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CONTROL, PREDICCIÓN, PARTICIPACIÓN EN EL MERCADO E IMPACTO EN LA RED DE LA FLEXIBILIDAD DE LA DEMANDA AGREGADA

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Universidad de Valladolid



PHD PROGRAMME IN INDUSTRIAL ENGINEERING

DOCTORAL THESIS:

**CONTROL, PREDICTION, MARKET
PARTICIPATION AND GRID IMPACT OF
AGGREGATED DEMAND FLEXIBILITY**

Submitted by Alejandro Martín Crespo in fulfilment of
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RESUMEN

En esta tesis doctoral se aborda la flexibilidad de la demanda, un tema de creciente relevancia en el contexto de la transición hacia sistemas energéticos descarbonizados. La flexibilidad de la demanda se refiere a la capacidad de los usuarios finales del sistema eléctrico de ajustar sus patrones de consumo en respuesta a señales de operación, cambios en los precios u otros factores, manteniendo el nivel deseado de utilidad. La gestión de la flexibilidad de la demanda permite estabilizar la red en situaciones de gran penetración de generación no controlable, como puede ser el caso de la energía renovable. Los aspectos fundamentales estudiados de la flexibilidad de la demanda son el control de las cargas eléctricas flexibles, la predicción de su comportamiento, la participación en mercados eléctricos y su impacto en la operación de la red eléctrica. Además, en este documento se analizan algunos aspectos de la situación de la flexibilidad de la demanda en España.

OBJETIVOS

Los objetivos de esta tesis doctoral son cuatro:

1. Estudiar el potencial de las cargas eléctricas flexibles agregadas, específicamente las cargas termostáticamente controladas (TCL), para evitar la congestión y los problemas de ajuste entre generación y demanda en las redes eléctricas, y por lo tanto promover la integración de fuentes de energía renovable y participar en los mercados eléctricos.
2. Desarrollar una arquitectura de control fiable para agregaciones de TCL que opere en tiempo real con un error mínimo, así como una metodología de predicción que permita planificar a corto plazo el uso de la flexibilidad de la demanda.
3. Estudiar el impacto de la integración de la flexibilidad de la demanda en la red eléctrica en tiempo real y a largo plazo, teniendo en cuenta las posibles restricciones técnicas y económicas que pueda conllevar.
4. Caracterizar la flexibilidad de la demanda residencial disponible en España y estudiar las condiciones y requisitos necesarios para su participación en los mercados eléctricos españoles.

METODOLOGÍA

La flexibilidad de las TCL se agrega en una batería virtual (VB), la cual es gestionada mediante un controlador. En su conjunto, la VB es capaz de proporcionar potencia flexible positiva o negativa y dispone de ambos tipos de capacidad energética. El uso del controlador permite predecir la flexibilidad de demanda que las TCL podrán aportar en instantes futuros. Una

vez realizada la predicción de la flexibilidad disponible, la agregación puede participar en los mercados eléctricos, donde habitualmente un proceso de subasta determina la cantidad y el momento en que la VB debe aportar dicha flexibilidad. Posteriormente, estos requerimientos son transmitidos al controlador, que identifica qué TCL deben modificar su comportamiento esperado para cumplir con la flexibilidad de la demanda requerida. Finalmente, la modificación del patrón de consumo de la agregación de TCL impacta en la red eléctrica. Este impacto se considera beneficioso, ya que puede favorecer la integración de energías renovables, reducir la generación a partir de combustibles fósiles y contribuir a la resolución de congestiones en la red.

RESULTADOS

Los principales resultados obtenidos en el desarrollo de la tesis doctoral han sido los siguientes:

1. Un controlador con el que gestionar la flexibilidad de VB formadas por agregaciones de TCL.
2. Un método de predicción de la flexibilidad que pueden proporcionar TCL agregadas en VB basado en simulaciones de Montecarlo y búsquedas de extremos por bisección.
3. Un método de cálculo del flujo de potencia para microrredes híbridas AC/DC basado en optimización.
4. Una evaluación tecnoeconómica basada en indicadores de rendimiento (KPI) para microrredes híbridas AC/DC.
5. Un estudio sobre el potencial en España de la flexibilidad de las VB formadas por TCL residenciales.

CONCLUSIONES

Los resultados obtenidos en esta tesis doctoral ponen de manifiesto el potencial de la flexibilidad de la demanda para mejorar la eficiencia, fiabilidad y sostenibilidad de los sistemas eléctricos, facilitando la integración de las energías renovables. Gracias al estudio de la flexibilidad de la demanda residencial, los ciudadanos, responsables políticos y las empresas podrán tomar las mejores decisiones para lograr el uso más justo, equilibrado y rentable de la misma.

ABSTRACT

This doctoral thesis addresses demand flexibility, a topic of growing relevance in the transition towards decarbonised energy systems. Demand flexibility refers to the capability of end-users to adapt their electricity consumption in response to operational signals, price variations, or other influencing factors, while preserving their desired level of utility. Proper management of this flexibility enables grid stabilisation under conditions of high penetration of non-controllable renewable generation. The thesis focuses on the control of flexible loads, the prediction of their behaviour, their participation in electricity markets, and their impact on grid operation. The main contributions are the design of an aggregated thermostatically controlled loads (TCLs) controller, the development of a method for demand flexibility prediction, the implementation of a hybrid AC/DC power flow calculation, and a techno-economic analysis of grid performance. In addition, the potential of residential demand flexibility in Spain is assessed together with the conditions for its effective integration into electricity markets.

KEYWORDS

Demand flexibility, Control, Prediction, Electricity markets, Grid operation, TCLs, Spain

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CHAPTER 1

INTRODUCTION

The aim of this section is to introduce the reader to the subject of this thesis, its objectives, its structure, the circumstances under which it has been elaborated, the published articles and the content.

1.1. Subject

The concern about the emission of greenhouse gases into the atmosphere and the progressive depletion of available fossil energy resources is leading to an increase in the use of clean and renewable energy for electricity generation [Kåberger, 2018, Holechek et al., 2022]. This approach is currently adopted by most countries in the world [Falkner, 2016], as well as by the European Union [Fetting, 2020] and, specifically, Spain¹. The main issue with renewables is that most of them are intermittent, difficult to predict accurately, and cannot be used on demand. Therefore, a greater inclusion of renewable energy in the power system results in increased variability and uncertainty in the grid. This leads to congestion problems in electrical networks and difficulties in balancing generation and demand at every moment [Ela and O'Malley, 2012, Jimeno et al., 2019, Babatunde et al., 2020].

There are several ways to deal with such problems. One is the use of conventional energy storage, such as pumped hydro, flywheels or batteries [Schmidt et al., 2019]. Demand flexibility is emerging as an alternative mechanism [Gottwalt et al., 2016, Sajjad et al., 2016]. It allows electricity to be absorbed or fed into the grid without major investment in installations or machinery, as it takes advantage of the flexibility of existing assets [Bertsch et al., 2016]. Usually, the best option is a combination of all the possible solutions, depending on the circumstances of the power system.

One of the types of electrical loads that can be used to provide demand flexibility are thermostatically controlled loads (TCLs). They make use of their thermal inertia to operate, which gives them the ability to shift their consumption over time [Hao et al., 2014, Martín-Crespo et al., 2021]. In this thesis, the demand flexibility of electrical loads, specifically aggregations of TCLs, is assessed by designing a controller, a method for predicting available demand flexibility and evaluating its impact on

¹Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO). Plan Nacional Integrado de Energía y Clima Actualización 2023-2030. https://www.miteco.gob.es/content/dam/miteco/es/energia/files-1/pniec-2023-2030/PNIEC_2024_240924.pdf

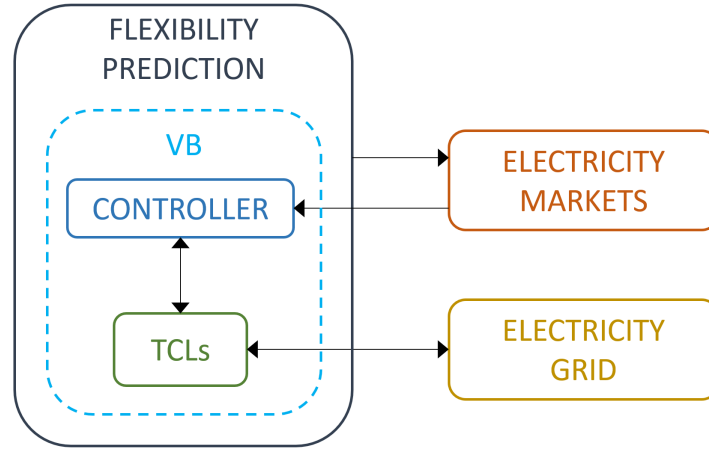


Figura 1.1: Demand flexibility with TCLs: relationships between actors

the grid and its participation in electricity markets. In addition, Spain is taken as a case study to estimate the potential of demand flexibility and its opportunities.

Figure 1.1 shows the relationship between TCLs, control, prediction, electricity markets and the electricity grid.

As it is explained in more detail in the following sections, the flexibility of TCLs is aggregated into a virtual battery (VB) that is managed by a controller. As a whole, the VB provides either positive or negative flexible power and has both types of energy capacity. By using a controller, the demand flexibility that TCLs can provide in future instants can be predicted. Once the prediction of the demand flexibility that will be available has been made, the aggregation can participate in the electricity markets, where typically a bidding process will decide how much and at what time the VB should provide the flexibility. These requirements are then transmitted to the controller, that had determined which TCLs are responsible for modifying their expected behaviour to obtain the required demand flexibility. Lastly, the modification of the consumption pattern of the aggregation of TCLs has an impact on the grid, which is expected to be beneficial due to the uptake of renewable power or decrease in generation with fossil fuels, as well as the solution of congestions.

1.2. Objectives

Once the subject of the thesis has been presented, its main objectives are introduced:

Objective 1. To study the potential of aggregated flexible electrical loads, specifically TCLs, to prevent congestion and matching problems between generation and demand in power grids, and therefore promote the integration of renewable energy sources and to participate in electricity markets.

Objective 2. To develop a reliable control architecture for aggregations of TCLs that operates in real-time with minimal error, as well as a prediction methodology that allows short-term planning for the use of demand flexibility.

Objective 3. To study the impact of integrating demand flexibility into the electricity grid in real-time and in the long term, taking into account possible technical and economic constraints that may be involved.

Objective 4. To characterise the residential demand flexibility available in Spain and to study the necessary conditions and requirements for its participation in the Spanish electricity markets.

1.3. Structure

This thesis is presented as a compendium of publications. The structure consists of five chapters and the bibliography. The chapters are described below.

Chapter 1. This chapter provides an introduction to the doctoral thesis and a comprehensive view of demand flexibility. It defines the concept and its importance, explains the main modelling, control, and prediction approaches, assesses its participation in electricity markets and impact on the grid, and finally analyses the current situation and potential in Spain, highlighting residential capabilities and market integration.

Chapter 2. This chapter has been published in a peer review journal as: Martín-Crespo, A., Saludes-Rodil, S., & Baeyens, E. (2021). Flexibility Management with Virtual Batteries of Thermostatically Controlled Loads: Real-time Control System and Potential in Spain. *Energies*, 14(6), 1711. <https://doi.org/10.3390/en14061711>

Chapter 3. This chapter has been published in a peer review journal as: Martín-Crespo, A., Hernández-Serrano, A., Izquierdo-Monge, Ó., Peña-Carro, P., Hernández-Jiménez, Á., Frechoso-Escudero, F., & Baeyens, E. (2024). AC/DC optimal power flow and techno-economic assessment for hybrid microgrids: TIGON CEDER demonstrator. *Frontiers in Energy Research*, 12, 1399114. <https://doi.org/10.3389/fenrg.2024.1399114>

Chapter 4. This chapter has been published in a peer review journal as: Martín-Crespo, A., Baeyens, E., Saludes-Rodil, S., & Frechoso-Escudero, F. (2025). Aggregated Demand Flexibility Prediction of Residential Thermostatically Controlled Loads and Participation in Electricity Balance Markets. *International Journal of Energy Research*, 2025(1), 8819201. <https://doi.org/10.1155/er/8819201>

Chapter 5. This chapter summarises the main conclusions reached in this thesis.

1.4. Background

The development of this thesis is part of the research strategy of the Smart Grids Area at the CARTIF Technology Centre. CARTIF² is a horizontal, private and non-profit research institution, whose main mission is to transfer innovative solutions to the industry to enhance their processes, systems and products, improving their competitiveness and creating new business opportunities. The Smart Grids Area³ focuses on research, development, and deployment of optimal planning systems for managing electricity grids with renewable generation, storage, and controllable loads, among other related topics.

The doctoral programme in which the thesis was conducted was complemented by

²Fundación CARTIF. Quiénes somos. <https://www.cartif.es/en/about-us/>

³Fundación CARTIF. Smart Grids. <https://www.cartif.es/en/research-areas/smart-grids/>

a three-month stay at the Center for Research on Microgrids (CROM) of the Aalborg University in Denmark in 2024⁴. The research stay allowed to increase the knowledge about hybrid microgrids and improve the AC/DC microgrid model explained in the following sections.

Special mention should also be made of CEDER-CIEMAT⁵. In this institution, the necessary experimental tests have been performed to verify the correct functioning of the power flow calculation method developed, as well as the validity of the techno-economic analysis.

This thesis will be awarded an Industrial Doctorate mention and an International Doctorate mention. The Industrial Doctorate mention was obtained due to the fact that the doctoral programme has been conducted under contract at the CARTIF Technology Centre. Several European, national and regional projects have helped the development of this thesis, among which OPTIGRID⁶, TIGON⁷, LocalRES⁸ and SunHorizon⁹ can be highlighted. The International Doctorate was obtained thanks to the three-month stay in Aalborg University, Denmark.

1.5. Additional articles

In addition to the three peer review articles included in this thesis (Chapters 2, 3 and 4), two more have been published in the context of this research. These articles are [Martín-Crespo et al., 2022] and [Hernández-Moral et al., 2022]:

- Martín-Crespo, A., Hernández-Serrano, A., Arnanz, R., Belda-González, A., & Moreno, A. G. (2022, May). SunHorizon advanced control system and proactive maintenance tool: Case study in Latvia. In CLIMA 2022 conference. <https://doi.org/10.34641/clima.2022.106>.

Abstract: Currently, buildings represent a large percentage of the energy consumption in the European Union. Increasing the introduction of renewable energy sources is becoming necessary to achieve an effective reduction of greenhouse gas emissions. SunHorizon project demonstrates the potential of combining solar appliances and heat pumps in buildings for meeting heating and cooling (H&C) demands in Europe. The energy systems are managed by an advanced Python-based control system. Using the forecast of the demand and occupancy of the building, a predictive controller calculates the optimal exploitation of resources and storage use in order to maximize the renewable energy use and cost performance. Furthermore, the control system operates in combination with a

⁴Aalborg University. Center for Research on Microgrids. <https://www.energy.aau.dk/research/research-groups/crom>

⁵CEDER-CIEMAT. CEDER-CIEMAT. <https://www.ceder.es/>

⁶OPTIGRID has received funding from the European Union ERDF (European Regional Development Fund) and the Junta de Castilla y León through ICE (Instituto para la Competitividad Empresarial) to improve innovation, technological development, and research, dossier no. CCTT1/17/VA/0005.

⁷TIGON has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 957769.

⁸LocalRES has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 957819.

⁹SunHorizon has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 818329

proactive maintenance tool that includes fault detection and maintenance surveillance capabilities. This tool is based on the Reliability-Centred Maintenance (RCM) strategy, which focuses on understanding the equipment failure modes, applying all the different possible maintenance strategies and considering consequences and cost of failures. To achieve this goal, several key performance indicators (KPIs) are defined, calculated in real-time operation and compared with simulation data to detect faults. When any failure is obtained, the system triggers specific alarms via web and email, hence notifying house operators or final users. KPIs are also evaluated to calculate their remaining useful life (RUL) and therefore predict future faults. The solution is applied in a building in Riga (Latvia) and the methodology beneath these tools is explained in this paper. The use of prediction for control and maintenance will allow the system to avoid wasting energy, increase self-consumption as well as to save costs on the energy bills.

- Hernández-Moral, G., Serna-González, V. I., Crespo, A. M., & Rodil, S. S. (2022). Multi-objective optimization algorithms applied to residential building retrofitting at district scale: BRIOTOOL. In E3S Web of Conferences (Vol. 362, p. 03002). EDP Sciences. <https://doi.org/10.1051/e3sconf/202236203002>.

Abstract: The design of district and urban energy efficient retrofitting projects is a major challenge if contrasted solutions want to be implemented. From the establishment of the criteria to the calculation of indicators, there are several aspects to be considered, such as evaluating a series of refurbishment solutions or establishing an adequate method to select the optimal solution. Apart from this process requiring a high number of time and resources, it can result in a number of inaccuracies, leading to inadequate decisions or designs. The main achievement of the BRIOTOOL solution proposed is the transformation of a subjective problem (what the best combination of energy conservation measures to implement is) into a mathematical problem, which ensures a more robust decision-making process. In particular, by analysing which multi-objective optimization method (NSGA-II, IHS, MHACO or NSPSO) is the most appropriate, based on execution time, number of different and optimal solutions, and hypervolume of the Pareto front generated. As a result, the time reduction and the increase in the accuracy of the process compared to business as usual practices shows the benefits of the solution in designing energy efficient retrofitting projects at district level.

1.6. What is demand flexibility?

In contemporary power systems, demand flexibility has emerged as a promising mechanism for enhancing the efficiency, reliability, and sustainability of electricity grids. In this section we define demand flexibility and related concepts.

1.6.1. Definition and types

Demand flexibility refers to the ability of electrical loads to change their consumption patterns in response to operator signals and changes in electricity prices, without compromising their utility [Grunewald, 2016, Ahmadihangar et al., 2020, Pavlidis et al., 2021]. This demand flexibility can appear through various mechanisms,

including but not limited to load shifting, peak saving, valley filling, load shedding, and the integration of electric vehicles (EVs) [Lund et al., 2015].

Demand flexibility can be classified as implicit and explicit. [Freire-Barceló et al., 2022]. Explicit demand flexibility, also known as market-based demand response, refers to an actively managed approach to adjust electricity consumption. It involves the participation of consumers in organized markets or programs where they receive compensation for altering their energy use based on predefined agreements or instructions from grid operators, aggregators, or utilities. Implicit demand flexibility, also known as price-based or tariff-driven demand response, involves changes in electricity consumption that occur as a reaction to incentive signals (e.g. price) rather than formal agreements or contracts. It relies on consumers responding voluntarily to dynamic electricity prices, which reflect real-time market conditions or grid constraints.

While both types of demand flexibility aim to make the most of electricity usage and support grid reliability, they differ significantly in terms of structure, incentives, and potential impacts:

- Explicit flexibility is proactive and often managed by aggregators or energy service providers, whereas implicit flexibility is more reactive and depends on individual consumer behavior.
- Explicit demand flexibility requires robust communication and control systems to ensure reliability, as grid operators need to know that demand adjustments will occur when needed. Implicit flexibility, on the other hand, is driven by economic information and does not guarantee a specific level of response.
- Explicit programs offer direct payments, which can be lucrative for participants but require more administrative complexity. Implicit programs provide cost savings through lower energy bills, making them simpler to implement but potentially less predictable in terms of impact on grid stability.

1.6.2. Why is it important?

In today's energy scenario, characterised by the increasing penetration of renewable energy sources [Deshmukh et al., 2023], ageing grid infrastructure [Ardito et al., 2013] and changing consumption patterns [Aroonruengsawat and Auffhammer, 2011], demand flexibility is very important for several reasons. Firstly, the growing deployment of intermittent renewable energy sources such as wind and solar power necessitates greater flexibility in demand to accommodate their variability [Holttinen et al., 2013, Chen et al., 2018]. Demand flexibility enables alignment between electricity consumption and renewable generation patterns, thereby facilitating higher penetration of clean energy while minimizing curtailment and grid congestion. Another reason is that demand flexibility enhances the resilience and reliability of power systems by alleviating stress during peak demand periods or unforeseen contingencies [Panteli et al., 2016, Alves et al., 2023]. By curtailing or shifting loads during times of strain, demand flexibility helps prevent grid instability, blackouts, and cascading failures, thereby ensuring uninterrupted electricity supply for critical services and industries.

In addition, flexible demand can lead to more efficient utilization of generation and transmission assets, reducing the need for costly investments in additional infrastructure or peaking power plants [Song and Amelin, 2015]. Moreover, demand-side management initiatives, such as time-of-use pricing or demand response programs, incentivise consumers to use electricity during hours when generation costs are lower, thereby optimizing resource allocation and minimizing overall system costs [Shalaby, 2021]. Furthermore, by enabling greater integration of renewable energy and facilitating the reduction of fossil fuel-based generation during peak demand periods, demand flexibility plays a crucial role in decarbonizing the power sector. The ability to adjust consumption patterns in response to carbon intensity or emissions targets enables stakeholders to align electricity usage with environmental objectives, fostering a transition towards a more sustainable energy ecosystem [Grijalva and Tariq, 2011, Agwan et al., 2023]. Additionally, this adaptability can support compliance with carbon emission rights or cap-and-trade schemes [He et al., 2023], offering both environmental and economic incentives for reducing carbon footprints.

Finally, demand flexibility empowers consumers by providing them with greater choice over their energy consumption, expenditure and revenues [Alhussein et al., 2024]. Through smart technologies, real-time feedback mechanisms, and participation in demand response programs, consumers can make informed decisions regarding their electricity usage, optimize their energy bills, and contribute to broader societal goals such as grid decarbonization and energy transition.

1.7. Modelling, control and prediction of demand flexibility

Flexible electrical loads are highly varied. This category includes, for example, batteries, electric vehicle chargers, and TCLs (refrigerators, heat pumps, etc.). All of these are used to meet users' needs, such as transportation, cement production, maintaining food at a specific temperature, or achieving comfortable thermal conditions in a commercial or residential building. Thanks to the flexible electrical loads ability to vary their consumption patterns while keeping their utility, they can be aggregated to provide ancillary services to the grid and to participate in the electricity markets. In Table 1.1, the main loads considered for demand flexibility, their flexibility characteristics and their potential grid services are listed [Strbac, 2008, Palensky and Dietrich, 2011, Aunedi, 2013, Siano, 2014].

Table 1.1: Overview of the main loads considered for demand flexibility

Load Type	Flexibility Characteristics	Grid Services
Electric Vehicles charger	Shiftable charging, high storage capacity	Peak shaving, energy arbitrage, frequency regulation
Batteries	Fully controllable, bidirectional operation	Energy arbitrage, frequency regulation, backup power
TCL	Fast response, no discomfort due to thermal inertia	Frequency regulation, reserves
Electric furnace / oven	Substantial demand, region-dependent	Load shifting, reserves
Smart lighting	Very limited flexibility	Peak shaving, emergency shedding
Water pump	Deferrable operation within daily cycles	Load shifting, peak shaving
Electrolyzer	Fast ramping, scalable	Energy arbitrage, frequency regulation, reserves

In this thesis, TCLs have been selected as case study because of their ubiquity in households, rapid response time, and ability to provide flexibility without disruption to the user. Their inherent thermal inertia decouples electricity consumption from im-

mediate service provision, making them particularly well suited to the needs of electricity markets where reliable, fast-acting flexibility is required. To achieve the provision of grid services from flexible electrical loads, control and prediction techniques must be used, along with sufficiently accurate models of the loads. All of them are discussed in this section.

1.7.1. Modelling

The flexible loads can be represented using various approaches. The most used models for flexible loads are those obtained with equation-based methods, machine learning techniques and hybrid methodologies. The three of them are explained below.

1.7.1.1. Equation-based models

Equation-based models use explicit mathematical descriptions to capture the physical dynamics of electric loads. This approach includes both individual and aggregated models. As advantages, the equation-based models are easy to be interpreted, as each parameter has a clear physical meaning, and the computational efficiency is high. As drawbacks, they have difficulties in capturing complex or uncertain behaviors, such as heterogeneity in load usage, and it is sometimes difficult (if not impossible) to know the real value of some parameters. This type of models are the ones used by the controller and the prediction method presented in this thesis.

1.7.1.1.1 Individual models

Individual models represent the intrinsic characteristics of loads through differential or algebraic equations. For example, in the case of TCLs, equations describing the energy balance between thermal gains, environmental losses, and contributions from devices such as heating or cooling systems are used. The most characteristic expressions are Equations 1.1 and 1.2 [Khan et al., 2016], which describes the TCLs internal temperature θ .

$$\theta = g \cdot \theta + (1 - g) \cdot (\hat{\theta}_a - u \cdot \theta_g) + \omega, \quad (1.1)$$

where

$$g = e^{-1/R_{th} \cdot C_{th}}, \quad \theta_g = R_{th} \cdot P \cdot \eta. \quad (1.2)$$

In the equation, u is the status of the TCL (0 is off, 1 is on), $\hat{\theta}_a$ is the forecasted ambient temperature, ω is the disturbance, R_{th} is the thermal resistance, C_{th} is the thermal capacity, P is the nominal power and η is the performance coefficient. ω encompasses inaccuracies in forecasting, modelling, and TCLs operation.

1.7.1.1.2 Aggregated models

For large groups of flexible loads, individual equations can be aggregated into macroscopic models using techniques such as master equations or probabilistic distribution approximations. For instance, these models allow the collective behavior of TCLs to be predicted as a VB that stores and delivers energy in the form of load variations

[Hao et al., 2014, Mathieu et al., 2014, Zhang et al., 2016, Zhao et al., 2017]. VBs are so named because their behaviour is equivalent to that of a conventional electric battery.

1.7.1.2. Machine Learning-Based Models

Machine learning models rely on analyzing large datasets to identify patterns and relationships between variables [Bhosekar and Ierapetritou, 2020, Alaraasakka, 2024]. These models are especially useful when a detailed physical description of the loads is unavailable, when the system exhibits a non-linear behaviour, or when a dynamic model that is executed very fast is required. This approach includes neural networks, among others. As advantages, machine learning models have flexibility to adapt to different types of data and scenarios, and capability to model complex systems where equation-based approaches fall short. The limitations are the great difficulty to be interpreted compared to equation-based models and the dependence on large volumes of high-quality data for training.

1.7.1.3. Hybrid Models

Hybrid models combine the best of both worlds, using physical equations to capture the fundamental dynamics of the system and machine learning to adjust certain parameters or model components that are difficult to be described analytically [Alaraasakka, 2024]. The strengths of the hybrid models are their balance between ease of interpretation and predictive capability and the greater robustness in the face of incomplete data or changing scenarios. As drawbacks, they increase the complexity in model implementation and require expertise in both physical modeling and machine learning.

1.7.2. Control

The control of flexible demand assets depends on their type and the environment in which they are used. An industrial, commercial or residential environment is not the same, as privacy requirements or assumable power measurement errors, for example, may vary. There are two main methods for the control of flexible electrical loads: direct control [Chauhan et al., 2024] and voluntary or contractual control [Saavedra et al., 2022].

Direct control involves a manager, whether the system operator or an aggregator, having direct access to specific devices or systems of consumers to adjust their consumption in real time or in response to specific signals. It is generally used in the case of explicit demand flexibility.

On the other hand, under voluntary or contractual control, users agree to modify their consumption under certain pre-established conditions. It is typically applied in situations involving implicit demand flexibility.

Implicit management of residential TCL flexibility is a desirable approach, as it eliminates the need for dedicated sensors and actuators inside dwellings. One methodologies used to check if load shifting has been carried out correctly are the non-intrusive load monitoring (NILM) algorithms [Zoha et al., 2012, Batra et al., 2014, Rafiq et al., 2024]. NILM is a technique used to monitor and analyze electrical energy

consumption at a single point. It uses high-frequency signal processing and machine learning algorithms to disaggregate the total power consumption into estimates of usage by individual devices. The key principles of NILM include detecting changes in electrical load patterns, identifying appliance-specific signatures, and associating these patterns with known devices. This process involves collecting data on voltage and current, often sampled at high frequency, and analyzing it to extract features such as power, harmonic content, or transient behaviors. However, NILM is not yet widely adopted because of existing accuracy and reliability issues, high computational complexity, lack of standardisation and privacy concerns.

The controller presented in this thesis brings explicit flexibility to the residential field, just by using Internet connection as in [Lakshmanan et al., 2016] and making use of the TCL aggregated model in VB. The priority control introduced in [Martín-Crespo et al., 2021] and improved in [Martín-Crespo et al., 2025] allows for a high level of precision in the tracking by the VB of the power signal of the system operator, what cannot be obtained with implicit demand management techniques. However, its use does not have to be limited to the residential sector, as it is also valid for all types and dimensions of TCLs.

1.7.3. Prediction

To properly manage demand flexibility, modelling and control is not enough. It is also necessary to predict the flexible power that will be available in the future, especially in the short term. In this way, aggregators will be able to anticipate bids in the electricity markets, or grid operators will be able to prevent possible grid problems.

In this thesis, specifically in [Martín-Crespo et al., 2025], a new flexible demand forecasting method is presented. The authors named it Monte Carlo and extremum search by bisection (MC&ESB), since it makes use of both techniques to calculate the maximum positive or negative flexibility that a load aggregation can provide for a certain period of time in the future. Prediction is done by statistically managing uncertainty.

Nevertheless, other demand flexibility forecasting methodologies are available, such as time series-based methods, consumer behaviour-based models and machine-learning-based models. All of them are described below.

1.7.3.1. Time Series-Based Methods

Time series methods are widely used for estimating demand flexibility. These methods utilize historical data to identify patterns and make predictions. Among the most common techniques are:

- Autoregressive Integrated Moving Average (ARIMA) [Lu et al., 2021]: Used to model and forecast stationary and non-stationary data, e.g. of the energy consumption of the aggregation of electric vehicles. Its simplicity and ability to capture trends make it suitable for predicting general demand behavior.
- Seasonal Models (SARIMA): An extension of ARIMA that includes seasonal components, which is helpful for capturing daily or seasonal cyclical fluctuations in demand flexibility. In [Kouzelis et al., 2015] SARIMA is used to make a one-hour

prediction of the overall consumption of the heat pump (HP), thus estimating its flexibility even without explicit measurements of the device.

- **Machine Learning-Based Models:** As for control, machine learning can be used to predict the flexibility available at a future point in time and the ability to adapt to the needs of the electricity grid [Salter et al., 2024]. How well it works depends largely on the quality of the data used for training.

These methods are limited by their heavy reliance on the quality and quantity of historical data and their inability to adequately capture unexpected behavioral changes.

1.7.3.2. Consumer Behavior-Based Models

Consumer behavior-based methods explicitly model how consumers respond to various stimuli, such as price changes or incentives. They include:

- **Econometric Models** [Lynch et al., 2012]: These use statistical techniques to estimate how changes in prices or policies affect demand, e.g., price elasticity of demand.
- **Agent-Based Models** [Bustos-Turu et al., 2014]: Simulate the behavior of individual consumers or groups in response to external signals, considering social, economic, and psychological factors.

While these models are useful for understanding specific dynamics, they often require detailed data on individual preferences and can be costly to implement.

1.8. Market participation and grid impact of demand flexibility

The availability of models describing load behavior enables their aggregation and control to leverage demand flexibility. If there is also a method to predict the available power flexibility, the aggregation can participate in electricity markets where demand is allowed to bid. If any demand flexibility is matched, the power signal is returned to the aggregation and, through the controller, the expected operation of the loads is modified in order to meet the set power requirement. The new behaviour of the flexible loads has consequences on the grid, which are assumed to be beneficial as a consequence of the market mechanism. This section discusses the participation of demand flexibility in electricity markets and how it impacts the grid.

1.8.1. Market participation

Demand flexibility can be used in the electricity system for a multitude of purposes: ancillary services, grid resilience, emergency response and participation in energy markets [Cui et al., 2020, Nawaz et al., 2022, Hussain et al., 2023]. In this thesis, market participation has been chosen as the object of study.

The market participation of demand flexibility typically occurs through two distinct mechanisms: energy markets and capacity markets¹⁰. In the energy markets, electricity is exchanged between a buyer and a seller, whereas capacity markets add an additional layer in which the availability to exchange electricity is negotiated in case it is required or if certain requirements are met, so that a certain reserve of energy can be ensured if necessary. Active demand participation in capacity or energy markets promotes greater competition, reducing the overall costs of the electricity system and benefiting consumers.

However, to unlock the demand flexibility full potential, certain challenges need to be overcome, such as the implementation of aggregation systems that allow small consumers to participate collectively, and the creation of regulatory frameworks that incentivise investment in demand-side management technologies. The European Union and the countries of the European region are working to facilitate the integration of demand flexibility in the electricity system and in the markets [Forouli et al., 2021, Valarezo et al., 2021]. The report 2023 Market Monitor for Demand Side Flexibility¹¹ provides valuable insights into the progress and barriers to integrating demand flexibility across European markets, highlighting advancements in regulatory frameworks, market access, and technological innovation. In the report, we can see that currently France, Great Britain, Germany and Netherlands are the most advanced European countries in the regulatory process of demand flexibility.

Complementing these efforts, the Universal Smart Energy Framework (USEF)¹² offers a standardized framework for enabling and optimizing demand-side flexibility, ensuring its effective integration into energy systems. USEF has been implemented in several schemes in Europe to drive innovation and ensure the long-term viability of smart energy projects.

1.8.2. Grid impact

To see how demand flexibility influences the grid, it is necessary to look at the physical, technical and economic aspects over different periods of time. These aspects are considered in [Martín-Crespo et al., 2024], which focuses on the development of two techniques to understand the operation of the grid in real time and also in the long term.

1.8.2.1. Real-time impact: power flow

A power flow analysis provides a detailed picture of the operational state of an electrical power system [Van Hertem et al., 2006]. By modeling the generation, transmission, and distribution of electricity, power flow calculations help to quantify how electricity is routed through the grid and identify the resulting voltage levels, power losses, and line capacities at each point in the network. Therefore, power flows enable

¹⁰NRG Editorial Voices. Electricity markets: what's the difference between a wholesale energy market and a capacity market? <https://www.nrg.com/insights/energy-education/electricity-markets-what-s-the-difference-between-a-wholesale-en.html>

¹¹smartEN. 2023 Market Monitor for Demand Side Flexibility. https://smarten.eu/wp-content/uploads/2024/12/Flex-Market-Monitor-2024_v05_DIGITAL-2.pdf

¹²USEF Foundation. A flexibility market design. <https://www.usef.energy/a-flexibility-market-design/>

the calculation of the demand flexibility required to ensure system stability, maintain voltage levels within acceptable limits, and optimize the dispatch of generation resources. In addition, they provide insight into how various demand-side interventions interact with renewable energy sources, whose inherent variability introduces further challenges to grid stability.

In [Martín-Crespo et al., 2024], an optimal power flow (OPF) calculation method for hybrid AC/DC microgrids is presented, allowing selection from four distinct cost functions based on the desired objective. The OPF considers the DC elements of the grid: Although AC has traditionally been the dominant standard for power transmission and distribution, recent advances in DC technologies, including cutting-edge batteries and electric vehicles, have renewed interest in these systems.

1.8.2.2. Long-term impact: techno-economic assessment

A techno-economic analysis integrates technical, economic, and operational factors to provide a comprehensive and critical perspective of the grid [Chai et al., 2022]. By combining quantitative assessments of energy system dynamics with economic modelling, this approach allows companies, researchers and policymakers to evaluate the cost-effectiveness, scalability, and technical feasibility of demand flexibility measures. For instance, techno-economic analysis can simulate how flexible demand reduces peak loads, optimizes resource utilization, and defers investments in grid infrastructure.

In the context of a decarbonising energy system, this analysis becomes even more valuable as it can model the integration of variable renewable energy sources, and evaluate the long-term implications for grid stability, emissions reductions, and energy costs.

In [Martín-Crespo et al., 2024] authors introduce a techno-economic evaluation for microgrids which uses eight KPIs to make informed decisions and ease the optimisation of the overall efficiency of the microgrid. These KPIs are electrical energy generated, CO₂ emissions, self-consumption percentage, storage flexibility, total life cycle income, total life cycle cost, payback, and levelized cost of energy (LCOE). They were selected for their usefulness in providing a complete analysis.

1.9. Demand flexibility in Spain: residential capabilities and market participation

Although demand flexibility is already being utilised in several European countries, it is starting to be applied in Spain. Thus, many companies are investing a lot of resources and efforts to benefit from the use of demand flexibility, and organisations have been created in this direction. One of the main associations is ENTRA¹³, in which Endesa, Aduriz Energía, Octopus Energy and Cuerva participate. This section discusses the situation of demand flexibility in Spain: its availability in the residential sector, the markets and mechanisms in which it can participate and the figure of the independent aggregator as a driver.

¹³Entra-Coalición. ENTRA Agregación y Flexibilidad. <https://entra-coalicion.com/>

1.9.1. Residential demand flexibility

Residential loads, including TCLs such as air conditioners, electric water heaters, and heat pumps, offer valuable flexibility to power systems. While industrial and commercial loads are often larger and more predictable, residential loads are more decentralized and diverse, requiring aggregation to maximize their flexibility potential. Moreover, residential demand flexibility is highly scalable due to the increasing deployment of smart home technologies, demand response programs, and distributed energy resources.

The amount of available demand flexibility in Spanish households is estimated in [Martín-Crespo et al., 2021]. Demand flexibility is assessed by climate zones, using a controller and information on the TCL equipment available per dwelling according to the SECH-SPAHOUSEC project¹⁴. The residential flexibility available depends on both meteorological and sociological factors, as demonstrated both in [Martín-Crespo et al., 2021] and [Ribó-Pérez et al., 2021]. For example, in colder areas demand flexibility does not have as much potential as in warmer areas due to the absence of air conditioning.

The demand flexibility that each dwelling can offer can be considered as very small (less than 6 kW [Martín-Crespo et al., 2021]), especially taking into account that many of the current markets in which demand can participate have a minimum power limit to bid. For instance, in the balancing markets in Spain the minimum power for bidding is currently at 1 MW [Martín-Crespo et al., 2025]. Therefore, the only way to operate residential demand flexibility is through aggregators. This actor of the electricity system is explained in more detail in Section 1.9.3 below.

1.9.2. Markets and mechanisms

Currently, the electricity markets in Spain where demand can participate are the balancing markets: *Regulación Secundaria* (aFRR), *Regulación Terciaria* (mFRR) and *Reservas de Sustitución* (RR). More information on these markets can be found at [Martín-Crespo et al., 2025]. Despite the fact that the regulation allows it, the technical and economic conditions are not good enough for demand to actively take part in the balance markets. For this and other reasons, a mechanism has also emerged, called *Servicio de Respuesta Activa de la Demanda* (SRAD)¹⁵. The SRAD is a mechanism that improves the flexibility of electricity system operations during specific cases of resource scarcity, where demand must adjust to match generation¹⁶. This mechanism succeeded

¹⁴Instituto para la Diversificación y Ahorro de la Energía (IDAE). Proyecto SECH-SPAHOUSEC. Análisis del consumo energético del sector residencial en España. https://www.idae.es/uploads/documentos/documentos_Informe_SPAHOUSEC_ACC_f68291a3.pdf

¹⁵Gobierno de España. Real Decreto-ley 17/2022, de 20 de septiembre, por el que se adoptan medidas urgentes en el ámbito de la energía, en la aplicación del régimen retributivo a las instalaciones de cogeneración y se reduce temporalmente el tipo del Impuesto sobre el Valor Añadido aplicable a las entregas, importaciones y adquisiciones intracomunitarias de determinados combustibles. <https://www.boe.es/buscar/act.php?id=B0E-A-2022-15354>

¹⁶Gobierno de España. Resolución de 19 de octubre de 2023, de la Comisión Nacional de los Mercados y la Competencia, por la que se aprueba el nuevo procedimiento de operación eléctrico 7.5 sobre el servicio de respuesta activa de la demanda y se modifica el 14.4 “Derechos de cobro y obligaciones de pago por los servicios de ajuste del sistema” <https://www.boe.es/buscar/doc.php?id=B0E-A-2023-22497>

in shifting 609 MW of demand four different days¹⁷.

In addition, the implementation of a new capacity market in Spain is planned¹⁸. This capacity market would be similar to those in other European countries, such as France¹⁹. It is expected that the effective implementation of this capacity market will facilitate the utilisation of demand flexibility.

1.9.3. Independent aggregator

Thanks to aggregators, small and medium-sized consumers can participate in those electricity markets and mechanisms that are suitable for demand flexibility, as well as save costs and reduce technical and administrative difficulties.

In order to enable the operation of aggregators, the European Union, Directive (EU) 2019/944²⁰, defined an independent aggregator as ‘a market participant engaged in aggregation who is not affiliated to the customer’s supplier.’ This directive mandates that all European Union member states establish regulatory frameworks to facilitate the participation of independent aggregators in their electricity markets. In consequence, Spain has transposed the directive through Royal Decree-Law 23/2020²¹, in which the independent aggregator is recognized. Its importance is also reflected in the National Integrated Energy and Climate Plan²².

Despite these legislative advancements, challenges remain in fully implementing the role of independent aggregators in Spain^{23,24}. Issues such as compensation mechanisms between aggregators and suppliers (similar to the regulation in French markets²⁵), as well as the development of standardized procedures for market participation, are problems that are still to be solved.

¹⁷Red Eléctrica de España. Activación del servicio. <https://www.esios.ree.es/es/activaciones-del-servicio>

¹⁸Comisión Nacional de los Mercados y la Competencia. La CNMC publica el informe sobre el Proyecto de Orden por la que se crea un mercado de capacidad en el sistema eléctrico español. <https://www.cnmc.es/prensa/cnmc-mercado-capacidad-20210728>

¹⁹RTE. Participate in the capacity mechanism. <https://www.services-rte.com/en/learn-more-about-our-services/participate-in-the-capacity-mechanism.html>

²⁰European Union. Directive (EU) 2019/944 of the European Parliament and of the Council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU. <http://data.europa.eu/eli/dir/2019/944/oj>

²¹Gobierno de España. Real Decreto-ley 23/2020, de 20 de junio, por el que se aprueban medidas en materia de energía y en otros ámbitos para la reactivación económica. <https://www.boe.es/buscar/act.php?id=BOE-A-2020-6621>

²²Ministerio para la Transición Ecológica y el Reto Demográfico (MITECO). Plan Nacional Integrado de Energía y Clima Actualización 2023-2030. https://www.miteco.gob.es/content/dam/miteco/es/energia/files-1/pniec-2023-2030/PNIEC_2024_240924.pdf

²³Entra-Coalición. El agregador independiente en España. <https://entra-coalicion.com/wp-content/uploads/2025/01/El-Agregador-Independiente-en-Espana.pdf>

²⁴Entra-Coalición. El desarrollo del agregador independiente en España. <https://entra-coalicion.com/el-desarrollo-del-agregador-independiente-en-espana/>

²⁵RTE. NEBEF compensation payment. <https://www.services-rte.com/en/learn-more-about-our-services/nebef-compensation-payment.html>

CHAPTER 2

FLEXIBILITY MANAGEMENT WITH VIRTUAL BATTERIES OF THERMOSTATICALLY CONTROLLED LOADS: REAL TIME CONTROL SYSTEM AND POTENTIAL IN SPAIN

Martín-Crespo, A., Saludes-Rodil, S., & Baeyens, E. (2021). Flexibility Management with Virtual Batteries of Thermostatically Controlled Loads: Real-time Control System and Potential in Spain. *Energies*, 14(6), 1711. DOI: <https://doi.org/10.3390/en14061711>

This chapter corresponds to the first of the three peer-reviewed articles that form the core of this doctoral thesis. This work addresses the initial component of the overarching research objective: the design and validation of a real-time control system for managing the flexibility of aggregated electric loads. The article introduces the operational concept of VB built from TCLs, and proposes a priority-based control architecture that enables the provision of flexibility services to the power system. The methodology developed is directly aligned with the theoretical background presented in Chapters 2 and 3, particularly regarding the aggregated modeling of TCLs and the explicit control approaches. The case study focuses on the Spanish context, and the results obtained serve as the foundation for the subsequent works presented in Chapters 7 and 8, which address the grid impact and market participation of aggregated demand flexibility, respectively.

CHAPTER 3

AC/DC OPTIMAL POWER FLOW AND TECHNO-ECONOMIC ASSESSMENT FOR HYBRID MICROGRIDS: TIGON CEDER DEMONSTRATOR

Martín-Crespo, A., Hernández-Serrano, A., Izquierdo-Monge, Ó., Peña-Carro, P., Hernández-Jiménez, Á., Frechoso-Escudero, F., & Baeyens, E. (2024). AC/DC optimal power flow and techno-economic assessment for hybrid microgrids: TIGON CEDER demonstrator. *Frontiers in Energy Research*, 12, 1399114. DOI: <https://doi.org/10.3389/fenrg.2024.1399114>

This chapter presents the second article included in this thesis, which focuses on the real-time operation and long-term evaluation of hybrid microgrids. The study introduces a novel OPF methodology for AC/DC hybrid microgrids, incorporating both technical and economic performance indicators. This dual analysis contributes directly to Objective 3 of the thesis, which involves assessing the real-time and long-term grid impact of demand flexibility. The methodology is validated using the TIGON-CEDER demonstrator, a real-world laboratory used as case study that highlights the practical applicability of the proposed model. This chapter provides the necessary technical groundwork for Chapter 8, where the focus shifts toward the market participation of the flexible resources under study.

CHAPTER 4

AGGREGATED DEMAND FLEXIBILITY PREDICTION OF RESIDENTIAL THERMOSTATICALLY CONTROLLED LOADS AND PARTICIPATION IN ELECTRICITY BALANCE MARKETS

Martín-Crespo, A., Baeyens, E., Saludes-Rodil, S., & Frechoso-Escudero, F. (2025). Aggregated Demand Flexibility Prediction of Residential Thermostatically Controlled Loads and Participation in Electricity Balance Markets. *International Journal of Energy Research*, 2025(1), 8819201. DOI: <https://doi.org/10.1155/er/8819201>

This chapter contains the third and final peer-reviewed article of this thesis. It builds on the technical foundations established in the previous chapters by addressing the short-term forecasting of aggregated demand flexibility and its application in electricity balance markets. Here, a new probabilistic prediction method named Monte Carlo and extremum search by bisection (MC&ESB) is introduced to estimate the maximum up and down demand flexibility available from residential TCL aggregations. This method is designed to support market operations by enabling aggregators to reliably bid into balancing markets. The work directly supports Objectives 2 and 4 of the thesis by combining short-term planning of demand flexibility with a detailed examination of the Spanish electricity balance market framework, including bidding requirements and aggregator roles. It also offers insight into the conditions necessary for broader adoption of demand-side resources in market mechanisms.

CHAPTER 5

CONCLUSIONS AND FUTURE WORK

This section presents the conclusions drawn from the research done in this doctoral thesis. Additionally, it outlines potential directions for future work, emphasizing opportunities to build upon the findings and address remaining challenges in the demand flexibility field.

5.1. Conclusions

This doctoral thesis has explored the concept of demand flexibility and its integration into modern power systems. The main contributions of this work and their progress beyond the state of the art are listed below:

- A real-time controller to manage the flexibility of VBs formed by aggregations of TCLs. This new priority-based method allows to follow a flexible power control signal with an absolute error that never exceeds half the maximum rated power of the TCLs in the VB, provided the signal is feasible.
- A method for predicting the flexibility that can be provided by VBs formed by aggregations of TCLs based on Monte Carlo simulations and extremum search by bisection. This contribution fills a critical gap in demand flexibility prediction by delivering a reliable probabilistic confidence measure while remaining fully compatible with load controllers that respect user constraints and real-time load conditions.
- A method for calculating power flow for hybrid AC/DC microgrids based on optimisation. Building on recent AC and DC load flow literature, the proposed method extends the state of the art by incorporating a broader range of system elements and introducing different formulation.
- A techno-economic evaluation based on KPIs, which is specifically adapted to hybrid AC/DC microgrids.
- A study on the potential of residential demand flexibility in Spain, as well as the conditions for participation in electricity markets. This study is novel in the case of Spain and uses of the controller introduced in this thesis. A highlighted finding

is the estimation of the maximum flexible power available per home by Spanish climate zone in 2019, both charging and discharging: between 1.13 kW and 5.29 kW, and between 0.19 kW and 1.39 kW, respectively.

The results show the potential of demand flexibility to enhance the efficiency, reliability, and sustainability of electricity systems, facilitating the integration of renewable energies and benefiting consumers. Thanks to the study of the residential demand flexibility, citizens, policy makers and companies will be able to make the best decisions in order to achieve the fairest, most balanced and cost-effective use of it.

5.2. Results transfer and applicability in the power system

In addition to its scientific contributions, this doctoral thesis provides tools with strong potential for transfer to key stakeholders in the electricity sector, including distribution system operators, aggregators, retailers, and regulatory bodies. The following are specific proposals to facilitate the practical implementation and adoption of the developed solutions:

- Development of applicable tools: The controller and the MC&ESB prediction model could be further developed into functional software prototypes, designed to integrate with energy management platforms and comply with sector standards.
- Participation in real-world pilots: The algorithms and methodologies developed in this thesis could be validated through collaborations with several entities. This pilots would help to resolve technical challenges and demonstrate the operational feasibility of the approach.
- Technical implementation guide: A practical guide is recommended for aggregators and technicians, outlining steps for aggregation setup, TCL device configuration, controller integration, and evaluation using additional key performance indicators.
- Translation into economic and regulatory language: To support adoption by commercial and policy stakeholders, the thesis results should be presented through applied use cases that quantify economic benefits and provide comparisons with traditional storage technologies.
- Dissemination and institutional alignment: The results are fully aligned with national and European energy transition strategies. Therefore, it is proposed to present the outcomes in technical forums, sector platforms, and standardization committees at national and European Union levels.

These actions will ensure that the contributions of this thesis go beyond the academic domain, actively supporting the modernization of the power system, increasing its flexibility, and promoting broader demand-side participation.

5.3. Future work

The work presented in this doctoral thesis and the interaction with different companies, universities and research centres give rise to further research on demand flexibility. Future tasks include the following:

- Updating the study on the demand flexibility available in Spain presented in [Martín-Crespo et al., 2021] with the most current dwelling equipment data, more detailed technical characteristics of residential TCLs, and using the latest version of the priority-based controller presented in [Martín-Crespo et al., 2025].
- Assessing the integration into the electricity system with batteries and thermal energy storage (TES) to further increase the flexibility potential of TCLs.
- Studying the potential impact of demand flexibility on other markets, including the new capacity market in Spain.
- Improving the hybrid AC/DC power flow introduced in [Martín-Crespo et al., 2024] with the restrictions of the ratio between active and reactive power in the converters and the primary and secondary control equations.
- Enhancing the techno-economic assessment presented in [Martín-Crespo et al., 2024] by choosing the most appropriate KPIs and focusing on comparing different options for demand flexibility and energy storage.
- Undertaking a project in which a demand aggregator adopts MC&ESB as a prior step to its use in the electricity system. This would solve all the implementation problems that may arise: data architecture, runtimes, etc.

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