the public policy process shown in Figure 1.4.1. In this framework, this thesis uses methodologies to understand, quantify, and improve specific policies that aim to position consumers at the centre of the system.

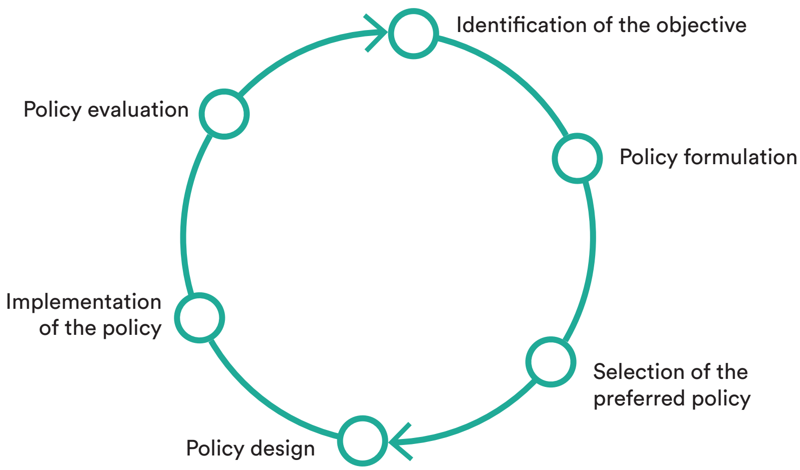

Figure 1.3.1: Public policy process studied in the thesis. Own elaboration based on [31, 32]

Power systems are complex and highly regulated systems. They are in a process of transformation to promote the required changes at economic, environmental, social, and technical levels. Therefore, our motivation is to study how to correctly formulate, design, and evaluate policies aiming to make this possible. We aim to deal with this topic from different angles and perspectives to fill research gaps that arise from this new paradigm.

1.4 Objectives

The general objective of this thesis is to analyse, quantify, and improve the energy policies that aim to achieve a consumer centred power system, but also to study and evaluate the challenges arising from it. The increasing participation of electricity consumers in the system, considering both their capacities to provide renewable generation at a decentralised scale and offering their demand flexibility, is not fully understood, nor their benefits quantified [24, 33]. The new paradigm will generate changes in almost all parts of the electricity sector such as its economic structure, technological needs, social acceptability, energy justice concerns, market mechanisms, regulatory settings, consumer attitudes, etc [10, 15, 16]. These changes will translate into new energy policies that policymakers need to design, evaluate, and improve with analytical and regulation tools [14].

To achieve a consumer centred system with high penetration of renewable energy sources is crucial to activating demand by making it more flexible and participatory in the process of continuously matching electricity supply and demand [13, 21], as is also exploring new forms of ownership regarding decentralised generation at both large and small consumption sites, and how these affect and improve the efficiency of the system. Thus, this thesis aims to study and understand how energy policies promote and enhance this change. This objective is vast and cannot be resolved in one thesis. Thus, the document focuses on four specific policies that are in one of the three steps previously mentioned. In order to fulfil the main aim of this research, the following specific objectives are proposed, which Figure 1.4.1 summarises.

Figure 1.4.1: Structure of the thesis objectives

Formulation of consumer centred energy policies

While aiming for a consumer centred system, systems must introduce new regulations and policies. This step comprises the evaluation of critical characteristics and details necessary to formulate policies that ensure a consumer centred system. In general, while drafting a new policy, there is the need to review similar policies and understand the circumstances in which the policy will take place. Thus, the two specific objectives answered in this thesis focus on developing methodologies for two phases of the design of an energy policy, revision and context understanding and quantification. In particular, the two specific objectives are:

1.4.1 Analysis, revision and classification of the existing regulatory frameworks to obtain the best practices in the usage of demand flexibility as a resource for system operation

Regulatory barriers remain an issue for the participation of demand in power systems [27]. Regulatory barriers relate to market designs that limit the participation of demand, forcing them to participate in markets designed for generators [28]. To overcome this, power systems regulators around the world are developing new and more dynamic programs to increase the participation of demand as agents, known as Balance Service Providers (BSP). These agents compete with other BSP of other flexibility resources, such as generators and storage technologies, in the system operation resource markets [15, 34, 35].

Nevertheless, when policymakers aim to generate new programs, no standard method to compare existing programs nor analyse their main feature exists. Thus, there is a need to provide a methodology to dynamically analyse the different country's programs under a framework of standardised parameters of both system operation and demand flexibility. Then, to compare different programs to use the demand flexibility using a common language to examine the benefits and drawbacks found in them, highlighting their main technical parameters and prices. These outcomes must result in the provision of recommendations to policymakers to improve the design of programs to increase the usage of demand flexibility.

1.4.2 Quantify the flexibility potential of residential consumers and the socioeconomic and geographical gaps associated with these potentials

There is a need to extend the usage of demand flexible resources to medium and small consumers, such as the residential sector, which represents between 30-40% of the final electricity consumption [36]. With this conception, it remains crucial to quantify the flexibility that residential consumers can provide to the system, and also, how these flexibility capacities are distributed among residential consumer types.

Unfavourable geographic and socioeconomic conditions may lead to inflexible consumption patterns, less ability to choose, and even exclusion from participating in new flexibility services [37, 38]. As consumers' flexibility is brought to the centre of electricity systems, the socioeconomic and geographic heterogeneity of the residential sector becomes a key aspect of policy definition and should be carefully studied to quantify the differences and gaps in the residential flexibility capacity.

Therefore, there is a need to provide a methodology to quantify and evaluate nationwide flexibility potential, but also the existing flexibility gaps in the residential sector across different levels of income and geographical locations. This will allow us to understand the main drivers of these gaps and to point out some recommendations and matters to consider.

Design of consumer centred energy policies

Once a decision is made to implement a policy aimed at improving the position of consumers and obtaining benefits for its activation, a quantification of its effects is essential. These policies have impacts and results as regards their main aim, but they also have other impacts, benefits, and drawbacks which arise and that need to be considered, quantified, and understood in order to offer a correct design. In particular, this thesis aims to evaluate the expected consequences of one specific policy in order to improve its design.

1.4.3 Analyse and quantify how increasing levels of solar self-consumption can affect the price and market power in wholesale electricity markets

Solar photovoltaic energy is an economically feasible technology for reducing emissions by generating energy, not just in centralised facilities, but also in a way known as solar self-generation [5]. As Solar rooftop panels are deployed, there is a need to analyse the effects of solar self-generation on individual incumbents and consumers in possible future scenarios. This information is highly relevant to policy making, and necessary in order to inform the social debate around RES support.

Larger penetrations of rooftop PV reduce prices through a merit order effect [39, 40], and also enhance competition in the market while reducing market power [41]. We aim to study the economic impacts on prices and market power that result from increased levels of PV self-generation. As the penetration of self-generation increases, models of wholesale electricity markets are necessary to study their impacts. This permits the quantifying of the effects of solar self-generation on individuals, and in the system as a whole in possible future scenarios.

Market power reductions do not affect all agents of the system equally. Thus, it remains essential to analyse how market power reduction and the entrance of new decentralised generation will affect companies with different portfolios of generation in very different ways. Afterwards, considering both elements it is necessary to analyse the implications of larger deployments of rooftop PV on total amounts of thermal generation and associated GHG emissions in the Spanish system, taking into account that energy demand is price-sensitive and therefore that solar self-generation does not wholly offset thermal electricity generation.

Evaluation of consumer centred energy policies

After designing and putting into place policies with the aim to activate consumers and increase their participation, policymakers have to quantify their effects and impacts to improve the design and future implementations of similar programs and policies. By evaluating how policies perform while there are in place, future policies can nurture good practices, avoid existing errors, and reduce their costs while improving their benefits. In particular, this specific objective aims to propose methodological steps to audit energy policies by evaluating one specific demand centred policy.

1.4.4 Improvement of the design and operation of interruptible demand response programs

Spain had in place an Interruptible Load program for five and a half years for large industrial consumers contracted by the Spanish Transmission System Operator (TSO) [42]. The TSO could use these demand resources by reducing their consumption to ensure the reliability of the system or due to economic reasons. However, the programs were underused as the activation of these resources remained low, many times not calling for a single hour in a year.

As demand flexibility programs are put into place, evaluations should consider their efficiency as they face social barriers related to the inelastic nature of demand and lack of habit of system operators of using demand resources [30]. Understanding their potential benefits, efficiency, and the way they are a valuable flexibility source for the system are key policy recommendation outcomes [43, 44].

Therefore, understanding how operators could have used the program and what resources were the most valuable is the aim of this specific objective to provide policy recommendations. This information at the evaluation stage can provide valuable information about how to design and operate future programs, so that regulators and operators can maximise the potential that a consumer centred program and policy can have, both for consumers and the system as a whole.

1.5 Methodology

This thesis follows a transdisciplinary approach that aims to achieve the above-mentioned specific objectives arising from the main objective. So, the method focuses on three steps of the policy cycle related to policy formulation, design, and evaluation. In each of these steps, this thesis sets the focus on a specific topic framed and analysed using diverse methodologies and frameworks. Moreover, in each chapter and section, the used methodology is presented with further detail.

The main body of the thesis has four papers focusing on the energy policy process with the objective to position electricity consumers in the centre of power systems. Figure 1.5.1 presents a summary.

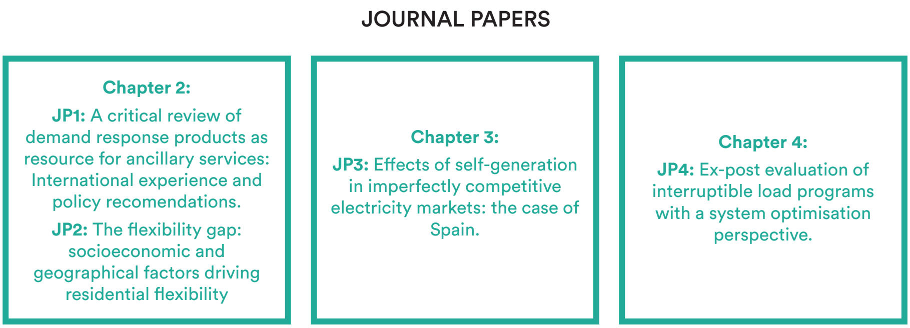

Figure 1.5.1: Structure of the thesis and composition of the core chapters by Journal Papers

The first paper analyses and classifies existing regulatory frameworks that use demand side flexibility as a resource to ensure power system stability. The method uses a literature review combining the current grid standards in both Europe and the USA, specific regulations, reports of programs' performance, and academic papers to obtain a holistic picture of the situation. Standardising programs and their main demand response parameters allows us to compare them and their main features, while obtaining valuable information for the design of future policies.

The second paper focuses on quantifying the existing residential potential as flexibility providers to the grid, the clustering of different residential typologies, and the quantification of the differences among them. To this end, we use a combination of statistical data to generate a new database to use as an input for physical models that simulate the performance of electrical appliances. The database combines geographical and socioeconomic data of different statistical surveys and databases from official sources. Then, this information is run through physical models that aim to reproduce the behaviour of residential consumption illustrated as a varying storage system to quantify the flexibility potential. Then equity concerns regarding flexibility differences related to temporal, socioeconomic, and geographical factors are discussed with a set of indicators developed with the available data. In this paper, the optimisation model to obtain residential occupancy is solved in Python with the package Pyomo and the rest of the mathematical and statistical formulation is performed in MATLAB.

The third paper focuses on the analysis and quantification of how increasing levels of solar self-consumption can affect the price and market power in wholesale electricity markets in order to improve the design policies that aim to increase self-generation penetration. The analysis of the impact of increasing levels of self-generation is performed by a game theoretic optimisation model that aims to understand the behaviour of generating agents of the wholesale electricity market. This game theoretic optimisation considers the physical and economic context and constraints existing in the system. Therefore, it allows us to analyse changes in demand patterns, greenhouse gas emissions, but also in prices and market power capacities from a system perspective. In this paper, the optimisation model is solved using the software AIMMS.

The fourth paper aims to understand how to achieve the demand activation at a competitive cost for the system. The model formulates a Mixed Integer Linear Problem (MILP) that runs five and a half years of the demand program scenarios to optimise from a techno-economic perspective. The optimisation considers physical and regulatory constraints to maximise the profit of the usage of these resources, and then, good practices and policy recommendations arising from the results of the model. In this paper, the MILP optimisation model is solved in Julia with the package JuMP and the rest of the mathematical and statistical formulation is performed in MATLAB.

To sum up, analysing energy policies combines different methodologies to evaluate the formulation, design, impacts, and evaluation of them. In particular, this thesis uses literature reviews, physical models, economic models, and game theory models as its range of tools for the analysis. In each particular section and journal paper, the detailed methodology is presented.

1.6 Structure

This Ph.D. is written following the journal publishing modality and consists of four main pieces of work. The document consists of six Chapters; four articles are the main body of Chapter 2 (two of them), Chapter 3 (one), and Chapter 4 (one).

In this first chapter, the document presents the introduction and general approach to present the context in which this thesis is framed. Then, it presents the background and motivation to show the research questions. Also, the objectives, specific objectives, methodology, and structure of the thesis appear at the end of this chapter.

Chapter 2 is composed of two articles. The first one *A Critical Review of Demand Response Products as a Resource for Ancillary Services: International Experience and Policy Recommendations* published in the Journal Energies by the publisher MDPI [45]. According to the Web of Science Journal Citation Reports (JCR) of 2019, this journal has an Impact Factor of 2.702 and occupies the third quartile in Energy & Fuels. The second one *The flexibility gap: Socioeconomic and geographical factors driving residential flexibility* published in the Journal Energy Policy from the publisher Elsevier [46]. According to the Web of Science Journal Citation Reports (JCR) of 2020, this journal has an Impact Factor of 6.142 and occupies the first decile in Energy & Fuels and Environmental Sciences.

Chapter 3 is composed of one article. The article *Effects of self-generation in imperfectly competitive electricity markets: The case of Spain* published in the Journal Energy Policy by the publisher Elsevier [47]. According to the Web of Science Journal Citation Reports (JCR) of 2019, this journal has an Impact Factor of 5.042 and occupies the first decile in Environmental Sciences and first quartile in Energy & Fuels.

Chapter 4 is composed of one article. The article *Ex-post evaluation of Interruptible Load programs with a system optimisation perspective* published in the Journal Applied Energy from the publisher Elsevier [48]. According to the Web of Science Journal Citation Reports (JCR) of 2019, this journal has an Impact Factor of 9.746 and occupies the first decile in Energy & Fuels and Engineering & Chemical.

Then, Chapter 5 presents the main conclusions of the Ph.D. and discusses the process of designing, evaluating, and improving the efficiency of energy policies that aim to achieve consumer centred power systems. The chapter finishes with a proposal for future research on the topic.

Finally, Chapter 6 ends with the list of published works in Journals and Conferences, and the participation in research projects during the four years that the development of this Ph.D. lasted.

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Chapter 2

Formulating consumer centered energy policies

Once defined the objective to promote consumer centered power systems, the scope of this chapter is to evaluate critical elements to effectively formulate policies to facilitate and ensure a consumer centered system. Once formulating energy policies, studying other systems to fully understand the current characteristics and potential existing in them remains essential to ensure the correct implementation of them. On the one hand, regulatory analysis of policies already in place helps new approaches by reducing uncertainties and avoiding problems already dealt with by them. On the other hand, understanding and quantifying the existing and potential resources allows setting realistic objectives and having the capacity to measure the impact of the policy to set in place.

The first section of the chapter performs an analysis of the regulation and Demand Response (DR) programs used for Ancillary Services (AS) existing around the World.

First, the section describes the two main grid standards in Europe and the USA. Then, it describes the main physical parameters and characteristics that define both an AS requirement by the System Operator and a DR action. The core of the study is an evaluation and synthesis of the existing DR programs for AS classified by region, Europe, North America, and the Asia Pacific. Finally, some policy recommendations are presented considering the most common features among the programs that relate both to physical and regulatory parameters but also the level of competition with generation resources or price levels.

The second section of this chapter quantifies the existing flexibility potential of the residential sector in Spain.

This section aims to map and put a number to the theoretical capacity and that residential consumers may have to provide flexibility to a concrete system, but also to understand the differences among different consumer types and their potential implication in energy inequality. This section starts by drawing around the potential of residential flexibility as a source of improving system competitiveness and reliability. Then, it presents the possible inequities that may arise from the energy transition if no correction measures are considered. To quantify this potential and differences among consumers, this section uses and develops physical models based on the performance of electrical appliances, which aim to replicate them as if they were a battery with time-varying parameters. The methodology is applied to mainland Spain by grouping residential consumers into 45 clusters based on geographical location and income characteristics. The results of this quantification show large flexibility potential gaps related to both income and geographical factors. This section finishes raising the reflection that while electrification of demand will reduce these geographical gaps, income gaps will tend to increase if no action is done. Thus, posing questions around the equity and acceptability of using residential flexibility as a resource to the system without considering the inclusion of lower income groups in the provision of these services.

The sequential investigation in this chapter presents a detailed analysis of two required elements once formulating and drafting new energy policies. The revision of existing policies, and the quantification of the potential and existing resources. The revision of existing policies helps to reduce uncertainty, adopt already existing good practices, and not incur faults and problems already dealt with in other systems. For instance, defining DR programs with high minimum capacities of delivery excludes large numbers of participants hampering both the usage of the theoretical potential and the possible competitiveness. The quantification of the consumer resources sets the limits around where a policy can move, allowing to define realistic objectives but also understanding some drawbacks or problems that policies that promote consumer centered systems may have.

2.1 A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations

[5] *David Ribó-Pérez, Luis Larrosa-López , David Pecondón-Tricas and Manuel Alcázar-Ortega. "A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations," Energies, vol. 14, pp. 846, 2021.*

Abstract

Demand response is a key element of future power systems due to its capacity to defer grid in-vestments, improve demand participation in the market, and absorb renewable energy source variations. In this regard, demand response can play an important role in delivering ancillary services to power systems. The lack of standardization and ancillary services programs prepared for traditional generators have blocked the participation of demand in these services. Nowadays, increasing needs to ensure the security of supply, renewable fluctuations, and information and communication technology advances are boosting the interest in demand response products to deliver ancillary services. While countries have had lengthy experience with these programs, others are starting from almost zero to develop these programs. To our knowledge, no analysis or standardized comparison exists of the different parameters and prices of demand response in ancillary services among different countries. Our study reviews more than 20 power systems around the world and their programs to classify them according to standard demand response parameters. At the end of the paper we discuss the main characteristics and prices that face demand response in ancillary services markets and a series of policy recommendations to policymakers to improve the deployment on demand participation in ancillary services.

Keywords

Demand Response; Ancillary Services; ENTSO-E; FERC; Standardization; Restoration Reserves; Operation Reserves

2.1.1 Introduction

Power systems are under a period of rapid evolution. The integration of renewable energy sources (RES) is necessary to achieve the Climate Change objectives [1], but it re-quires new solutions and more flexible power systems to achieve it at a reasonable cost [2]. A decentralized and dynamic paradigm is replacing the old centralized and rigid one [3, 4]. Now, operators use all kinds of flexible resources to preserve balance, ensure the security of supply, and improve the efficiency of the system. New flexibility resources as Demand Side Management (DSM) require operators and policymakers to work together to create the appropriate legal and economic framework [5] and to establish the terms of flexibility.

Demand Side Management (DSM) refers to planning, implementing, and monitoring the use of electricity to generate changes in the consumers' demand profile to adapt to different needs [6, 7]. DSM solutions are a valuable tool to smooth demand peaks [8], avoid blackouts, reduce investments on the grid [9] and absorb fluctuations of Renewable Energy Sources (RES) power output [10]. Nevertheless, these uses were marginal since power systems treated consumers as passive agents without the capacity to modify their loads and relied on the flexibility of fossil generators [3]. But now, when flexibility needs arise due to RES variability [2, 11], thanks to the advances in Information and Communication Technologies (ICT), DSM counts as necessary infrastructure to fully participate in the system flexibility throughout Demand Response Products (DRP) [12, 13].

Demand Response Products (DRP) are not new; many countries have used this kind of program to accommodate them through the years with satisfactory results. The use of Demand Response (DR) was mainly set to avoid extreme and rare events as system blackouts and severe grid conditions to reduce grid decay [14]. Nowadays, the advances in ICT shows that DR has greater reliability to provide flexible services to the system than conventional generators [15]. First, DR can have lower costs than other flexible resources and can provide economic profits to the system as a whole and the consumers that provide it [16–18]. Second, DR presents an on-site solution to enable efficient integration of Distributed Energy Resources (DERs) that activate new market agents and open new business opportunities [19–21]. Third, DR can provide cheap and reliable Ancillary Services (AS) that were exclusively provided by generators, and as well as other consumer-based solutions, can help to reduce market power [22].

However, regulatory barriers remain an issue for the participation of demand. Regulatory barriers relate to market designs that limit the participation of demand, forcing them to participate in markets designed for generators. For instance, imposing large minimum bidding capacities or long time maintenance requirements that make difficult or even impossible the participation of most consumers [20]. To overcome the lack of scale, aggregators are gaining increasing attention in many policy interventions [23, 24]. Aggregation is the activity of grouping several consumers to perform as one entity to respond to the operator in the market. An aggregator is an organization that deals with markets, System Operators (SO), and consumers, acting as the intermediary party to exploit the valuable resources that consumers under a contract can provide [25].

Therefore, power systems around the world are developing new and more dynamic programs to increase the participation of demand as agents, known as Balance Service Providers (BSP), which act as Demand Response Providers (DRPV) in direct competition with other BSP of other flexibility resources in the Ancillary Services (AS) markets [26] that are now open to DR.

To our knowledge, no analysis or comparison exists of the different parameters and prices of DRP in AS among different countries. On this basis, this article aims to provide a reference point to policymakers and researchers that work with DRP in the AS markets around the world. The article provides an analysis of the different country programs under a framework of standardized parameters of both AS and DRP. Hence, this work out-lines a methodology to compare different DRPs under a common language to analyze the benefits and drawbacks found in them, taking special attention to their main technical parameters and prices. Finally, some policy recommendations for new DRP are presented.

The rest of the paper is organized as follows. Section 2 presents the methodology used to analyze the different DRP for AS. Section 3 provides information on the DRPs of different power systems in the different continents. The discussion arises in Section 4, where a comparison between programs and prices appears. Finally, the main conclusions are stated in Section 5.

2.1.2 Materials and Methods

2.1.2.1 Standards to Classify Operation Services

Systems use different nomenclature for AS across the world. In some regions exist degrees of standardization created by Transmission System Operators (TSOs) from neighboring countries and regions. Two of the best-known are the European and the North American standards, developed by the European Network of Transmission System Operators for Electricity (ENTSO-E) and the Federal Energy Regulatory Commission (FERC), respectively. Figure 2.1.1 provides a summary of the described standards.

ENTSO-E

ENTSO-E stands for European Network of Transmission System Operators for Electricity. It is an organization that represents 42 TSOs from 35 European countries. Among many other functions, ENTSO-E coordinates most of the European TSOs and drafts common network codes for the countries. The nomenclature for the European AS is as follows [27]:

- Frequency Containment Reserve (FCR). This service aims to automatically stabilize the frequency after the occurrence of small and unpredictable imbalances. Actions within this type of service must start no later than 30 s from the imbalance, while the response covers up to 15 min. Another common name for this service is Primary Re-serve.
- Frequency Restoration Reserve (FRR). This service intends to respond to imbalances too long or too large to be solved by FCR. Therefore, its objective is to restore frequency and replace FCR. There are two versions of this service.
  - Automatic Frequency Restoration Reserve (aFRR). It works between 30 s and 15 min from the frequency deviation. Also known as Secondary Reserve.
  - Manual Frequency Restoration Reserve (mFRR). It responds manually no later than 15 min from the imbalance. Also known as Tertiary Reserve.
- Replacement Reserve (RR). This service complements and/or replaces FRR when needed. It is a complementary reserve prepared for additional imbalances, which is manually activated no sooner than 15 min after the frequency deviation takes place.

FERC

FERC stands for Federal Energy Regulatory Commission. It is “an independent agency that regulates the interstate transmission of electricity, natural gas, and oil” in the United States [28]. Included among its many responsibilities is "to protect the reliability of the high voltage interstate transmission system through mandatory reliability standards". As part of this responsibility, the FERC has developed a nomenclature that classifies ancillary services over the United States and part of Canada. The services are divided into two groups ac-cording to the nature of the frequency disturbance.

- Operating Services for Normal Conditions. These services are designed to deal with unpredictable frequency deviations mainly caused by inaccuracy on demand prediction and/or renewables production forecasts. There are three types of service within this group [29]:
  - Frequency Regulation. This service is based on Automatic Generation Control (AGC) and responds immediately to changes in frequency. It must be fully activated 10 s after the frequency disturbance started, and the activation normally lasts from a few seconds to several minutes.
  - Regulating Reserve. AGC responds to the System Operator (SO) requests to bring back frequency or interchange programs to target. It must respond between 4 s and 1 min and lasts several minutes.
  - Load Following. This service bridges between regulation and intraday energy markets. It is like the Regulating Reserve but with slower starts and longer activity periods. It must respond between 5 and 10 min, while the activation can last from 10 min to a few hours.
- Operating Services for Contingency Conditions. These services provide a reserve to face a contingency event (predicted or not) and keep frequency on its normal value. At the same time, they replace other activated reserves so that the system returns to the same level of balance before contingency. There are three types of service:
  - Spinning Reserve. It is defined as unloaded generation synchronized to the grid (rotating mass) that can be activated in case there is a frequency deviation caused by a contingency. The definition includes non-synchronized capacity that, by its technical traits, can be connected and activated as quickly as conventional Spinning Reserves. This service activates in less than 10 min from the contingency (normally much faster) and lasts up to 2 h.
  - Non-spinning Reserve. This resource has the same target as Spinning Reserve, but it includes offline resources that can connect and be fully active within 10 min and work for up to 2 h.

– Replacement or Supplemental Reserve. This service acts to restore Spinning and Non-Spinning reserves to the status they had before the contingency. The service must be active 30 min after the contingency.

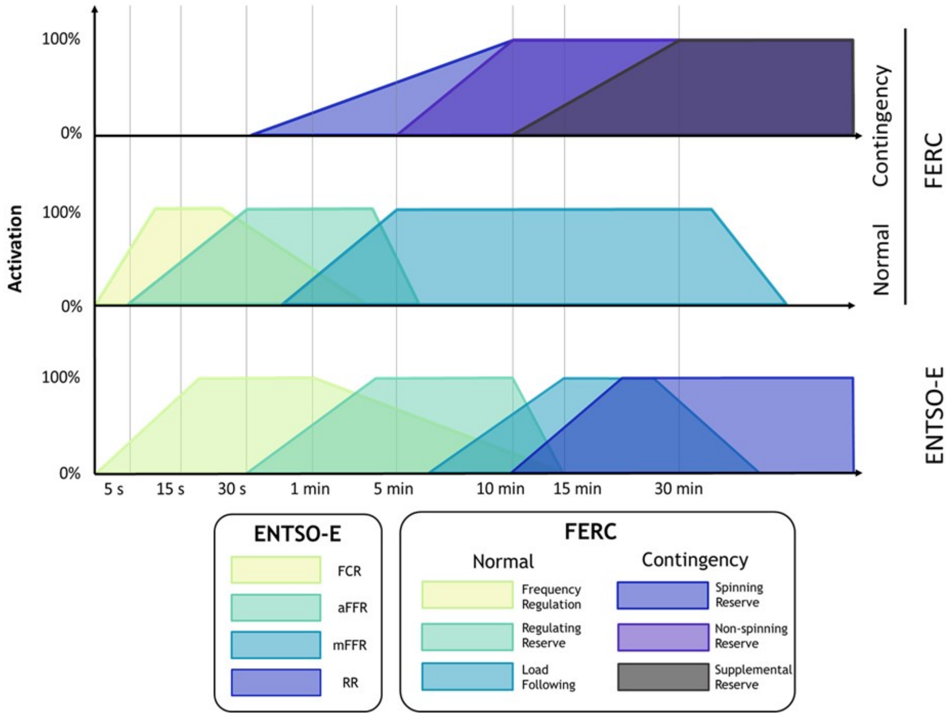

Figure 2.1.1: Comparison of European Network of Transmission System Operators for Electricity (ENTSO-E) and Federal Energy Regulatory Commission (FERC) nomenclature. FCR: frequency containment reserve; aFRR: automatic frequency restoration reserve; mFRR: manual frequency restoration reserve; RR: replacement reserve.

2.1.2.2 Ancillary Services Parameters

Table 2.1.1 describes the most important parameters that characterize a general AS defined in [25], which Figure 2.1.2 summarises. These listed parameters consider times, power requested, and characteristics as the type of activation.

Table 2.1.1: List of Ancillary Services parameters.

Parameter	**Symbol**	**Description**
Character (optional/compulsory)	n/a	In optional services, Balance Service Providers (BSP) decide to provide or not the service. In such cases, BSPs normally will not receive any compensation if they chose not to activate their resources. Compulsory services force BSPs to provide reserve when asked, either by contract or as a binding auction result, resulting in fines for the non-provision of it.
Type of activation (manual/automatic)	n/a	Manual activation is done after the Transmission System Operator (TSO) sends a request so that operators apply the correspondent protocol to provide the reserve needed. This type of activation is frequent among services with long T_{RES} (several minutes or more), such as RR and Supplemental Reserve. Automatic activation is in place for faster responses (a few seconds to a few minutes).
Moment to present bids	n/a	Agents present bids up to a certain time before the action occurs (daily, weekly, monthly, yearly, or only when the TSO requires additional reserve). Yearly, monthly, and weekly auctions tend to have associated capacity payments. Sometimes, BSPs can modify bids up to real time.
Notification time	T_{NOT}	Moment when the TSO asks to provide the action
Maximum Response Time	T_{RES}	The maximum admissible time between the TSO's notification and the BSP's full activation. BSP achieves full activation when it provides all the requested reserve.
Ramp time	T_{RAM}	Time taken by the BSP to modify its power (either demand or production), from the beginning of the modification until the achievement of the targeted power. Many AS programs do not have any specific T_{RAM} but are only dependent on T_{RES} .
Maximum duration	T_{MAX}	The maximum time that the TSO can ask to sustain the action.
Minimum capacity	ΔP_{min}	Minimum reserve that a BSP has to be able to provide to participate in an AS program. It tends to have the same value as the minimum size of a bid to be accepted in a market, but not always.
Type of payment (capacity/energy/security of supply).	n/a	There are three ways to remunerate these services. A capacity payment that rewards based on the amount of power that a BSP has available during a certain period. This price has monetary units per MW and time period. This reserve can be total or partially activated in case the TSO requests it, but the BSP obtains the payments regardless of its activity during the imbalance. An energy payment values the amount of energy provided by the BSP during service activation. This price has monetary units per MWh. Security of supply payment guarantees the energy supply without interruptions to the agents.

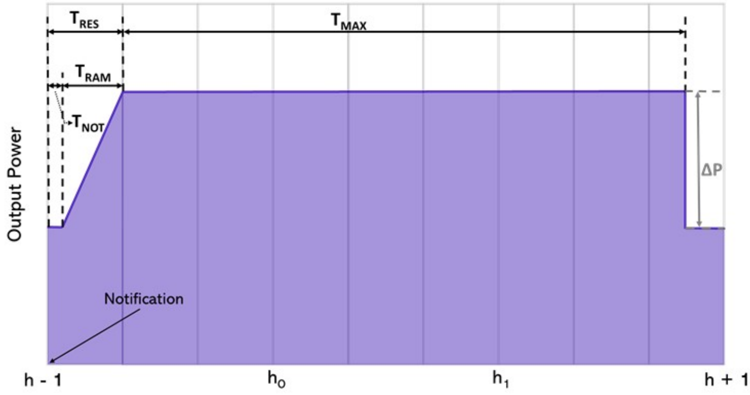

Figure 2.1.2: Representation of an ancillary service's requirements. T_{RES}: maximum response time; T_{MAX}: maximum duration; T_{RAM}: ramp time.

2.1.2.3 Demand Response parameters

The most significant parameters that characterize a general DR product are described in Table 2.1.2. Technical requirements are also represented in Figure 2.1.3

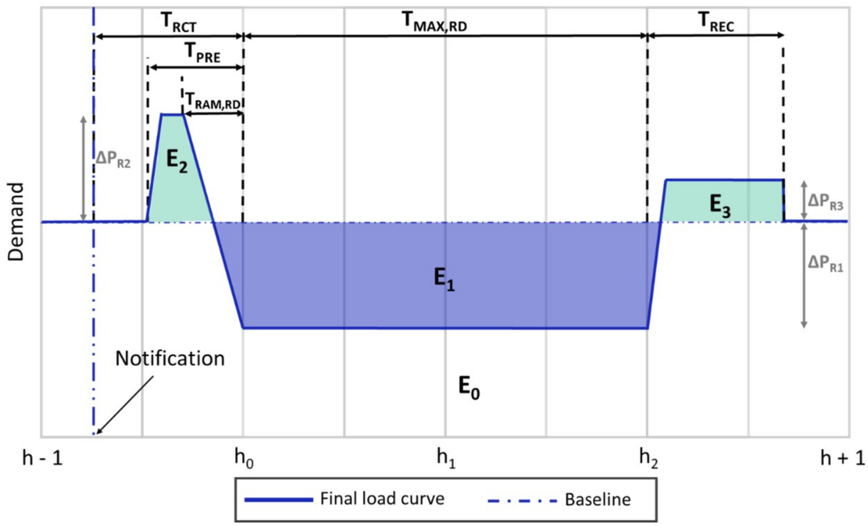

Figure 2.1.3: Representation of a DR action and its main parameters.

Table 2.1.2: List of Demand Response (DR) parameters.

Parameter	Symbol	Description
Flexible power	ΔP_R	This is the amount of power that the Demand Response Providers (DRPV) can increase and/or decrease during a response action by managing loads or turning off/on their energy sources. E_1 represents this parameter in the figure and serves to calculate the energy payment.
Maximum length of the action	$T_{MAX,RD}$	This parameter represents for how long the DRPV can keep the response action working, the maximum time during which the DRPV can modify its demand from the baseline.
Time of reaction	T_{RCT}	It represents the minimum time that the DRPV needs to achieve full activation of the response action
Extra power before the flexibility action	ΔP_{R2}	Additional maximum power that the DRPV may request before the response action to prepare its facility. Not all DRPVs need extra power before the action takes place. E_2 represents this extra energy consumed during the preparation.
Extra power after the flexibility action	ΔP_{R3}	Additional maximum power that the DRPV may request once the response action is overdue to technical reasons. Not all DRPVs need extra power after the action takes place. E_3 represents this extra energy consumed during the recovery.
Duration of the preparation	T_{PRE}	The portion of T_{RCT}, during which the DRPV demands ΔP_{R2}.
Duration of the recovery	T_{REC}	Time after the response action during which the DRPV demands ΔP_{R3}.
Flexible energy	E_1	This is the amount of energy that the DRPV can consume or stop consuming during a response action by managing loads or turning off/on their energy sources. It serves to calculate the energy payment.
Extra energy before the flexibility action	E_2	Additional energy that the DRPV may request before the response action to prepare its facility. Not all DRPVs need extra energy before the action takes place.
Extra energy after the flexibility action	E_3	Additional maximum energy that the DRPV may request once the response action is overdue to technical reasons. Not all DRPVs need extra energy after the action takes place.
Ramp time	$T_{RAM,RD}$	The portion of TRCT used by the DRPV to adapt its consumption from the baseline to the targeted power. It is the time taken from the start of demand modification until the achievement of the targeted power.
Operation times	n/a	Times slots when the DRPV declares that its services can be activated. This can include schedules depending on the day (weekday or weekend) or available days within a season, according to the technical flexibility of the DRPV. Also known as the “availability window”.
Minimum time between interruptions	n/a	The time that the DRPV needs to take between two consecutive actions. The time between the end of one action and the beginning of the next one.
Baseline	n/a	Load curve that the DRPV would have theoretically had if it had not performed a response. It is crucial for the calculation of the energy payment received by the DRPV. This parameter must be exhaustive and clear, and the contract between the two parties must reflect it. ENERNOC presents different methodologies to calculate the baseline [30].
Type of activation	n/a	Agents activate DR either automatically or manually, depending on DRPV’s flexibility and technical resources. Actions can have a manual activation and still be mandatory for the DRPV.

2.1.2.4 Assessment Methodology

Figure 2.1.4 shows the developed methodology to study and compare the different DRP. The first action of the developed methodology consists of the gathering and filtration of general information to construct a list of DRPs. For this first gathering of information, general reports serve as a start. DR works not only as a balancing tool but also in the spot markets [15]; these programs are out of the scope of this analysis. Here, the methodology discards all the products that do not provide AS.

The information needs a common structure, but products coming from several TSOs have different parameter names when in fact, they represent the same concept due to the lack of standardization [31]. To homogenize this series of products, the methodology uses the same terms for the same concept, regardless of their original names. A list of DR parameters like the one presented in Section 4.2.3 has this purpose. The output of this process is a list of metricized products.

Once all products are characterized, it is possible to classify them according to the criterion of interest. For instance, depending on the T_{RCT}, the method sets several intervals of time and places each product on its corresponding rank. In our case, the classification follows the ones used by FERC and ENTSO-E. First, we check what kind of services both nomenclatures consider and how they define each of them. After this, we compare our list of metricized products with these definitions so that it was effortless, for instance, to classify the European products under the American nomenclature and vice versa.

After the classification, the method continues with a review of the success or failure of every product and relate it to their traits and circumstances. The output of this analysis is a series of conclusions regarding what aspects influence the effective participation of DR in the AS and to what extent.

2.1.2.5 Consulted Documents

Regarding the search for DR products, there are several reliable sources to start with; depending on the country of interest, the information is normally provided by the TSO or market operator. For a more general view, in the case of the European countries, there is an extensive report prepared by the Smart Energy Demand

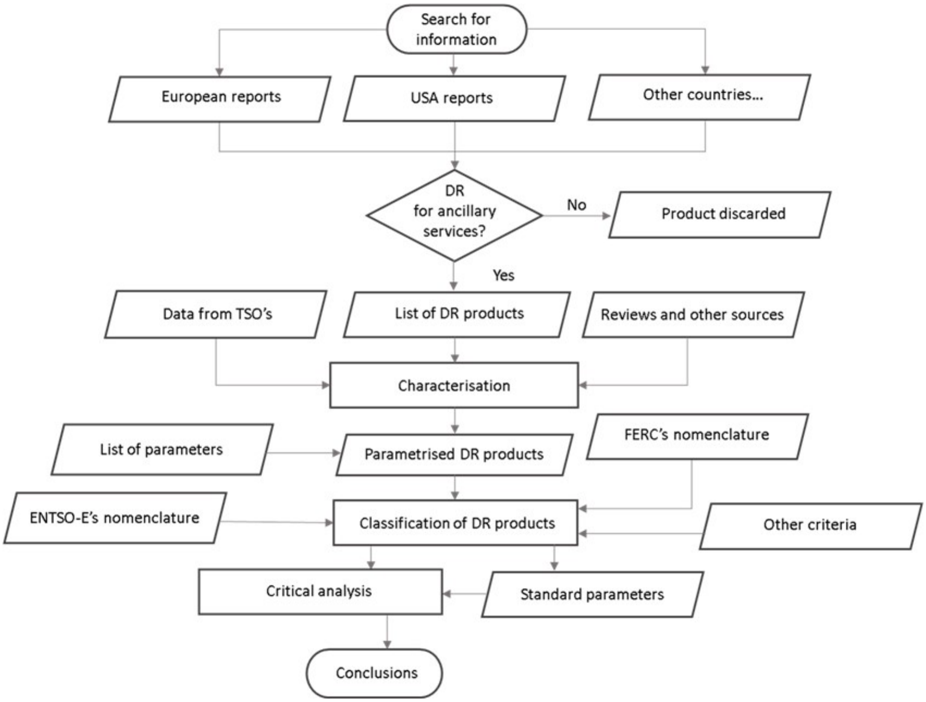

Figure 2.1.4: Proposed methodology.

Coalition [32] with information about DR programs from 18 different European countries. However, this report came out in 2017, and since DR is rapidly growing in Europe [15], some of its information is already out of date.

The Regulatory Assistance Project prepared in 2013 a report which presents the history and trends of DR in the United States [33]. Another source that is interesting and more updated is the Independent System Operator and the Regional Transmission Organization Council's document referenced in [34].

The Asia-Pacific region was reviewed by [35]. In some cases, especially when a country's electricity system has been recently open to DR, there may not be enough information to correctly characterize its products. Normally, in these countries, data is very short and/or has no English translation. Another problem that can be even harder to tackle is restricted or private information. Some TSOs prepare reports with technical and economic data on DR regularly, but they are only available for market participants. In this case, unless the TSO allows the researchers to access such reports, it will be harder to identify the state of DR in these countries. In this case, the best possible action seems to be to use a secondary source, such as general reports or reviews prepared from these primary sources.

Finally, DR information becomes rapidly out of date due to the quick evolution of electricity markets. In some cases, either because of imperfect market design, unexpected reactions of the stakeholders, or incapacity to encourage demand participation. Consequently, TSOs may want to modify their rules or even withdraw them from the market. Additionally, prices and the share of demand side on AS may widely vary from one year to another. To avoid using outdated information, we searched for the most recent reports and reviews. Furthermore, when it was possible, we contrasted data from international reviews with numbers in reports prepared by each TSO. In some cases, we found recent data on prices and energy volumes, but also old data on market rules and procedures that are three to six years old. In front of these situations, we assume that rules have stayed unchanging during the last years, adding some uncertainty to the analysis.

2.1.3 Demand Response Around the World: Main Application

2.1.3.1 Europe

Many European countries opened most of their AS to DR with the same rules as generation resources to compete to provide capacity. Many TSOs adjusted the technical requirements of these services to match what DRPVs can do. In many other cases, TSOs only developed special programs for Demand Side Resources (DSR) to assure DR participation in front of strong competitors or too demanding technical requirements. At the end of this section, Tables 2.1.3, 2.1.4, 2.1.5 and 2.1.6 contain the main parameters that characterize the different programs open to DR in European AS markets.

Belgium In Belgium, both FCR and mFRR are open to DR. Moreover, there is an Interruptible Service especially designed for load curtailment and a Strategic Reserve, in which DSR represented 10% of total reserves in 2017 [32]. However, AS exclude residential consumers even if they could provide more than 4700 MW of reserve [32]. The Belgian mFRR has two different resources. On the one hand, monthly bids on the market of Reserved Volumes, where the service only has an availability payment, and technical requirements vary between Standard R3 and Flex R3 product. The DRPV can choose which kind of product to offer according to their flexibility. Successful bidders in these auctions acquire the responsibility to respond under TSO's request subject to fines. On the other hand, DRPVs can present bids continuously on the market of Non-Reserved Volumes, up to 15 min before the service activation, to obtain an energy payment [36]. Regarding the Interruptible Service, as in the case of Reserved Volumes, there are three products with different requirements. In all cases, the maximum response time (T_{RES}) has the same value, but the maxi-mum duration (T_{MAX}) is very different from one product to another [32]. This principle makes it easier to match what DSRs can do with what TSO needs.

Denmark DR activity in Denmark remains low, even if all electricity markets are open to it. A generator-based design and the scarce need for reserve in this country may be the main reasons for this slow development. Nevertheless, the constant growth of renewable energies will likely increase the necessity of DR to assure the system's reliability. Denmark divides its power system into two zones. DK1, on the West, is part of the joint continental FCR market, while DK2, on the East, is part of the Nordic synchronous area. Therefore, FCR functions differently according to the corresponding zone [37]. On the contrary, mFRR rules are the same, regardless of the zone of application. In this service, bids can be upwards or downwards, but a combination of both is not acceptable. The service is remunerated with an energy payment whose minimum (or maximum, for the downwards re-serve) price is the electricity price in the spot market.

Finland All AS accept DR in Finland, although its participation varies among the different services. For instance, the DR share in aFRR was absent in 2018, while in mFRR it reached 400 MW. Close to the aFRR's case, DR reserves on FCR added only 4 MW [38]. Some of the most relevant barriers identified are lack of economic benefit, absence of a communication standard, and low motivation for consumers to be involved in load management [39]. Still, around 1800 MW of loads can be remotely controlled. This represents more than 10% of peak demand in Finland, which in 2014 reached 14,200 MW. FCR is procured through an annual and hourly market, in both cases paid with an availability payment only. In the annual auction, BSPs receive the price for their reserves, which will vary from one day to the next one, and the Finnish TSO acquires all usable capacity at the price determined in the auction. On the other hand, other BSPs can present bids with their reserves daily, and the TSO purchases only the amount needed [40]. There is a Strategic Reserve used to compensate for higher demand in winter. Technical requirements are like mFRR, and the remuneration is agreed upon in a private contract. In 2018, DR reached 22 MW of capacity in this service [38].

France France was one of the first European countries to open its electricity markets to DR. In 2003, industrial consumers were already able to offer their flexibility on the balancing mechanism. In 2011, mFRR opened to DR, and in 2018, it accounted for more than 50% of the Rapid Reserve. Since 2014, industrial consumers larger than 1 MW have got the chance to participate in FCR [41]. The energy used in the French balancing mechanism, all provided by DR reached 22 GWh in 2018, and the maximum DR reserve activated simultaneously exceeded 1000 MW [41]. There is also a mechanism in France called "Demand Response Call for Tenders", designed to promote DR development. It is closed for conventional means of self-generation, and consumers already benefited from the Interruptible Load service. The total capacity provided by this mechanism reached 2900 MW in 2020. In aFRR, BSPs have three products, each of which has its own T_{RES} requirement. Bids in this service require symmetry and activate at the pro rata of the BSP's obligation. On the other hand, mFRR and RR have very similar traits, with the biggest difference in T_{RES} and the price of the payments, being RR cheaper as it is a less demanding service (higher T_{RES}).

Germany Germany has a strong industrial sector that has a potential of 6.4 GW DR capacity available for 1 h at least [42], with DR investments around 10 times smaller than capacity provided by traditional generation, while operation and maintenance costs are dependent on each manufacturing process [43]. Estimations show that the tertiary sector could provide up to 3.8 GW [44]. FCR, aFRR, and mFRR services are all open to DR, and there is an Interruptible Service especially designed for DSRs. aFRR bids are weekly presented in a joint market with Austria. The service requires full availability for 12 h a day and a minimum size of the bid of 5 MW (1 MW if only one bid is presented) [45], but these requisites will be modified soon to fit more DR to AS [32]. mFRR auctions occur only during week-days, and availability is required for 4 h instead of 12. It is possible that coming changes would make new aFRR's design more like current mFRR's.

Ireland The rapid growth of wind energy in Ireland has created an increasing need for flexibility, so the Irish TSO works on specific programs to take advantage of DSRs. In 2017, 19 DRPVs were registered to provide a reserve, with a total capacity of 362 MW [46]. Demand Side Units (DSUs) are DRPVs participating in the capacity market, with a reserve no smaller than 4 MW that can be aggregated from smaller units, not subject to further size limitations. These units are asked to manually modify their load curve with a T_{RES} of 1 h, and they will be rewarded with an annual capacity payment since they must be available any day, at any time. Powersave is a service designed to reduce load when total demand is close to the available generation capacity. DRPVs with a reserve no smaller than 0.1 MW can participate during working days in exchange for an energy payment [32].

The Netherlands Most of the AS in the Netherlands are open to DR. In 2017, the Dutch TSO purchased 1.5 GW of capacity provided by DSRs, with a total activation of 500 GWh. Distribution System Operators and retailers are starting to see demand management as an attractive business [32]. One particularity of aFRR in the Netherlands is its activation logic. When the TSO detects an ordinary frequency deviation, it activates the reserves by merit order, so that only those BSPs who presented the cheapest bids are activated. However, if the TSO detects an "extraordinary" deviation, it will activate all resources at the pro rata of the BSP's obligation to achieve the biggest possible power ramp [47]. This solves the contingency faster, and BSPs get a higher energy payment. There is also a capacity payment determined in an annual auction. The Dutch mFRR services treat upward and downward reserves separately. A single unit can only present one type of reserve, while groups of BSPs can participate in both markets at the same time. Consumers with a contracted power of 60 MW or higher must present their reserves in mFRR. T_{RES} and the calculation of the price for the energy payment are different for upward and downward reserves. Such prices depend on the spot market price.

Sweden Sweden is divided into four zones, SE1, SE2, SE3, and SE4. Sometimes certain parameters of AS vary within those zones. Sweden is a country with large water resources, and its capacity reserves come from northern hydroelectric plants. Some thermal plants also activate when there is a congestion problem or during peak load periods. Swedish FCR, aFRR, and mFRR are all open to DR and aggregation, but sometimes technical requirements prevent many DRPVs from participating in them. For instance, the minimum capacity (ΔP_{min}) is 5 MW in SE4 and 10 MW in the rest of the country, making it difficult for most consumers to meet such requirements and enter the mFRR market. The service has an energy payment only [32]. There is a Strategic Reserve to be 25% provided by DSRs. The technical requirements of the Strategic Reserve are like mFRR's, but the service has a capacity and an energy payment.

Switzerland In 2013, Switzerland became one of the most advanced countries in DR development in Europe. The legislation clearly defines BSP's roles and mitigates costs and risks. The closure of nuclear power plants and water scarcity may increase the need for flexibility in Switzerland in the coming years [48]. All AS are open to DR and aggregation, and in 2017, DR provided 3 MW of reserve in FCR, 10 MW in aFRR, and 49 MW in mFRR [32]. aFRR in Switzerland has some particularities. Bids take place in a weekly auction and must be symmetric, while the activation occurs at the pro rata of the BSP's obligation. ΔP_{min} is 5 MW, and the remuneration is based on a capacity payment dependent on the weekly auction and an energy payment dependent on the spot market price [49]. Bids for mFRR take place weekly and daily. The weekly auction accepts bids for any hour during the week, while the daily auction has six blocks of 4 h. Products do not have to be symmetric in this service, but they must be larger than 5 MW too. T_{RES} depends on the direction of the reserve (upwards or downwards) and the type of auction [50].

United Kingdom Most of the British ASs are open to DR and aggregation, although its participation remains low in some of them. The British TSO adjusted several market rules and requirements to increase this participation that had as main barriers to the complexity and excess of regulatory changes [32]. Demand Turn Up is a service designed to decrease generation or increase consumption in times of low demand and high renewable generation. The activation of this service can only be done within a certain schedule, and T_{RES} and T_{MAX} do not have fixed values but are based on what each BSP can offer. In 2018, 115 MW of reserve provided this service, with total usage of 1465 MWh. Short-Term Operating Reserve (STOR) used to be the most important program in the UK, but decreasing prices have discouraged many DRPVs from participating in it. This service is like ENTSO-E's standard Supplemental Reserve. There are three different products within the STOR program, with technical traits and a reward based on capacity and an energy payment. Annual auctions of BSPs determine prices for the next seasons [51]. The Fast Reserve demands a ΔP_{min} of 25 MW, where only very large consumers can access it and compete with generators and storage units. Rapid Reserve's technical requirements make it like aFRR, and the service rewards three concepts: capacity, energy, and nomination. Nomination payment depends on the time provided and not on actual activation nor capacity provided [52, 53].

Table 2.1.3: FCR programs in Europe open to DR: Main parameters.

Product / Service (Country)	**Type of Activation**	T_{RES}	ΔP_{min}	T_{MAX}	**Type(s) of Payment**
RR (France)	Manual	30 min	10 MW	90 min	Capacity and energy
Demand Turn Up (United Kingdom)	Manual	Variable, Average: 6h	1 MW	Variable, Average: 4.5h	Energy only
Short-Term Operating Reserve (STOR) (United Kingdom)	Manual	Variable, 20 min–4h	3 MW	n/a (min: 2h)	Capacity and energy
Interruptible Service (Belgium)	Manual	15 min	5 MW	4-12 h	Capacity only
Strategic demand reserve (Belgium)	Manual	90 min	1 MW	4 h	Capacity and energy
FCR (Finland)	Automatic	3 min	0.1 MW	n/a	Capacity and energy
FCR (Sweden)	Automatic	3 min	0.1 MW	n/a	Capacity and energy

Table 2.1.4: aFRR programs in Europe open to DR: Main parameters.

Product / Service (Country)	**Type of Activation**	T_{RES}	ΔP_{min}	T_{MAX}	**Type(s) of Payment**
aFRR (France)	Automatic	60–100 s	1 MW	n/a	Capacity and energy
aFRR (Germany)	Automatic	5 min	5 MW	n/a	Capacity and energy
aFRR (The Netherlands)	Automatic	>30 s	1 MW	15 min	Capacity and energy
aFRR (Sweden)	Automatic	120 s	5 MW	n/a (min 1h)	Capacity and energy
aFRR (Switzerland)	Automatic	200 s	5 MW	n/a	Capacity and energy
Rapid Reserve (United Kingdom)	Automatic	2 min	25 MW	15 min	Nomination, capacity, and energy

Table 2.1.5: mFRR programs in Europe open to DR: Main parameters.

Product / Service (Country)	**Type of Activation**	T_{RES}	ΔP_{min}	T_{MAX}	**Type(s) of Payment**
mFRR-Reserved Volumes (Belgium)	Manual	15 min	1 MW	2–8 h	Capacity only
mFRR-Non-Reserved Volumes (Belgium)	Manual	15 min	1 MW	2–8 h	Energy only
mFRR (Denmark)	Manual	15 min	5 MW	n/a	Energy only
mFRR (Finland)	Manual	15 min	5 MW	n/a	Capacity and energy
Strategic Reserve (Finland)	Manual	15 min	10 MW	n/a	According to contract
mFRR (France)	Manual	13 min	10 MW	2 h	Capacity and energy
mFRR (Germany)	Manual	15 min	1MW	4 h	Capacity and energy
mFRR (The Netherlands)	Manual	10–15 min	20 MW	1 h	Energy only
mFRR (Sweden)	Manual	15 min	10 MW	n/a	Energy only
Strategic Reserve (Sweden)	Manual	15 min	5 MW	n/a	Capacity and energy
mFRR (Switzerland)	Manual	15–35 min	5 MW	n/a	Capacity and energy

Table 2.1.6: RR programs in Europe open to DR: Main parameters.

Product / Service (Country)	**Type of Activation**	T_{RES}	ΔP_{min}	T_{MAX}	**Type(s) of Payment**
Interruptible Service (Belgium)	Manual	15 min	5 MW	4–12 h	Capacity only
Strategic demand reserve (Belgium)	Manual	90 min	1 MW	4 h	Capacity and energy
RR (France)	Manual	30 min	10 MW	90 min	Capacity and energy
Demand Turn Up (United Kingdom)	Manual	Variable, Average: 6h	1 MW	Variable, Average: 4.5h	Energy only
STOR (United Kingdom)	Manual	Variable, 20 min–4h	3 MW	n/a (min: 2h)	Capacity and energy

2.1.3.2 North America

Many North American systems allow DR to access AS markets with similar rules than generation resources to compete to provide capacity. Several TSOs adjusted the technical requirements of these services to match what DRPVs can do. In many other cases, TSOs developed only special programs for DSRs to assure DR participation in front of strong competitors or too demanding technical requirements. At the end of this Section, Table 2.1.7 and 2.1.8. contain the main parameters that characterize North American AS for DR.

California Independent System Operator (CAISO) California Independent System Operators (CAISOs) DRPs participate directly in the region capacity market jointly with the other products [54, 55], and California DSOs have maintained traditional load disruption and load shifting programs [56]. California has 1612 MW of DR resources in economic programs that reduce the load based on anticipated offset prices in real-time markets [57]. The most relevant DRP in the region is a Load Following Service, which is part of the CAISO regulator. As in most of the country's products, aggregation is allowed. The remuneration is based on a capacity payment where CAISO, in accordance with clients, must agree when they have to offer the service. In turn, and depending on the agreement signed, they are notified in advance in the Day-Ahead Market (13:00), and in Real Time (based on the offer options): 2.5 min, 22.5 min, 52.5 min. The T_{REC} depends on the parameters of the resources used. Other relevant products of the electricity system have also been developed from different TSOs and DSOs in California. The Pacific Gas and Electric Company (PGE), Southern California Edison Company (SCE), and San Diego Gas and Electric Company (SDGE) have also specific programs used during critical periods of demand, contributing to load shifting.

Electric Reliability Council of Texas (ERCOT) The Electric Reliability Council of Texas (ERCOT) has several DRP that participate in AS like Non-Spinning Reserve Services, Supplemental Reserve Services (Climate-sensitive, Non-climate-sensitive, and Load Resource), and Regulation Services [58, 59]. Due to its climatic conditions and particularities, ERCOT has a different range of DRP regarding if they occur on a normal basis or under specific climatic conditions. The Non-Climate-sensitive products can be identified as Non-Spinning Reserve and Supplemental Reserve, which features a ΔP_{min} of 100 kW and a minimum reduction amount of 100 kW for both T_{RAM} options, 10 min or 30 min. Remuneration is in the form of security of supply, the T_{MAX} will last 12 h, and the period in which customers must offer the service will be established based on the service paid time [60]. The

Climate-sensitive products are similar to the previous ones, with the main differences that Climate-sensitive programs are used during the peak loads in summer and winter seasons, have a ΔP_{min} of 500 kW with a minimum reduction amount of 500 kW and a shorter T_{MAX} of 3 h. The Non-Spinning Reserve Service "Load Resource" has similar characteristics as the Non-Spinning Reserve/Non-Climate-sensitive service, with the differences that aggregation is not allowed, the T_{MAX} where the period in which customers must offer the service will be an agreed interval is shorter and the T_{RAM} is 10 min (Verbal), 30 cycles (Retransmission) [61]. The Regulation Service does not allow aggregation, the remuneration will be in the form of security of supply, and the period in which customers must offer the service will be an agreed interval [61].

New England Independent System Operator (NE-ISO) The New England Independent System Operator (NE-ISO) spent many years designing the first installed capacity market in the country [62]. With the adoption of the direct capacity market, DR could participate directly in the market, and two capacity programs were established: real-time demand response and real-time emergency generation. Real-time demand response refers to a reduction in energy use at an end-use customer's facility, while Real-time Emergency Generation refers to a customer-controlled on-site generator, which has environmental permits that limit its operation to "emergency" hours when the system operator calls them to avoid lowering the load. The NE-ISO offers several programs that are active today. Regarding AS managed by the NE-ISO, Regulation Services are the main activity to handle demand flexibility, and they include seasonal and no seasonal products [63]. The Regulation service products have a common ΔP_{min} of 100 kW, a minimum reduction amount of 1 kW. The period in which customers must offer the service could be seasonal and in peak hours, in summer between June and August (14:00 to 17:00) and in winter from December to January (18:00 to 19:00) or in summer between June and August and in winter from December to January, on non-holiday days. The notification of the action is defined by market regulators, which inform the members of the pro-gram some months or years in advance on when they must provide the service. Therefore, the contract includes a capacity payment on an annual basis [64, 65].

Midcontinent Independent System Operator (MISO) The Midcontinent Independent System Operator (MISO) is a TSO responsible for managing 180 GW of installed power to supply around 670 TWh of electricity to 42 million people each year [66]. MISO distinguishes between two types of DRPV. Type I supplies a fixed reserve by load curtailment only, and it does not have generation resources. Type II supplies a continuous range of reserve through load curtailment or self-generation [67]. Regarding AS managed by MISO, Regulation, Spinning Reserve, and Supplementary Reserve are all open to DR, with a common ΔP_{min} of 1 MW. Regulation is only open to DRPV type I and requires a very demanding T_{RES} (4 s). BSPs must respond automatically to deviations in frequency and provide both upwards and downwards reserve [68]. Spinning Reserve and Supplementary Reserve are open to DRPV type I and type II. Any DRPV qualified for Regulation is qualified for Spinning Reserve too, and any DRPV qualified for Spinning Reserve is also qualified for Supplementary Reserve [68]. This is due to the respective technical requirements of each service since Regulation is the most demanding while Supplementary Reserve is the least.

New York Independent System Operator (NYISO) The New York Independent System Operator (NYISO) manages its Installed Capacity Market to guarantee the adequacy of the resources for its territory of a state with a maximum load of just over 33,000 MW [69]. The operator of the New York Independent System (NYISO) offers four DR programs that could be identified as Spinning Reserve Service, Regulation Service, and two Supplemental Reserve Services [70]. The DRPs of Spinning Reserve Service, the first Supplemental Reserve Service, and the Regulation Service have a ΔP_{min} of 1 MW, a minimum reduction amount of 1 MW. The remuneration is economic (based on the capacity provided) in the three programs, the action lasts the established interval (between NYISO and the agent), and the period in which the clients must offer the service is continuous. Prior notification is made in the Daily Market (11:00) and in real time (75 min, 5 min if Regulation Service). The second Supplemental Reserve Service has a ΔP_{min} of 100 kW (per zone), a minimum reduction amount of 100 kW (per zone). Remuneration is in the form of security of supply, the action will be during the window of action established by the program, and the period in which customers must offer the service will be seasonal. It is advisable to make a prior notification in the Daily Market, and a prior notice will be made on the day of the action (120 min) [70].

Pennsylvania-New Jersey-Maryland Interconnection LLC (PJM) The Pennsylvania-New Jersey-Maryland Interconnection (PJM) manages a total of 13 states with more than 65 million people. It also has an installed generation capacity of 180 GW, and the total energy delivered in 2018 was 807 TWh [71]. There are mainly three AS open to DR: Day-Ahead Scheduling Reserve, Synchronized Reserves, and Regulation, in which DRSs can provide up to 25%, 33%, and 25% of the total capacity, respectively [72]. Day-Ahead Scheduling Reserve has the traits of Supplementary Reserve. In all cases, ΔP_{min} is very accessible (0.1 MW), but DRPVs must send information regarding their consumption every 1 min [73].

Regarding Synchronized Reserves, DRPVs present bids in a Day-Ahead or in an Intraday market. In 2017, the average DR hourly capacity activated was 110 MW, from which 76% were industrial loads, while the participation of residential loads remained very limited. On the contrary, regulation, which activates as soon as possible, had a remarkable share of residential loads. 79% of DSRs in this service in 2017 came from water heaters, and 9% came from batteries. The average DR hourly capacity provided was 10 MW.

Canada—Independent Electricity System Operator (Ontario) The Canadian State of Manitoba belongs to MISO's electricity system, so all its programs and market rules apply in this State too. On the other hand, Alberta Electricity System Operator contracted 150 MW of DR in 2011 with Enel X, and now, a new advance on DR development as reserves is being contracted by Enel X on the basis of 10 to 60 min contracts with particulars through bids on the day ahead [74]. Apart from Ontario, the rest of the States are still vertically regulated. Independent Electricity System Operator (IESO) launched the first Demand Response auction in 2015. Before that, IESO had secured up 70 MW of DR through a competitive procurement in which bids as small as 1 MW were accepted. The project intended to assess DSRs ability to provide ancillary services. The loads participated in one program [75]. DRPVs commit to curtailing their loads on a day-ahead or four-hours ahead basis, acting like a Supplemental Reserve. IESO manages an annual DR auction in which DRPVs present bids with the capacity they are willing to provide for a defined period. DR offers are expressed in $/MW month or year, and successful providers will receive a payment according to the capacity awarded and the resulting clearing price [76].

Table 2.1.7: Normal FERC programs in North America open to DR: Main parameters.

Product / Service (Country)	**Type of Activation**	T_{RES}	ΔP_{min}	T_{MAX}	**Type(s) of Payment**
Load Following (CAISO)	Manual	10 min	0.5 MW	n/a	Capacity only
Regulating Reserve (ERCOT)	Manual	Immediate	0.1 MW	n/a	Security of supply
Regulating Reserve (NE-ISO)	Automatic	Immediate	0.1 MW	n/a	Capacity only
Regulating Reserve (MISO)	Automatic	4 s	1 MW	60 min	n/a
Regulating Reserve (NYISO)	Automatic	Immediate	1 MW	n/a	Capacity only
Regulating Reserve (PJM)	Automatic	Immediate	0.1 MW	n/a	Capacity and energy

Table 2.1.8: Contingency FERC programs in North America open to DR: Main parameters.

Product / Service (Country)	Type of Activation	T_{RES}	ΔP_{min}	T_{MAX}	Type(s) of Payment
Spinning Reserve (MISO)	Manual	10 min	1 MW	n/a	n/a
Spinning Reserve (NYISO)	Manual	10 min	1 MW	n/a	Capacity only
Non-Spinning Reserve (ERCOT)	Manual	10 min	0.1 MW	12 h	Security of supply
Non-Spinning Reserve (ERCOT)	Manual	10 min	0.5 MW	3 h	Security of supply
Non-Spinning Reserve (ERCOT)	Manual	10 min	0.1 MW	3 h	Security of supply
Supplemental Reserve (ERCOT)	Manual	30 min	0.1 MW	12 h	Security of supply
Supplemental Reserve (ERCOT)	Manual	30 min	0.5 MW	3 h	Security of supply
Supplementary Reserve (MISO)	Manual	10 min	1 MW	n/a	n/a
Supplemental Reserve (NYISO)	Manual	30 min	1 MW	n/a	Capacity only
Supplemental Reserve (NYISO)	Manual	2 h	0.1 MW	n/a	Capacity only
Day Ahead Scheduling Reserve (PJM)	Manual	30 min	0.1 MW	n/a	n/a
Synchronized Reserves (PJM)	Manual	10 min	0.1 MW	30 min	n/a

2.1.3.3 Asia and Oceania

In Asia and Oceania, systems partially allow DR to access AS markets to compete with generation resources. Some TSOs adjusted the technical requirements of these services to match what DRPVs can do. But mostly, TSOs developed special programs only for DSRs, to assure DR participation in front of strong competitors or too demanding technical requirements. At the end of this Section, Table 2.1.9 contains the main parameters that characterize Asia and Oceania AS for DR.

Australia Australia has a highly branched and poorly meshed electrical network that suffers from imbalances that dramatically increase prices [77]. One of the measures taken to carry a decentralization of energy production is to invest in flexibility to provide AS, which represents an opportunity to demand [78]. The service that most concerns DR is the Frequency Control AS, which Australian Energy Market Operator (AEMO) uses to maintain the adequate frequency of the electrical system. There are two types of frequency control in Australia: Regulatory and Contingency. The regulatory control of the frequency presents two programs whose objective is to correct slight drops and rises that may impair the optimal functioning of the system [79]. As for contingency programs, two types exist depending on the ramp of action required by the action, and in FERC's nomenclature, they would be identified as Regulating Reserves and Load Following Services.

New Zealand New Zealand is another country that has been investing in the implantation of renewable energies and monitoring infrastructures [80], and betting progressively on demand flexibility. The first projects were based in the residential sector, which is controlled through monitoring-controlled air conditioning, lighting, and certain household appliances during peak loads [81]. The New Zealand Electricity Authority (NZEA) is the regulatory organization for the country's electricity market and is, in turn, the promoter of different demand-side flexibility pilot projects. NZEA is currently working on defining AS and DR for the country due to the great number of renewable resources installed, which proves great potential for demand flexibility in New Zealand.

China The State Electricity Regulatory Commission (SERC), together with the National Energy Commission (NEC), oversees promoting and implementing projects that provide greater demand flexibility, thus improving the potential of the electric system. Various demand management programs have been implemented by the Chinese government, which focus on administrative and technical measures. Pilot demand management programs have been carried out in four major cities in the country (Suzhou, Beijing, Foshan, and Tangshan) [82]. These programs require an advanced measurement infrastructure (AMI) to measure baseline and consumption in real time and communication devices to inform users of Smart Demand Response (SDR) activities and analyze their reduction commitment [83]. SDR refers to DR products managed automatically by the country's large telematic infrastructure, which is adapted to the needs, prices, and system circumstances. The two most important SDR programs are the Interruptible Loads program and the Direct Load Control program. Both receive the same economic incentive in exchange for energy reduction. The mentioned programs can compare to FERC Supplemental Re-serve Services standards.

South Korea Currently, the effective DR program in Korea is not based on a system of offers but on contracts that decide the incentives, the participation interval, the notification time of the event, etc. However, a bid-based DR program was recently conducted but did not have a major impact [84]. The need for a DSM program is becoming a major problem in Korea and is recognized as a necessary element to solve the demand problem [85]. The load management programs implemented since 2009 in Korea use the regular KPX (Korean Power Exchange) fund bidding system and a voluntary reduction of the summer load, which KEPCO (Korean Electric Power Corporation) coordinates and carries out during the summer holiday period [86]. Coordination of the summer vacation period is used to reduce peak summer demand; its objective is the residential client and the industrial client that surpasses a demand of 100 kW (ΔP_{min}) with an economic incentive. The Load Following Service reduces demand during peak summer afternoon hours are targeted to residential, industrial, and educational customers, who receive an economic incentive that is paid in 30 min rates (T_{MAX}) depending on the power provided. This system contributes to reducing maximum demand, but it will be more difficult to implement since industry labor regularity is more important than the decrease in the price of electricity in an advanced country. Through these satisfactory experiences, South Korea is willing to continue carrying out DR projects and demand flexibility.

Japan The catastrophes that occurred in the country caused the nation to feel threatened by the serious lack of electricity supply. These events sparked the national debate regarding nuclear energy and the approach it should take in the future [87], and one of the measures that were decided to tackle was to encourage the flexibility of the demand for a better insertion of renewable energies. A unique feature of the Japanese approach is the promising role of the business sector, as some of the large Japanese conglomerates such as Toyota, Mitsubishi, Sharp, Toshiba, Fujitsu, Panasonic, NEC Corporation, and Nissan Motors are involved in these projects. Notwithstanding the absence of defined DR programs, due to the massive industry trying to incorporate demand flexibility to their standards, there is great potential for DR in Japan. The main obstacle is found in the massive financing that the deployment of means that the creation of an intelligent network requires; this has been identified as a key barrier for DR [88].

Singapore The Singapore Energy Market Authority (EMA) is responsible for demand easing projects and introduced DR programs to improve competition in the Singapore National Electricity Market (NEMS). Consumers can participate directly or through DR retailers or aggregators. The Load Following Service establishes that all customers who can offer a ΔP_{min} of 0.1 MW for half an hour (T_{MAX}) can participate. Consumers participating in the program share a third of the savings from lowering electricity prices as incentive payments, up to the limit on wholesale electricity prices. Registered consumers can temporarily provide the required reduction by turning off non-critical equipment, reducing HVAC or pumping system power, or even using backup generators on-site for short periods.

Table 2.1.9: Asian and Oceania ancillary services open to DR: Main parameters.

Product / Service (Country)	Type of Activation	T_{RES}	ΔP_{min}	T_{MAX}	Type(s) of Payment
Regulating Reserve (Australia)	Manual	60 s	0.1 MW	n/a	Capacity only
Load Following (Australia)	Manual	5 min	0.1 MW	n/a	Capacity only
Load Following (South Korea)	Manual	n/a	0.1 MW	30 min	Capacity only
Load Following (Singapore)	Manual	n/a	0.1 MW	30 min	Capacity only

2.1.3.4 Africa and Latin America

Africa and Latin America are also regions with a great DR potential, but DR programs have not yet been developed. Nevertheless, countries like South Africa are investigating and proving the viability of demand side management and the regulation of electricity demand from the consumer side [89].

2.1.4 Discussion

As it is proved with the range of DR products from different continents presented in this review, many countries all over the world have developed and keep improving their programs to manage DSRs. DR is one of the elements which are going to characterize electricity markets shortly. A new perspective of decentralized systems, based on Renewable Energy, Distributed Energy Resources, Smart Grids, Virtual Power Plant, and Aggregators, is dominating the debate on how future electricity systems should be, and DR is an essential part of such scenario. The sooner and more efficiently DR is properly implemented in a system's electricity market, the sooner its society will benefit from it, so it is recommendable for all regions to start working on programs like these shortly.

As it is stated in Section 4.2.1, neighboring countries tend to have similar market designs when it comes to general services. Commonly they even create their nomenclature so that communication between such countries becomes easier and collaboration is more profitable. On the other hand, every TSO has its strategies to face particular issues of its country and, consequently, it designs specific DR products to manage them. For instance, Strategic Reserve in Finland is specially designed to face high winter demands, and Demand Turn Up in the UK is used in times of low demand and high renewable generation. These services are uncommon in other countries without such issues. Regarding ΔP_{min} in AS programs open to DR, the most repeated value is 1 MW, especially in Europe. Other countries in Asia, America, and Oceania show ΔP_{min} of 0.1 MW in their programs, a more flexible requirement that facilitates DSRs participation on AS. Normally, aggregators can overcome a technical barrier such as this, but with ΔP_{min} of 20 or 25 MW (as found in Europe), even aggregators have difficulties meeting the requirements, and only the largest industrial consumers can access those services.

The search for DR products has revealed a pending global issue: the lack of standardization. TSOs from diverse parts of the world use different terms for similar concepts and design AS in a distinct way. Therefore, it often becomes hard to understand a description of a service from another part of the world. Besides, this fact can make it impossible to apply the same strategy to manage loads in two different countries because technical requirements may not be met in both places. Research shows that countries with standardization, such as European countries or the USA, tend to develop appropriate DR programs more quickly. Nevertheless, even if organizations like ENTSO-E and FERC have worked to develop a regional nomenclature accepted by all nearby countries, the standardization must become global to accelerate DR growth all over the world.

Regarding prices for the remuneration of AS provided by DSRs, the prices presented must be considered as an approximation since most of them vary continuously. All energy prices presented refer to upwards activationS, that is, a curtailment of load or an increment of generation:

- aFRR or Secondary Reserve. In services classified as aFRR, most of the European TSOs offer availability and an energy payment. Prices for the availability concept are around 18 /MW/h (France), 13 /MW/h (Finland), 22 /MW/h (Switzerland) and even 200 /MW/h (the UK). Prices for the energy concept are around 20–40 /MWh (Finland), 70 /MWh over the spot market price (the Netherlands), and 50 /MWh (Switzerland).
- mFRR or Tertiary Reserve. TSOs typically pay successful activationS of mFRR and similar services with an energy payment only, although there are some exceptions. Prices found for the availability payment are around 5-6 /MW/h (Belgium) and 3 /MW/h (Finland). For the energy payment, average prices are around 47 /MWh (France) and 41 /MWh (Sweden). In Denmark and

The Netherlands, the minimum price is the correspondent spot market price, and in the latter, there is an upper limit of 200 /MWh.

- RR or Complementary Reserve. As with the mFRR case, most TSOs pay this service with an energy payment only. Typical prices for the availability payment are around 2 /MW/h (the UK) and 7 /MW/h (Ireland), and for energy, the payment is around 45 /MWh (France), 73 /MWh (the UK), 75 /MWh (Belgium) and between 380–950 /MWh (Ireland).

Rewards tend to be more generous when the service is more demanding. That explains why aFRR normally has two payments, and mFRR and RR typically only have a utilization payment. Prices are also higher when technical requirements are tougher. Energy payments are especially common in Europe, while most DR services in other continents tend to apply for a capacity payment only. Security of supply is an interesting way to remunerate DR actions, although it would only apply to countries with weak and tricky networks, being an insufficient reward otherwise.

DR's success and participation on AS are more common in services with high T_{RES}, such as mFRR and equivalents, but consumers are getting involved in FCR and aFRR gently. In the USA most of the services characterized are equivalent to the spinning reserve, but there are also many products designed to be triggered immediately, probably due to the earlier use of DSRs to provide AS.

DR's success is dependent on several factors, such as load traits (residential, industrial, and commercial), the share of renewables in a country's electricity system, or generator competition. A key aspect results from the inclusion of residential consumers in DR programs, which are currently excluded from many markets such as Belgium. This will result from the integration and massification of aggregation services as a key element to untap the residential flexibility as it occurs in most USA systems and South Korea.

To improve the possibility of DR prosperity, all these factors must be analyzed before the design of products, and the conclusions of such analysis must be considered when establishing technical requirements and new market rules. Still, experience proves that some aspects are essential for a prosperous DR progress, such as low ΔP_{min}, and the acknowledgment of independent aggregators. Moreover, products' impact on market efficiency and DR development must be tracked to introduce the changes needed.

2.1.5 Conclusions

To conclude, DR proves to be a valuable resource to ensure the security of supply while reducing demand peaks, avoid blackouts, reduce investments on the grid, and absorb renewable fluctuations. To do so, programs to allow and enhance the participation of DR in AS have been occurring throughout the globe. Many countries aim to mobilize their demand resources to provide reserves and directly compete with generation in AS markets. DR usage is still scarce, and, in most countries, its deployment is low or inexistent due to inexistent regulation, technical parameters drafted for generators, and lack of experience. Even though most countries follow regional grid standards, where DR programs for AS exist, these do not follow common parameters and lack standardization due to the different parameters involved as a DRPV. In this regard, no analysis or comparison appears in the literature of the different parameters and prices of DRP in AS among different countries.

The contribution of this work is to provide an academic, precise, and concise analysis of the different country programs under a framework of standardized parameters of both AS and DRP. First, the paper has defined the grid standards developed by ENTSO-E and the FERC, the AS associated with them, and their main technical characteristics. Second, we have presented the DRP existing in the different countries and systems around the world that have incorporated DRP in their AS. The programs are presented systematically with their main characteristics such as the minimum response time, the type of payment and activation form, minimum and maximum times, minimum power required to participate, and if aggregation is allowed or not. Third, a review of the average and most common prices and forms of payment and the main policy conclusions around the programs are presented. Our work shows how countries with wider participation have lower minimum power levels and allow aggregation. It is important to note that higher penetrations of renewables, the electrification of demand, and more extreme climate conditions associated with the effects of climate change will impose extra needs on the system, to which DR results in a valuable resource to help to balance it.

Author Contributions

Conceptualization, D.R.P. and M.A.O., methodology, D.R.P., L.L.L. and M.A.O.; formal analysis, D.R.P., L.L.L., and D.P.T.; resources, M.A.O.; data curation, L.L.L.

and D.P.T.; writing—original draft preparation, D.R.P., L.L.L. and D.P.T.; writing—review and editing, D.R.P. and M.A.O.; supervision, M.A.O.; project administration, M.A.O.; funding acquisition, M.A.O.

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Abbreviations

aFRR	Frequency Restoration Reserves with Automatic Activation
AGC	Automatic Generation Control
AS	Ancillary Services
BSP	Balance Service Providers
CAISO	California Independent System Operator
DEG	Distributed Energy Generation
DER	Distributed Energy Resources
DR	Demand Response
DRPV	Demand Response Provider
DRRQ	Demand Response Requester
DSR	Demand Side Resources
DSM	Demand Side Management
ENTSO-E	European Network of Transmission System Operators for Electricity
ERCOT	Electric Reliability Council of Texas
FCR	Frequency Containment Reserve
FERC	Federal Energy Regulatory Commission
FRR	Frequency Restoration Reserve
ICT	Information and Communication Technologies
ISO	Independent System Operator (in USA)
mFRR	Frequency Restoration Reserves with Manual Activation
MISO	Midcontinent Independent System Operator
NE-ISO	New England Independent System Operator
NYISO	New York Independent System Operator
PJM	Pennsylvania-New Jersey-Maryland Interconnection LLC
RR	Replacement Reserve
RTO	Regional Transmission Organization (in USA)
SO	System Operator
STOR	Short-Term Operating Reserve
TSO	Transmission System Operator
T_{MAX}	Maximum length of a DR action
T_{PRE}	Duration of the preparation for a DR action needed by the DRPV
T_{RAM}	Maximum duration for a BSP to adapt its power curve to the given setpoint, from the start of the modification

T_{MAX}^{RD}	Maximum duration of a DRPV's activation
T_{RAM}^{RD}	Time used by a DRPV to adapt its power curve to the given setpoint, from the start of the modification
T_{RCT}	Total time that a DRPV needs to achieve the given setpoint, from the arrival of the TSO's notification
T_{REC}	Duration of the recovery from a DR action needed the DRPV
T_{RES}	Maximum admissible time between a TSO's notification and a BSP's full activation
ΔP_{min}	Minimum capacity that needs to be demonstrated by a BSP to access a specific ancillary service
ΔP_R	Flexible power of a DRPV
ΔP_{R2}	Extra power consumed before the DR action by the DRPV
ΔP_{R3}	Extra power consumed after the DR action by the DRPV

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2.2 The flexibility gap: socioeconomic and geographical factors driving residential flexibility

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Abstract

Residential consumers are moving to the center of electricity systems and their flexibility is seen as a key resource to integrate renewable energy sources and support the grid. However, residential flexibility capacities are not homogeneous, as they depend on household appliances, comfort patterns, occupancy, and climate conditions. Here, we calculate the technical flexibility capacities of 45 consumer types in mainland Spain, organised according to income and regional criteria. We show that flexibility gaps exist at both regional and socioeconomic (income) levels with flexibility differences of up to 10 times more capacity between the household groups from the lowest to the highest capacities. These geographical and socioeconomic gaps in flexibility can lead to distortions in national markets and have the potential to exclude citizens from the provision of flexibility services. Our results show in quantitative terms that a consumer-centered approach without considering correcting measures nor these gaps in drafting energy policies may lead to increasing inequality levels in the residential sector. Under an economic competitive paradigm, households with lower income levels or located in regions with lower flexibility potential may be excluded from the provision of flexibility to the detriment of households with larger potential, raising justice concerns in a flexibility-based energy transition.

Keywords

Residential flexibility; Energy inequality; Energy transition; Spain

2.2.1 Introduction

If we aim to stay under a 1.5ºC above pre-industrial levels climate scenario, Renewable Energy Sources (RES) will supply over 85% of electricity by 2050 [1]. This means a dramatic increase in the penetration of RES not only at the transmission and sub-transmission level (wind, hydro and large PV units) but also in the form of distributed generation, connected into the distribution grids, such as small scale PV combined with storage technologies [2]. This massive integration of intermittent generation that will substitute fossil generation requires an increase in new flexible resources to maintain the stability and security of power systems at reasonable costs [3]. Currently, this flexibility is mostly provided by centralised dispatchable generation (e.g. gas and hydro turbines) but, shortly, new forms of decentralised flexibility are expected from the demand side [4]. These resources can bring enormous benefits to the system, including loss reductions [5], increases in competition due to reductions in market power [6], as well as investments deferral and operational savings [7].

From a technical perspective, demand side management and demand response are forms of providing additional ancillary services to the grid, either through direct or indirect incentives given to consumers [8]. These resources have promising impacts on markets and system operations as well as introducing new opportunities for business models such as aggregators, energy communities, and energy services companies [9]. These flexible services from demand resources are necessary for the system to ensure the security of supply and the reliability of the grid. From a policy perspective, the challenge is to unleash these flexible resources and create practical conditions for the massification of the flexibility services. After opening some ancillary services markets to large industrial consumers, the priority is now to extend these services to medium and small consumers, such as the residential sector, which represent between 30-40% of the final electricity consumption [10]. To achieve this, several initiatives have been created to introduce the figure of the aggregator, allowing economies of scale in market participation [9], as well as to promote flexibility markets [2], and energy communities [11].

At the level of the European Commission, these legal instruments and new business models have been introduced by recent directives [12] with the aim of placing consumers in the center of the energy system, acting as rational and participatory agents in the market that provide flexibility services. The EU looks for consumers that generate their own electricity, choose better supply opportunities and deliver flexibility to the system in response to economic payments and incentives. Nevertheless, rational self-interest incentives are not the only driver of households' energy consumption or situation [13]. The heterogeneity of the residential sector may lead to different levels of engagement and potential flexibility across consumers [14]. For example, the capacity to provide flexibility at the residential level is strongly linked with socioeconomic factors (such as income) as well as meteorological characteristics determined by the place where consumers are located. These factors are regionally determined and create regional gaps between the flexibility capacities of residential households. Thus, a significant portion of the electric flexibility is not determined by the consumers' behavior, but by their geographical and socioeconomic conditions. Unfavourable geographic and socioeconomic conditions may lead to inflexible consumption patterns, less ability to choose, and even exclusion from participating in new flexibility services. This exclusion may endanger the social objectives of the energy transition, especially in the context of the existing energy inequities already identified in both quantitative and qualitative terms [15]. Thus, as consumers' flexibility is brought to the center of electricity systems, the socioeconomic and geographic heterogeneity of the residential sector becomes a key aspect of policy definition and should be carefully studied to understand the differences and gaps in this capacity [16].

This paper contributes to the debate around the justice and distributional implications of energy transition by quantifying nationwide flexibility gaps in the residential sector across different levels of income and geographical locations in Spain. The analysis assumes clusters containing 1000 consumers. We build annual flexibility profiles of socioeconomic and regional clusters considering three income levels and fifteen regional locations. Then we obtain control groups at national, regional, and income levels by combining clusters according to their statistical representation in the population of the group. Finally, we create two simple indices to compare the clusters: 1) regional and seasonal flexibility gaps are described as a percentage difference in relation to the national average; 2) Socioeconomic flexibility gaps are described based on the ratio between AMI and LI groups. We find that citizens with economic conditions Above the Median Income (AMI), i.e. mid and high income groups, present 50 % more flexibility capacity than the Low Income (LI) group and regional gaps add up to 4 times more capacity. When combining geographic and socioeconomic gaps, it is possible to find capacity differences in a magnitude of 10 between LI groups in regions with lower flexibility and AMI groups in regions with higher flexibility. We believe that there is a need to point to and understand these gaps to address distributional issues in energy policies that will focus on untapped residential flexibility potential and at the same time, ensuring energy justice.

The rest of the paper is organised as follows. Section 2 presents the methodology background and the demand flexibility model of residential appliances. Section 3 provides information about the data and assumptions used in the study. The results and discussion arise in section 4, where the different flexibility gaps are presented. Section 5 concludes and draws the policy implications of this study.

2.2.2 Methodology

2.2.2.1 Background

Unlike the flexibility of dispatchable generators, which can be directly derived from the technical limits and ramping characteristics of the generators, the quantification of demand flexibility is difficult to standardise, as it depends on a larger set of parameters including subjective factors such as comfort or consumption patterns. The definition of demand-side flexibility might change with the type of application, but it can be summarised as the availability of loads to respond with energy and power variations of consumption to an external signal sent by the system [3]. Electricity consumption can be postponed or advanced thanks to thermal inertia or the possibility to defer certain loads without affecting comfort. In this sense, consumers can offer increases or reductions in the power demand with a time availability that relates to the energy that they can use but they do not.

In literature, several authors have modelled and quantified flexibility either from the perspective of the potential services or based on the nature of the consumption. The first approach quantifies flexibility considering the economic value of the demand participation in a specific service or market, including large-scale reserve and ancillary services [17–19] or local markets at the distribution grid level [7]. The second is agnostic to the flexibility valuation and focuses on the theoretical energy and power capacity potentials of demand change per consumer segments, either divided by continental regions [20] and individual countries [21] or by sectors of activity, such as residential [22], office buildings [23], and industries [19]. The methodology used in this paper belongs to the latter category. We extend the existing literature by looking at the demand potential within the residential sector, considering both socioeconomic and geographical factors. The objective is to evaluate the fundamental differences in flexibility quantities, understood as the technical capacity that different clusters of residential households can offer the system fulfilling all comfort patterns, before assuming any particular flexibility service or value.

Two types of flexible loads in residential buildings are considered in this study: Shiftable Loads (SL) and Thermostatically Controlled Loads (TCL). The first group comprises household appliances that can be shifted in time, such as Dishwashers (DW), through behavioural changes or automatic control, whose flexibility is defined by an energy invariant time window [24]. These demands are characterised by a determined consumption during consecutive time periods. They can be moved as a block from one time slot to another inside a range of hours established by household consumption patterns. The second group, TCLs, relates to loads that operate within a temperature band, such as Electric Heaters (EH) or Air-Conditioners (AC), acting as an energy reservoir that allows control without affecting consumers' comfort [22, 25]. The thermal comfort is a characteristic embedded in the control of these loads [26], while the energy needs and the flexibility are derived as a result of the consumers' comfort patterns and settings [27]. Our analysis is focused on the current individual household appliances that include Dish Washers (DW) and Washing Machines (WM) as SL and Electric Heaters (EH), Air Conditioners (AC), and Heat Pumps (HP) as TCLs with variable temperatures and Fridges and Freezers as base TCLs appliances. Other sources of flexibility in the future, namely the electric vehicles and household electrochemical storage, are out of the scope of our study.

TCLs are bounded to a dead band to fulfill their thermal comfort loads as presented by [26, 28, 29]. These physical models are commonly used to characterise residential demand flexibility [30, 31]. [27] linearised this method into a time varying battery model to become computationally optimal by separating the control and optimisation of TCLs. The method considers the physical characteristics of TCLs by keeping track of their associated battery values, energy, power up, and power down capacities, which are time-varying by the nature of the resource, therefore not simplifying TCLs behaviour into a battery with constant parameters. We use the time varying batteries framework [27, 32] to quantify the flexibility of TCLs and extend it to include SLs, achieving a complete household flexibility model. Thus, we represent the flexibility of each residential cluster by an equivalent battery with time-varying characteristics described in three dimensions: energy capacity, power up capacity, and power down capacity. These three dimensions of the flexibility vary hourly with several geographical and socioeconomic factors, such as the existence of flexible loads in the building, consumption and comfort patterns, occupancy of the household, and climatic characteristics.

By adding these individual household flexibilities, and taking into account the presence of appliances across different socioeconomic and geographic groups, we are able to construct time varying battery profiles, each one representing the aggregated flexibility of 1000 residential consumers in a group. We aggregate different consumer clusters representing multiple regions and income levels to compare these three dimensions of the flexibility and produce annual, seasonal, and hourly analysis. The resulting aggregated profiles are affected by consumption patterns, climate conditions, and household occupancy of the different socioeconomic and regional groups that compose these aggregated groups.

2.2.2.2 Occupancy

The occupancy characterisation in the proposed methodology follows previous work done by [33], which analyses the interplay between occupancy, simultaneity, and electricity consumption in households. We built the household occupancy profiles across the different socioeconomic and regional groups based on the time spent at home by each group compared with the average hourly profile Oc_t since specific socioeconomic and regional information is only available as a daily sum DT_i. We generate hourly occupancy factors for each type of consumer, $oc_{t,i}$, by scaling up or down the national daily occupancy curve to ensure that the sum of the hourly occupancy matches with the time spent at home during a day. We minimise the scaling factor α_i that increases or reduces the hourly occupancy during daytime hours and in night hours (from midnight to 7 am), we assume the same occupancy for every type of consumer, which is the available hourly data Oc_t. Thus, the total hours spent at home DT_i for each type of consumer are equal to the sum of the hourly occupancy during a day, the occupancy of each consumer group is equal to the average occupancy during night hours and proportional to an element α_i but never larger than 1 during the day. To obtain this household occupancy factor we apply a Mixed Integer Linear Programming algorithm, which is solved with the big M formulation of the problem to provide differences in usage by time period and type of consumers.

$$min \quad \alpha_i \tag{2.2.1}$$

Subject to the following restrictions.

$$\sum_{t}^{T} oc_{t,i} = DT_i \quad \forall i \tag{2.2.2}$$

$$oc_{t,i} = \begin{cases} Oc_t, & if\, t \in N \\ \alpha_i \cdot Oc_t, & \text{if } \alpha_i \cdot Oc_t \leq 1 \quad \& \quad t \notin N \\ 1, & \text{if } \alpha_i \cdot Oc_t > 1 \quad \& \quad t \notin N \end{cases} \tag{2.2.3}$$

2.2.2.3 Time varying batteries

The flexibility of individual appliances is subjected to the fulfilment of certain constraints such as physical proprieties, comfort, current and previous usage, etc. This flexibility can be viewed as a battery, though with time-dependent energy and power capacities to meet the temporal characteristics of those constraints [27]. This is to say that a group of consumers, for flexibility representation purposes, can be modelled as a battery, with energy capacity, power up and power down parameters that vary in time in according to the availability given by their loads and their comfort patterns. We model the flexibility of a cluster of consumers, i, with a number and type of appliances, z, based on this analogy, and determine the corresponding battery power and energy capacities in each time, t, according to (2.2.4)-(2.2.9).

$$\sum_{z=1}^{Z} P_{i,z,t}^{min} \leq \sum_{z=1}^{Z} oc_{t,i} \cdot p_{i,z,t}^{BL} + p_{i,t}^{f} \leq \sum_{z=1}^{Z} P_{i,z,t}^{max} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.4}$$

where $P_{i,z,d}^{min}$ and $P_{i,z,t}^{max}$ show the maximum and minimum power limits of each appliance z. $p_{i,t}^{BL}$ and $p_{i,t}^{f}$ represent the power base load of each appliance of each class and the power used for flexibility purposes. In a similar pattern, the available energy stored at certain period of time also depends on the previous demand. The timely varying energy limits per appliance are included as $S_{i,z,t}^{min}$ and $S_{i,z,t}^{max}$. The demand resource of each group i of components vary over the time and its limits are presented by:

$$\sum_{z=1}^{Z} S_{i,z,t}^{min} \leq s_{i,t} \leq \sum_{z=1}^{Z} S_{i,z,t}^{max} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.5}$$

where $s_{i,t}$ is the state of demand of the battery associated to the customers class, which can be understood as the state of charge of a battery and evolves as:

$$S_{i,t+1} = S_{i,t} + (p_{i,t}^{f} + oc_{t,i} \cdot p_{i,t}^{BL})\Delta t + \sum_{z=1}^{Z} S_{i,z+1,t}^{In} + \sum_{z=1}^{Z} S_{i,z+1,t}^{Out} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.6}$$

where $S^{In}_{i,z,t+1}$ and $S^{Out}_{i,z,t+1}$ represent new energy resources that are included or ejected from the battery availability. This capacity that goes in or out evolves with the availability of the demand resources and its expected baseline evolution. Both power and capacity come from two main types of loads, TCLs and SLs.

Finally, to assess the capacity of the aggregated batteries, we assume three main parameters, Energy Up, Power Up and Power Down capacities that represent the battery capacity to provide flexibility and are defined as follow:

$$S_{i,t} = \sum_{z=1}^{Z} S^{max}_{i,z,t} - \sum_{z=1}^{Z} S^{min}_{i,z,t} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.7}$$

$$PUp_{i,t} = \sum_{z=1}^{Z} P^{max}_{i,z,t} - \sum_{z=1}^{Z} oc_{t,i} \cdot p^{BL}_{i,z,t} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.8}$$

$$PDn_{i,t} = \sum_{z=1}^{Z} oc_{t,i} \cdot p^{BL}_{i,z,t} \quad \forall i \in \mathscr{I}, t \in \mathscr{T} \tag{2.2.9}$$

Thermostatically Controlled Loads flexibility model TCLs such as ACs, HPs or EH work maintaining temperatures within temperature bands. This implies that, as long as these loads operate inside the bands, they can be modified without disrupting the comfort of the consumer [27]. A modelling framework for these types of loads is presented in [26], adapted to the flexibility context in [32], and used to map the aggregated flexibility of TCLs into time varying batteries in [27, 34, 35]. Within this framework, the thermal characteristic of a cooling load is given by:

$$\theta_{z+1,i} = a_i \theta_{z,i} + (1 - a_i)(\theta^a_{z,i} - \tau_{z,i} \theta^g_j) \tag{2.2.10}$$

where $\theta_{z,i}$ is the temperature at the TCL space i at time step z, $\theta^a_{z,i}$ is the outdoor ambient temperature and θ^g_i is the temperature gain of the TCL, equal to $R_z \cdot COP_z \cdot P_z$, thermal resistance of the cooled room, Coefficient Of Performance (COP) of the TCL and power applied respectively. a_i is a dimensionless parameter defined as $\exp^{-h/C_i R_i}$, where h is the time control that we set in 15 minutes. Following the criterion adopted in [35], P_i is positive for cooling TCLs. Finally, $\tau_{t,i}$ represents a binary variable that is equal to 1 when the TCL is on and 0 when it is off, where we assume that TCLs are not available when temperatures are above or below their working bands. For cooling, TCLs availability in the model evolves:

$$\tau_{z,i} = \begin{cases} 0, & \theta_{z,i} < \theta^{min}_{i,z} \\ 1, & \theta_{z,i} > \theta^{max}_{i,z} + \theta^g_i \\ 0-1, & \text{otherwise} \end{cases} \tag{2.2.11}$$

The TCL works with θ_i^{min} and θ_i^{max} representing the minimum and maximum temperatures between where a user is comfortable. These two are defined by a set temperature (θ_i^{Set}) and a comfort band (ζ_i), which is chosen by the residential consumer, $\theta_i^{min} = \theta_i^{Set} - \zeta_i/2$ and $\theta_i^{max} = \theta_i^{Set} + \zeta_i/2$. These parameters set the temperature band within the TCLs can be flexible. To derive the different time varying batteries' parameters, the model assumes dependence of the internal temperature over a finite ambient temperatures and defines the duty cycles.

$$\Delta_{i,z} = \frac{h_{i,z}^{ON}}{h_{i,z}^{ON} + h_{i,z}^{OFF}} \tag{2.2.12}$$

$h_{i,z}^{ON}$ and $h_{i,z}^{OFF}$ are the times that TCL i takes to travel from one limit of the temperature band to the other in the on and off states. Both parameters are defined as follows:

$$h_{i,z,t}^{ON} = -C_{z,i} R_i \ln \frac{\theta_i^{min} - \theta_{t,i}^{a} + \theta_i^{g}}{\theta_i^{max} - \theta_{t,i}^{a} + \theta_i^{g}} \tag{2.2.13}$$

$$h_{z,i}^{OFF} = -C_{z,i} R_i \ln \frac{\theta_i^{max} - \theta_{t,i}^{a}}{\theta_i^{min} - \theta_{t,i}^{a}} \tag{2.2.14}$$

Only positive numbers are used to compute $\Delta_{z,i}$. When $h_{z,i}^{OFF}$ is negative or non positive, the TCL is not available, $\Delta_{z,i} = 0$, while negative or non positive $h_{z,i}^{ON}$ force the $\Delta_{z,i} = 1$. With these auxiliary parameters the baseline power $P_{z,i}^{BL}$ and maximum power can be obtained as:

$$P_{z,i}^{BL} = \begin{cases} P_{z,i}\Delta_{z,i}, & \text{if available} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.15}$$

$$P_{z,i}^{max} = \begin{cases} P_{z,i}, & \text{if available} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.16}$$

The maximum capacity is estimated as follows:

$$S_{z,i}^{max} = \begin{cases} P_{z,i} h_{t,i}^{ON}(1 - \Delta_i), & \text{if available} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.17}$$

And the expected $S_{t,z}^{In}$ is correlated with the expected baseline power:

$$S_{z,i}^{In} = P_{z,i}^{BL} \Delta z \tag{2.2.18}$$

Finally, following the convention in [35] $S_{t,i}^{min}$ and $S_{t,i}^{Out}$ are all equal to zero.

Shiftable loads flexibility model SLs such as DWs and WMs, are characterised by fixed load parameters and their consumption can be moved throughout the day according to starting and finishing times defined by consumers. In this work, we extended the concept of Time Varying Batteries from TCLs to SLs, following a similar modelling strategy adopted in [36]. Considering specific load parameters such as $P_{t,z}$, power of the appliance, D_z, duration of the process, T_z^{av}, time availability, T_z^{st}, starting time and E_z, energy consumed per period by the appliance once started, the time-varying battery model is given by (2.2.19)-(2.2.21).

$$P_{z,t}^{max} = \begin{cases} P_{t,z}, & i => T_z^{st} \ \& \ t < T_z^{st} + T_z^{av} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.19}$$

$$S_{z,t}^{max} = \begin{cases} S_{z,t-1}^{max} + E_z, & t > T_z^{st} \ \& \ t <= T_z^{st} + D_z \\ S_{z,t-1}^{max}, & t > T_z^{st} + D_z \ \& \ t < T_z^{st} + T_z^{av} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.20}$$

$$S_{z,t}^{min} = \begin{cases} S_{z,t-1}^{min} + E_z, & t => T_z^{st} + T_z^{av} - D_z \ \& \ t < T_z^{st} + T_z^{av} \\ 0, & \text{otherwise} \end{cases} \tag{2.2.21}$$

Whenever the S_j^{max} gets back to 0 after its use, $S_j^{out} = S_j^{max}$ and the appliance stops providing flexibility.

2.2.2.4 Measuring flexibility gaps

The flexibility ratios reflect differences among the considered groups. National, regional and income groups are determined by the weighted addition of each of the 45 clusters of consumers and compared among themselves. The income gap is defined with an Above the Median Income/Low Income ratio (ratio AAI/LI) that determines how much more flexibility capacity an AMI group has compared with a LI group. The regional and seasonal ratio compares the flexibility potential of the regions as a percentage above or below the average yearly national flexibility potential.

$$ratio \ AMI/LI = \frac{\bar{S_r^{AMI}}}{\bar{S_r^{LI}}} \tag{2.2.22}$$

$$RS = \frac{\bar{S_r} - \bar{S_N^y}}{\bar{S_N^y}} \tag{2.2.23}$$

Where $\bar{S_r}$ represent the mean energy capacity of a region, $\bar{S_N}$ the national mean energy capacity and $\bar{S_r^{HI}}$ and $\bar{S_r^{LI}}$ the Above the Median Income and Low Income energy capacities of a particular region. These ratios are also used for power up and down capacities.

2.2.3 Data and Assumptions

We take as an example one of the most diverse countries in Europe, Spain, where we map these flexibility gaps introduced by household income levels and regional characteristics associated with electricity consumption. Indeed, Spain provides a good case to assess the impact of both parameters as the residential consumption accounts for 31.5 % of the total electricity consumption [37], and it presents diversity in both income factors and geographical conditions. To assess the national flexibility of the residential sector in Spain, we aggregated consumers' baseline profiles based on the geographical location and household consumption patterns. We build annual flexibility profiles of 45 clusters considering 3 income levels - Above Median Income (AMI), Median Income (MI), and Low Income (LI) - in 15 administrative regions of mainland Spain.

We determine the hourly flexibility during 2018, taking into account demographic and socioeconomic information from three different surveys conducted by the National Statistics Institute (INE, initials in Spanish) [38–40]. Additionally, we use statistical data characterisation reports from the Institute for Energy Diversification and Savings (IDAE) [41–44], which provide information regarding residential occupancy, electricity bills as well as the presence and type of household appliances.

Based on this information we build 45 groups of representative consumers. In terms of meteorological conditions, the regions are represented by their main city or capital, and their temperatures are taken from COPERNICUS database ERA5 [45]. Socioeconomic groups are formed according to the monthly household income, divided into three categories as presented in INE reports: less than 1000 /month, assumed as LI; between 1000-1999 /month, assumed as MI; and more than 2000 /month assumed as AMI.

We build the household occupancy profiles across the 45 different socioeconomic and regional groups based on the occupancy time data presented in the INE survey [39]. We assume that the occupancy time is composed of the sum of three activities declared in the survey: personal care, household/family, and media. Hourly data of these three items are only available for the aggregated Spanish profile Oc_t, while specific socioeconomic and regional information is only available as a daily sum DT_i.

The statistical surveys characterise electric appliances and usage patterns across regions and socioeconomic groups. For example, the report [40] collects information regarding appliances per income group and location in a separate manner. To combine this information we assume that the regional distribution of appliances across income groups follows the national trends. Therefore, the percentage of citizens per cluster with a determined number of appliances can be obtained by the percentage of citizens by income group in the region [40] and the national average per income groups [38].

Since the thermal parameters of TCLs are not provided in any survey, we generalise these characteristics by generating a random set of resistances, R, between 1.5 and 2.5 (°C/kW), and thermal capacities, C, between 1.5, and 2.5 (kWh/°C) associated with space heating/cooling devices (AC, HP, and EH). We set the nominal power from AC, HP and EH as a normal distribution from 2.5 to 5 kW and COP at 2.65, 3.65 and 1 respectively according to [43, 44]. We assume 2 devices for consumer groups declaring the presence in more than one room, and 4 devices for consumers declaring devices in all rooms [40]. Temperature set points for these appliances are assumed homogeneous across income and regions based on [40], with a comfort band between δ between 0.5 and 2°C. Analogously, for refrigeration systems, we estimate a thermal resistance between 80 and 105 (°C/kW), a thermal capacitance C between 0.4 and 0.8 (kWh/°C) and an external temperature of 20°C. We also assume a nominal power within [0.2, 0.5 kW], a COP within [1.5 and 2.5] and set point temperatures in the ranges of [1.5, 4°C] and [-6,-3°C] for refrigerators and freezers, respectively [32].

We assume random starting times for SLs within the actual hourly ranges declared in [46]. DW nominal powers are obtained via a normal distribution within [0.5, 1.5kW], a 4 to 5 hours shiftable time is assumed and the starting time is considered within the slots: 14-15:30 and 20:30-21:30. Similarly, WM nominal power is generated within [0.75, 1.75 kW], shiftable time is assumed to be 3 to 4 hours and the starting time within the following slots: 10-11:30, 15-16 and 18:30-20. The duration of these appliances operation is assumed to be between 1 and 2 hours.

2.2.4 Results and discussion

In this section, we present the results and compare them, considering three flexibility capacity parameters: energy, power up, and power down of residential households. As discussed in section 3.1.2, we measure geographical and seasonal gaps comparing the regional flexibility capacities with the national average represented by the weighted addition of the 45 clusters analysed. Then we present this gap as a percentage variation over the national yearly average. We measure the socioeconomic gap as the number of times that AMI groups have more flexibility capacity over the flexibility that LI groups have.

2.2.4.1 National flexibility: the seasonal gap

Figure 2.2.1 shows the average flexibility of a residential consumer in Spain considering the three dimensions: energy capacity, power up and power down, as well as the seasonal flexibility gaps, measured as a percentage deviation of the annual national average. Power up and down represent the capacity of a household to increase and decrease its consumption while the energy capacity represents the amount of energy that appliances can consume in excess or defer without affecting comfort patterns.

The flexibility from residential loads has time scale variations based on intra-day and seasonal factors [27, 32]. Seasonal differences are related to residential TCLs, which vary with ambient temperature and heating/cooling needs [47], while the consumption patterns associated with SLs were assumed constant throughout the year. In this sense, SLs result in a constant flexible capacity during the whole year with a stable hourly pattern. Thus, the main differences associated with SLs appliances are the amount of them in households. WM present a constant distribution between regions and incomes and DW are homogeneous between regions but present a wide divergence between income groups. The behavior of TCLs explains the relatively low flexibility values in the winter seen in Figure 2.2.1 as well as its increase during the mild temperature seasons (spring and autumn). Among these two seasons, spring has the largest energy capacity, as it combines months of relatively low heating and cooling requirements with a better flexibility performance of EH.

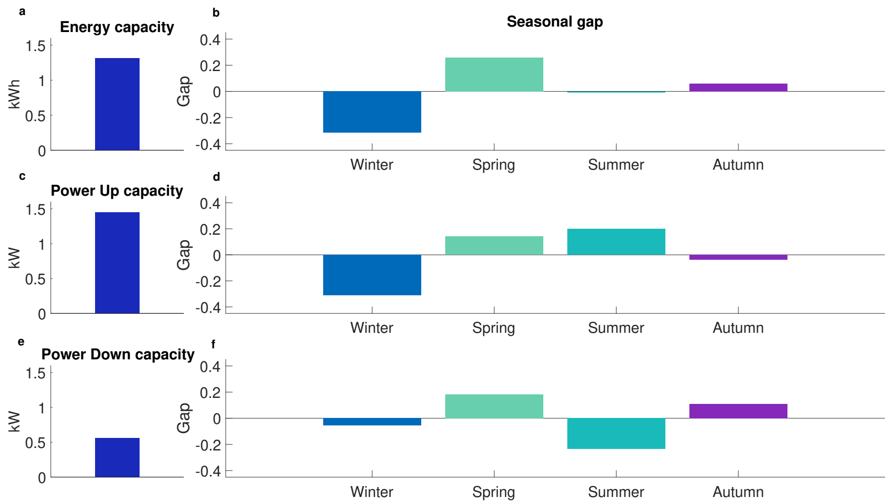

Figure 2.2.1: National flexibility parameters and seasonal gaps. a, c and e show the year average of the flexibility parameters. b, d and f present the percentage seasonal gaps compared with the year average, each colour represents the seasonal gaps of the three capacities. Winter presents the least flexibility while Spring shows the most except in the Power Up capacity presented in Summer.

It is interesting to observe that, during the summer, residential consumers offer high power up flexibility together with low energy and power down capacities. This can be explained by the hourly distribution of the cooling needs, which increase during the day when the majority of consumers are not at home. Therefore, as ACs are not operating, the energy and the power down flexibilities are insignificant, but this large population of devices can be switched on if power up capacity is needed.

To better understand the variation of TCLs' flexibility with temperature and thus its implication in the seasonal gaps, Figure 2.2.2 presents how the TCLs' flexibility of the national average cluster of households vary with ambient temperature.

The TCLs' flexibility varies depending on the ambient temperature, mid temperatures allow TCLs to have a more flexible operation than extreme temperatures when TCLs must be on to guarantee comfort patterns [27]. For example, heating TCLs (EHs and HPs) provide more flexibility capacity when working in mild temperatures, i.e. with lower heating needs, which allow them to be switched on and off for longer periods without affecting consumers' comfort. In contrast, when the ambient temperature falls below certain levels, the heating TCLs must operate at their rated capacity, limiting the flexibility [25].

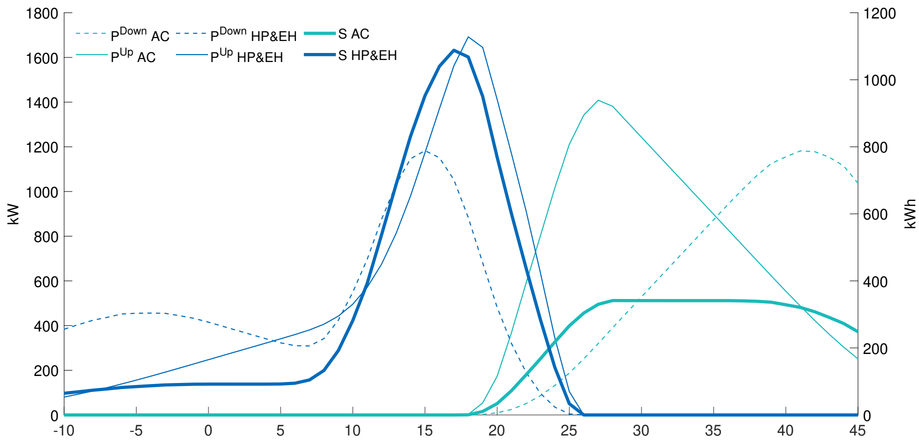

Figure 2.2.2: Variation of the TCLs' flexibility capacity with temperature.

2.2.4.2 The regional flexibility gap

Figure 2.2.3 shows the regional flexibility gap per season, comparing the energy capacity of individual regions with the national average.

Maximum flexibility potentials concentrate in the southern and eastern Mediterranean areas, where the energy capacity can be 100% higher than the national average during the mild temperature seasons, i.e. spring and autumn. In contrast, minimum flexibility potentials (75% lower than the average) occur in the central and northern regions during winter. This can be explained by two factors. First, in central and northern locations, households still rely on other heating sources, mostly gas, and flexible electric devices, such as HPs, are present in less than 1% of the buildings as presented in Table 2.2.1, which shows the TCL penetrations by region. Second, the few EH installations in the region need to operate at nominal levels during the winter due to the low temperatures, which excludes them from flexibility provision. In comparison, the regions of the south, besides the lower heating needs, rely more on EHs and HPs that translates into more flexibility capacity in the winter. When summer arrives, all households rely on electric ACs, and not on other energy sources, to cool their houses. This reduces the regional gaps in flexibility capacities in summer compared to winter, and a more homogeneous flexibility potential can be seen across the country.

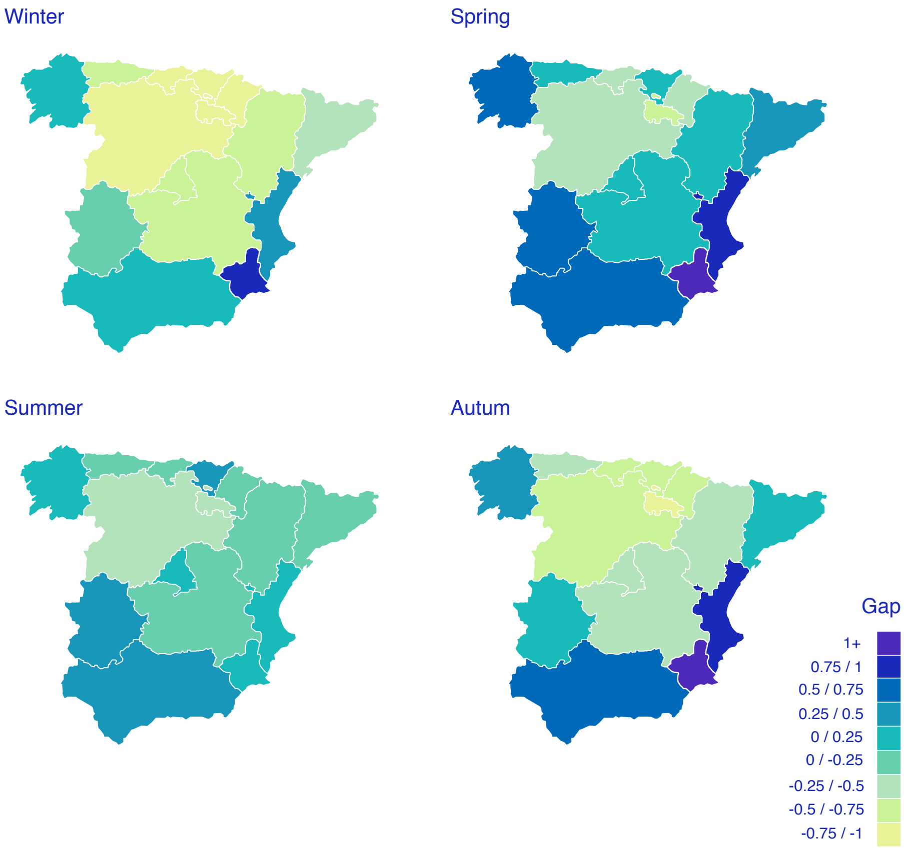

Figure 2.2.3: Seasonal flexibility gap by regions. Each map represents the seasonal difference of each region with the national yearly average. Lighter colours show negative gaps with the national mean while darker colours represent positive gaps.

The role of TCLs in the overall flexibility capacity is crucial. Figure 2.2.4 shows how the flexibility capacity varies with the penetration of TCLs in the flexible load, defined as the ratio between the installed power of TCLs appliances over the installed power of flexible loads. The results of the 45 clusters show how as TCL penetration increases, so too does the energy flexibility capacity. Nevertheless, this increase is not linear as the behaviour of each type of TCL and ambient temperatures are also key in determining the overall TCL flexibility capacity as shown in Figure 2.2.2. For instance, fridges and freezers provide a stable energy capacity and their use is not dependent on the external temperature but with more limited power up and down capacities than heating and cooling TCLs.

Table 2.2.1: Distribution of TCL penetration by region [40]

Region	HP	EH	AC
Andalucía (And)	3.8	23.5	57.4
Aragón (Ar)	2.7	13.2	37.4
Asturias (As)	-	17.5	0.4
Cantabria (Can)	1.2	13.1	0.7
Castilla y León (CyL)	0.4	8.6	3.3
Castilla La (CLM)	2.0	15.3	36.2
Cataluña (Cat)	7.1	15.4	36.1
Comunitat Valenciana (CV)	20.8	23.9	54.5
Extremadura(Ext)	14.4	28.3	58.0
Galicia (Ga)	1.3	14.8	1.0
Madrid (Mad)	2.3	15.6	43.5
Murcia (Mur)	28.1	40.6	63.9
Navarra (Na)	0.9	10.2	11.4
País Vasco (PV)	0.8	22.0	1.7
La Rioja (LR)	0.4	7.8	13.3

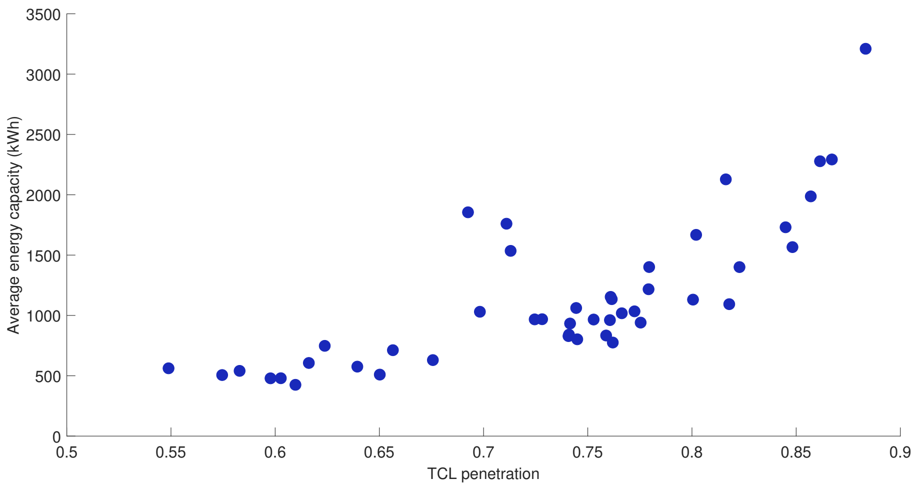

Figure 2.2.4: Variation of energy flexibility capacity with TCL penetration in the flexible load.

2.2.4.3 The socioeconomic gap of flexibility resources

Figure 2.2.5 presents the annual and monthly gaps between residential consumers with different levels of income. As described in section 3.1.3, the temperature and comfort patterns are assumed to be homogeneous between socioeconomic groups. Therefore, the only thing that differentiates flexibility between socioeconomic clusters is related to the appliances that people have at home and occupation patterns. The higher socioeconomic gaps occur in the power up component of flexibility, which reflects the capacity of the consumers to increase their load momentarily. Higher income consumers tend to have better equipped houses, both in terms of SLs and TCLs, and to spend less time at home, resulting in more availability to increase consumption when such services are requested. If power up flexibility is required, AMI households can switch on their TCL loads to preheat or precool their houses prior to arriving at their houses. In contrast, lower income households that spend more time at home, are already using the appliances and cannot provide that power up capacity. In particular, LI groups spend, on average, 2 additional hours per day at home [39], leading to a limited power up capacity. Regarding the type of appliances, LI consumers have 50% fewer DWs, ACs, and EH than AMI consumers [40], which represents a structural barrier to the provision of potential flexibility services. Due to this inequality in household equipment, the flexibility gaps across different socioeconomic groups are aggravated by the extreme temperatures, as seen in the bottom part of Figure 2.2.5.

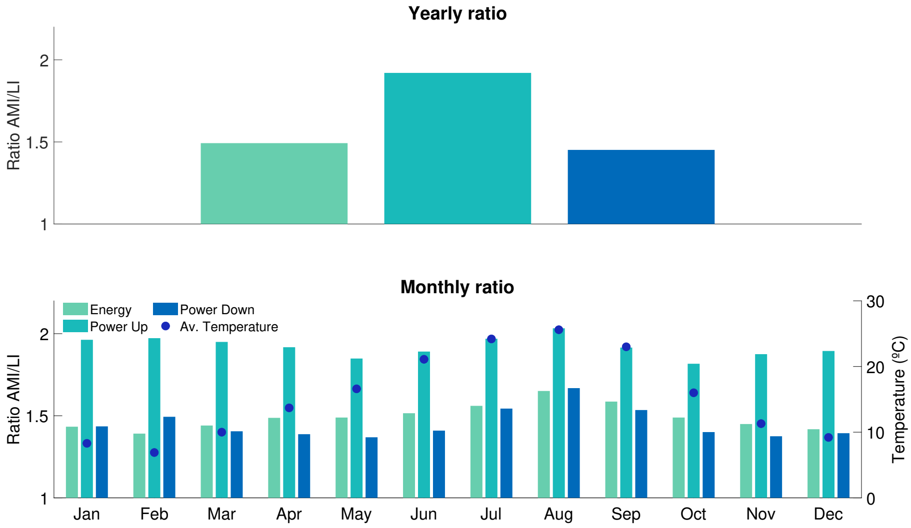

Figure 2.2.5: Income flexibility gaps. The ratios are obtained by comparison of a national control group of AMI and LI. a shows the yearly mean differences of the three flexibility parameters. b shows the monthly differences and Spanish mean temperature of the month.

Regarding the income gap among citizens of the same region, Figure 2.2.6 plots the AMI/LI ratio versus the energy capacity ratio of the 15 regions analysed. As seen in Table 2.2.1 we observe two types of regions: 1) the ones where flexibility income gaps grow with the overall flexibility of the region; 2) the ones where the gaps are relatively stable and do not depend on the flexibility capacity. Regions in the center, south, and Mediterranean area represent the first type. These regions have warmer climates and larger penetration of EH and AC, which are always above 15 % and 35 % respectively [40]. The second group contains northern regions, characterised by colder climates with milder summers where the penetration of electric TCLs is relatively low (e.g. AC devices only exist in 15% of the residential buildings).

Thus, the difference between these groups in terms of the penetration of TCLs shows an important conclusion: the electrification of heating and cooling needs can aggravate the flexibility gaps associated with socioeconomic conditions. In other words, the more thermal-related flexibility in a region, the higher inequalities in the potential provision flexibility services across socioeconomic groups. Again, this can be explained by the fact that not all consumers are able to equip their houses with electric TCLs, which has the potential to exclude a significant part of the population from the participation in flexibility services.

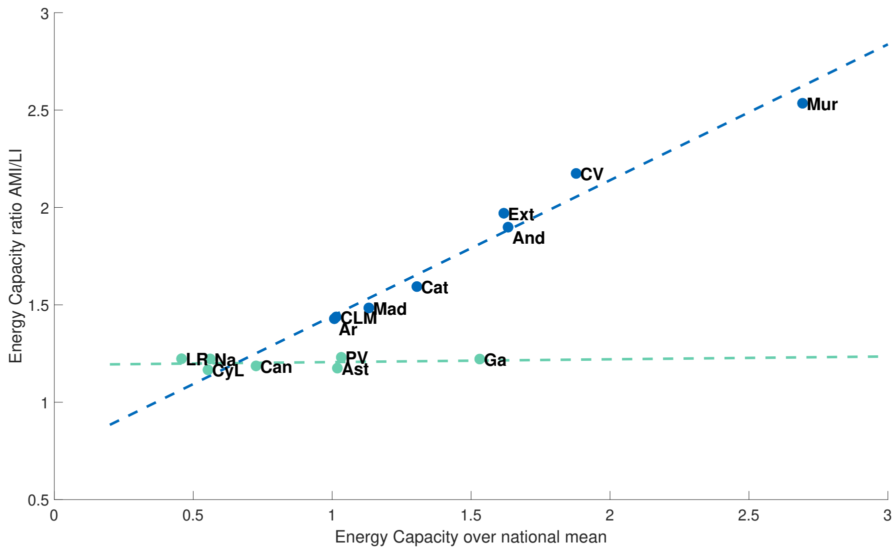

Figure 2.2.6: Flexibility income gap versus region flexibility. Lighter dots represent regions from the north of Spain while darker dots represent regions from the Mediterranean area, center and south of Spain. The linear correlation of the first groups is $y = 1.19 + 0.014x$ (adjusted $R^2 = 0.0419$) and the second group has a linear correlation $y = 0.74 + 0.70x$ (adjusted $R^2 = 0.97$). Each region is represented by the acronym shown in Table 2.2.1

2.2.4.4 Overall flexibility gap

Figure 2.2.7 plots the power up and energy capacities of the 45 groups analysed in this paper, showing the total residential flexibility gaps in a heterogeneous country like Spain. The colors and shapes associated with each group reveal, respectively, the geographical and socioeconomic flexibility gaps in the country. Consumer clusters from northern regions concentrate in the 50% of the population with the lowest energy and power flexibility capacities, due to the colder winters in the region combined with a strong dependence on non-electric heating sources. In contrast, southeastern regions have more potential flexibility caused by lower heating needs and larger penetrations of TCLs. These regions are in the upper quartile of the measured flexibility parameters, with a potential flexibility four times higher than the northern part of the country. Socioeconomic gaps are also seen in the graph, with two thirds of the LI consumers located in the lower quartile of flexibility and, regardless of the region, no presence among the 25% higher flexibility groups. This combination of geographical and income differences results in a significant flexibility gap: households with higher income in Mediterranean regions have 10 times more flexibility than lower income groups located in the North. At the same time, regions with higher flexibility capacities have proportionally larger gaps associated with socioeconomic conditions. In sum, existing socioeconomic and regional flexibility gaps are large, not homogeneous between regions, and therefore a significant part of the population can become excluded from participation in flexibility mechanisms.

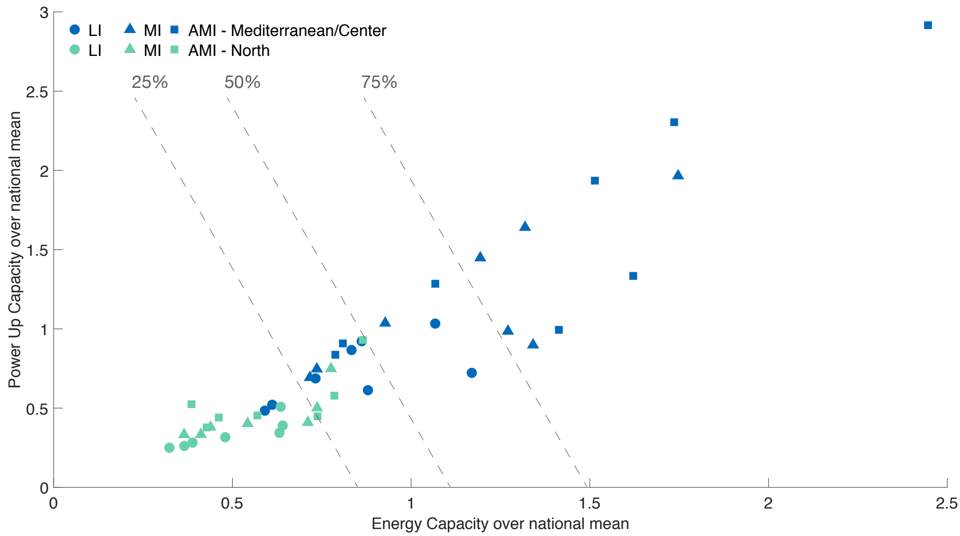

Figure 2.2.7: Overview of flexibility capacities of the 45 control groups. Lighter dots represent regions from the north of Spain while darker dots represent regions from the Mediterranean area, center and south of Spain, circles represent LI groups, triangles MI groups and squares AMI groups. Power up and energy capacity have a positive correlation.

2.2.5 Conclusions and policy implications

Significant geographical and seasonal variations exist in the flexibility of residential consumers in Spain. In this paper, we measured and analysed these gaps, and concluded that they are tied to meteorological and socioeconomic conditions, which indicates that similar gaps can be found in other countries and regions. Potential implications of these gaps in the development of policies to promote residential flexibility are threefold.

First, these gaps pose important challenges when conceiving national and continental services (e.g. reserves) supported by residential flexibility. In fact, centralised services benefit from the homogeneity of the flexible resources across the territory, providing better commitment and dispatch options for system operators. However, we showed that residential flexibility is a volatile and heterogeneous resource that may introduce seasonal and geographical distortions in national flexibility markets, making it less attractive for centralised system services. Additionally, when integrating this flexibility in a market context, an important aspect is the price-elasticity of the flexible resource, i.e., how can consumers change their behaviour to provide more flexibility in the system in relation to prices. Our analysis shows that while some residential flexibility can come from changes in comfort patterns, which comprises a behavioural nature, a large portion of the flexibility is dependent on pre-existing household equipment and meteorological conditions. This means that, in most cases, increasing flexibility is not an option for residential consumers. Thus, in the design of future residential flexibility markets, it is important to note that residential flexibility is very inelastic, geographically heterogeneous, and very dependent on meteorological and socioeconomic factors.

Second, some of these geographical and seasonal gaps can be corrected by energy policy measures. For example, as discussed above, the low winter flexibility in the north of Spain can be explained by the reliance on non-electric sources to supply heating needs. In this case, the electrification of space heating systems would increase the flexibility resources in the region during the winter, mitigating a seasonal and geographical gap. Alternatively, policies that increase the overall flexibility of the sector may attenuate geographical differences. For instance, policies that incentivise the adoption of electric vehicles would introduce a new flexible resource, with the advantage of being independent of the meteorological conditions and making the residential flexibility more homogeneous across seasons.

Third, policies exclusively focusing on the energy systems are not enough to address all the flexibility gaps. When analysing the impact of household living conditions on the potential flexibility, we conclude that poorly equipped houses and longer occupancy times impose severe limitations to the flexibility on low income consumers. More importantly, we observe that the flexibility gap between high and low income groups grows with the average flexibility of the region. This means that increasing the overall flexible resources does not necessarily correct the flexibility gaps, as they reflect the asymmetries in socioeconomic conditions. Without correcting these asymmetries, energy policies aimed at homogenising flexibility profiles will be limited. Going back to the example of the electric vehicle, and assuming that the adoption of private cars is significantly lower among low income consumers, it is clear that the EVs would increase the overall flexibility of the residential sector, but they would aggravate the flexibility gaps between income groups.

At the time where governments are putting consumers in the centre of the energy systems, and demand-side flexibility services gain relevance in energy transition policies, socioeconomic flexibility gaps become a serious challenge. In fact, in the process of extending flexibility services to the residential sector, the risk of exclusion of a significant segment of the population cannot be neglected. In that scenario, the massification of flexibility services has the potential to become a factor in exacerbation of economic inequalities. If flexibility markets or flexibility payments are established without aiming to include all kinds of residential consumers, most of these economic incentives will end up in the households with the most flexibility capacity, high income households, leading to an unjust energy transition model. Thus, important decisions around flexibility remuneration, market design, legal requirements for aggregators, tariff allocation of system flexibility costs, etc., should consider these socioeconomic gaps to guarantee equity standards in access and provision of flexibility services.

CRediT authorship contribution statement

David Ribó-Pérez: Conceptualization, Methodology, Software, Data Curation, Writing - original draft, Writing - review & editing. Miguel Heleno: Conceptualization, Methodology, Writing - review & editing, Supervision. Carlos Álvarez-Bel Writing - review & editing, Supervision.

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Chapter 3

Designing consumer centered energy policies

Once decided the objective of a policy, its impacts must be properly quantified to design it. In this sense, energy policies might not only produce impacts and results on their main objective but also have collateral impacts, which might be positive or negative. Therefore, the quantification and understanding of these impacts can help policymakers to set into place compensatory actions to reduce negative effects, or evaluate the need to further promote the policy to take advantage of the rest of the collateral benefits. *Ex-ante* policy analysis and impact assessment also help during the implementation and first developments of a policy as they allow comparisons between the expected results and the real impacts and outcomes of a policy.

The section of this chapter aims to analyse the potential impacts that increasing levels of Solar PV self-generation would have on the Spanish electricity market. The past legislation, RD 900/2015, was not favourable to the installation of Solar PV and deferred consumer investments in their own generation facilities. Assuming a more favourable regulation regarding solar SG, as it occurred with the RD 244/2019, the section presents an analysis of the impacts of increasing levels of SG with Solar PV. By modelling the behaviour of consumers that turned into prosumers, the impact overconsumption, market power, and the current electricity generation companies is quantified. The results show that the effects of increasing levels of SG have several implications. SG can lead to reductions in market power and wholesale electricity prices by enhancing competition on the system. The penetration of SG generates a rebound effect due to obtaining electricity at lower costs than in the market. In line with other energy rebound effects, known as the Jevons paradox, SG can increase energy consumption undermining efficiency and primary energy reduction objectives. Finally, increasing levels of SG show that not all the companies of the system would be equally affected, being the ones with the largest share of thermal generation, this is to say pivotal generation, the most affected due to the lowering purchase quantities in the market.

The investigation on the impact of energy policies with a consumer centered approach shows how policies have not only the intended effects but also collateral effects, both positive and negative. Promoting consumer empowerment and activation relates to increasing levels of decentralised RES, which increase competition and reliability to the system. But such policies also generate an increase in the electricity consumed due to their low marginal cost. In this sense, the quantification of these effects helps policymakers to design policies with elements to reduce their negative effects and enhance their positive ones. Self-generation policies can be complemented with education policies where consumers shift consumption to sunny hours. This might help to enhance consumer empowerment, reduce market power through even more hours of the day as demand reduces during the whole day, and help the system to increase its resilience.

3.1 Effects of self-generation in imperfectly competitive electricity markets: The case of Spain

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Abstract

Domestic rooftop photovoltaic (PV) energy can reduce net electricity demand, and therefore reduce energy prices through a merit-order effect. This reduces profits of all incumbents in the electricity markets. In addition, in imperfectly competitive markets, PV self-generation reduces prices through a reduction in market power. The first effect may warrant additional policy interventions to maintain cost recovery, but the second is much more desirable, as it simultaneously helps increase sustainability and competition. However, unlike a simple reduction in market prices, the competition effect affects all incumbents differently. Since resistance from incumbents can be a significant barrier to energy policy change, it is important to understand the distribution of effects. This paper does so for the Spanish market. A Nash-Cournot model and a simplified representation of the Spanish electricity market is used to determine the merit-order and competition effects of an increase in solar self-generation. We conclude that both are important, and that their analysis is essential to inform the social debate around PV policy.

Keywords

PV; Self-generation; Wholesale Electricity Market; Imperfect Competition; Modelling

3.1.1 Introduction

Scientific evidence overwhelmingly shows that climate change threatens our habitat and is a global risk that needs to be addressed universally and urgently [1, 2]. This issue has generated much discussion about the necessity for reducing emissions and how this can be accomplished. One of the main foci of greenhouse gas (GHG) emissions reduction has been electricity generation, as this has traditionally been based on fossil fuel burning. Renewable energy sources (RES) are offering an alternative that is currently paving a way to decarbonise the sector.

Solar photovoltaic energy is becoming an economically feasible technology for reducing emissions by generating energy, not just in centralised facilities, but also in a way known as solar self-generation (SG). With SG systems, electricity consumed in buildings is generated locally by the installation of PV panels, normally deployed on rooftops. This new way of generating has become feasible after large reductions in Photovoltaic (PV) costs of around 6-7% per year since 1998 [3, 4]. Nowadays, PV is reaching economic competitiveness and represents a viable alternative to other generating sources in many parts of the world. This is a massive opportunity, since approximately 20% of all GHG emissions result from energy consumed in buildings [2]. Besides GHG emission reduction, self-generation has a number of other advantages: electricity is produced where it is consumed, so reliance on transmission infrastructure is reduced; private investors face the cost of deploying new generating capacity instead of the governments; and reductions on countries' energy dependence.

However, this concept embodies a significant legal and economical shift in a sector where previously only a few players existed. In the past, a small number of firms owned large generating facilities (taking advantage of economies of scale) from where they produced electricity that was then distributed to the loads. This contrasts with the multitude of homeowners, offices, small business and industry who now have the capability to generate their own electricity and who want to sell their excess generation back to the grid. RES has been widely promoted by the European Union (EU), where a series of goals have been set to reduce carbon emissions. To meet these, different supporting policies to back RES and PV self-generation have been put into place in most countries. The Spanish case deserves specific attention. A shifting regulatory environment and the 2008 financial crisis moved the country from encouraging RES deployment to a legally adverse scenario, where the government was putting legal and economic barriers up in a way of discouraging new project installations [5]. However, the new government has recently shifted this position to again engage with the energy transition.

In this paper, we present a study of the economic impacts on prices and market power that result from increased levels of PV-self-generation. We use a Nash-Cournot model of the Spanish electricity market to simulate profit-maximisation behaviour of all players in an imperfectly competitive market. This allows us to analyse the effects of solar self-generation on individual incumbents and on consumers in possible future scenarios. This information is highly relevant to policy, and necessary to inform the social debate around RES support.

We aim to make three contributions to the existing literature. First, we present a novel analysis that demonstrates how larger penetrations of rooftop PV reduce prices through a merit order effect, but also enhance competition in the market and reduce market power . To do so, a Nash-Cournot model is applied to a simplified representation of the Spanish electricity system. Second, our analysis illustrates that these two forces affect companies with different portfolios of generation in very different ways, which suggests one way to understand resistence to PV subsidies from incumbents. Third, we analyse the implications of larger deployments of rooftop PV on total amounts of thermal generation and associated GHG emissions in the Spanish system, taking into that energy demand is price-sensitive and therefore that solar self-generation is not wholly offsetting thermal electricity generation.

The remainder of this paper is structured as follows: Section 4.2 sets out the current state of the art. Section 4.3 outlines our mathematical methods. Section 4.4 deals with specific characteristics of the Spanish case study. Section 5 presents the results of our numerical analysis. Section 4.6 discusses these results, followed by a conclusion in Section 4.7.

Nomenclature	
Indices	
i	Nodes
f	Firms
h	Generation technologies
k	Lines
t	Time periods
Parameters	
$MD_{i,t}$	Maximum demand of electricity at node i during time period t
$MaxP_{i,t}$	Maximum price at node i during time period t
$\epsilon_{i,t}$	Elasticity at node i during time period t
Q_t	Total electricity consumption during time period t
$q_{i,t}$	Quantity of electricity consumed at node i during time period t
$RV_{i,h}$	Regional variation at node i of generation technology i
$CF_{i,h}$	Capacity factor at node i of generation technology h
$C\bar{F}_{i,h}$	Mean capacity factor of generation technology h
$PTDF_{i,k}$	Power Transfer Distribution Factor of line k, node i
$\bar{X}_{f,i,h,t}$	Maximum generation capacity of technology h from firm f at node i
$-\bar{X}_{f,i,h,t}$	Minimum generation capacity of technology h from firm f at node i
$SG_{i,t}$	Solar PV self-generation at node i during time period t
MF_k	Capacity of line k
Variables	
$s_{f,i,t}$	Sales of firm f at node i during the time period t
$x_{f,i,h,t}$	Generation of firm f at node i with technology h during time period t
B_f	Profits of firm f
$W_{i,t}$	Transmission cost at node i during time period t
$\rho_{f,i,h,t}$	Dual variable of the maximum generation bound of technology h from firm f at node i. time period t
$\beta_{f,i,h,t}$	Dual variable of the minimum generation bound of technology h from firm f at node i, time period t
$\theta_{f,t}$	Dual variable of the within-firm energy balance constraint, for firm f at time period t
$\lambda^+_{k,t}$	Dual variable of the upper thermal limit of line k at time period t
$\lambda^-_{k,t}$	Dual variable of the lower thermal limit of line k at time period t

3.1.2 Existing literature

3.1.2.1 Impacts of RES on energy prices

Approaches to energy planning and policy require more sophisticated and analytical tools than the ones previously used to model other sectors [6]. Over the years, modelling has proved its usefulness, and it has been widely used as a decision support tool. However, it is important to consider that models are all based on simplifications, assumptions and often require data which may not exist. Whilst they are extremely powerful tools to analyse different policy options and economic trends, their results must not be taken as undeniable truths. It is important to highlight how an inaccurate description of energy problems might lead to inappropriate policy recommendations and actions [7].

The effects of a high penetration of RES on prices in liberalised electricity markets have been studied extensively. Most of these markets, which were traditionally ruled by an established merit order, have seen the entrance of new competitors with lower marginal costs which has pushed traditional technologies out of the margin. The entrance of RES, historically boosted with subsidies, has generated an intense and controversial debate. These studies have mainly focused on the analysis of national or regional markets such as Germany and Austria [8–11], Australia [12], Israel [13] or Italy [14, 15] . These studies have approached the issue mainly through simulation based models and statistical analysis.

Simulation methods have focused on estimating the reductions in prices due to the merit order effect mentioned above. For instance, McConnell et al. [12] state that policy incentives have produced net gains if wholesale price reductions and financial support is accounted for.Cludius et al. [9] show how the merit order effect overcompensates some privileged groups of large consumers while negatively affecting domestic consumers. On the other hand, statistical analysis have been mainly based on econometric models such as Gelabert, Labandeira, and Linares[16], who perform an ex post analysis of the influence of renewable energy on the wholesale market prices.

The case of Spain has been widely studied due to its pioneering role in promoting large-scale deployment of solar PV. The Spanish government, in 2007, created a scheme that granted investors an extremely attractive Feed-In-Tariff. This generated a boom for Solar PV in 2008 with almost 3 GW of new capacity installed, while the technology was perhaps not mature enough, generating an economic deficit [17]. Along a similar line, another study from Azofra et al. [18] concludes that while Spanish subsidies to wind power have saved costs to the whole system, solar PV subsidies have generated an increase in total costs. Another study reflects the decrease in prices and the reduction of price spikes due to larger RES deployment [19]. The merit order effect of wind energy in the Iberian market and its effect on domestic consumers was studied by [20], who also conclude that consumers benefit less from this effect. Finally, Gelabert, Labandeira, and Linares [16] argued the unsustainability of the subsidies in Spain due to low reductions in the wholesale prices compared with the cost of subsidies. However, they surmise that large firms were exercising market power to push prices up and compensate the impact of renewables. Therefore, the merit order effect that RES created was being eliminated throughout illicit practices, as the 25M fine imposed by the National Market Commission (CNMC by initials in Spanish) to a Spanish electricity utility due to price manipulations [21] also suggests.

Hence, the effect that imperfectly competitive markets have had in all of this has been mentioned but generally not included in studies. Not taking into account this characteristic might have led to misleading policy interventions [15]. The literature around the effects of RES in imperfect markets is still scarce. Closest to this study, Milstein and Tishler[13] simulated imperfect competition markets in Germany and the effect of RES in them. Cournot oligopoly models were used and their conclusions contradict the existing literature on the topic, showing how FITs may actually increase prices due to enhanced market power. Another analysis that takes into account imperfectly competitive markets is presented by Gullì and Balbo[15]. Here, the authors conclude that PV generation might produce immediate reductions in electricity prices. However, PV capacity is able to erode the market power that large firms are able to exert. We will see similar effects in our analysis below. All these studies remain at the macro level and do not analyse the effect that an increasing capacity of solar PV has on individual incumbent's revenues and therefore the attitudes to RES developments that each of them might have in the near future.

3.1.2.2 Modelling energy markets

Optimisation models are widely used to analyse energy markets. These generally assume that the market is perfectly competitive, among a number of other assumptions. Like many other markets, real-world power markets usually present a degree of market power. Depending on market design, firms may be able to deliberately congest the network, bid strategically and/or withhold generating capacity. These issues have an even greater impact in electricity markets then they would in others, as supply and demand must match at any time due to physical requirements and because there is limited scope for intertemporal arbitrage. This affects not only prices and firms' profits but also consumers' economic welfare, and can lead to efficiency reductions. [22].

Simple optimisation models cannot capture these effects, so more advanced models, based on game theory, have been developed. Defined as "the study of mathematical models of conflict and cooperation between intelligent rational decision-makers" [23], game theory principles have been extensively applied to social science analysis. In particular, game theory has played a key role in the understanding of behavioural patterns of market players. Mathematically, they can be represented by equilibrium models, which are playing an increasingly important role in power market analysis. These equilibrium models assume that each player individually maximises its own objective, usually profit, and find a solution by simultaneously solving these optimisation problems for all players. They are a powerful tool that can be used to analyse a wide range of settings, including regulation and deregulation, imperfect competition, and other features of real-world electricity markets. They are, however, more complex to solve than simple optimisation problems, and are usually formulated as non-linear optimisation or feasibility problems, or as complementarity problems, as we will do below.

Within an equilibrium framework, assumptions have to be made about what it is that firms are maximising, and which variables they control. When analysing behaviour of firms, competition and economic trends in power systems, Nash-Cournot competition is most commonly assumed [22]. In a Nash-Cournot equilibrium, firms maximise profits, deciding on their quantities of production. This concept has stood the test of time and has been used extensively since the liberalisation of electricity markets (e.g.,[24–27]). Currently, this concept is still applied in many different power system applications such as the analysis of transmission infrastructure investment [28]; the integration of charging stations for electrical vehicles in large cities [29] or the evaluation of the risk of supplying electricity in uncertain markets with high penetration on RES [30]). There are alternatives, including supply function equilibrium models and Nash-Bertrand models. Supply function equilibrium models, in which firms decide price and quantity combinations, work well in small networks but in large networks are very computationally expensive. Nash-Bertrand models assume that firms set prices rather than quantities. This is appropriate for some markets, but the specific features of electricity markets, in which long-term decisions are typically related to quantities, make Nash-Cournot models more appropriate. Agent-based models are also commonly used in energy applications, but these are more appropriate for simulating the behaviour of a large number of players (e.g., consumers) which cannot be assumed to be rational profit maximisers, as opposed to the small number of large industrial players in wholesale energy markets.

Although they are able to capture more details of real-world markets than simple optimisation models, Nash-Cournot models, like any other modelling approaches, cannot precisely predict prices in imperfect markets, since invariably some market detail is assumed away. Nevertheless, they are a crucial tool for gaining insights on behavioural modes, efficiency differences between players, price levels, and other market outcomes of market designs [27]. Due to its wide range of application areas, many of these models have been developed and are still being developed [31–35], and we will use this same approach in our analysis below.

3.1.3 Methodology

3.1.3.1 Model overview

The model presented here is a Nash-Cournot model, which we will use to analyse the effects of self-generation impacts on the wholesale electricity market. It is based on the Hobbs[27] POOLCO model, and separately includes renewable generation and solar PV self-generation. Since the main intention is to understand market behaviour, some technical characteristics have not been included in the model. These include variable marginal costs, ramping constraints, reserve and future markets and the uncertainty of renewable output. Although it is still highly simplified, the model represents (Figure 3.1.1) how actors use their market power to increase electricity prices above marginal costs. Nevertheless, we recognize that some authors (e.g., [36]) have shown that ignoring these technical characteristics may generate distortions in the economic and policy consequences for the power system. Our quantitative results, like the results of any modelling study, should therefore be used with care, and we will focus on the more general insights derived from them.

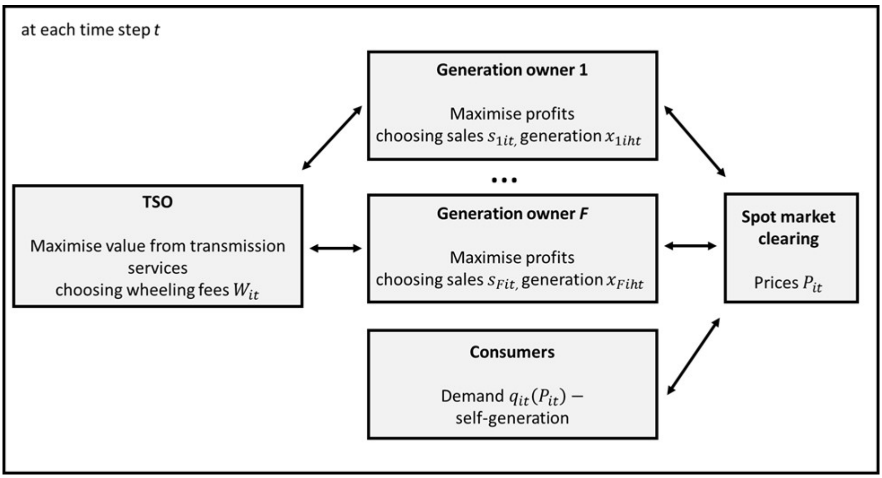

Figure 3.1.1: Block diagram of the POOLCO model.

In this model, each generation owner decides how much electricity to produce each hour, using its portfolio of power plants. Because of the computation expense of our modelling approach, we model representative 24-hour days, in this example the extreme cases of one winter and one summer day are presented. An exact quantification of prices would require more than three years of modelling, because of varying climates. However, this would be very computationally intensive without bringing significantly more insight. Moreover, solar generation patterns, which are the key parameters in our model, are relatively regular and predictable in Spain, in comparison to other countries. Thus, in our specific case, modelling two representative days, in the two extreme seasons of a year, is sufficient to establish the competitive and merit order effects of solar self-generation.

We use a Direct Current (DC) load flow approximation of a 12-node reduction of the Spanish high-voltage transmission network to approximate power flows. It is important to remark that the model proposed here considers that the network and generation infrastructure remains constant; that is, it ignores the transmission and generation expansion opportunities. Although expansion has an important relationship with market operation and can be included in game-theoretical [37–39] we do not include them here, as the Spanish transmission network is relatively uncongested (and hence, transmission expansion would not significantly affect our results), while generation expansion is highly politicised and therefore cannot be modelled as an individual generator's decision. Demand is price-sensitive, with a low price elasticity. Variable renewable generation is modelled using historical hourly capacity factors. For simplicity, we assume a nodal pricing market, but since the Spanish system is relatively uncongested congested, this does not have a significant impact on our results; we present weighted average prices in our results. Section 3.2. below list our assumptions in detail.

3.1.3.2 Model assumptions

Network We estimate power flows using a linearised DC load flow approximation. Instead of including both Kirchoff's laws of current and voltage, linear equations approximate the flow in a DC version of the laws. This simplification is widely used in power economics modelling [22]. It assumes that the line resistance is irrelevant compared with the reactance. Therefore, voltage magnitudes are equal to the nominal voltage level at all nodes. This implies that all nodes' voltages hover around 400 kV. We can then presolve for voltage angles and instead use

PTDFs, power transfer distribution factors, which represent the increase in flow going through a line as a result of an injection of power in a node.

If the flow is defined as t_k, the total flow that is being transmitted through a line is represented by a summation of the electricity transmitted from each node i (y_i) and the $PTDF_{i,k}$ of the combination of node and line:

$$t_k = \sum_i PTDF_{i,k} \cdot y_i \qquad \forall k \tag{3.1.1}$$

To take into account the system losses and the reactive power that is consumed in real-world AC networks, we increase demand by 3%.

Generating facilities The generating facilities that have been taken into account in the model are: wind, hydro, nuclear, combined cycle gas turbines, coal, cogeneration and biomass, solar and self-generation. The complete list of generators has been aggregated by firm and node, such that every firm owns one generator of each type at each node, which represents the total amount of generation capacity of that type owned by the firm in that location. Ramping constraints have not been included; instead, in order to approximate the most important operational constraint in the Spanish system, minimum running levels have been included for nuclear generators. The minimum level at which nuclear plants can run in the model is 85% of their maximum capacity.

The marginal costs of the generating facilities are constant and only differentiated by type – they are not location or firm dependent. This approach has been used in other studies, as firm-level cost data is unavailable and plants using the same technologies can reasonably be assumed to behave similarly [34, 40].

Demand We assume that demand is price-sensitive and linear in prices, with a relatively low value for the slope, which has been established to be the case in the empirical literature [41, 42].

$$P_{i,t} = MD_{i,t} - \epsilon_i \cdot y_i \qquad \forall i, t \tag{3.1.2}$$

Spatiotemporally differentiated demand in the Spanish system is difficult to obtain. Hence, we apportion demand to the different nodes using constraint fractions, which are calculated using annual consumption data:

$$q_{i,t} = \%_{i,t} \cdot Q_t \qquad \forall i, t \tag{3.1.3}$$

Even though this is a simplification, the sizes of the consumption at each node are large enough to aggregate out any variation in demand structures because of regional variation in types of customers.

Renewable output

The variability of the renewable output is modelled using hourly capacity factors, which are estimated using two years of historical data, validated against existing empirical studies [43–46]. This is done individually for each node, since climate conditions differ between nodes. For computational convenience, a new parameter defined as Regional Variation (RV) is added. This parameter shows the deviation from the national mean capacity factor for each technology at each node.

$$RV_{i,h} = 1 + \frac{\left(CF_{i,h} - \bar{CF}_h\right)}{\bar{CF}_h} \qquad \forall i \tag{3.1.4}$$

Therefore, the maximum hourly capacity of the renewable generator is constrained. Since we are solving for electricity production over a relatively short time span, conventional generators have an hourly capacity factor equal to 1.

$$x_{f,i,h,t} = RV_{i,h} \cdot CF_{i,h} \cdot \bar{X}_{f,i,h,t} \qquad \forall f, i, h, t \tag{3.1.5}$$

Self-generation

Since self-generation is generally non-dispatchable, we model it as an effective reduction in net demand, where capacity penetration levels are a percentage of demand. For instance, if the initial consumption in a node is 1000 MW, a level of 2% of penetration means that 20MW of solar PV is installed at the node. Apart from its non-dispatchability, self-generation is treated as any other renewable generating facility. Therefore, SG is subject to the same solar capacity factor and nodal deviation from the mean as dispatchable solar generation. Self-generation levels have been assessed from 0% up to 32%, this late number would account for around 10 GW of Solar PV between residential and commercial sector in the Spanish scenario, where some studies suggest that up to 16.5 GW of Solar PV could technically be installed [47]).

3.1.3.3 Mathematical formulation

We assume that each firm f chooses electricity generation $x_{f,i,h,t}$ at each of its type of generating facilities h at each node i and its sales $s_{f,i,t}$ at each node i, to maximise its profits at each time period t, where profit is defined as the difference between the revenues from electricity sales minus generation and transportation costs:

$$MaxB_i = \sum_i \left[\left(P_{i,t} - W_{i,t} \right) \cdot s_{f,i,t} \right] - \sum_{i,h} \left[\left(MC_h - W_{i,t} \right) \cdot x_{f,i,h,t} \right] \qquad \forall i,h \tag{3.1.6}$$

Subject to:

$$x_{f,i,h,t} \leq RV_{i,h} \cdot CF_{i,h} \cdot \bar{X}_{f,i,h,t} \qquad \left(\rho_{f,i,h,t} \right) \qquad \forall f,i,h,t \tag{3.1.7}$$

$$x_{f,i,h,t} \geq \bar{X}_{f,i,h,t} \qquad \left(\beta_{f,i,h,t} \right) \qquad \forall f,i,h,t \tag{3.1.8}$$

$$\sum_{i,h} x_{f,i,h,t} = \sum_i s_{f,i,t} \qquad \left(\theta_{f,t} \right) \qquad \forall f,i,h,t \tag{3.1.9}$$

$$x_{f,i,h,t} \geq 0 \qquad \forall s_{f,i,t} \tag{3.1.10}$$

Where $P_{i,t}$ represents the price of electricity at the node i at the hour t, which is defined as:

$$P_{i,t} = MaxP_{i,t} - \epsilon_{i,t} \cdot \left(\sum_i s_{f,i,t} \cdot SG_{i,t} \right) \qquad \forall i,t \tag{3.1.11}$$

$MaxP_{i,t}$ represents the maximum price at the node i at the hour t, $\epsilon_{i,t}$ represents the inverse demand function slope, and the consumption quantity q is assumed to be equal to the self-generated energy and the purchased energy in the node (equal to the sales). $SG_{i,t}$represents the amount of self-consumed energy, which is assumed to have a zero marginal cost and which can be or consumed or exported to the grid. This is the case in many countries, including Spain, which recently passed legislation specifying that self-generation can act as any other type of generation [48]. $W_{i,t}$ represents the transmission wheeling fee and MC_h is the marginal cost of generation, which is assumed to be constant and equal for generation facilities using the same type of energy source. Regarding the constraints, $\bar{X_{f,i,h,t}}$ is the maximum installed capacity. The terms $RV_{i,h}$ and $CF_{h,t}$ are introduced to show the RES availability: $CF_{h,t}$ is the global capacity factor of RES in the system and $RV_{i,h}$ represents the variation in terms of RES availability between different nodes of the system. $-X_{f,i,h,t}$ is the minimum running level of a block of generators and $\rho_{f,i,h,t}$, $\beta_{f,i,h,t}$ and $\theta_{f,t}$ are the dual variables for the above mentioned constraints. The producers' Karush-Kuhn-Tucker (KKT) conditions for the above problem are:

$$0 \leq s_{f,i,t} \perp MaxD_{i,t} - \epsilon_{i,t} \cdot \left(s_{f,i,t} + \sum_{i} s_{f,i,t} SG_{i,t} \right) - W_{i,t} - \theta_{f,t} \leq 0 \qquad \forall i,t \tag{3.1.12}$$

$$0 \leq x_{f,i,h,t} \perp \left(MC_h - W_{i,t} \right) - \rho_{f,i,h,t} + \theta_{f,t} + \beta_{f,i,h,t} \leq 0 \qquad \forall i,h,t \tag{3.1.13}$$

$$0 \leq \rho_{f,i,h,t} \perp x_{f,i,h,t} - RV_{i,h} \cdot CF_{h,t} \cdot \bar{X_{f,i,h,t}} \leq 0 \qquad \forall i,h,t \tag{3.1.14}$$

$$0 \leq \beta_{f,i,h,t} \perp \bar{X_{f,i,h,t}} - x_{f,i,h,t} \leq 0 \qquad \forall i,h,t \tag{3.1.15}$$

$$\sum_{i,h} x_{f,i,h,t} = \sum_{i} s_{f,i,t} \qquad \forall t \tag{3.1.16}$$

We assume that the transmission system operator is a price-taker, which maximises revenues from providing transmission services, such that its maximisation problem is:

$$Max \qquad \sum_i W_{i,t} \cdot y_{i,t} \qquad \forall t \tag{3.1.17}$$

Subject to:

$$\sum_i PTDF_{i,k} \cdot y_{i,t} \leq MF_k \left(\lambda^+_{k,t}\right) \qquad \forall t \tag{3.1.18}$$

$$-\sum_i PTDF_{i,k} \cdot y_{i,t} \leq MF_k \left(\lambda^-_{k,t}\right) \qquad \forall t \tag{3.1.19}$$

Where $y_{i,t}$ represents the flow on each line transmitted to the node i, MF_k represents the maximum thermal capacity of each line k and $\lambda_{k,t}$ represents the dual variable associated with the maximum and minimum flow constraints on the lines. Therefore, the KKT conditions for the grid owner are:

$$W_{i,t} + \sum_i PTDF_{i,k} \cdot \left(\lambda^-_{k,t} - \lambda^+_{k,t}\right) = 0 \qquad \forall i, t \tag{3.1.20}$$

$$0 \leq \lambda^+_{k,t} \perp \sum_i PTDF_{i,k} \cdot y_{i,t} - MF_k \leq 0 \qquad \forall k, t \tag{3.1.21}$$

$$0 \leq \lambda^-_{k,t} \perp -\sum_i PTDF_{i,k} \cdot y_{i,t} - MF_k \leq 0 \qquad \forall k, t \tag{3.1.22}$$

Finally, a transmission market clearing constraint must be satisfied, which specifies that the supplied transmission capacity is equal to demand for transmission:

$$\sum_i s_{f,i,t} - \sum_{i,h} x_{f,i,h,t} = y_{i,t} \qquad \forall i, t \tag{3.1.23}$$

3.1.4 Case Study: Spanish market

Since 1998, the Spanish electricity sector has been restructured according to the Electricity Sector Act 54/1997. This act aimed to introduce competition into both electricity generation and retail markets. On the other hand, transmission and distribution are natural monopolies and remain highly regulated markets. Although liberalised, the Spanish electricity market presents a distinctive model since it permits vertically integrated firm holdings with generation, distribution and retail services [49].

Currently, the Spanish generating market is dominated by three main firms, Endesa, Gas Natural Fenosa (recently renamed to Naturgy) and Iberdrola. Each hold more than 12% of the market share, and combined the three firms were responsible for 60% of the generating capacity, 55% of the generated electricity and 80% of the retail market during 2014 [50]. EDP and Viesgo (owned by the German firm E.ON) are the other two main players on the market. They each own more than 5% of the generating capacity and have a strong position on the retail market.

The electricity is traded in a joint market with Portugal (MIBEL). The preferred marketplace for electricity transactions is a day-ahead market, often referred to as spot market. This market represents more than 70% of the total purchased electricity of Iberian market [51], while the future market represents only 30% and contracts are normally indexed to spot prices. The market works as a two-sided auction, where producers submit offers for delivering electricity at a certain price and time of the next day and are merged by the Market Operator with a marginal pricing system. This market is regulated and transparent. However, market power has been still been observed.

Market power has been legally proven, as demonstrated by, for instance, a fine imposed in 2015. The CNMC (National Commission on Markets and Competition) fined an electricity utility 25M for voluntary curtailing hydro production to obtain higher prices in the spot market [21]. This market power in the Spanish sector has been widely studied since the creation of the liberalised market. Fabra and Toro[52] conclude that Spanish generating firms were probably engaged in tacit agreements to distort the market outcomes. Ciarreta and Espinosa[53] find that larger operators were able to increase considerably the prices above competitive levels. And, Nuño, Pereira, and Machado-Ferreira[54] show how an increasing wind penetration on this market has shifted some of the market power of these firms to the capacity market.

Physically, Spain has a large and well-diversified generation system. The system has a high reliability and has successfully integrated a large share of RES with little generation curtailment [55]. The Spanish network is characterised by its robustness. The transmission network has a large degree of reliability and flow constraints are not normally binding [56]. Even though the internal system is highly reliable, since the Iberian Peninsula has a low cross-border capacity [55], any intermittency in the Iberian system must be dealt within the region. Therefore, the Iberian electricity system operates almost as an island in Europe.

3.1.4.1 Input data

In order to reproduce the Spanish market, we use a reduced network model that only covers the 400 kV lines in Spain. These lines are the major source of transport capacity in the peninsula with 21,094 km of lines installed at the end of 2014 [44]. The initial network data was obtained from a model of the European network [57]. The Spanish nodes have been reduced to 12 nodes, one for each Spanish region, with the exception of the "North" node, which contains Asturias and Cantabria, and "Basque Country", which groups the Basque Country, Navarra and La Rioja. These 12 nodes are connected with 23 lines. These nodes have been chosen because they provide enough detail to analyse the Spanish system for the purpose of policy making. By aggregating generators and loads by region, reliable data from the TSO is available. The extra peninsular systems (islands) and international connections have not been considered. Therefore, Portuguese, French and Moroccan generation and consumption have not been taken into account. To model the system, PTDFs have been calculated using a lossless DC approximation of the network and taking Andalucia as the slack bus; the resulting data is presented in Table 3.1.1.

We only model the firm-specific strategic behaviour of Iberdrola, Endesa, Gas Natural (recently renamed to Naturgy, but still operating under its old name during the modelled period), E.On, EDP and GDF Suez, since the rest of the facilities are owned by a large number of smaller firms. In order to include the behaviour of these firms, we group them into five renewable energy firms, each with a 3% market share. This allows the model to include all renewable generation without giving these aggregate firms significant market power. In a similar way, a catch-all firm representing all the thermal generation not owned by the main electricity utilities has been created (named "Other Thermal" in the results). Firms have very

Table 3.1.1: PTDFs, Spain 12 node system

PTDF	Andalucía	Aragon	Castilla LM	Castilla Leon	Cataluña	Extremadura	Galicia	Madrid	Murcia	Norte	País Vasco	Valencia
L1	-	-0.364	-0.301	-0.422	-0.359	-0.667	-0.422	-0.399	-0.238	-0.422	-0.41	-0.302
L2	-	-0.195	-0.2	-0.172	-0.198	-0.097	-0.172	-0.175	-0.378	-0.172	-0.177	-0.23
L3	-	-0.456	-0.507	-0.416	-0.461	-0.24	-0.416	-0.434	-0.391	-0.416	-0.425	-0.477
L4	-	0.2	0.028	-0.144	0.195	-0.032	-0.146	-0.025	0.03	-0.142	-0.072	0.054
L5	-	0.146	-0.007	0.075	0.131	0.017	0.075	0.016	-0.023	0.075	0.09	-0.055
L6	-	0.23	0.032	-0.165	0.224	-0.037	-0.168	-0.029	0.034	-0.171	-0.295	0.062
L7	-	0.117	-0.022	0.079	-0.842	0.021	0.086	0.012	-0.035	0.084	0.091	-0.088
L8	-	0.307	-0.031	0.154	0.289	0.031	0.153	0.026	-0.007	0.155	0.186	0.027
L9	-	0.084	0.128	0.087	0.081	0.055	0.087	0.102	-0.383	0.087	0.087	0.032
L10	-	0.021	0.033	0.01	0.022	-0.036	0.01	0.014	0.025	0.01	0.012	0.029
L11	-	-0.203	0.093	-0.085	-0.247	-0.003	-0.084	0.016	-0.182	-0.086	-0.11	-0.651
L12	-	-0.058	0.209	-0.278	-0.038	-0.226	-0.279	-0.541	0.143	-0.277	-0.232	0.139
L13	-	0.243	-0.023	0.461	0.225	0.024	0.462	-0.139	-0.006	0.46	0.415	0.018
L14	-	-0.005	-0.001	0.003	-0.001	0.001	-0.052	0.001	-0.001	-0.933	-0.029	-0.001
L15	-	0.004	0.001	-0.003	0.007	-0.001	-0.954	-0.001	0.001	-0.035	-0.003	0.001
L16	-	0.171	0.08	0.245	0.166	-0.089	0.245	0.088	0.067	0.245	0.23	0.092
L17	-	-0.217	-0.03	0.155	-0.209	0.035	0.156	0.027	-0.032	0.125	-0.682	-0.058
L18	-	0.189	-0.008	0.095	0.262	0.021	0.094	0.021	-0.028	0.095	0.115	-0.066
L19	-	-0.183	-0.191	-0.173	-0.185	0.211	-0.172	-0.299	-0.149	-0.173	-0.175	-0.185
L20	-	0	0	0	-0.001	0	0.057	0	0	-0.031	-0.001	0
L21	-	-0.005	-0.005	0.008	-0.008	0.009	0.009	0.023	-0.013	0.008	0.006	-0.031
L22	-	-0.119	-0.073	-0.09	-0.129	-0.043	-0.09	-0.075	0.246	-0.09	-0.096	-0.199
L23	-	-0.009	-0.001	0.007	-0.009	0.002	0.009	0.001	-0.001	0.044	-0.028	-0.002

different portfolios of generation. These are presented in Table 3.1.2 and have been estimated using a number of sources [44, 58–62].

Table 3.1.2: Firms' portfolio by source

	Acciona	E.On	EDP	Endesa	Gas Natural	GDF Suez	Iberdrola	Other Thermal	Other RES I, II, III, IV
Coal	0%	19%	52%	27%	20%	0%	3%	9%	0%
Nuclear	0%	0%	0%	17%	0%	0%	16%	0%	0%
Wind	80%	6%	3%	9%	0%	0%	21%	0%	67%
Hydro	15%	15%	15%	26%	17%	0%	38%	0%	0%
CCGT	0%	60%	30%	21%	63%	100%	21%	91%	0%
Solar	4%	0%	0%	0%	0%	0%	0%	0%	0%
Cogeneration	1%	0%	0%	0%	0%	0%	0%	0%	0%
% of total	6.56	5.33	3.21	20.25	12.32	2.23	29.64	3.78	3.34

For instance, while Acciona and the aggregated small renewable generation owners ("Other RES") have only renewable facilities; E.ON, EDP, GDF Suez, Gas Natural and Other Thermal have a portfolio based on thermal generators and hydro. Iberdrola and Endesa have a well-diversified portfolio of generating facilities. The marginal cost (MC) of each generation technology (Table 3.1.3) is based on [40] and translated to current prices. This is an obvious simplification, as in reality different plants using the same fuel may have slightly different fuel costs. Moreover, specific studies in Spain like Ciarreta, Espinosa, and Pizarro-Irizar [63] show inelastic supply offers from technologies like coal, nuclear, and hydro. However, as previously mentioned, detailed marginal cost information for individual power plants is confidential and cannot be accessed.

Table 3.1.3: Marginal costs by energy type

MC	/MWh
Coal	20.54
Nuclear	2.15
Wind	0.01
Hydro	1.95
Gas	35.8
Solar	0.01
Cogeneration	11.85

Although there is no wide variety of energy demand studies for Spain, there is evidence that the electricity demand is relatively inelastic [64–66]. The elasticities estimated in these studies vary between 0.05 in the short term, to 0.21 in the long term. We use a linear demand function with a slope of 0.07, similar to [64].

Energy demand data for each node, as a fraction of total Spanish demand, was obtained from [44] and is presented in Table 3.1.4.

Table 3.1.4: Percent demand by node

Node	Demand	Node	Demand
Andalucia	15.61%	Galicia	7.99%
Aragon	4.05%	Madrid	11.84%
Castilla la Mancha	4.59%	Murcia	3.52%
Castilla Leon	5.31%	Norte	6.01%
Catalunya	19.00%	Pais Vasco	9.57%
Extremadura	1.76%	Valencia	10.76%

The regional variations considered for the different renewable sources can be seen in Table 3.1.5, which are retrieved from [43, 44]. Finally, hourly historical capacity factors were retrieved from the REE database [45].

Table 3.1.5: Nodal regional variations by source

Node	Wind	Hydro	Solar	Node	Wind	Hydro	Solar
Andalucia	0.98	0.488	1.172	Galicia	1.048	1.28	0.811
Aragon	1.048	1.225	1.022	Madrid	1	1	1.052
Castilla la Mancha	0.92	0.684	1.082	Murcia	0.787	0.684	1.142
Castilla Leon	0.876	1.313	1.022	Norte	0.968	1.28	0.721
Catalunya	0.847	1.225	0.932	Pais Vasco	1.229	1.28	0.721
Extremadura	0.992	0.488	1.142	Valencia	0.964	0.684	1.052

We consider two days with identical levels of self-generation: a typical winter day (a working day in February 2014) and a typical summer day (a working day in

July 2014). The variations between these two scenarios is considerable, due to the climatic characteristics of Spain and its spatial location (an average latitude of 40 degrees), with long summer days and short winter days, which will significantly affect PV performance. The winter day is characterised by only 5 hours of sunlight. Moreover, the intensity of the sun is relatively low and solar capacity factor is around 30% of its nominal value at solar noon. Figure 3.1.2 shows the winter demand curve (not including reductions due to solar self-generation) and the hourly solar capacity factor.

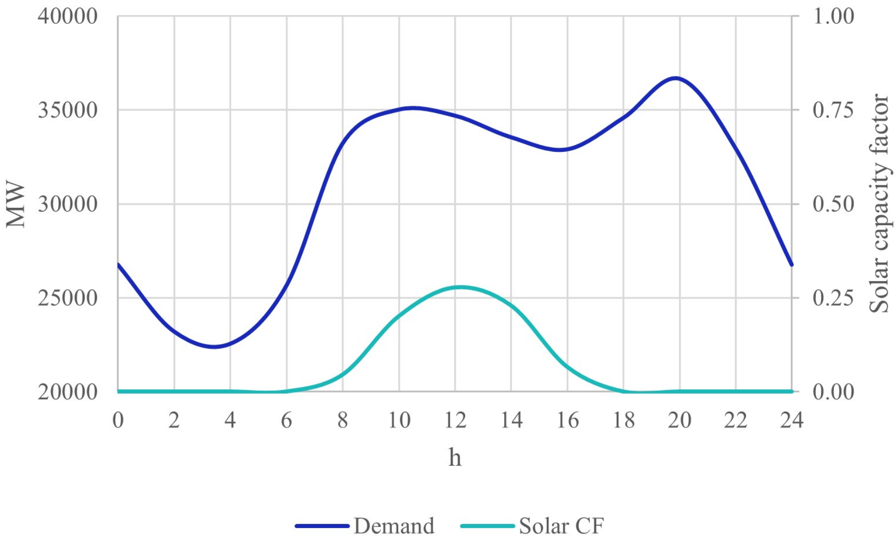

Figure 3.1.2: Winter demand curve.

During the summer period simulation, the sun shines between 7am until 10pm. In addition, the levels of irradiation are much higher than the ones experienced in winter. Figure 3.1.3 shows the summer demand curve.

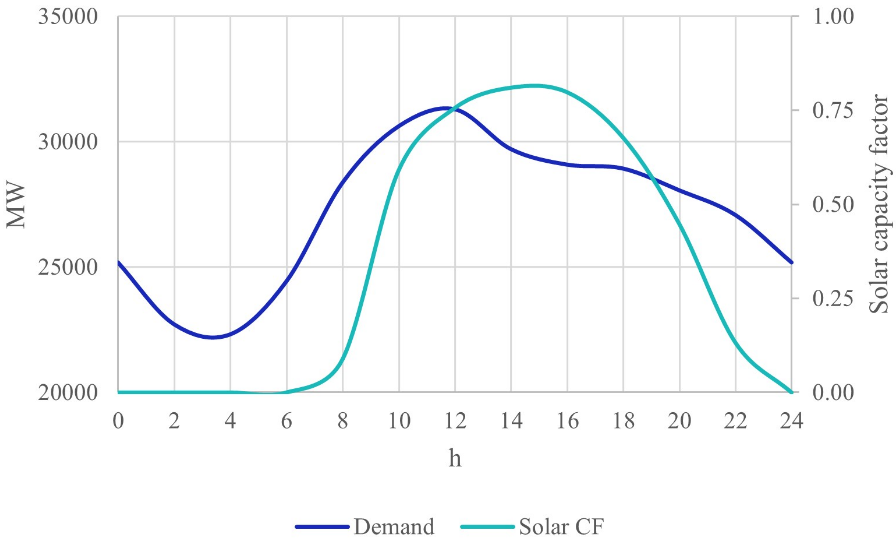

Figure 3.1.3: Summer demand curve.

3.1.5 Results and Discussion

3.1.5.1 Overall results

This section presents the results and discussion of the Spanish market response to an increasing level of self-generation. As explained above, we will consider a typical winter day and a typical summer day. Although there are important differences between the two days, in both seasons the market experiences similar qualitative responses to self-generation. In general terms, the competitiveness of the market is enhanced, since both prices and market concentrations decrease. As the penetration of solar self-generation increases, prices move significantly closer to the marginal cost of the last unit dispatched (CCGT).

The overall consumption of electricity, including self-generation and centrally produced electricity, increases. In contrast, less electricity is purchased from the grid. The reduction in purchases is lower than the self-generated electricity since lower prices incentivise consumers to purchase more. This rebound effect reduces the carbon savings of self-generation, but represents an increase in consumer utility and, in the longer run, better living standards and economic performance.

Finally, as self-generation increases, the affected large-scale generators are mainly thermal plants, which have a higher marginal cost. There is little impact on centralised renewable energy output. On the other hand, some low marginal cost generators, including mainly hydro and some nuclear plants, have their output reduced, partly in an effort by firms to maintain higher prices. The voluntary curtailment of hydro, which as explained above has been observed in the Spanish market, represents some evidence that the model does reflect the realities of the Spanish market reasonably well.

3.1.5.2 Winter day

The winter day is characterised by only 10 hours of sunlight. Moreover, the intensity of the sun is relatively low and the solar production is around 30% of its nominal value at solar noon. In general terms, average daily prices are reduced by 2% with a 32% of SG penetration. The baseline price without SG is 51.5 per MWh, a price similar to the average price on the Spanish market the modelled day (50.3 per MWh).

Average daily consumption goes up by less than 1-2%, even at very high SG penetrations, mostly due to the low price elasticity of demand. However, there is a larger increase in consumption during the hours with sunlight, increasing the correlation between energy availability and consumption (Figure 3.1.4).

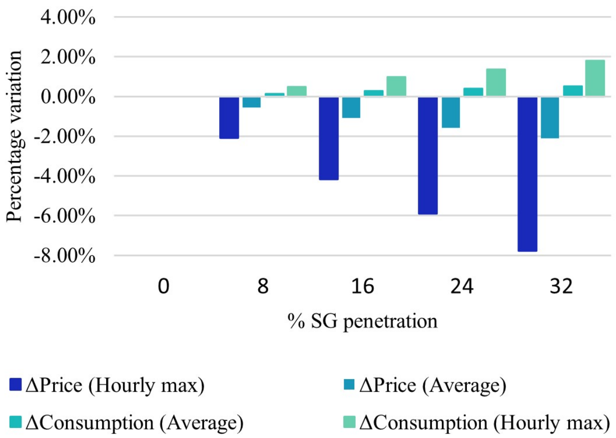

Figure 3.1.4: Price and consumption variations. Winter day.

Figure 3.1.5 shows the levels of consumption and electricity purchased from the grid at different levels of SG. Only sunlight hours are shown, as there is no change when it is dark. As it can be seen in the figure, as the amount of SG increases the amount of electricity purchased from the grid decreases, whereas the overall consumption increases. This occurs because consumption of zero marginal cost electricity decreases wholesale market prices through a merit order effect and decrease in market power. The variations in consumption and purchases are largely dependent on the assumed elasticity of the Spanish consumers.

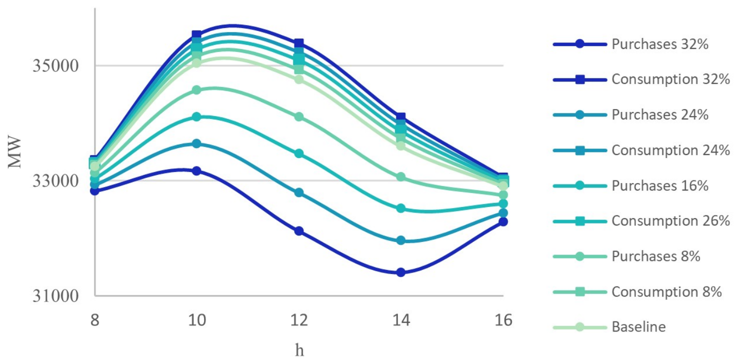

Figure 3.1.5: Electricity consumption and purchases from the grid at different levels of SG penetration. Winter day.

Delving deeper in to these results, Figure 3.1.6 and Figure 3.1.7 show the percentage reductions in generation and profits of the various incumbents. It is important to note that these are future projections obtained from a highly stylised model: we are not accusing any of the firms mentioned of current or future anti-competitive behaviour beyond what has been legally established so far, but simply highlighting what would happen if they responded only to economic incentives.

In terms of generation by firm, the firms with an exclusively renewable generation portfolio are not affected in terms of production; they experience no merit order effect, and have little market power to begin with. This can be seen with the aggregated producer Other RES and Acciona. Naturally, these producers still see lower profits because of a reduction in prices. On the other hand, the firms that only own thermal units, such as GDF Suez, Other Thermal, E.On and EDP, are the ones most affected; they are more likely to be pushed out of the margin, and lose market power. Although they have gas and coal facilities, Endesa and Iberdrola mainly rely on their nuclear and RES to produce electricity, since these have lower marginal costs. Hence, Iberdrola manages to hold on to its market share and keep its profits high by reducing its output to maintain higher prices. Endesa is not affected during the winter period since it benefits from Iberdrola's capacity withholding. It is necessary to highlight that the decrease in generation never exceeds 10% for a single firm, despite increasing SG up to 32%. Profits decrease more, but still only by a modest 11% in the worst case. This is significant, but unlikely to have immediate solvency consequences for the firms concerned.

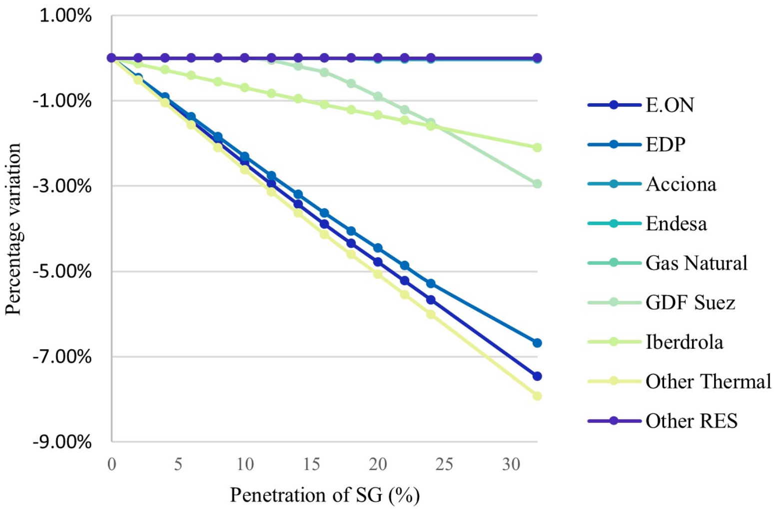

Figure 3.1.6: Reduction of firms' generation. Winter day.

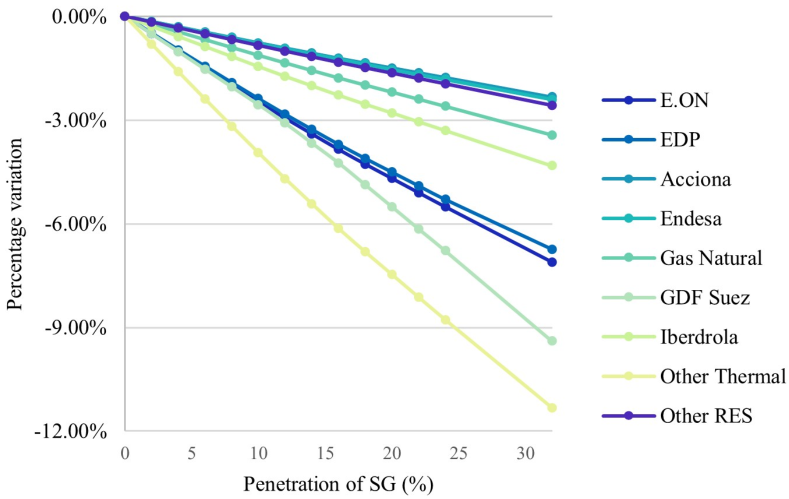

Figure 3.1.7: Reduction of firms' profits. Winter day

In terms of generation by source, the following figures represent the hourly generation by source. Starting from the winter baseline scenario without SG in Figure 3.1.8, a scenario with 32% of SG capacity penetration with respect to the maximum hourly demand is pictures in Figure 3.1.9. Between 8am and 16pm, SG reduces conventional generation. CCGTs are rapidly curtailed by firms with other generating sources in their portfolio. The high marginal of this technology makes it less attractive with prices getting closer to marginal cost. Another interesting feature is that the other source curtailed is hydro, despite having a lower marginal cost than coal. This happens because these hydro plants belong to Iberdrola, the largest player in the market, which cuts their output to maintain higher prices. This has happened in reality, with fines being imposed on hydro curtailing.

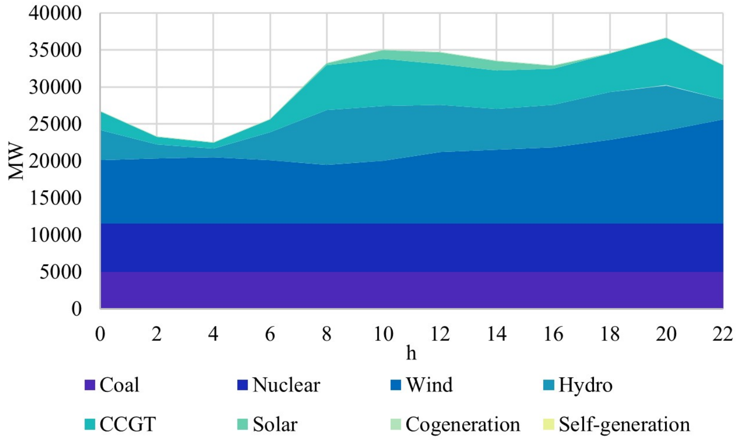

Figure 3.1.8: Generation by source. Baseline scenario. Winter day

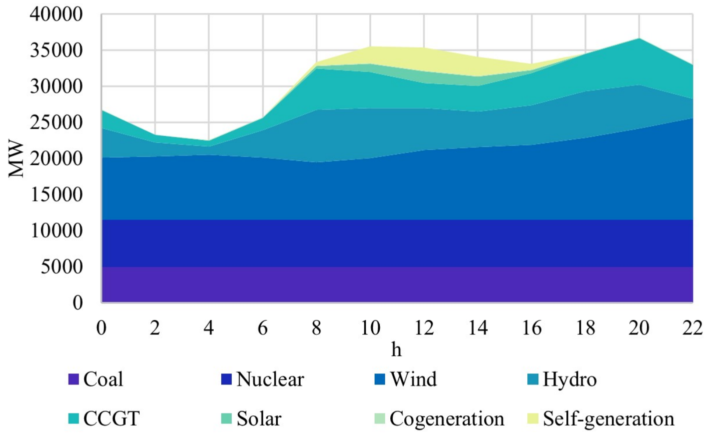

Figure 3.1.9: Generation by source. 32% SG winter day

Although the solar resource is poorer in winter, wind and hydro resources are better. Consequently, the hour-to-hour variation in winter market prices does not change substantially with the introduction of SG.

3.1.5.3 Summer day

The effects that occur in summer are similar to the ones occurring in winter but are larger in magnitude. This happens because, in summer, the sun is up between 7am until 10pm; a much longer period. In addition, the levels of irradiation are much higher than the ones experienced in winter. Summer demand, on the other hand, is lower. Consequently, the effects of SG prices and consumption are almost five and seven times higher, respectively. Price reductions accentuate the competitive differences between firms: some of them are pushed out of the market almost completely, while others are able to resist the downwards pressure on profits. The effects of an increase in SG penetration on prices and consumption are presented in Figure 9. It is interesting to point out that the maximum variations on hourly prices result in prices below the marginal cost of a gas-fired power plant, driving this technology completely out of the market during most of the day. In this case, overall consumption grows by 1-4% on average, because, even though the price elasticity is demand is low, the large solar potential that Spain has during summer months leads to a substantial reduction in prices (Figure 3.1.10).

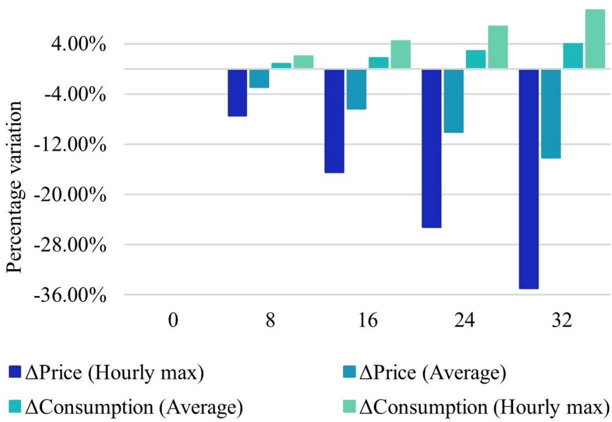

Figure 3.1.10: Price and consumption variations. Summer day.

Figure 3.1.11 shows purchased and consumed electricity. The purchases from the grid tend to reduce rapidly during daytime hours. Moreover, a high penetration of SG therefore significantly changes consumption patterns. Low electricity prices during the day lead wholesale consumers to behave differently, concentrating electricity consumption during peak hours and reducing consumption during night hours. In the longer term, having SG and low-cost electricity can perhaps make consumers more price responsive (e.g., through households becoming price responsive, in addition to the already responsive industry) and change the inelasticity of electricity demand. Additional studies should be undertaken in the area in order to analyse the long-term effects of changing price patterns.

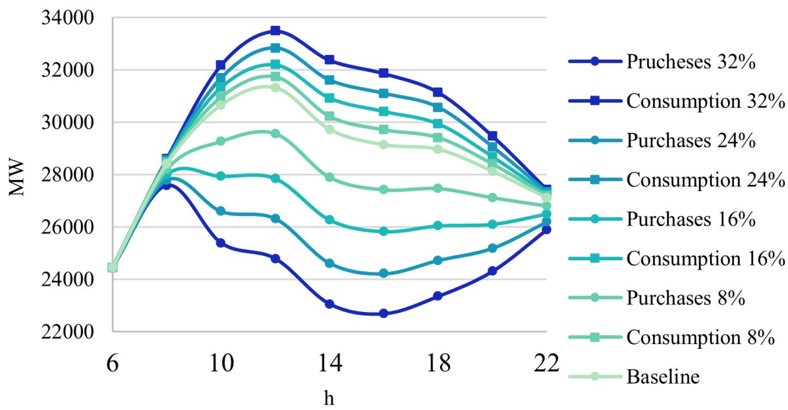

Figure 3.1.11: Electricity consumption and purchases at different levels of SG penetration. Summer day.

The generation profiles by firm shown in Figure 3.1.12 follow a similar trend to the one experienced in winter but, again, with a larger magnitude. In this case, Endesa does not just free ride on Iberdrola's capacity withholding but reduces its own generation to maintain higher prices. In terms of production, all firms are now affected to some extent, except the ones with only RES on their portfolio. Their zero marginal cost allows them to dispatch all their available electricity even though prices have come down. Although all firms follow a decreasing trend, each firm presents particularities depending on their specific portfolio. Gas Natural starts to decrease its generation with 20% of SG penetration. E.On stops decreasing its output at around a 21% decrease, which occurs at a 24% SG penetration. On the other hand, Endesa and Iberdrola present a linear trend, a behaviour based on maintaining the prices high to maximise their profits.

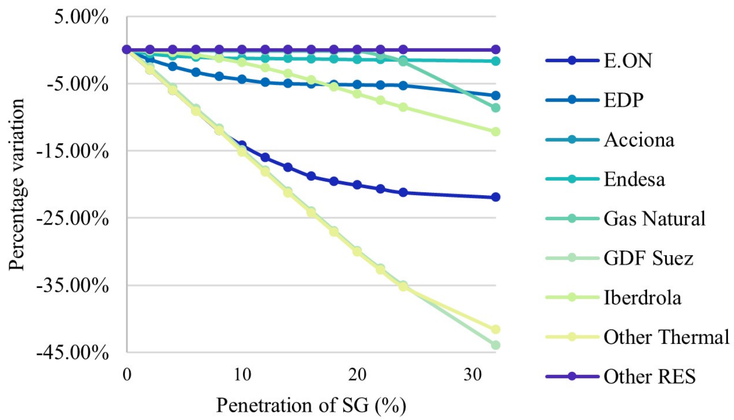

Figure 3.1.12: Reduction of firms' generation. Summer day.

Changes in profits can be found in Figure 3.1.13 . This figure shows how the firms that only own thermal generators are almost driven out of the market since their profits are reduced by 50%. The rest of the players face a reduction of profits of around 20%. While Acciona only loses 15% of its profits, E.On sees them reduced by 28%.

Three main conclusions arise from these results. First, the figures show the market power that firms currently have. Facing reductions of 12% in prices and reductions of around one third of the sales, most are, in all likelihood, still able to stay in the market and only see their profits reduced by less than a quarter. Secondly, if price reductions are passed down to end users, along with the increase of "free"self-generation, expenditure on electricity will decrease significantly. This effect follows the economic belief that as markets gets closer to perfect competition, consumer surplus is increased. Finally, if the idea of having a liberalised market is to enhance market efficiency, the implementation of SG proves to be a measure that aligns with this objective. Increasing levels of SG bring prices closer to marginal costs, which itself decrease, enhancing efficiency in the sector.

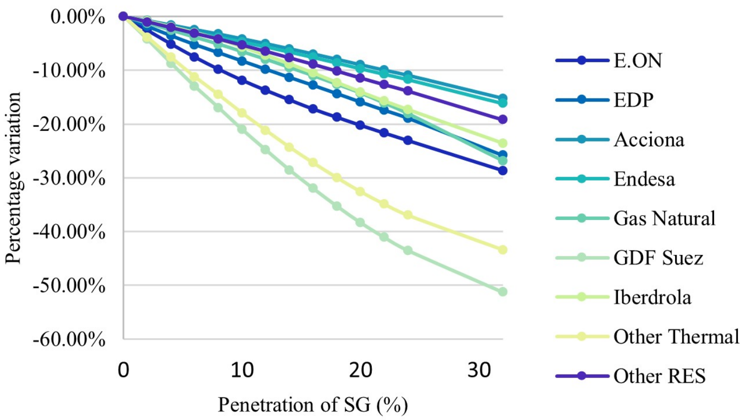

Figure 3.1.13: Reduction of firms' profits. Summer day.

Figures 3.1.14 and 3.1.15 show how the generation mix changes as a result of a high SG penetration on a summer day. Compared to the winter day, wind and hydro generation have a lower contribution in the electricity mix while solar has a higher contribution due to seasonal effects. As renewable sources other than PV produce less in summer and the demand is lower than in winter, the share of nuclear generation is increased.

When SG starts to penetrate in the system, CCGTs are rapidly removed from the mix. At 32% of penetration, CCGTs are no longer generating. Here, the price of electricity is below the marginal cost of gas-fired generators. The other source that reduces its output is hydro. As previously mentioned, Iberdrola, Endesa and Gas Natural reduce their output by reducing hydro production. In terms of coal production, it is not until a 24% SG penetration that a reduction in coal production can be seen. Coal's marginal cost is still competitive at low market prices and many firms rely on these producing facilities to generate profits.

Hence, coal use is reduced less than gas use. This has a major implication in terms of GHG emissions since coal emits more than gas and, obviously, than hydro. Nevertheless, the majority of reduction in generation takes place in sources that emit GHGs. Consequently, a higher SG penetration would not only enhance competition and reduce prices, but also reduce the GHG emission of the electricity sector.

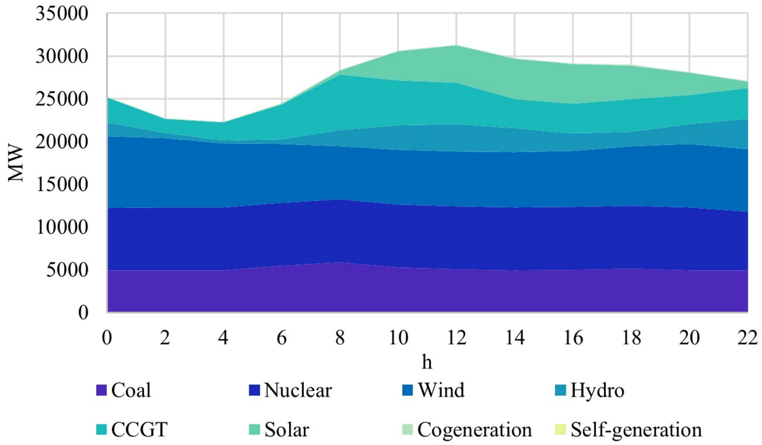

Figure 3.1.14: Generation by source. Baseline scenario. Summer day.

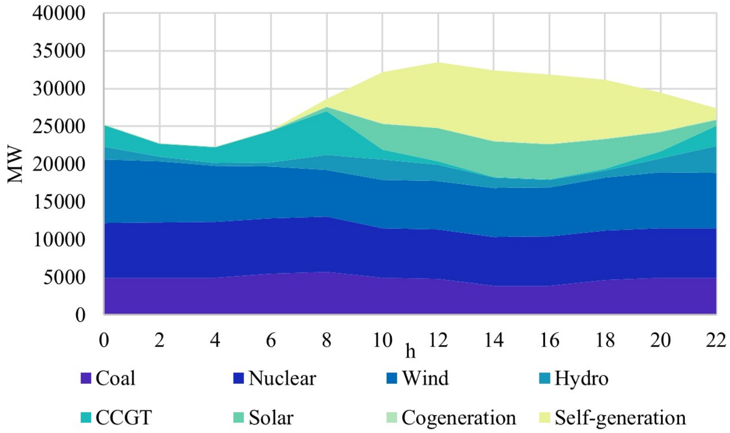

Figure 3.1.15: Generation by source. 32% SG scenario. Summer day.

To sum up, the results obtained from the model that simulates the Spanish electricity system with increasing levels of solar SG have been presented for both a winter and a summer day. The effects occurring in summer and winter are similar in qualitative terms but with a larger quantitative impact during the summer period. These effects can be summarised in four main points:

1. The deployment of SG enhances competition and reduces wholesale market prices.

2. SG does create some rebound effects. Increasing levels of SG results in increasing levels of electricity consumption, but grid electricity demand is reduced.

3. Firms with a high percentage of RES on their portfolio are less affected than the ones that mainly rely on thermal generators, although even those that rely on thermal generators are affected differently depending on their current market power.

4. SG reduces thermal generation. Consequently, GHG emissions are reduced as well.

Our base case results are consistent with historical prices; given historic demand data, prices are never more than 5% from their actual levels.

3.1.6 Conclusions and policy implications

In this paper, the impact of increasing levels of self-generation on the wholesale electricity market have been studied and the Spanish market has been used as a case study. This market is characterised by market power and a generally negative attitude towards self-generation developments because of strong lobbying by incumbents. A Nash-Cournot model has been used to simulate the market with different scenarios of SG penetration to consider their effects on prices, electricity demand and profits of different incumbents. The result of the study shows how an increase in self-generation reduces prices in two ways: through a merit-order effect and through a reduction in market power. Hence, although it is positive for consumers, it is understandable that the incumbent electricity suppliers are not enthusiastic about increasing the SG penetration. However, as we have also shown, the effects are far from uniform and affect different incumbents differently. Moreover, even if SG capacity was expanded to account for up to 32% of the peak hour demand as modelled in the maximum case the total SG electricity would still be less than 15% of the total market. Increasing SG does change the market but is not a radical reshaping of the current status quo.

Moreover, the presented results suggest that the usage of complementarity models in the analysis of self-generation provides valuable insights. Results like those above can contribute to the social discussion about the desirability of SG developments, and increase transparency about who wins and who loses. In addition, analyse if these losses are just correcting a current market failure (if they originate from reduced market power) or originate from fundamental changes in the cost structures of the market (in the case of a merit order effect).

Further research remains essential. There are many opportunities to further refine this type of analysis This can range from increasing the detail in the model such as more nodes and more firms as well as introducing new features like demand alignment or ramping constraints. It is particularly recommended that in addition to the variability of RES and SG, its stochasticity is incorporated into the model and that the modelling of behaviour of the market players is considered carefully and include new policy constraints that address these issues. Future developments should implement a more complex and realistic situation showing the particularities of markets. In terms of self-generation, behavioural patterns as demand alignment with generation or technicalities such as the installation of batteries could be included too. Nevertheless, the above analysis presents a first attempt to quantify how self-generation affects imperfect electricity markets.

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Chapter 4

Evaluating consumer centered energy policies

When new policies are set into place, their objectives can not be fulfilled or undesired and unexpected effects may happen. To analyse and try to improve policies, *ex-post* analyses help to progress in their performance. This has special relevance when new implementing policies to promote actions that were not occurring before. For instance, to increase the participation of consumers in power systems. In this regard, energy policies that aim to activate the demand side considering all the theoretical and expected benefits can face that in their application some of them are not fully achieved. If the aim is to have consumer centered power systems, policies must be revisited and audited to correct their implementation and obtain the maximum potential that they can provide. Therefore, once policies are set into place and tested over time, auditing them to improve their performance becomes essential.

This chapter aims to audit five and a half years of a consumer centered energy policy in the Spanish power system. The analysed policy is an Interruptible Load program for large industrial consumers contracted by the Spanish Transmission System Operator (TSO). The TSO could use these demand resources by reducing their consumption to ensure the reliability of the system or due to economic reasons. The system was in place from 2015 to July 2020, however, the high costs and future substitute programs made the Spanish government to stop it. The evaluation shows that the TSO could have used them to save the system over 150 M. Moreover, by not optimising its usage. the program costs ten times more expensive than generation reserve resources on the market. Moreover, the analysis also shows how smaller resources result in a more cost-effective solution and promote more competition than larger resources. Thus, this analysis provides recommendations for future policies that aim to use demand resources as reserves. And also, it provides a set of parameters to help the TSO to use these resources optimally .

This chapter presents the process of evaluating a policy once set into place. *Ex-post* policy evaluation and especially energy policy evaluations receive little attention. Nevertheless, auditing policies remain essential to improve them and obtain the maximum value from the existing resources. Especially under this new paradigm of consumer centered power systems, going back and analysing the policies set in place can help policymakers not to fail in designing new policies and actions that aim to unlock the potential of consumers. If power systems with proactive and empowered consumers are going to be design, policies and regulations are condition *sine qua non* for their success. Therefore, designing and improving policies based on their historical performance becomes essential.

4.1 Ex-post evaluation of Interruptible Load programs with a system optimisation perspective

[5] *David Ribó-Pérez, Alicia Carrión-García, Javier Rodríguez-García, Carlos Álvarez-Bel. "Ex-post evaluation of Interruptible Load programs with a system optimisationperspective" Applied Energy, vol. 303, pp. 117643-117659, 2021.*

Abstract

The deployment of demand response in reserve markets has been widely discussed. Interruptible Load programs contract demand capacity from consumers in exchange for fixed and variable payments. System operators contract these resources to increase system resilience and use them for economic purposes. Although common, no ex-post evaluations of the program's performance and efficiency exists in the literature. To fill this gap, the paper presents a procedure to evaluate the optimal usage of these resources from a system operator perspective. A Mixed Integer Linear Problem is set to minimise the overall cost of the system using the participant demand resources in the tertiary reserve market, while ensuring that all technical and regulatory constraints are fulfilled in the evaluation. The proposed method describes a series of metrics to compare the optimal performance with the current scenario, and we draw a set of conclusions and policy recommendations from it. We apply the method to the Spanish Interruptible Load program. Our results show that during the five and a half years of the program, demand resources could have provided savings to the system of up to 23 % of the cost of tertiary reserve.

Keywords

Interruptible Load; Ex-post evaluation; Spain; MILP optimisation

4.1.1 Introduction

Traditionally, power systems relied on fossil generators with the capability to adapt their power generation to demand fluctuations to ensure the electricity balance.

The ongoing energy transition from fossil fuel power generation to renewable energy sources generation challenges this situation as they have a stochastic nature and are not freely dispatchable [1]. Thus, the system requires increasing levels of flexible resources to secure the grid operation [2, 3]. Demand Response (DR) can provide this flexibility to the system by adapting and controlling itself to fulfill system needs in a decentralised way [4], therefore, arising as a potential and prominent solution to be exploited to improve the system's operation achieving operational improvements and economic savings [5, 6].

DR refers to modifications in consumers' consumption patterns to respond to signals provided by market agents or electricity prices [7]. DR actions can refer to load-shifting actions or load-shedding actions [8]. The first actions relate to postponing or moving part of the electricity consumption from one hour to another, while the second refers to the interruption of the energy consumption without considering a recovery. DR actions are achieved through incentive-based and economic-based programs. The programs that aim to obtain load-shedding responses through economic incentives are known as Interruptible Load (IL) programs, and they are the focus of this study.

Authors state that DR can deliver benefits by supplying services at a lower cost than traditional generation [9, 10]. In particular, IL programs are services that System Operators (SO) use to ensure the security of supply and grid reliability [11]. However, many System Operators are still reluctant to use DR as generation resources and tend to use these demand programs as a last resource reserve without optimising their participation in the overall system operation. This aversion to DR usage has a technical nature related to its constraints such as time availability and power response capacity. Besides, DR also faces social constraints associated with consumers' preferences, the inelastic nature of electricity demand, and operators' habits of using the generation side to balance the grid [12]. In this regard, there is a need to analyse the usage, performance, and efficiency of these programs in real environments to understand their real costs and potential benefits [12]. Moreover, there is a need to provide system-wide analysis and policy recommendations to improve their performance [13, 14] and understand what the benefits of IL programs from a system wide perspective are [15].

IL programs exist around the world, but to our knowledge, no *ex-post* evaluations about their specific performance and hypothetical optimal use exist in the literature. To address this gap, we aim to contribute by providing a methodical analysis and a set of comparison parameters to evaluate IL programs. We use this approach to analyse five and a half years of the Spanish IL program (SI, for its initials in

Spanish) by responding to the following questions. First, how the Spanish SO used the SI program, under what conditions it use the demand capacity, and what cost it represented to the overall system. Second, what could the optimal usage of this program have been to optimise the available resources? In particular, when should the SO have used demand resources, and what the extra costs paid to consumers by the system would have been? Third, what insights the public policy evaluation presented can provide for both SOs and policymakers. Particularly, to determine if the Spanish IL program could have been cost competitive compared with the traditional resources or the price paid was above the average prices during the period.

We implement the analysis by formulating a Mixed Integer Linear Program (MILP) that considers the technical and regulatory characteristics of an IL program to optimise the hypothetical optimal usage of the demand resources by the system operator and defines a set of economic metrics. With the data provided by the Spanish SO [16], we analyse the eight periods of the Spanish SI program considering historical data and the program characteristics. Then, we optimise its performance under a system perspective, evaluating the participation of these demand resources in the tertiary reserve market and we extract a set of conclusions and policy and operational recommendations.

The rest of the paper is organised as follows, Section 4.1.2 discusses the current literature around DR, especially IL programs, section 4.1.3 presents the case study and the mathematical formulation to optimise and assess the program. Section 4.1.4 shows the results from the different simulations and discusses them and their implications. Finally, section 4.1.5 concludes summarising the main findings of the paper.

Nomenclature

Indices

t	Time index [hours]
p	Period index
s	Index of small capacity products
l	Index of large capacity products
m	Index of months

Sets

S_p	Set of all small capacity products in a period p
L_p	Set of all large capacity products in a period p
T_m	Set of all time periods in a month m
T_p	Set of all time periods in a period p
T	Set of all time periods
P	Set of all periods

Parameters

Q_t^T	Tertiary reserve originally used in t [MWh]
Q_t^{SI}	SI originally used in t [MWh]
Q_t^{Tmax}	Tertiary reserve and SI used in t [MWh]
π_t^T	Price of tertiary reserve in t [/MWh]
π_p^{ref}	Reference price for SI usage in p [/MWh]
k_p^{ref}	Tertiary usage factor for SI price in p
π_t^{SI}	Price of SI in t [/MWh]
π_t^{SPOT}	Spot price in t [/MWh]
K^T	Maximum consecutive usage of a SI product [h]
K^{MS}	Maximum usage of a small capacity products in a month [h]
K^{ML}	Maximum usage of a large capacity products in a month [h]
K^{YS}	Maximum usage of a small capacity products in a year [h]
K^{YL}	Maximum usage of a large capacity products in a year [h]
SI^{max}	Maximum SI capacity usage in t [MW]
SI^{min}	Minimum SI capacity usage in t [MW]
N_p^S	Number of small capacity products in p
N_p^L	Number of large capacity products in p
P_p^S	Power of the small capacity products in p [MW]
P_p^L	Power of the large capacity products in p [MW]
Δt	Time range used in the program [h]
FC_p^S	Price of the small capacity products in p [/MW/year]
FC_p^L	Price of the large capacity products in p [/MW/year]
M_p	Months of p
B^M	Sensibility usage coefficient of monthly resources [%]
B^Y	Sensibility usage coefficient of yearly resources [%]

Variables	
q_t^T	Tertiary reserve used from the system after optimising SI [MW]
$\alpha_{t,s}^S$	Binary variable that is equal to 1 if the small capacity product is used in the time period t
$\beta_{t,l}$	Binary variable that is equal to 1 if the large capacity product is used in the time period t
γ_t	Auxiliary binary variable that is equal to 1 if any SI product is used in the time period t
Metrics	
TC_p^{SI}	Total cost of the SI program in p [M]
CF_p	Fixed cost of the SI program in p [M]
CV_p^{SI}	Variable cost of the optimised SI program in p [M]
CV_p^T	Variable cost of the optimised tertiary reserve in p [M]
CV_t^{SI}	Variable cost of the optimised SI program in t []
CV_t^T	Variable cost of the optimised tertiary reserve in t []
$\bar{CV}_p^{SI}$	Average variable cost of the optimised SI program in p [/MWh]
$\bar{C}_p$	Average cost of the optimised products in p [/MWh]
$\bar{C}_p^S$	Average cost of the optimised small capacity products in p [/MWh]
$\bar{C}_p^L$	Average cost of the optimised large capacity products in p [/MWh]
S_p	Savings with the optimised SI program in p [M]
$\bar{\pi}_p^T$	Mean price of the tertiary reserve in p [/MWh]
π_p^U	Tertiary triggering price [/MWh]

4.1.2 Related work

4.1.2.1 Demand response benefits and potential

The literature related to DR states that wider inclusions of DR in the system provide benefits to the system as a whole. These range from economic benefits related to investment deferral [17], cost reductions [10, 18], impact on spot prices [14] and increasing market competition [19]. Environmental benefits associated with reductions in fuel generation and improvements in grid operation and reliability [20], and positive impacts for the different stakeholders of the system such as cost reductions due to consumer engagement [15]. However, the full implementation of DR also suffers a wide range of barriers and handicaps associated with regulatory, economic, and social aspects [21, 22].

The DR potential is calculated either by defining the physical parameters and nature of the consumer flexibility capacity or by considering an economic profit of its usage related to both the SO or the consumer. The physical calculation does not evaluate the economic profits associated with DR usage and focuses on the physical energy and power parameters of DR, which has been characterised by regions [23], countries [24], or by sectors of activity such as meat industries [25], the residential sector [26–28], service sector [29], and commercial buildings [30]. In contrast, the profitability approach includes the valorisation of DR in specific markets such as day ahead [8], large-scale reserve and Ancillary Services (AS) [31–33], and local electricity markets at the distribution grid level [5].

Finally, as digitalisation advances in the utilities sector, the usage of modelling and control techniques such as Machine Learning and Artificial Intelligence represents an opportunity to enhance the participation of DR in the system [34]. These algorithms are effective to improve predictive and optimisation models for the participation of demand in the system [35]. These approaches are useful and have been studied at the household level [36], commercial level [37], electric vehicle level [38], and at the industrial level [39]. Presenting at all subsectors great potential due to the increasing importance and benefits of Energy Management Systems.

4.1.2.2 Demand response in Ancillary Services

SOs are the responsible agent to ensure the security and reliability of the transmission grid and have to ensure power stability to avoid quality deterioration and ultimately system blackouts [40]. To do so, SOs use a combination of operation markets, auctions, and contracts to ensure sufficient reserves to provide AS. The SEDC report presents the situation of European countries relating DR and the inclusion of them in AS markets [41] and a classification of these programs based on their main economic and physical parameters is performed in [11]. Although DR can now participate in several countries, in most of them, this participation remains low or faces different barriers such as minimum capacity constraints, generation structured programs, or the impossibility to provide DR from aggregated resources.

These difficulties to participate contrast with the potential and benefits the authors estimate in the participation of DR in AS markets and contracts. Koliou et al. study the participation of DR in the German balancing mechanisms and conclude that these resources may be of most value for the system [40]. Mathieu, Dyson, and Callaway show the benefits of the participation of residential consumers according to their DR potential in the CAISO AS market [42]. Rodríguez-García et al. present the benefits associated with the optimum usage of the flexibility of a meat factory in the Spanish tertiary reserve market [43]. Finally, the economic evaluation of reserve provision from a chlor-alkali industrial process is analysed in [13].

4.1.2.3 Evaluation of IL programs

IL programs use interruptible parts of consumer load during high peak or emergency periods to obtain reserve capacity to rapid responses to solve these situations and increase system reliability. The most common way to use IL is by signing contracts between SOs and particular consumers [44]. These contracts agree in the conditions to interrupt the electricity usage of the consumer under specific contexts established by the operator willing to obtain operation reserves. In return, the consumer receives a payment from the operator related to the offered capacity, the energy delivered, or both [45]. Traditionally, these contracts only involved large industrial consumers that could be easily monitored and had a large response in critical moments [11]. In contrast, advances in monitoring and control technologies allow the opening up of these contracts to small and medium consumers, either via direct contract or through intermediaries that aggregate resources.

Strategies on how to operate and the benefits of IL programs and actions have been studied. Different authors present studies such as a Markov decision process to assess the use of the IL resources [12], the usage for the operation of power transformers [46], its operation in microgrids [47], and in primary frequency response [48]. However, these analyses do not consider the system as a whole, do not have real case studies, nor intend to provide any operational recommendations to the SOs. In this sense, auditing and optimising the usage of IL programs remain essential to continue improving system operation and including DR resources in power systems.

In this regard, there is a need to assess and use metrics to analyse and quantify the real impact and efficiency that IL programs could have had in real situations. Following a system perspective approach, we aim to understand the potential benefits of an IL program for the whole system and fill the analysis gap found in the literature related to *ex-post* IL program evaluation and operation. We provide a MILP method to evaluate a real IL program and set a series of efficiency metrics to compare the IL program under both real and optimised scenarios with traditional generation resources.

4.1.3 Case study, formulation and metrics

This section presents the methodology followed to perform the *ex-post* evaluation of the Spanish IL program. The procedure is suitable to analyse other programs.

Nevertheless, the lack of standardisation among DR programs requires a case by case analysis of their technical and regulatory constraints, when the resource participates and payments types [11]. Therefore, first, we describe the Spanish IL and the tertiary reserve where the IL is used. Then the section focuses on the mathematical formulation of the problem that we use to optimise the IL usage, the considered scenarios, and the metrics used for the analysis.

4.1.3.1 Spanish IL: Sistema de Interrumpibilidad

The Spanish system presents a type of DR reserve product know as *Sistema de Interrumpibilidad* (SI), where only large industrial consumers participate. The program provides flexible and rapid responses to the operator in situations when generation and demand are not balanced. Interruptibility corresponds to reductions in demand after a notification by the Spanish SO, Red Eléctrica de Espña (REE), in charge of the transmission system. The service is also contracted by REE, who can use it as a last-resort reserve to ensure the reliability of the system under emergencies with less than 15 minutes warning in advance [49]. REE can also use this product under economic criteria as a last-resort tertiary reserve [49, 50]. In case of need, REE can call the contracted consumers, this compels consumers to respond in a contractually determined timer period, facing penalties if not delivering the service. This service is contracted by REE with a periodic auction where power packages are assigned in a decreasing price order. REE auctioned the service annually in 2015, 2016, and 2017; held two auctions per year in 2018 and 2019; and in 2020 REE called the last auction for 6 months. Since then, REE has not called any other auction and is rethinking if whether to extend the use of this program or not.

In the auctions, for each assigned bid, REE pays to the consumer according to the capacity provided with a price of /MW per year. Two types of products exist regarding their capacity,both small and large products. Small products have a capacity of 5 MW and large products had 90 MW from 2015 to 2018 and in the second auction of 2018 they changed to 40 MW [49, 51]. When REE contracts a product, REE can use it at any time, no matter the day or hour during the period. If the program is activated, the consumer receives an extra payment according to parameters determined in each auction by REE. The payment is different if the activation is for emergencies (less than 15 minutes notice), or tertiary reserve (at least 15 minutes notice). The variable (energy) price paid for the usage of this product was set as a fixed price per period [49] but in 2017 this price became variable on an hourly basis and dependent on the spot market [52].

$$\pi_t^{SI} = \begin{cases} \pi_p^{ref} \cdot k_p^{ref} & \forall p \in [2015-2017] \\ \pi_p^{ref} \cdot k_p^{ref} - \pi_t^{SPOT} & \forall p \in [2018A-2020A] \end{cases} \tag{4.1.1}$$

The usage of the interruptible loads must fulfil a series of technical and regulatory specifications. Its application is carried out by simply reducing the demand of the contracted consumer when it is needed. Each type of product has the maximum amount of hours that can be mployed during a month, a year, and in consecutive hours. Thus, the small products (5 MW) may be employed a maximum of 40 h/month and 240 h/year, while the large products (40/90 MW) may be employed a maximum of 60 h/month and 360 h/year. The hourly constraint limits the usage of any product to a maximum of 2 consecutive hours. These constraints have been constant throughout the different periods. Finally, when REE uses the SI program as a tertiary resource, the legislation forces REE to use the hourly capacity in a range from 200 MW to a maximum of 500 MW. Table 4.1.1 presents the main parameters of each auction.

Table 4.1.1: Data summary of the different SI auction periods [51, 53–59]. * Refers to the data used in the optimisation model.

Period	2015	2016	2017	2018A	2018B	2019A	2019B	2020A
Dates	01/01/2015-31/12/2015	01/01/2016 - 31/12/2016	01/01/2017 - 31/12/2017	01/01/2018 - 31/05/2018	01/06/2018 - 31/12/2018	01/01/2019 - 30/06/2019	01/07/2019 - 31/12/2019	01/01/2020 - 30/06/2020
M_p	12	12	12	5	7	6	6	6
k_p^{ref}	0.281	0.926	0.253	0.751	0.751	0.910	0.828	0.828
π_p^{ref}	92.95	77.13	75.12	72.20	72.20	91.24	79.14	79.14
P_p^S	5 (20)*	5 (20)*	5 (20)*	5 (20)*	5 (20)*	5 (20)*	5 (20)*	5 (20)*
FC_p^S	121,725	134,808	127,536	108,245	63,168	64,624	75,307	8,764
N_p^S	442 (110)*	434 (108)*	415 (104)*	376 (94)*	320 (80)*	352 (88)*	340 (85)*	200 (50)*
P_p^L	90	90	90	90	40	40	40	40
FC_p^L	294,875	292,013	289,125	235,167	174,174	105,429	96,925	0
N_p^L	9	8	10	8	25	21	16	0
CF_p	507.9	502.8	524.8	155.3	160.6	101.1	95.0	4.4

Figure 4.1.1 presents the usage of the service for economic purposes during the eight periods. The usage of the SI is rare, with no use in half of the periods, and only in the first period of 2018 the usage exceeded 10% of the available capacity. The tertiary price used to trigger the service ranged from 0 /MWh to a maximum of 107 /MWh during 2018, showing that REE did not use clear critera to trigger

the service with economic purposes and posing the question about the optimal use of this resource.

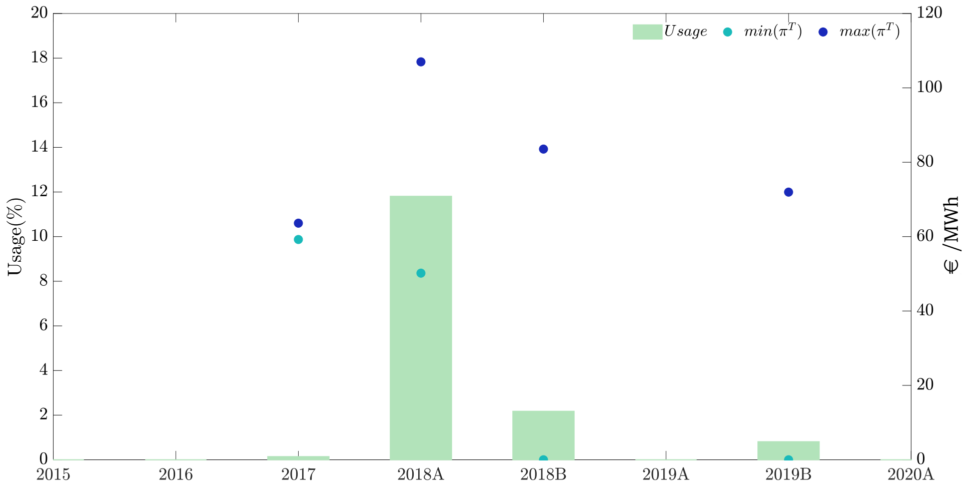

Figure 4.1.1: Summary of the historical SI usage [16].

4.1.3.2 Tertiary reserve

REE is in charge of ensuring the reliability of the power system with different reserve products. During the daily operation, REE uses tertiary reserve, Replacement Reserve in ENTSO-e terminology, by dispatching price-quantity bids in a real time based market. Tertiary reserve is not used every hour of the year, but only when the system requires reserve. The demand side cannot participate in this market and the price paid to the generators that procure tertiary reserve is based on an hourly marginal price. Figure 4.1.2 represents the price distribution of the tertiary reserve market during the analysed periods, the mean values vary around 60 /MWh in each period with some periods having extreme values over 100 /MWh.

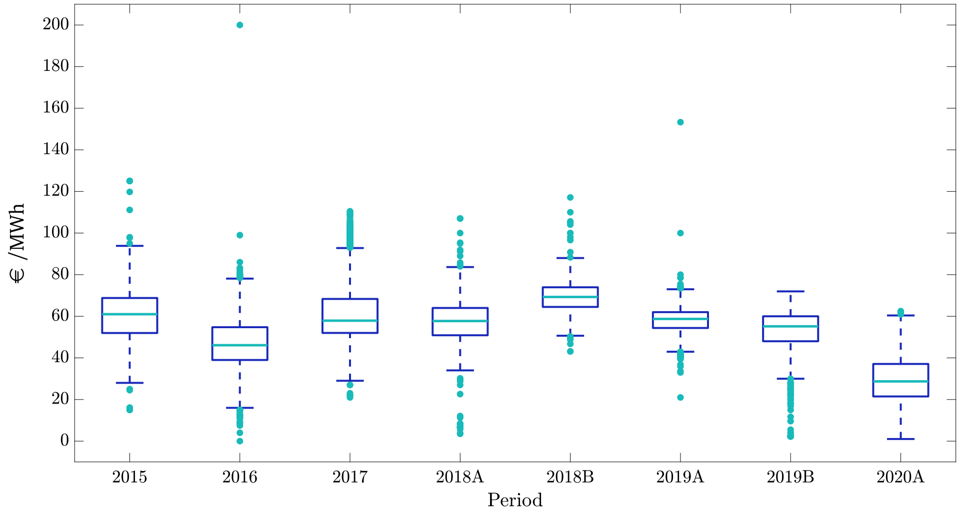

Figure 4.1.2: Price distribution of the tertiary reserve in the Spanish system by period [16].

For instance, Figure 4.1.3 represents the evolution of the tertiary reserve price during a day with high prices during 2017. This evolution shows how during certain hours there is no reserve requirements while the optimisation of the usage needs to cover several options with similar high prices.

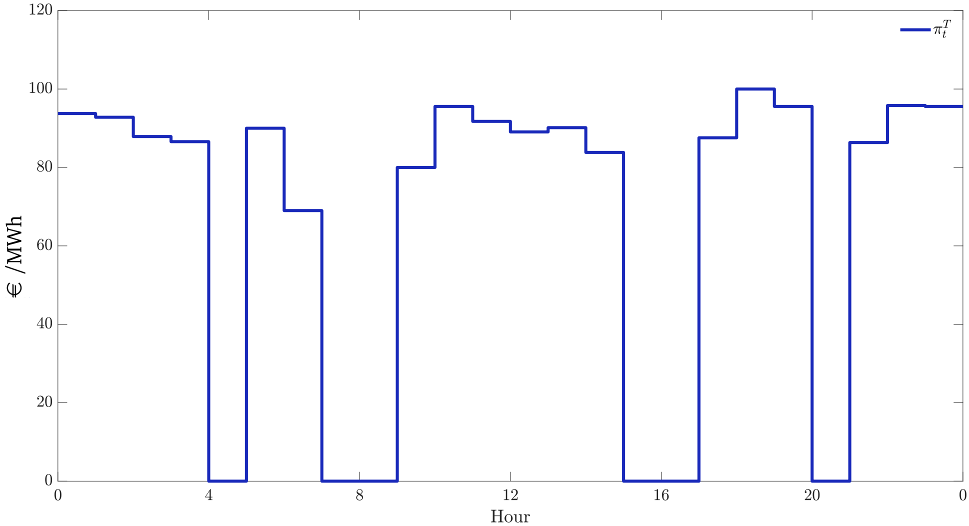

Figure 4.1.3: Evolution of the tertiary reserve price during January 21 2017[16]

4.1.3.3 Assumptions and scenarios

The *ex-post* evaluation hereby presented is framed under a series of assumptions and limitations. First, the participation of each SI product is assumed to operate at a constant rate during each hour that REE activates it. Thus, if employed during one hour, the product will remain active until the next hour, when REE can decide to use it or not. Second, the usage of IL products only affects the tertiary reserve, it is activated 15 minutes in advance, and it does not affect the hourly price of the tertiary reserve considered in the market. Even though the tertiary reserve has a marginal market price, the reductions in price that arise from a reduction in the quantity are not considered. Third, due to tractability and computational limitations, the small products (5 MW) are modelled as a mixture of 4 small products resulting in modelling products of 20 MW. This simplification does not have a major impact as the minimum SI hourly capacity results is 200 MW, forcing the aggregation of DR resources to activate the program. Fourth, no recovery periods with energy increases are considered. In this sense, the SI products are modelled as pure load shedding DR and not considering any load shifting or recovery in the product. Fifth, we assume that consumers will not fail to deliver the contracted capacity and no reductions in the participation would have arisen from a more active usage of the program. We derive this assumption from the particularities of the program, in which the failure to deliver the contracted capacity more than once means exclusion from participation and retribution during the whole period [49]. Moreover, the penalty arising from failing to deliver the demanded capacity would entail a payment that would overcome the extra cost in extra reserve. Finally, the historically used IL capacity in the different hours is added to the tertiary needs of the corresponding hour to consider the historical system needs. Furthermore, as the analysis considers an evaluation of a past policy, no time burdens exist regarding computational times as no short term operation is assumed.

We perform two sensitivity analysis with two scenarios. The first scenario of analysis considers all the technical and regulatory constraints existing in the program, maximum consecutive hours, maximum monthly and yearly hours, and minimum and maximum capacity used per hour. The second scenario eliminates this last requirement and does not constrain REE to have maximum and minimum usage boundaries during each hour. In this sense, the SI program can provide the total amount of tertiary required in an hour even when large quantities are demanded. We do not consider these boundaries in the second set of scenarios as they represents a regulatory constraint that could not exist as it does not have technical implications.

Regarding the sensitivity analysis, two security parameters are included in the model to safeguard SI capacity to use it for security reasons without violating the hourly limits. One parameter limits the monthly hours that IL can be used for economic reasons, while the other limits the yearly hours used. Both parameters vary in steps from 10% to 100% and aim to deliver the marginal profits that arise from a percentage usage of the IL products.

4.1.3.4 Mathematical formulation

The presented mathematical formulation results in a Mixed Integer Liner Problem, whose objective is to minimise the cost of providing tertiary reserve to the system by using the existing resources but also optimising the SI resources of a period. The SI costs only consider variable costs as the fixed costs are assumed to be a sunk cost for the system.

Therefore, the objective function is:

$$min \qquad Cost_p = \sum_{t}^{t \in T_p} \left(CV_t^{SI} + CV_t^T \right) \qquad \forall t \in T_p \tag{4.1.2}$$

where CV_t^{SI} and CV_t^T represent the hourly cost of providing the tertiary reserve needed by the system. The first one is a sum of small and large SI resources used during the time period t, while the second quantifies the needs of the tertiary reserve from traditional sources after the usage of SI resources.

$$CV_t^{SI} = \pi_t^{SI} \left(\sum_{s}^{S} \alpha_{t,s} \cdot P_p^S \cdot \Delta t + \sum_{l}^{L} \beta_{t,l} \cdot P_p^L \cdot \Delta t \right) \tag{4.1.3}$$

$$CV_t^T = \pi_t^T \cdot q_t^T \tag{4.1.4}$$

Subject to:

$$\sum_{s}^{S} \alpha_{t,s} \cdot P_p^S \cdot \Delta t + \sum_{l}^{L} \beta_{t,l} \cdot P_p^L \cdot \Delta t + q_t^T \geq Q_t^{Tmax} \qquad \forall t \in T_p \tag{4.1.5}$$

$$Q_t^{Tmax} = Q_t^T + Q_t^{SI} \qquad \forall t \in T_p \tag{4.1.6}$$

$$q_t^T \geq 0 \qquad \forall t \in T_p \tag{4.1.7}$$

where Q_t^{Tmax} is the total tertiary reserve required in the system at an hour t that calculated the used SI and the tertiary bought in the market. And q_t^T forces the variable quantity of tertiary reserve to be positive.

$$\sum_{s}^{S} \alpha_{t,s} \cdot P_p^S + \sum_{l}^{L} \beta_{t,l} \cdot P_p^L \leq SI^{max} \cdot \gamma_t \qquad \forall t \in T_p \tag{4.1.8}$$

$$\sum_{s}^{S} \alpha_{t,s} \cdot P_p^S + \sum_{l}^{L} \beta_{t,l} \cdot P_p^L \geq SI^{min} \cdot \gamma_t \qquad \forall t \in T_p \tag{4.1.9}$$

Eq. (4.1.8),(4.1.9) ensures that if the system uses SI, the total amount used has to be within limits. Besides, Eq.(4.1.10)-(4.1.13) limit the number of uses in the whole period of the auction and they include a parameter to vary these limits. Finally, (4.1.14),(4.1.15) ensure that a resource cannot be used more than K^T consecutive hours.

$$\sum_{t}^{t \in T_m} \alpha_{t,s} \leq K^{MS} \cdot B^M \qquad \forall s \in S_p, m \in M_p \tag{4.1.10}$$

$$\sum_{t}^{t \in T_m} \beta_{t,l} \leq K^{ML} \cdot B^M \qquad \forall l \in L_p, m \in M_p \tag{4.1.11}$$

$$\sum_{t}^{t \in T_p} \alpha_{t,s} \leq K^{YS} \cdot B^Y \cdot \frac{M_p}{12} \qquad \forall s \in S_p \tag{4.1.12}$$

$$\sum_{t}^{t\in T_p} \beta_{t,l} \leq K^{YL} \cdot B^{Y} \cdot \frac{M_p}{12} \qquad \forall l \in L_p \tag{4.1.13}$$

$$\alpha_{t-2,s} + \alpha_{t-1,s} + \alpha_{t,s} \leq K^{T} \qquad \forall s \in S_p, t \in T_p \tag{4.1.14}$$

$$\beta_{t-2,l} + \beta_{t-1,l} + \beta_{t,l} \leq K^{T} \qquad \forall l \in L_p, t \in T_p \tag{4.1.15}$$

4.1.3.5 Metrics

The potential impact and benefits arising from an optimal usage of the SI program are analysed based on the following metrics. The first approach is to understand the total cost of SI in the case of optimal usage. This cost collects both the fixed cost and the variable costs of the optimised program as shown in Eq (4.1.16). The second element to consider is the associated savings of the optimised SI program for the whole system. Eq. (4.1.17) presents the comparison between the current cost of providing the tertiary reserve acquisition with providing this service as a combination of the SI program and the tertiary reserve market.

$$\begin{aligned} TC_p^{SI} &= CF_p + CV_p = \\ &= (FC_p^S \cdot N_p^S + FC_p^L \cdot N_p^L) + \sum_{t}^{T}\left(\pi_t^{SI}\left(\sum_{s}^{S}\alpha_{t,s} \cdot P_p^S \cdot \Delta t + \sum_{l}^{L}\beta_{t,l} \cdot P_p^L \cdot \Delta t\right)\right) \end{aligned} \tag{4.1.16}$$

$$S_p = \sum_{t}^{T_p}\left(\pi_t^T \cdot Q_t^T + \pi_t^{SI} \cdot Q_t^{SI}\right) - \sum_{t}^{T_p}\left(CV_t^{SI} + CV_t^T\right) \tag{4.1.17}$$

Regarding the efficiency of the program, Eq (4.1.18-4.1.20) present the weighted average cost per unit of energy used. Eq (4.1.18) presents the Levelised Cost of Energy /MWh of the optimised SI program for the period p, while Eq (4.1.19) and Eq (4.1.20) disaggregate these costs for the small products and the large products, which have a different fixed cost FC_p^S, FC_p^L. These metrics serve as a way to compare the efficiency of the program with the costs of acquiring tertiary reserve in the market.

$$\bar{C_p} = \frac{TC_p^{SI}}{\sum_t^{T_p}\left(\left(\sum_s^S \alpha_{t,s} \cdot P_p^S \cdot \Delta t + \sum_l^L \beta_{t,l} \cdot P_p^L \cdot \Delta t\right)\right)} \tag{4.1.18}$$

$$\bar{C_p^S} = \frac{FC_p^S \cdot N_p^S + \pi_t^{SI}\left(\sum_s^S \alpha_{t,s} \cdot P_p^S \cdot \Delta t\right)}{\sum_t^{T_p}\left(\sum_s^S \alpha_{t,s} \cdot P_p^S \cdot \Delta t\right)} \tag{4.1.19}$$

$$\bar{C_p^L} = \frac{FC_p^L \cdot N_p^L + \pi_t^{SI}\left(\sum_l^L \beta_{t,l} \cdot P_p^L \cdot \Delta t\right)}{\sum_t^{T_p}\left(\sum_l^L \beta_{t,l} \cdot P_p^L \cdot \Delta t\right)} \tag{4.1.20}$$

To assess the efficiency of the program without considering the sunk costs, Eq (4.1.21) present the weighted average variable cost per unit of energy used.

$$C\bar{V}_p = \frac{CV_p^{SI}}{\sum_t^{T_p}\left(\sum_s^S\left(\alpha_{t,s} \cdot P_p^S \cdot \Delta t\right) + \sum_l^L\left(\alpha_{t,l} \cdot P_p^L \cdot \Delta t\right)\right)} \tag{4.1.21}$$

π_p^U represents the minimum tertiary price at which the SO triggers SI resources. These prices are the result of obtaining the minimum π_t^T at which the optimised SI program used DR resources in a given period.

As already mentioned, these metrics are useful to compare different scenarios such as the current situation with the optimal usage of the program, but also with new scenarios relaxing some constraints, such as the maximum and minimum capacity, and including a sensitivity analysis of the security coefficients.

4.1.4 Results and discussion

This section presents the results of the evaluation of the SI program and the potential of the optimised usage of it. We provide a general overview on how REE used this program and a comparison with the *ex-post* optimised case with a period by period analysis of the potential benefits and the main metrics analysed. Then we present a sensitivity analysis regarding both the security coefficients B^M and B^Y and the scenario of not considering maximum and minimum hourly constraints. Then, we compare the performance of optimised results of the program with and without maximum and minimum hourly capacity requirements. Due to extension considerations, when analysing detailed data of a period, we have included in the main body the 2017 period as an example, and we present the analogous figures for the rest of the periods in the Appendix.

4.1.4.1 Overall results of the program

Figure 4.1.4 presents the aggregated results of the program. During the five and a half years of the program under the Current Scenario (CS), the SI had a total fixed cost of 2,049.6 M with an almost nonexistent variable cost associated with the lack of use of it. During those years, the total cost that the Spanish SO paid for tertiary reserve added up to 707.4 M. Therefore, only the fixed costs of the SI program accounted for almost three times the total value of the tertiary reserve market, the market where SI is intended to operate for economic reasons. In this sense, it is clear that this DR program derives in a non cost-effective manner of delivering reserves due to the high fixed cost that it has. Nevertheless, if properly operated, the program could have reported over the years total savings of 163.2 M. With an economic optimal usage of the program by the SO, the cost of the program would add up to 2,049.6 Min fixed costs and 61.9 Mof variable costs. The analysis does not intend to optimise the fixed costs, which are considered as a given parameter. The savings would represent up to 7.96 % of the fixed cost that representing the SI program and 23.07 % of the cost of using tertiary reserve during these last five and a half years.

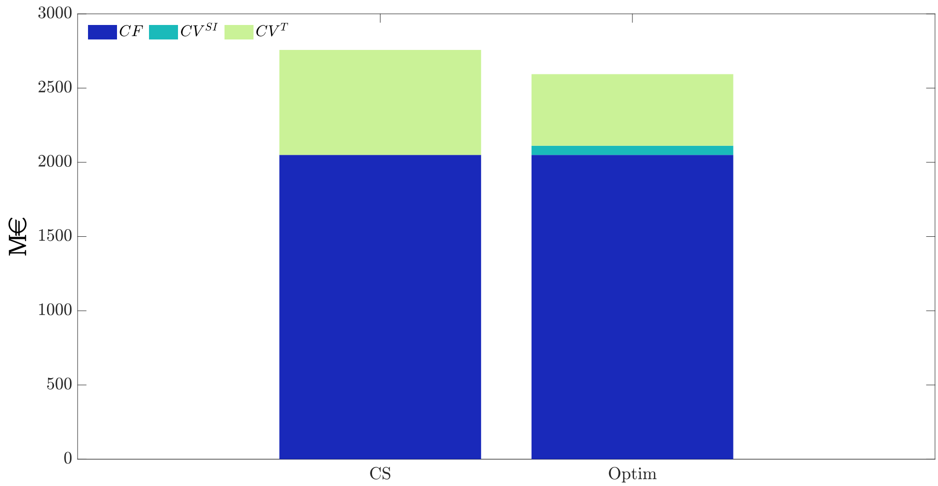

Figure 4.1.4: Summary of the potential benefits obtained with an optimised performance of the SI program.

When going to each period of the program, the differences in efficiency and savings largely differ. Figure 4.1.5 presents the results of the program by period. The results show how during 2015, 2017, 2018A, 2018B, 2019A, and 2019B the savings ranged from around 6 Mto 52 M, while 2016 and 2020A only added up to around 0.5 and 3 M respectively. Focusing on the first group of six periods, we appreciate a similar optimum operation of the program, using DR to cap the higher costs of the tertiary reserve market with variable costs of the program lower than the market. The variations between these years refer to two main parameters, first differences between high tertiary prices and extreme price events, second the characteristics defining the SI's prices π_t^{SI}. Focusing on Figure 4.1.2, price differences in the tertiary market, and especially, with the extreme events that occur with tertiary prices above 100 /MWh. For instance, 2017 presents a greater number of hours with extreme high prices while the second part of 2019 shows a lower mean and non existing extremely high events, thus a lower saving potential. Second, Table 4.1.1 presents the parameters k_p^{ref} and π_p^{ref} that define the SI price π_t^{SI}. From 2015 to 2017, SI prices were constant while in the last five periods these prices were linked to the hourly wholesale electricity price.

Therefore, under the optimised scenario, the variable costs of SI are higher in 2015 than in 2017, producing lower savings in the former. In contrast, the variable costs of the last five periods show that in these periods, the interplay among wholesale, SI, and tertiary prices triggers the usage of DR. In particular, during 2018B, the maximum benefit resulted from combining these parameters and obtaining usage prices per hour close to zero, with almost zero variable costs during the period.

This results in low variable costs of the program with similar savings in comparison with other periods in the tertiary reserve acquisition, and in sum, higher total savings.

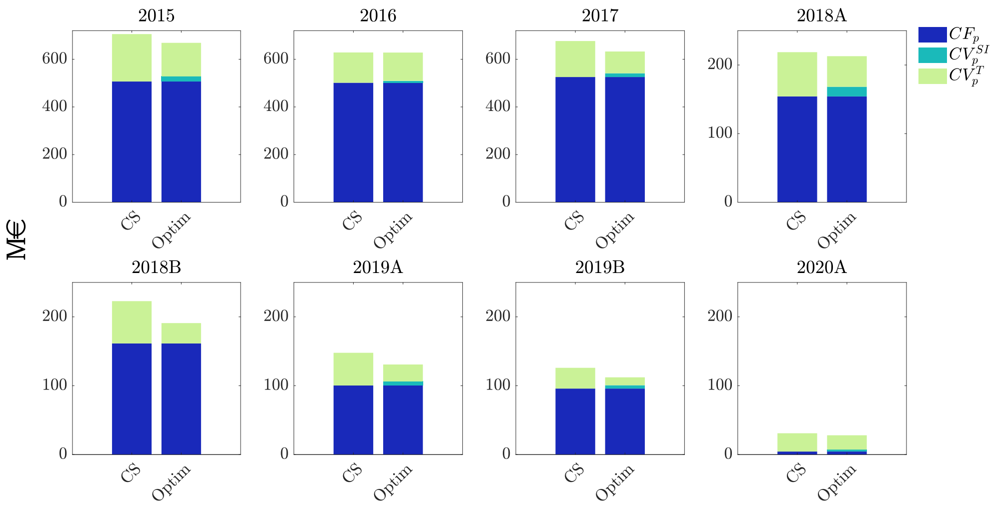

Figure 4.1.5: Summary of the potential benefits obtained with an optimised performance for each SI period.

In contrast, 2016 had high variable prices for the usage of SI, which resulted in a small usage of the resource during optimal operation, as it was not efficient to use it compared with the tertiary reserve market. This price, set by REE, was between 3 and 4 times higher than in 2015 and 2017 due to the high value of k_p^{ref}. When *ex-post* optimising the SI resource, this high price leads to in not using the total DR capacity during the available hours, which means savings are around one hundred times lower compared with other periods. Finally, the sixth group of columns, 2020A, differs from the others since it covers six months and REE contracted around half of the small products compared to the rest of the periods and no large products. This resulted in lower total costs, but also lower absolute savings.

4.1.4.2 Economic efficiency and usage of the program

To analyse the potential efficiency of the program, we compare in Figure 4.1.6 the average cost of the optimised program with the average price that the tertiary reserve market had during the reference period. In this sense, we see that even considering an optimised usage of the service, the SI program had an average cost ranging from five to ten time higher than the average tertiary reserve price during the periods 2015, 2017, and both periods in 2018 and 2019. In 2016 this cost adds up to more than 90 times higher while in 2020A the cost is only 1.6 times higher. The variability between these metrics largely relies on the initial fixed costs paid to the availability of these resources. While during the first years of the program the fixed cost meant the impossibility of having competitive costs with the traditional market, during the last periods of the SI these fixed costs are sensibly reduced, resulting in a resource with lower differences within the market and even competitive with the price spikes during 2020A. As previously discussed, 2016 is an an anomaly since the optimisation of the program does not generate a relevant improvement of the efficiency of the program due to the high variable costs.

The other logical but relevant result is the comparison between the large and small products. While large products provide more power, their cost once optimised is between 50% to 100 % times higher than the cost of small products. The large products became more cost-competitive once they reduced the power provided from 90MW to 40MW in the period 2018B. The variability of costs is mainly related to two elements. First, providing on the one hand more power, which is more valuable for the system. Second, fewer consumers can provide larger quantities of power, which results in lower competition in the assignation of these products. These two elements result in higher prices as regards the large capacity products, as Figure 4.1.6 shows for six of the periods analysed. 2019B is the only period with different results due to a higher usage of large products with lower variable prices and a lower gap between the fixed costs of the small and large products. Thus, if the SO now has the capacity to better control and coordinate resources due to the digitalisation of the grid, having a myriad of smaller resources will be more cost-effective than having large resources, which are scarce and less competitive with each other.

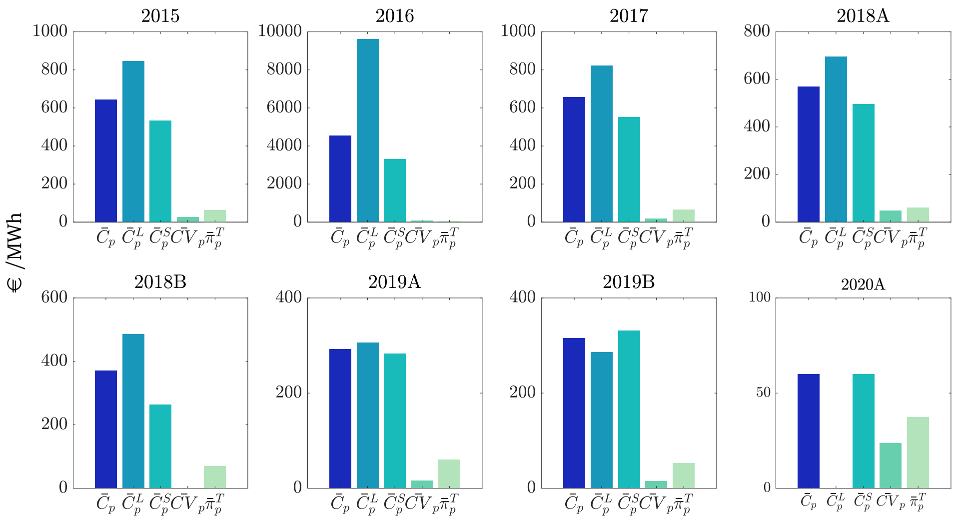

Figure 4.1.6: Summary of the main economic metrics obtained with an optimised performance for each SI period.

Figure 4.1.7 shows the minimum triggering price of the SI program (π^U_p) at which REE should have used the resource and the average tertiary prices with their standard deviation during each period. Thus, during the hours when prices were higher than the reference price, the SO should have considered using the SI to reduce costs to provide tertiary reserve. While during some periods the reference price is above the average of the tertiary reserve price, the trend shows that SI usage can be interesting for the SO at several times of day and during some periods in practically every time period, as the variable costs are reduced or almost non-existing.

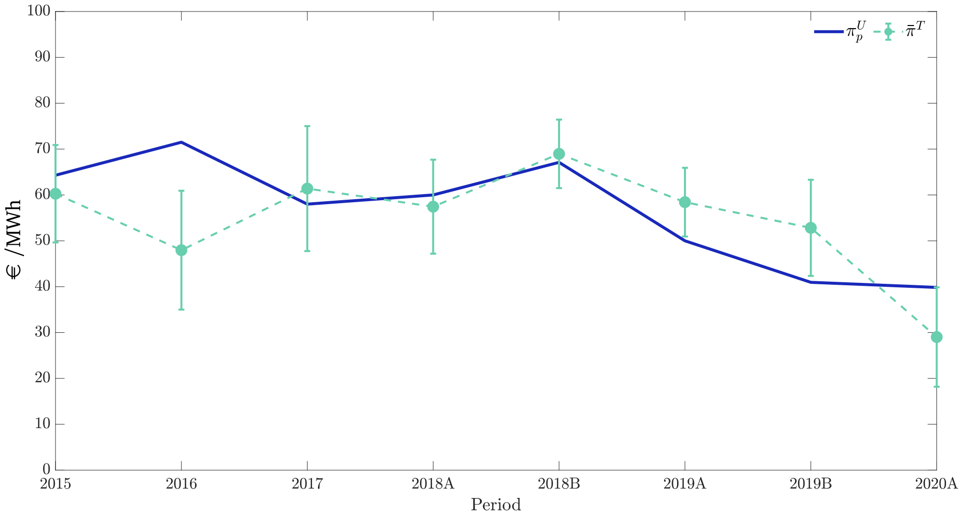

Figure 4.1.7: Minimum tertiary price per period where SI is used.

4.1.4.3 Sensitivity of the security coefficients

As the SI program also has the objective of being an emergency resource for the SO, we considered different security coefficients of usage for economic reasons to leave part of the available resource as an emergency resource to the SO. Figure 4.1.8 shows how the economic efficiency of the program evolved based on different yearly and monthly security coefficients during 2017. In the annex, there is a similar figure for each period. B^Y represents the percentage of total hours of the year used for economic reasons while B^M represents the monthly hours available, which are constant throughout the period. In this sense, the right side shows how the most critical element to economically optimise the usage of SI is the yearly constraint, to say, the total number of hours that the program can be used. In contrast, while increasing B^M helps to improve the performance, it is not that critical as price hours are spread throughout the year.

In other words, while limiting B^Y caps the potential benefits of the economic usage of the program, B^M does so but not in such a critical way, especially once you range 0.5 of the monthly usage, when increasing this parameter does not affect at all the final optimum savings. The figure shows how increases in the B^Y parameter achieve diminishing improvements in the economic efficiency of the optimised program. When reducing B^Y the economic efficiency improves at a diminishing ratio with more important but declining variations of B^M when increasing B^Y.

Thus, while the economic efficiency improvement from B^Y at 0.1 to 0.2 moves from around 4,030 /MWh to 2,020 /MWh, moving from 0.5 to 0.6 only implies a reduction from 800 /MWh to 665.5 /MWh. In the case of B^M this only occurs until a certain level. While Figure 4.1.8 shows the 2017 period, the rest of the years present a similar trend.

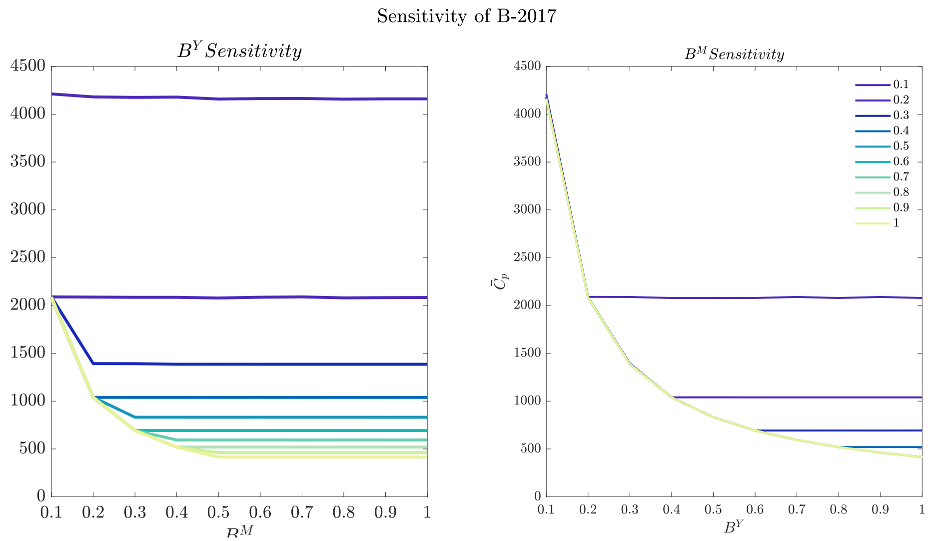

Figure 4.1.8: Sensitivity analysis of the economic efficiency of the SI program regarding B^Y and B^M metrics

In this sense, we argue that if REE aims to reduce the initial cost, the yearly and monthly restrictions of the program can be reduced to use the program less but during the hours when the program provides the most benefits to the system. Specially, having the program monthly constraints above 0.5 from the actual constraint does not provide added value to the economic optimisation. The DR resource never reaches the maximum constraint level in any particular month. Thus, if reducing this constraint implies reductions in the fixed cost, the SO must consider this option as it does not affect the final optimum. Moreover, if reducing the total amount of yearly hours also implies a reduction in the fixed cost, the SO can obtain an improvement of the economic efficiency of the program. A trade-off exists between the marginal benefits of using the SI program for economic purposes and a reduction of the fixed costs of the program. Therefore, the last resources of DR used by the SO do not provide such benefits as the marginal savings obtained are considerably reduced after shaving the highest tertiary prices.

4.1.4.4 Scenario without maximum and minimum capacity constraints

To not only analyse the *statu quo*, we also considered removing the regulatory parameters that force the SO to use the SI program between the range of 200 MW and 500 MW. We call this scenario Optimised Unconstrained (Optim - UC) and we compare it with the Constrained scenario. In this case, the optimal usage of SI concentrates in the hours with the larger price differences between supplying the tertiary reserve with the current market mechanisms and generation capacity.

Figure 4.1.9 shows the hourly distribution of the usage of the SI program during 2017 under the constrained scenario. The usage never goes above 500 MW or below 200 MW and concentrates in the morning hours associated with the demand ramp at the start of the working day and during the colder months at the end of Autumn and Winter. The annex shows an hourly distribution of the SI of each period.

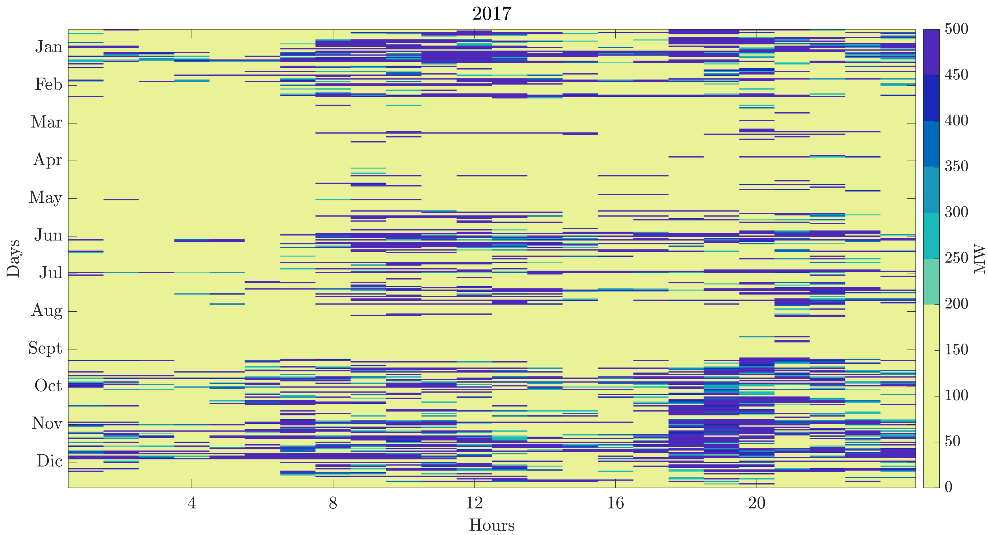

Figure 4.1.9: Hourly capacity of the optimised SI program used in 2017

In contrast, when no maximum hourly capacities are considered, during some hours, the SI program supplies all the needed capacity of tertiary reserve. Consequently, as the total capacity is the same, the SI resources concentrate in fewer hours but provide more capacity. Figure 4.1.10 shows the hourly distribution of the usage of the optimised SI program during 2017. Compared with Figure 4.1.9, the usage is more concentrated in fewer hours and the SO ends up using up to 3,000 MW in an hour, five times more than the maximum capacity stated by the program.

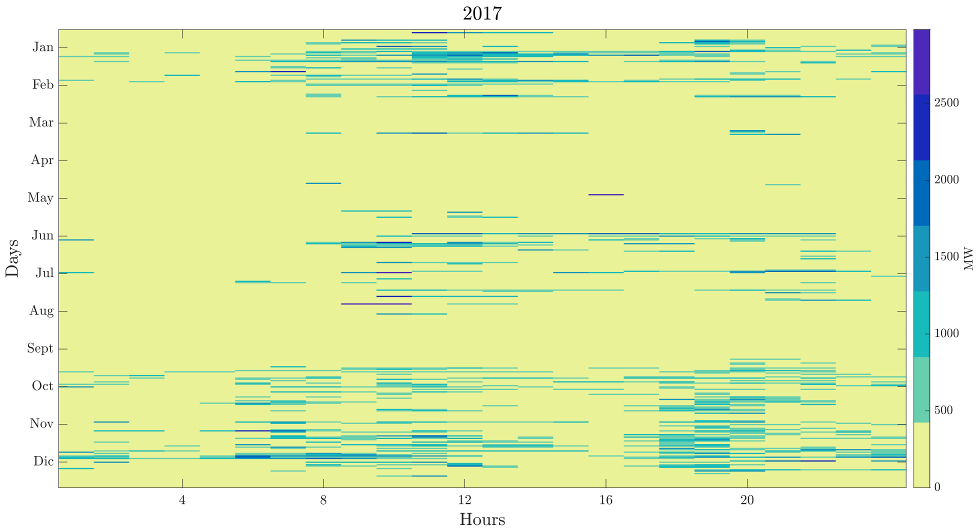

Figure 4.1.10: Hourly usage of the optimise SI program without capacity constraints in 2017

Figure 4.1.11 presents the Monotone usage curve of the SI program during the 2017 period. As mentioned above, the usage is concentrated in lower hours but with a larger application by the SO. While the SO uses fewer hours of the program, during more than 250 hours the program delivers more than 1,000 MW, achieving up to 3,000 MW at the maximum hours. If the constrained application uses SI resources 1,850 hours, the unconstrained optimisation reduces this to only 1,230 hours. Nevertheless, relaxing this constraint does not imply substantial improvements in the total performance of the program. In total, relaxing the constraints implies 14 M. Figure 4.1.12 shows the resulting savings of each year under this scenario. During the years when all the SI resources are used to optimise the system costs (2015, 2017, 2018, 2019, and 2020), savings relate to shifting DR resources to the most profitable hours. On average, relaxing these constraints results in a 10% improvement in the total savings. In 2016, when the profitable hours are less due to the high variable costs of the year, savings are doubled as the usage of the resource is increased from the constrained scenario. In contrast, during the first half of 2020 savings only increase by 3 %. This results from an initial lower availability of resources that results in not being able to use much more capacity per hour than the 500 MW set by the regulation.

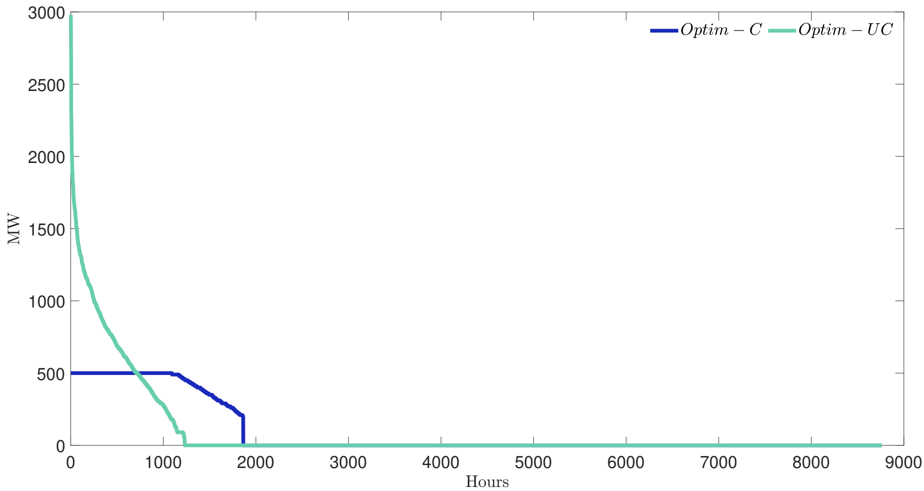

Figure 4.1.11: Monotone SI usage curve with and without constraints in 2017

Figure 4.1.12: Hourly usage of the optimise SI program without capacity constraints in 2017

4.1.4.5 Policy recommendation for IL programs

The analysis of the Spanish SI program reveals several key elements to consider when designing and operating IL programs for both economic and security reasons from a SO perspective. These programs combine the DR usage in AS markets with

DR as a capacity or last resort resource. Fixed costs are the principal burden to have cost efficient resources. If IL programs coexist with market prices of other services, a weighted fixed cost to obtain the demand reduction capacities is key in order to compete with other market resources. Mechanisms to quantify the real costs incurred by consumers participating in these programs are crucial to reduce the initial capital cost prices. Therefore, policy instruments such as resource specific auctions (only DR) and service auctions (DR and generation) can be seen as potential elements to improve programs' efficiency.

IL programs are profitable to use during critical hours, using fewer resources of the market and thus generating savings for the system as a whole. These resources cap the usage of more expensive resources when prices rise above certain levels. In this sense, having an analysis of price triggering elements results in a valuable policy tool for SO. These reference prices are a guide to help operators in their daily operation. When reserve prices are above these levels, they should consider the usage of IL resources. In this sense, future studies should consider how using these resources in reserve markets with marginal price structures can provide further savings as they reduce the price of the whole market.

4.1.5 Conclusions

This paper presents an *ex-post* evaluation of the Spanish Interruptible Load program regarding its economic efficiency, real impact, and specific parameters associated with an optimal usage it. The method used consists in an Mixed Integer Linear Problem optimisation formulation that consider the physical and regulatory constraints of these types of programs. To compare and evaluate the efficiency we also present a set of economic metrics that permit the comparison with complementary resources.

We use the method to analyse five and a half years of the SI program in the Spanish power system. The optimisation shows that under the current conditions of the program, the economic efficiency of the DR resources largely differs from obtaining tertiary reserve resources from the market. After the Demand Response optimisation, these resources are four to ten times more expensive than the average tertiary reserve procured in the market. Only in 2020, when the fixed cost was largely reduced and the SO procured less Demand Response resources did these become cost competitive with the most expensive hours of tertiary reserve. The efficiency parameters are also highly dependent on the usage. Reductions of the amount of the SI resources used for economic purposes to save some resources for technical constraints show how the last elements of capacity are the least valuable for the system. In other words, the usage of DR resources for economic purposes has decreasing marginal savings.

In sum, the results show how the Spanish system operator did not operate to optimise the economic performance of the program. Thus, the specific economic objective of the program has failed to deliver its potentialities. If used under a cost minimisation strategy, this resource would have saved the system a total of 163 M . If the current constraints of maximum and minimum hourly usage capacity are relaxed, savings would increase by 14 extra M . Both savings represent a small fraction of the historical total fixed costs of the program but around a quarter of the tertiary reserve needs of the system.

Interruptible Load programs provide a valuable resource for the system as a whole, but detailed and systematic analysis of their potential benefits and optimal operation in real environments are lacking in the literature. The method hereby presented shows a usage strategy and a detailed analysis of a specific program and then presents a set of conclusions to apply to the design and usage of these types of programs. From a system perspective, Interruptible Load resources present savings that diminish with their usage. Topics for further research are the impact of these resources in marginal price markets, comparisons of the costs of capacity payments to demand and generation resources, and the co-optimisation of these resources in several markets such as secondary and tertiary reserve with a system optimisation perspective.

CRediT authorship contribution statement

David Ribó-Pérez: Conceptualization, Methodology, Software, Data Curation, Writing - original draft, Writing - review & editing. Alicia Carrión: Methodology, Data Curation, Writing - review & editing. Javier Rodríguez-García: Methodology, Data Curation, Writing - review & editing. Carlos Álvarez-Bel Conceptualization, Writing - review & editing, Supervision.

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4.1.6 Appendix

All case studies have been solved using Gurobi under Julia.JuMP [60], while the data treatment has been performed in MATLAB. We have used an Intel (R) Core (TM) i7 computer at 1.99 GHz and 16 GB of RAM. Each simulation takes between a couple of minutes up to less than one hour depending on the amount of variables, period and security coefficients. All optimisations are performed with a MIPGap of 1e-3

Additional figures

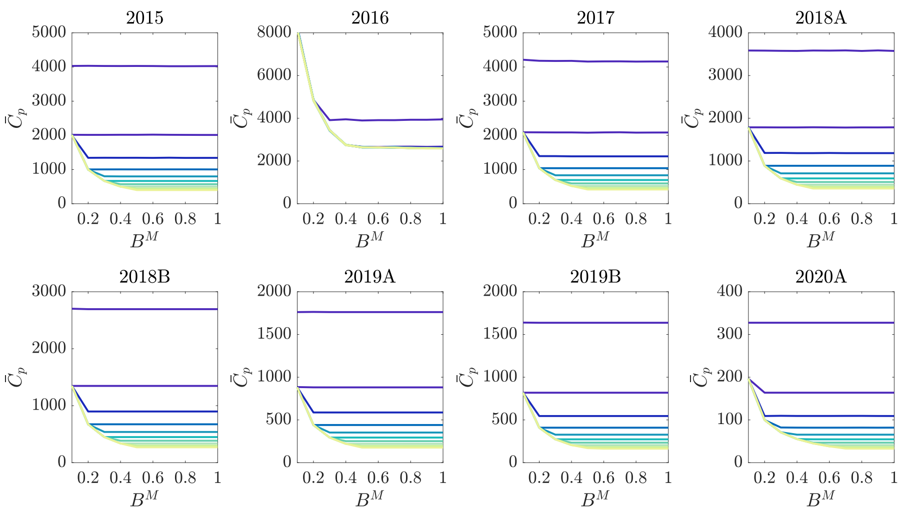

Figure 4.1.13: Sensitivity analysis of the SI program regarding B^M metrics

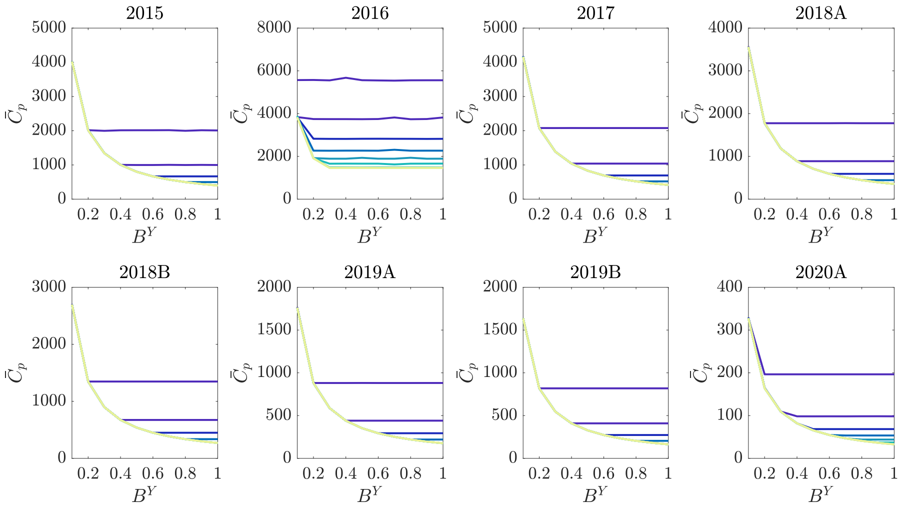

Figure 4.1.14: Sensitivity analysis of the SI program regarding B^Y metrics

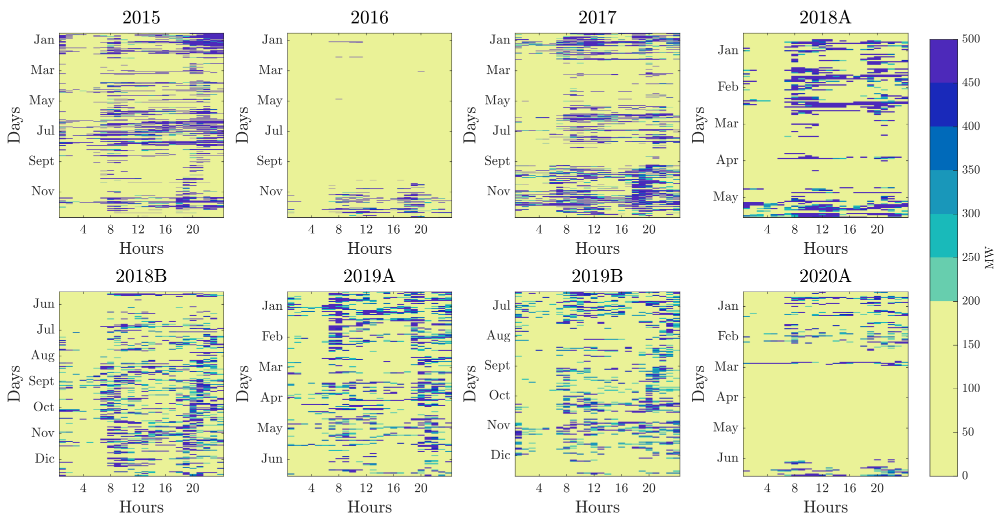

Figure 4.1.15: Hourly usage of the optimised SI program during the eight periods of study

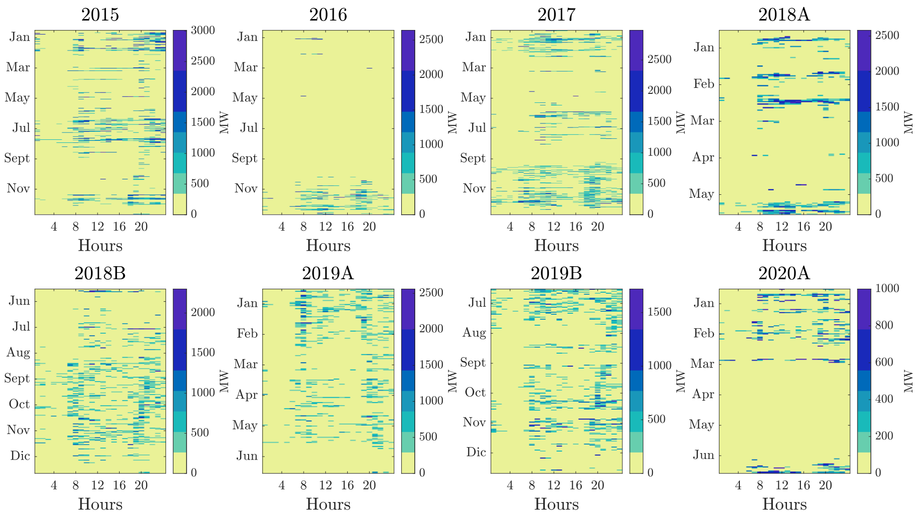

Figure 4.1.16: Hourly usage of the optimised unconstrained SI program during the eight periods of study

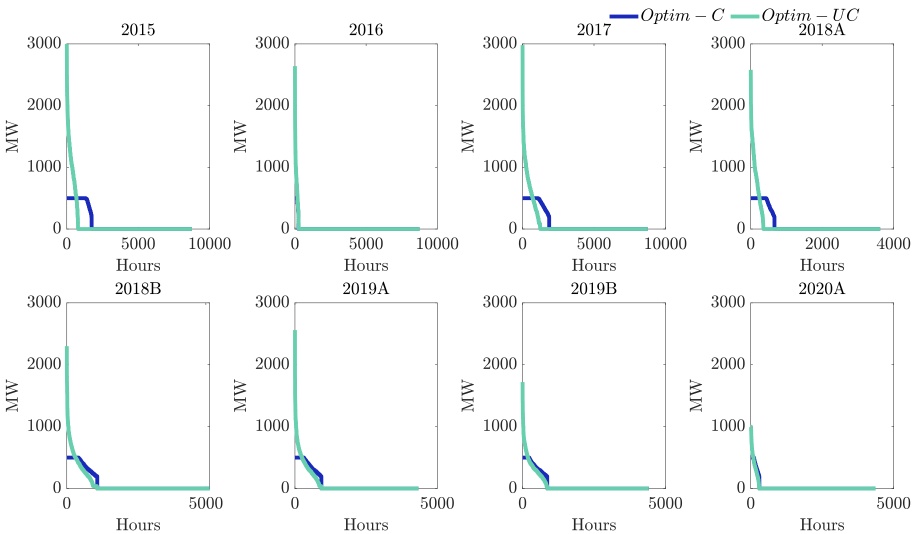

Figure 4.1.17: Monotone curves of the SI program during the eight periods of study

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Chapter 5

Conclusions and future research

5.1 Conclusions

This thesis studies the benefits of a consumer centred power system, analysing elements and policies to achieve it, as well as its implications. Some of them are the reduction of market power, increasing competitiveness, the inclusion of new resources, flexibility provision, and the activation of the demand side through the spreading of energy infrastructure control.

However, a consumer centred system has challenges and barriers under the current legislative framework. This means that new policies, programs, and regulations need to be set into place to unlock the potential benefits of a consumer centred system. But, these have to minimise the risk arising from this paradigm shift and promote the change in an efficient way.

This thesis states that an improvement in the whole public policy process is required. From the formulation step, passing through the design and evaluation of the policies. Policymakers are drafting and will draft legislation in the coming years in a scenario of uncertainty, which is not fully understood, quantified, nor retrospectively evaluated. Thus, evaluations in all stages of the process are required.

Regarding the formulation, this thesis presents two main contributions.

First, the proposed methodology to analyse the international legislation and programs existing to use demand resources for ancillary services can be dynamically used for future analysis. The current revision of programs delivers a set of standard parameters that allow policymakers to compare programs among themselves and draw conclusions and good practices around critical elements of policy design. These definitions of parameters such as minimum power, time requirements, or the possibility to aggregate resources will define future programs. Consequently, while formulating policies with this purpose, these elements must be carefully considered and discussed so as not to fail in situations already faced by other regulators and policymakers.

Second, this thesis presents a quantification of the flexibility potential that residential consumers have in the Spanish power system. Besides quantifying the potential with an enlarged time-varying battery methodology, the thesis raises a point that may have not been considered. Flexibility gaps exist between residential consumer types regarding their socioeconomic, geographical, and temporal characteristics, meaning that residential flexibility is not homogeneous but varying and dependant on external factors. Thus, when designing policies aiming to use this potential, there is a need to consider these gaps and promote measures or compensations to ensure equitable impacts.

At a design level, this thesis focuses on studying the impact of increasing levels of solar PV self-generation in the Spanish wholesale electricity market. When designing consumer centred policies, the collateral effects of these need to be considered. Increasing levels of rooftop solar energy leads to reductions in market power on the actual marginal price system. This translates into price reductions but also to increases in electricity consumption. Policies aiming to increase the penetration of self-generation should be considered also as a policy to reduce market power, but need to be accompanied by policies aiming to mitigate this rebound effect in electricity consumption.

Finally, the document evaluates the performance of five and a half years of an interruptible load program managed by the Spanish Transmission System Operator. The main finding concludes that the program was inefficiently operated, showing room for improvement and showing the way of doing it. The proposed optimisation of this program results in recommendations at both the design and operation stages, thus, proving the potential and usefulness of this type of *ex-post* evaluation methodologies, which can nurture future formulation, designs, and operation of consumer centred policies.

To sum up, this thesis focuses on analysing and quantifying energy policies aimed at putting the consumer at the centre of the energy system. This overall objective needs policies and new regulations to make it happen and beneficial for both consumers and the system as a whole. Policymaking should focus on all the stages of the policy life cycle to ensure the efficiency and equity of the policies. By improving processes and analysis at the three stages of the cycle, formulation, design, and evaluation, energy policies aiming to put consumers at the centre of the system will increase their chances of achieving its objectives.

5.2 Future research

This thesis focuses on specific policies that aim to set the consumer at the centre of energy systems. Thus, with the energy transition in place, further policies and programs are being and will be implemented. In this regard, following the approach presented in this thesis, future lines of research aim to assess the whole policy process of current and future consumer centred energy policies. Some of the most relevant future lines of research are:

- To study and design policies that enhance the deployment of DERs with new property structures such as energy communities. The new regulation in Spain, but also in other countries, opens the door for these new forms of ownership that entail innovative operation and usage dynamics of multiple energy infrastructures, in particular the optimisation of future dynamic coefficients, understanding the barriers to these types of forms, and their impact at the low and medium voltage levels.
- To analyse current network tariffs and their impact on consumers and propose new forms of designing and evaluating them, new electricity tariffs are being designed and implemented to accommodate DERs and increase electrification. These tariffs aim to reflect this paradigm shift but they can fail to fulfil some of their principles such as cost recovery, non-discrimination, or equity, in particular, understanding the trade-offs between the multiple objectives of a tariff or different processes to establish them are among pending research questions.
- To optimise the regulatory design for the effective participation of aggregators with DER. To study the capacities of aggregators to effectively participate

as providers of operation resource. To understand the trade-offs, equity concerns, and possible regulatory failures associated with unexpected usage of the infrastructures.

- To evaluate the evolution of self-generation and its impacts on the power system. With the increasing penetration of self-consumption, to understand policies that promote it and how to quantify their effects, future impacts and propose correcting and promoting measures.
- To analyse and explore new policies and programs that aim to compensate regressive impacts of the energy transition. For instance, compensations to lower-income groups in contrast to early adopters of Electric Vehicles or energy infrastructure that are currently being subsidised.

Chapter 6

Publications and developed activities

6.1 Peer review Journals

Corresponding to the main focus and objectives of the thesis.

- A. Manso-Burgos, D. Ribó-Pérez, M- Alcázar-Ortega, T. Gómez-Navarro, Local Energy Communities in Spain: Economic Implications of the New Tariff and Variable Coefficients, Sustainability, vol. 13 pp. 10555, 2021.
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- D. Ribó-Pérez, L. Larrosa-López, D. Pecondón-Tricas, M. Alcázar-Ortega, A Critical Review of Demand Response Products as Resource for Ancillary Services: International Experience and Policy Recommendations, Energies, vol. 846, pp. 1-24, 2021.

- J. Rodríguez-García, D. Ribó-Pérez, C. Álvarez-Bel, E. Peñalvo-López, Maximizing the Profit for Industrial Customers of Providing Operation Services in Electric Power Systems via a Parallel Particle Swarm Optimization Algorithm, IEEE Access, vol. 8, pp. 24721-24733, 2020.
- D. Ribó-Pérez, A. Van der Weijde, C. Álvarez-Bel, Effects of self-generation in imperfectly competitive electricity markets: The case of Spain, Energy Policy, vol. 113, pp. 110920, 2019.
- J. Rodríguez-García, D. Ribó-Pérez, C. Álvarez-Bel, E. Peñalvo-López, Novel Conceptual Architecture for the Next-Generation Electricity Markets to Enhance a Large Penetration of Renewable Energy, Energies, vol. 13, pp. 1-23, 2019.

Corresponding to collaborations performed during the period in which this thesis has been developed.

- J. Peris-Blanes, S. Segura-Calero, N. Sarabia, D. Ribó-Pérez, Inquiring into the urban transformative capacity of València, Spain, Environmental Innovation and Societal Transitions (*Accepted*).
- D. Ribó-Pérez, A. Herraiz-Cañete, P. Casamayor-Segarra, K. Del Castillo Velázquez, T. Gómez-Navarro, S. Zelaya-Bonilla, Electrificación de la última milla del corredor seco mesoamericano, enerLAC, vol. 5, pp. 10-33, 2021.
- D. Ribó-Pérez, A. Herraiz-Cañete, D. Alfonso-Solar, C. Vargas-Salgado, T. Gómez-Navarro, Modelling biomass gasifiers in hybrid renewable energy microgrids; a complete procedure for enabling gasifiers simulation in HOMER, Renewable Energy, vol. 174, pp. 501-512, 2021.
- D. Ribó-Pérez, P. Bastida-Molina, T. Gómez-Navarro, E. Hurtado-Pérez, Hybrid assessment for a hybrid microgrid: A novel methodology to critically analyse generation technologies for hybrid microgrids, Renewable Energy, vol. 157, pp. 874-887, 2020.
- D. Bejarano-Cáceres, D. Ribó-Pérez, M. Alcázar-Ortega, Electrification of the boat fleet of the Albufera Natural Park of Valencia: methodology, economic and environmental assessments, Renewable Energy and Power Quality Journal, vol. 18, pp. 144-149, 2020.

- T. Gómez-Navarro, D. Ribó-Pérez, Assessing the obstacles to the participation of renewable energy sources in the electricity market of Colombia, Renewable and Sustainable Energy Reviews, vol. 9, pp. 131-141, 2018.
- P. Bastida-Molina, D. Ribó-Pérez, T. Gómez-Navarro, E. Hurtado-Pérez, What is the problem? The obstacles to the electrification of urban mobility in Mediterranean cities. Case study of Valencia, Spain, (*Submitted*).
- M. Auguadra, D. Ribó-Pérez, T. Gómez-Navarro Storage deployment in electricity systems for the integration of high shares of renewables (*Submitted*).
- A. Herráiz-Cañete, D. Ribó-Pérez, P. Bastida-Molina, T. Gómez-Navarro, Forecasting energy demand in isolated rural communities: a comparison between deterministic and stochastic approaches, (*Submitted*).

6.2 Research stays

- TU Delft Technology, Policy and Management Energy & Industry Delft, The Netherlands 01/06/2021 - 31/08/2021
- Lawrence Berkeley National Laboratory Energy Technologies Area Grid Integration Group Berkeley, Unites States of America 04/09/2019 - 03/12/2019

6.3 Conferences

6.3.1 International Conferences

- P. Bastida-Molina, D. Ribó-Pérez, T. Gómez-Navarro, E. Hurtado-Perez, Assessing the barriers to the development of electric vehicles in the urban transport network of Valencia, 16th International Symposium on the Analytic Hierarchy Process (ISAHP 2020). pp. 1-4 2020
- D. Doménech-Canosa, D. Ribó-Pérez, M. Alcázar-Ortega, Manuel, Design and inclusion of an electric propulsion system in a traditional boat in La Albufera, 2020 Global Mosharaka Congress on Electrical Engineering (GMC-ElecEng 2020), pp-112-117 2020

- L. Larrosa-López, D. Pecondón-Tricas, D. Ribó-Pérez, M. Alcázar-Ortega, Design and inclusion of an electric propulsion system in a traditional boat in La Albufera, 2020 Global Mosharaka Congress on Electrical Engineering (GMC-ElecEng 2020), pp-112-117 2020

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- D. Ribó-Pérez, S. Mateo-Barcos, M. Alcázar-Ortega, J. Rodríguez-García, Can we build them from scratch? Viability of municipal retail companies in Spain, 15th Conference on Sustainable Development of Energy, Water and Environment Systems. pp. 1-8 2020

- D. Ribó-Pérez, Á. Herráiz-Cañete, D. Alfonso-Solar, C. Vargas-Salgado, T. Gómez-Navarro, Modelling a gasifier with HOMER for the simulation of off-grid hybrid renewable energy microgrids, 15th Conference on Sustainable Development of Energy, Water and Environment Systems. pp. 270-271 2020

- D. Ribó-Pérez, P. Bastida-Molina, T. Gómez-Navarro, E. Hurtado-Perez, Choosing the Best Configuration for a Hybrid Microgrid of Renewable Energy Sources by means of the Analytic Network Process, 14th Conference on Sustainable Development of Energy, Water and Environment Systems. pp. 1-8 2020

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- J. Peris-Blanes, S. Segura-Calero, N. Sarabia, D. Ribó-Pérez, Inquiring into urban transformative capacities of Valencia, Spain, 10th International Sustainability Transitions Conference (IST 2019), pp. 1-39 2019

- M. Pozuelo Monfort, S. Lopez Oña, D. Ribó-Pérez, S. Djokic, Modelling and Evaluating Performance of Large Off-Grid PV Systems for Water Pumping, 8th IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT-Europe 2018), pp. 1-6 2018

- D. Ribó-Pérez, Social acceptance of demand response and Virtual Power Plants, Eu-SPRI Early Career Researcher Conference (ECC 2018). Science, Technology and Innovation: New challenges and practices, pp. 1-15 2018

6.3.2 National Conferences

- M.A. Nadal-Grau, D. Ribó-Pérez, M. Alcázar-Ortega, Diseño y análisis de mecanismos de participación de la demanda en servicios complementarios del sistema eléctrico español. VII Congreso Smart Grids, Madrid (Online), pp. 126-131 2020.
- L. Larrosa-López, D. Ribó-Pérez, M. Alcázar-Ortega, Análisis del efecto de las tecnologías de generación eléctrica, demanda y de las conexiones internacionales en el precio del mercado diario del MIBEL mediante modelos de regresión multivariable, VII Congreso Smart Grids, Madrid (Online), pp. 247-252 2020.

6.4 Books and chapters

- K. del Castillo, M. Giancristofaro, A. Mori; D. Ribó-Pérez, S. Zelaya-Bonilla, Meeting the climate change mitigation commitments of Least Developed Countries, Food and Agriculture Organization of the United Nations, 978-92-5-131607-8 2019
- D. Ribó-Pérez, P. Casamayor, A. Herraiz, A. Pons, T. Gómez-Navarro, S. Zelaya-Bonilla, V. Ferreira, L. Moro. K. del Castillo; Aumentando la resiliencia y mitigando el cambio climático para el desarrollo rural: una experiencia en Honduras, Food and Agriculture Organization of the United Nations, 2021

6.5 Competitive Research projects

- T. Gómez-Navarro D. Ribó-Pérez, E. Hurtado-Perez, A. Fernández-Baldor, C. Vargas-Salgado, P.Bastida-Molina, D. Alfonso-Solar, Microred Inteligente Hibrida de Energias Renovables para Solucionar el Trilema Agua-Alimentacion-

Energia en Una Comunidad Rural de Honduras (2020/ACDE/000306), Agencia Española de Cooperación Internacional (AECID) 18/01/21 - 30/10/21

- T. Gómez-Navarro D. Ribó-Pérez, E. Hurtado-Perez, A. Fernández-Baldor, C. Vargas-Salgado, P.Bastida-Molina, D. Alfonso-Solar, Microred Inteligente Híbrida de Energías Renovables para solucionar el Trilema Agua-Alimentación-Energía en una comunidad rural de Honduras (2019/ACDE/000842), Agencia Española de Cooperación Internacional (AECID) 27/02/20 - 27/08/21
- M. Alcázar-Ortega, Manuel, D. Ribó-Pérez, Validación de mecanismos de participación de la demanda en servicios complementarios del sistema eléctrico español: diseño e implementación de plan piloto, Fundación Iberdrola España 15/09/20 - 15/06/21
- M. Alcázar-Ortega, Manuel, D. Ribó-Pérez, Diseño y Analisis de Mecanismos de Participacion de la Demanda en Servicios Complementarios del Sistema Electrico Español, Fundación Iberdrola España 15/09/19 - 15/06/20

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- Ayudas complementarias para beneficiarios de ayudas (FPU): Estancias Breves y Traslados Temporales. 2020
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