Universidad de Salamanca

Doctoral Thesis

Implementation of Demand Response Programs in Intelligent Energy Management Systems Based on Distributed Control System

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Thesis Type

This thesis has been conducted based on published papers in international journals and conferences by the author of the thesis during his Ph.D. work. The main parts of the results have been published in four international journals indexed in SJR [1], which are referred as "Core Publications" in this thesis. The rest of the publications used in this thesis are auxiliary to support the "Core Publications". The list of these four "Core Publications" is as follows:

1. Omid Abrishambaf, Pedro Faria, and Zita Vale, "Ramping of Demand Response Event with Deploying Distinct Programs by an Aggregator," Energies, vol. 13, no. 6, p. 1389, Mar. 2020. Doi: 10.3390/en13061389 (**Impact Factor is 2.707**);

2. Omid Abrishambaf, Fernando Lezama, Pedro Faria, and Zita Vale, "Towards transactive energy systems: An analysis on current trends," Energy Strategy Review, vol. 26, p. 100418, Nov. 2019. Doi: 10.1016/j.esr.2019.100418 (**Impact Factor is 3.895**);

3. Omid Abrishambaf, Pedro Faria, Zita Vale, and Juan Manuel Corchado, "Energy Scheduling Using Decision Trees and Emulation: Agriculture Irrigation with Run-of-the-River Hydroelectricity and a PV Case Study," Energies, vol. 12, no. 20, p. 3987, Oct. 2019. Doi: 10.3390/en12203987 (**Impact Factor is 2.707**);

4. Omid Abrishambaf, Pedro Faria, Luis Gomes, João Spínola, Zita Vale, and Juan Manuel Corchado, "Implementation of a Real-Time Microgrid Simulation Platform Based on Centralized and Distributed Management," Energies, vol. 10, no. 6, p. 806, Jun. 2017. Doi: 10.3390/en10060806 (**Impact Factor is 2.707**);

[1] Scientific Journal Rankings (SJR); https://www.scimagojr.com/journalrank.php

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Salamanca, September 09, 2020

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STATEMENT

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Porto, September 09, 2020

Pedro Nuno Silva Faria

For all those interested in science.

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Abstract

Over the last decades, the hierarchical and centrally controlled approach of existing power distribution is moving toward a smart power grid paradigm. Nowadays, consumers are becoming part of the solution in the power system operation problem, where the role of aggregator and demand response are being legalized in several countries. Therefore, technical features and economic aspects of the consumer's participation in demand response programs, namely through an aggregator, require intensive modeling and validation.

The main contribution of this thesis is modeling of an aggregator that is responsible for demand response programs and respective events implementation and validation by simulating, emulating, and performing actual control of devices. The proposed approach also considers both consumer participation in demand response events and the individual appliances used to obtain the required demand reduction.

In the scope of the main contribution, the DEEPDISEM platform, designed and developed in this thesis, provides support to the demand response implementation in the context of intelligent energy management. DEEPDISEM integrates realistic network models using real-time simulation, hardware-in-the-loop, several loads and distributed generation emulators, and real devices. The diversity of capabilities and features of DEEPDISEM make it a powerful tool to assay the demand response models by providing actual load management in the end-users. To run the realistic simulation, OP5600 is used as the real-time simulator machine to control laboratory emulators from the simulation environment and obtain realistic results. Also, DEEPDISEM utilizes several distributed programmable logic controllers and single-board computers for decentralized management, running linear programming, and intelligent approaches like decision trees and rule-based decisions.

Besides this, several key contributions are gathered together to accomplish and support the core contribution. These key contributions are classified in two main categories: a) power and energy system, and b) computer science. The key contributions related to the power and energy systems include demand response programs definition, resource aggregation, demand response gathering, distributed generation and demand response scheduling, renewables integration, local markets and communities, and irrigation management. The key contributions related to computer science consist of distributed control and intelligent applications. All these key contributions in both categories are validated through Supervisory Control And Data Acquisition systems, real-time simulation, laboratory emulation, and case studies.

The presented approach in this thesis is supported through various developed methods, aiming at practical features of demand response implementation and validation through a diversity of case studies, both simulated and comprising actual physical equipment. Various models, decision-making methods, and applications, from an isolated farm to a large aggregator (i.e., 220 consumers and 86 producers) with several types of end-users, have been tested using the DEEPDISEM platform. The results of DEEPDISEM show significant energy savings and cost reductions for both the aggregator and the end-user. Also, the results demonstrate the actual impact of demand response implementation through actuation in the actual devices. Thus, the feasibility of field implementation and widespread of innovative demand response models, which used to be mostly done by simulation models, disregarding the actual impact in the physical devices, was achieved

Keywords: Aggregator, Demand Response, Energy Resources Scheduling, Laboratory Emulation, Real-Time Simulation, Distributed Control, Decision Tree.

Resumen (In Spanish)

En las últimas décadas, el enfoque jerárquico y controlado de forma centralizada en la distribución de energía existente se está moviendo hacia el paradigma de red eléctrica inteligente. En la actualidad, los consumidores se están convirtiendo en parte de la solución del problema de funcionamiento del sistema eléctrico, donde el papel del agregador y la respuesta a la demanda se están legalizando en varios países. Por lo tanto, las características técnicas y los aspectos económicos de la participación de los consumidores en los programas de respuesta a la demanda a través de un agregador requieren modelizaciones y validaciones intensivas.

La contribución más relevante de este trabajo es el modelado de un agregador que es responsable de programas de respuesta a la demanda y de la implementación de los respectivos eventos y validación mediante la simulación, la emulación y la realización de control real de los dispositivos. El enfoque propuesto también tiene en cuenta tanto la participación de los consumidores en los eventos de respuesta a la demanda como los respectivos aparatos que se utilizan para obtener la reducción de la demanda requerida.

En el ámbito de la contribución principal, la plataforma DEEPDISEM, diseñada y desarrollada en esta tesis, proporciona apoyo a la implementación de respuesta a la demanda en el contexto de la gestión inteligente de la energía. DEEPDISEM integra modelos de red realistas utilizando simulación en tiempo real, hardware especializado, emuladores de generación distribuida y dispositivos comerciales. La diversidad de capacidades y características de DEEPDISEM lo convierten en una potente herramienta para ensayar los modelos de respuesta a la demanda, proporcionando una gestión de carga de la demanda en los usuarios finales. Para ejecutar una simulación realista se utiliza el OP5600 como simulador en tiempo real para controlar los emuladores de laboratorio desde el entorno de simulación y obtener resultados creibles. Además, DEEPDISEM utiliza varios PLCs distribuidos y ordenadores convencionales, para la gestión descentralizada, la ejecución de modelos inteligentes creados con árboles de decisión y algoritmos de decisiones basadas en reglas.

Además de esto, varias contribuciones clave se reúnen para lograr y apoyar la contribución principal. Estas contribuciones clave son clasificadas en dos categorías principales: a) potencia y sistema de energía, y b) ciencias computacionales. Las contribuciones clave relacionadas con los sistemas de potencia y energía incluyen la definición de programas de respuesta a la demanda, agregación de recursos, recopilación de respuesta a la demanda, generación distribuida y programación de respuesta a la demanda, integración de energías renovables, mercados y comunidades locales y gestión del riego. Las contribuciones clave relacionadas con las ciencias computacionales consisten en el control distribuido y las aplicaciones inteligentes. Todas estas contribuciones clave en ambas categorías se validan a través de sistemas de control de supervisión y adquisición de datos, simulación en tiempo real, emulación en laboratorio y casos de estudio.

El enfoque presentado en esta tesis está respaldado a través de varios métodos desarrollados, con el objetivo de características prácticas de implementación y validación de la respuesta a la demanda a través de una diversidad de estudios de casos, tanto simulados como otros que comprenden equipos físicos reales. Se han probado varios modelos, métodos de toma de decisiones y aplicaciones, desde una granja aislada hasta un gran agregador (es decir, 220 consumidores y 86 productores) con varios tipos de usuarios finales, utilizando la plataforma DEEPDISEM. Los resultados de DEEPDISEM muestran reducciones significativas de energía y costos tanto en los modelos de agregación como para los usuarios finales. Además, los resultados demuestran el impacto real de la implementación de respuesta a la demanda a través de acciones en los dispositivos reales. Así, los resultados obtenidos validaron la viabilidad de su implementación en el mundo real y la generalización de modelos innovadores de respuesta a la demanda, lo que hasta ahora solo se estimaba mediante modelos de simulación, sin tener en cuenta el impacto real en los dispositivos físicos.

Palabras clave: Agregador, Arboles de decisión, Respuesta a la demanda, Control distribuido, Programación de recursos energéticos, Emulación de laboratorio, Simulación en tiempo real.

Index

List of Figures

List of Tables

List of Abbreviations

BRP	Balance Responsible Party
CS	Computer Science
CSP	Curtailment Service Provider
DER	Distributed Energy Resource
DG	Distributed Generation
DLC	Direct Load Control
DR	Demand Response
DSO	Distribution System Operator
DT	Decision Tree
HEMS	Home Energy Management System
HIL	Hardware-In-the-Loop
IoT	Internet-of-Things
ISO	Independent System Operator
P2P	Peer-to-Peer
PES	Power and Energy System
PLC	Programmable Logic Controller
PV	Photovoltaic
RER	Renewable Energy Resource
RTP	Real-Time Pricing
SCADA	Supervisory Control And Data Acquisition
TE	Transactive Energy
VPP	Virtual Power Player

Chapter 1

Introduction

1 Introduction

This chapter presents an introductory discussion about the motivation of this thesis in section 1.1. Then, the objectives of the thesis are outlined in section 1.2, which are related to the aspects identified in section 1.1. The contributions of the thesis, and the related publications are provided in section 1.3. The research projects that are in the scope of this thesis are listed in section 1.4. Finally, the outline and organization of the thesis are exposed in section 1.5.

1.1 Motivation

Over the last decades, the approach of centrally-control power distribution is moving toward a smart power grid paradigm in which the unforeseen peaks of distributed local energy production and uncertainty of renewables can be appropriately managed [1]. The increase of renewables and prosumers [2] as means of electricity production is expected to rise in years to come up to around 50% by 2024 comparing with 2019 [3] and up to two-thirds of energy consumption by 2050 [4].

Smart grids are intelligent electrical networks employed for enhancing critical features of the current power system, such as flexibility, reliability, sustainability, efficiency, etc. by making the grid controllable, automated, and fully integrated [5]. In such a new paradigm, the concepts of Demand Response (DR) programs, aggregators, Transactive Energy (TE) systems are widely discussed in the scientific and research societies, all with the same purpose, which is balancing the network in terms of consumption and generation [6]. The use of Distributed Generation (DG), including Renewable Energy Resource (RER), is essential in the smart grids and microgrids implementation [7]. These impacts of resources can be fully integrated with DR programs and aggregating concepts [8].

DR programs can bring flexibility to the grid operation by paying incentives to electricity consumers to alter their consumption profiles [9]–[11].

DR programs consist of two main types, incentive-based and price-based [12]. Each has its specifications that are applicable depending on technical or economic reasons related to the electricity operation. Furthermore, aggregators can enable all small and medium scale DR and DG resources to have active participation in the local electricity markets and energy communities [13]. Generally, electricity markets consist of a market operator that manages the financial transactions and implements market rules. Also, there is an independent system operator (ISO) in the electricity markets to manages the network, including sellers and buyers who negotiate in the market [14]. In this context, local markets and energy communities improve the social acceptance and motivation of the end-users to participate in the DR programs [15]. However, this participation requires end-users to be equipped with energy management systems to perform decision-making distributed and locally [16], [17].

Intelligent energy management systems (namely smart grid) provide a basis for implementing DR programs and aggregating models. Several requirements are essential in this context, such as two-way communication, information and communication technologies, intelligent and remote supervision, advanced metering infrastructure, and smart metering [18]. Peer-to-Peer (P2P) energy management systems can also be applied using intelligent devices in which each device has its own decision and objective [19].

Both DR and aggregation concepts open new opportunities in the power network regarding the optimization of power flows, the stability of the grid, and energy efficiency. Simultaneously, distributed resources used for these concepts are intermittent (e.g., in the case of renewables) and nonuniformly deployed, which possess new challenges to be faced in the management of resources [20]. Therefore, it is required to integrated solutions that support a set of related fields, including DR programs, consumer aggregation, communications, and resource optimization [21]. This integration leads to take full advantage of consumer´s demand flexibility to improve the efficiency of the whole power distribution network [22].

The power system management can be tackled through centralized and decentralized approaches, each with its advantages and disadvantages [23]. Therefore, each methodology should be well tested and validated through several realistic case studies to identify its strengths and weaknesses. Besides this, both scientific and practical features of any model should be scrutinized, learning from past experiences to estimate and prevent future issues. To do this, adequate realistic models and laboratory tools are essential to test and verify the functionalities of any developed model. As an example, in [24], a campus network has been employed as a case study for validating demand-responsive air conditioners; and in [25], 47 commercial buildings were used to evaluate several machine learning methods (namely artificial neural networks) in the aggregated level to forecast energy consumption. However, research works similar to [24] and [25] are few in the current literature. Therefore, the lack of a model´s implementation in real field and case studies is considered the main motivation to focus on and develop this thesis. In this context, distributed control models and intelligent decision-making methodologies are validated in this work through real-time simulation, and laboratory emulation approaches.

1.2 Objectives

Demand response programs are a feature in the upcoming distribution network to connect low carbon technologies to reduce the reinforcement of infrastructure structure [26]. By promoting DR programs, all players, from system operators to the end-users, can benefit from these advantages. Besides, the aggregator as a third-party entity enables all small and medium scale resources to participate in DR programs and having an active role in the electricity market negotiations and energy communities.

Many interesting models and research works can be found in the literature focusing on the aggregation concept and implementation of DR programs in the power distribution network. However, models have been mostly tested and verified through numerical case studies and computational models. Few of them moved towards testing the model on real field and laboratory infrastructures. Therefore, this gap brings out the need for:

- Conceiving and developing innovative DR models in aggregation models;
- Conceiving and developing simulation models for DR and DG aggregator;

- Conceiving and developing simulation, emulation, and device control models for players operating under the management of the aggregator;
- Developing a distributed control system for intelligent energy management;
- Designing a flexible energy management system compatible with computational intelligence approaches;
- Assessing and validating the developed DR, simulation, emulation, and control models through realistic case studies.

The role of aggregators in DR implementation has been legalized in several countries. This shows the need for a decision support tool to validate the concepts of DR and aggregator model. To address this gap, considering the objectives pointed out above, the research question of this thesis is:

> *How can DR programs be accomplished at the building (house, office, etc.) level with the support of aggregator considering the uncertainty of consumers' response and computational intelligence approaches?*

To answer this research question, a survey on the literature has been carried out in two contexts of Power and Energy System (PES), and Computer Science (CS). In PES survey, the requirements for DR implementation in demand-side; aggregator performance during ramp period and DR event; the role of aggregator in TE systems and local electricity markets; and automatic load control in residential, commercial, and agriculture consumers, have been pointed out. A survey on application of intelligent systems and computational intelligence approaches has been done in the scope of CS analysis. From these PES and CS surveys, it has been realized that there is a need for designing a decision support platform to address the implementation of DR programs from concept to a realistic environment using computational intelligence approaches.

1.3 Contributions and Publications

The work in this thesis focuses on addressing the identified barriers, which are mainly the lack of actual models to test and validate the aggregation features and DR programs. Consequently, a decision support platform has been designed and developed in this thesis to technically validate the use of DR programs by an aggregator. For this purpose, Demand rEsponse Programs DIstributed control System for intelligent Energy Management (DEEPDISEM) has been designed and developed in the scope of this thesis. Despite a diversity of decision-making approaches addressed in this work and technical capabilities of DEEPDISEM, the core contribution is approaching of an aggregator that is responsible for DR programs and respective events implementation by simulating, emulating, and performing actual control of devices. The proposed approach considers both consumer participation in DR events and the respective appliances used to obtain the required demand reduction. A more detailed description of simulated and emulated approaches will be presented in section 3.2. Besides the proposed core contribution of this thesis, the PES contributions concerning specific objectives are as follow:

- Demand Response Programs Definition – introducing various types of DR programs, including incentive-based as well as price-based, by the characterization of each program;

- Resources Aggregation – defining aggregation approaches to implement clustering of consumers, obtaining groups for consumers to participate in DR programs;

- Demand Response Gathering – proposing methodologies that the aggregator employs during the ramp period before the DR event, to reach the desire reduction;

- Distributed Generation and Demand Response Scheduling – developing optimization algorithms for optimal use of DG and DR resources to minimize the operational costs of aggregator;

- Renewables Integration – addressing how small and medium RERs size in the demand side can be integrated and associated with an aggregator as flexibility resources;

- Local Markets/Communities – addressing the concepts of local electricity markets for aggregator models in the scope of TE systems and P2P energy trading;

- Irrigation Management – designing and implementing optimal energy scheduling approaches for an agriculture irrigation system to be used as an asset for DR program implementation.

In addition, CS contributions concerning specific objectives are as follow:

- Distributed Control – identifying opportunities to integrate distributed control approaches for an aggregator in network management strategies, such as DR program implementation and energy scheduling;
- Intelligent Applications – utilizing several intelligent approaches in different levels of distribution networks, namely clustering methods in aggregator level and decision tree approaches for energy scheduling in end-users.

While the contributions mentioned above focused on designing and developing in both PES and CS contexts separately, the following contributions mainly aim at models/methods implementation and validation on both PES and CS contexts at the same time:

- SCADA Systems – designing and implementing automation infrastructures in the scope of the Supervisory Control And Data Acquisition (SCADA) system in the end-users, and using such a system as a DR facility in demand-side;
- Real-Time Simulation – developing and integrating network simulation models for an aggregator, in a real-time simulator, and validating consumers and producers behaviors using actual consumption/generation profiles adapted from Hardware-In-the-Loop (HIL) connected devices;
- Laboratory Emulation – employing various types of consumer and producer emulators for laboratory validation under network instabilities, voltage and frequency variations;
- Case Studies – design and analyze a diversity of case studies to assess the proposed models and approaches, and demonstrate their effectiveness for accomplishing the core contribution of this thesis.

The results of the developed work in this thesis have been published in thirty scientific papers in international journals and conference proceedings. From these publications, four most relevant papers have been selected as “Core Publications”, and eight more papers have been selected as “Other Publications” to support the contents of the thesis. In these twelve papers, all as first author, the four “Core Publication” have been published in international journal indexed at SJR ([27],[28],[29], and [30]), and the eight “Other Publication” have been published in international journals without impact factor ([31], and [32]) and relevant international conference proceedings ([33], [34], [35], [36], [37], and [38]).

Full versions of all “Core Publications” and “Other Publications” are available in Appendix A. Besides these 12 papers that present direct contributions to this thesis, several others have been published during the development of the Ph.D. work in collaboration with other authors. The scientific relations of “Core Publications” with the contribution of this thesis will be discussed in Section 3.1. Each key contribution listed above will be described in detail in chapter 3. Furthermore, the relation of each published paper in this thesis with each of these key contributions will be explored.

1.4 Related Projects

The findings and outcomes achieved in the scope of this thesis have contributed to the objectives and results of various research projects under FCT (Fundação para a Ciência e a Tecnologia), H2020 (Horizon 2020 – European Commission Research and Innovation programme), ITEA (EUREKA – Cluster programme supporting innovative, industry-driven, pre-competitive R&D projects in the area of Software-intensive Systems & Services), QREN (Quadro de Referência Estratégico Nacional) and P2020 (Portugal 2020), with the participation of Research Group on Intelligent Engineering and Computing for Advanced Innovation and Development (GECAD, www.gecad.isep.ipp.pt). These research projects include:

- DREAM-GO – Enabling Demand Response for short and real-time Efficient And Market Based smart Grid Operation – An intelligent and real-time simulation approach, H2020-PEOPLE – RISE, reference no. 641794 – (http://dream-go.ipp.pt/). Thesis contribution: real-time simulation, distributed generation and demand response scheduling;
- DOMINOES – Smart distribution grid: a market-driven approach for the next generation of advanced operation models and services, H2020, reference no. 771066 – (http://dominoesproject.eu/). Thesis contribution: local markets/communities;

- Eco Rural IoT – Application of techniques and intelligent algorithms aimed to reduce the consumption of power and water in a mixed farming environment, H2020 Tetramax, reference no. 761349 – (http://www.gecad.isep.ipp.pt/EcoRuralIot/). Thesis contribution: irrigation management, intelligent applications, laboratory emulation;

- NetEfficity – Implementing an intelligent and decentralized management system for energy resources and consumers, P2020, reference no. UID/EEA/00760/2013 – (http://community-s.vps.energy/). Thesis contribution: real-time simulation, laboratory emulation, distributed control;

- COLORS – Contextual load flexibility remuneration strategies, FCT, reference no. PTDC/EEI-EEE/28967/2017 – (http://www.gecad.isep.ipp.pt/COLORS/). Thesis contribution: demand response programs definition, demand response gathering;

- AVIGAE – An intelligent virtual assistant for managing active energy in buildings, P2020, reference no. UID/EEA/00760/2013 – (http://avigae.vps.energy/). Thesis contribution: resources aggregation, renewables integration, laboratory emulation;

- GREEDi – Intelligent and secure platform for energy resources management in large-scale buildings, P2020, reference no. P2020-33/SI/2015-17822 – (http://greedi.ipbrick.com/). Thesis contribution: intelligent application, SCADA systems.

1.5 Thesis Outline

This thesis includes four main chapters. After this introductory chapter, chapter 2 discusses a review on the state-of-the-art with a specific focus on the current trend of DR programs and the aggregator role in electricity distribution.

After then, chapter 3 provides a list of key contributions of the thesis and demonstrates how these key contributions accomplish the core contribution of the thesis. Moreover, the relation and role of the published papers in each of these key contributions are discussed.

In the final stage, chapter 4 exposes the main outcomes and findings achieved through this thesis. Also, it provides several paths for future research worth to be explored.

Chapter 2

Background

2 Background

The ascending trend of electricity demand in the last decades causes a peak in greenhouse gas emissions [39]. Using DG, especially RERs, contributes to overcoming this issue. Although these resources make networks unstable as they have variations in generation over time. Thus, some strategic actions, like DR programs and energy resource scheduling, are required, which can be implemented by a third-party entity, such as an aggregator. The concepts of DR programs and aggregators, the integration of renewable resources in DR programs, decentralized network management strategies, and flexibility capabilities in the demand side are the topics discussed in this chapter.

2.1 Demand Response Concepts

The new and advanced technologies promote a revolution in the power system, aiming to enhance the wholesale market efficiency [40]. Interactive participation of the demand side, such as residential consumers, has a key role in this context [41]. DR is one of the concepts presented in these technologies that begins to be widely used nowadays [42]. There are various definitions in the literature for DR programs. While each definition has its strengths and weak points, the most commonly accepted one is defined by the Federal Energy Regulatory Commission (FERC) [43] as:

"Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

According to the definition mentioned above, DR can be described as the reaction of electricity consumers to the price signals considered as incentives to reduce/modify the electricity use pattern. There are two types of DR programs: price-based and incentive-based [44]. The price-based is a type of DR where time-varying electricity prices or network tariffs are considered.

In this condition, the consumers react to the DR event by modifying their consumption patterns depending on the electricity prices at the moment, considering their restrictions and preferences [45]. Time-of-use, critical peak pricing and real-time pricing are three sub-categories of this type of DR program [32]. The Incentive-based type considers that incentive payments are provided by the DR aggregator (or energy retailer or Distribution System Operator–DSO etc.), in exchange for the modification of the consumer's consumption profile. This means that the consumers who can be flexible in their consumption can reduce their energy costs [46]. Direct load control, emergency demand response service, capacity market programs, interruptible demand response programs, and demand bidding/buyback are the sub-categories of incentive-based DR programs [47].

The timescale and objectives of DR programs, from long-term to real-time, are shown in Figure 2.1. In fact, short and real-time DR programs are more common comparing to other programs. The reason is they are usually implemented for improving or maintaining power quality as well as security of the power distribution network (e.g., voltage and frequency stability issues) [48]. In this context, incentive-based DR programs are mostly implemented in short-term to real-time timescale, especially less than 15 min [46].

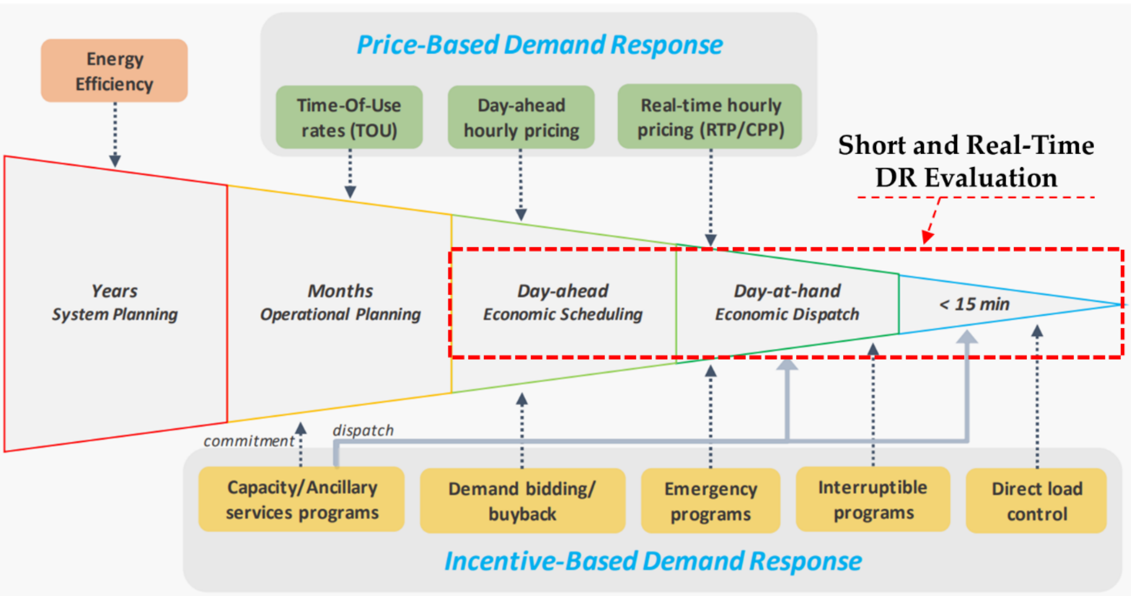

Figure 2.1. The timescale of DR implementation (Adapted from [49]).

Each program has its specifications that are applicable depending on technical or economic reasons. For example, the ERCOT market in Texas utilizes emergency DR service to maintain network stability in emergency conditions to reduce power outages. In this market, emergency DR service participants can provide DR reduction within a 10 to 30 min ramp period in advance to the event [50].

To automatically execute the DR event on the end-user side, basic automation is required [26]. This raises several issues, such as what is the framework for DR data transmission from the promoting entities to the end-user? Or is there any bidirectional communication standard? Open ADR is a comprehensive and complete solution for these questions. It is referred to as a standard method for the transmission of DR events data between the utility operators, aggregators, and consumers [51]. In this way, Open ADR offers a data transmission framework for DR, allowing communication between the promoting entity (Virtual Top Node – VTN) and the consumer's end-node (Virtual End Node – VEN). The end-node device can be an energy management system or an event receiver [52], [53]. Open ADR is built upon the convenience of ADR implementation in the demand side [53]. Moreover, the participant response to the DR requests is approved or not by the customer; thus, they can individually decide to participate in the DR event or not [54], [55]. In this context, Open ADR is a useful approach for the interaction between nodes, such as the consumer and the DR provider, since it provides a communication standard for the application of flexibility programs [56].

2.2 Resources Aggregation

While the smart grids concepts are integrated into the power distribution network, DR and DG resources intend to have active participation in the network management and electricity markets [57]. If the reduction or generation capacity of DR and DG resources are not significant, the network management would be more difficult for system operators. Therefore, the need for a third party, namely an aggregator, is evident to gather all these small-scale DR and DG resources [58]. According to the surveyed references [36], [59], [60], the minimum reduction capacity for a consumer who intends to have an active role in the electricity market negotiations, is various depending on the DR type, typically from a few kilowatts to megawatts. In other words, this makes small scale consumers almost incapable to directly participate in electricity markets

[61], [62]. To overcome this barrier, aggregator [37], [63], Curtailment Service Provider (CSP) [64], [65], and Virtual Power Player (VPP) [30], [66], are third-party entities between the upstream and downstream sides of the network. In fact, these entities aggregate small and medium scales DR and DG resources and provide them as a unique resource in the electricity market negotiations [67]. This simplifies the process of energy negotiation in electricity markets [68].

Moreover, if other players, such as Balance Responsible Party (BRP), exist, the role of aggregator would be more efficient [69]. Nowadays, several European countries employ the aggregator concept for electricity consumers [70]. As an example, France accepted aggregated loads in every ancillary service program, and BRPs and aggregators have been reorganized based on [71], [72], performing electricity market negotiations. To calculate compensation costs by the aggregator for BRP, the aggregator has no direct interaction with BRP; however, the aggregator establishes a contract with an electricity supplier to have flexibility services.

In fact, an aggregator is accountable for both DG, especially RERs, and DR programs. The role of aggregator in terms of DR programs is to gather all electricity consumers who can participate in DR programs and present them as one [73]. Therefore, it can be considered as a flexible player [70]. Thus, the aggregator can establish bidirectional contracts with end-users for DR programs to manage consumption resources, and consequently, to have flexibility in electricity market negotiations. To manage the generation of end-users, which are considered as prosumer (a consumer who can produce electricity), the aggregator can play the role of VPP to minimize the operational costs and fair remuneration of resources [11], coordinate the Distributed Energy Resource (DER) under microgrid paradigm [74], and to replace conventional power plants in the future power system [75].

The aggregator can directly be in touch with the demand-side, coordinating the enrolled customers, including consumers and prosumers, and assigning the costs and remunerations among the customers [76], [77]. To implement this concept, an energy management system with several layers can be utilized in the community of enrolled customers [78]. The base layer of this energy management system is the measurement devices, which measure the real-time state of the consumption and generation. In the top layer of the energy management system, the aggregator can compute the coordination signals, such as power references or price signals. Also, there is a communication layer between the base and the top layers of the energy management system, which is responsible for transmitting the measured data from the users to the aggregator as well as moving the coordination signals from the aggregator to the customers [79].

By a simple look on the current trends of aggregator models, many papers and research projects can be found that is focused on the concepts of aggregator, as its role is being legalized in several European countries (e.g., France, Finland, Austria, Denmark, etc.) [49]. Ramping of DR event and the way that aggregator deals with this period before the DR event is deployed is a critical discussion in terms of DR implementation. Incentive calculations and payments between aggregator and DR participants during the ramp period require information exchange between aggregator and network operators (e.g., ISO) during the ramp period. Several other aspects, such as remuneration using actual profiles in ramp period [27], devices response time, and the gaps between the real and expected results [36] need to be discussed before the models move from the theoretical phase towards the implementation level.

2.3 Demand Response and Renewable Resources

Electrical energy demand has significantly increased in the last decades. This has led to a massive peak of greenhouse gas emissions to supply the required demand [39]. In the past decades, fossil fuels were the raw materials for electricity production [80]. However, nowadays, several low carbon technologies, including RERs, have been utilized to produce electricity [81]. The large-scale integration of RERs in the power system is probably the main challenge that must be overcome in the near future [82]. According to the Directives of European Union (2009/28/EC, 2012/27/EU, and 2019/944/EU), it has been guaranteed that RERs will supply 27% of the energy consumption in all European countries by 2030 [83]. In the United States, 15% of the electricity generation was produced by RERs in 2016 [84], and 17% in 2017 [85]. This shows in countries over the world provided a green light for massive investment on RERs, as these are considered as a clean, sustainable, and zero-emission resource of energy. The generation variation in RERs is a topic on focus in many research works since these have a key role in nowadays power system [86], [87]. By appropriate management of the consumption in the demand side, energy efficiency and optimal energy usage should be addressed [88]. From the system operators (i.e., ISOs or DSOs) standpoint, high penetration of RERs by their intermittent nature may bring network management issues [89], [90]. Although, from the electricity customer's standpoint, RERs are interesting since they can reduce electricity bills by consuming their own generated energy [91].

DG and RERs are considered as one of the key features of smart grids and microgrids implementation [7]. To overcome the high penetration intermittent RERs in the smart grids, DR programs are considered as a solution to mitigate the network fluctuations [8] and improve the safety and efficiency of the network [92]. DR programs provide an approach to use the surplus of produced energy by RERs [93]. Through an alternative method, the high consumption periods can be shifted to the high generation periods of RERs. Therefore, not only the network congestions are reduced, but also the local consumptions are being supplied by the local energy resources leading to an increase in the efficiency of the entire power system [94]. In other words, a DR program is considered as an alternative and a flexible resource for supporting the uncertainty of generation rates in RERs.

2.4 Intelligent Systems for Demand Response

Intelligent systems and computational intelligence approaches provide a diversity of prospects for the future in the context of an intelligent electric power grid [95]. Indeed, computational intelligence techniques, such as Internet-of-Things (IoT) for decision-making in the power system, are relevant research topics [96], [97]. The use of computational intelligence in the smart grids can quickly improve the efficiency of the network, while the penetration rate of RERs is being increased [98]. In other words, intelligent systems provide an excellent opportunity for addressing decision-making, as involved players can achieve satisfying results through fast and cost-effective computational techniques [99]. These new concepts, such as IoT, address the necessities for integrating new optimization techniques, sustainable energy systems, distributed intelligence, and new neural networks to overcome complexity and stochastics issues [100]. This can be done through distributed computing and solving the network problems in the smaller nodal, similar to the performance of multi-agent systems [101]. The consideration of several nodes in the multi-agent systems makes each agent autonomous and responsible for its actions represented by a given consumer [102].

Furthermore, various approaches, such as artificial neural network, fuzzy logic modeling, and evolutionary algorithms [103], [104], accelerate forecasting services, optimization methods, distributed control approaches, data-mining techniques [105], and cloud-based computing [106]. All these features can help to implement a dynamic, adaptive, and efficient power system [103].

In fact, forecasting services are an essential point in the real-time operation of intelligent power systems [107]. Those services enable different players to forecast various network parameters, such as energy consumption patterns and predict the electricity cost to make the most efficient and cost-effective decision to minimize the operational costs [108], [109]. Besides, cloud-based computing and IoT technologies [110] provide computational resources, which can be used for energy and cost-saving, scalability of the power system, and flexibility of the entire power system [111].

The idea of DR program implementation makes the role of an intelligent system more important than before. In fact, the traditional approaches, where a central controller gathers all data and manages the related resources, will be infeasible in the near future [112]. Fully distributed DR programs are becoming more popular in the context of intelligent systems [113].

The integration of smart buildings into grid management is a key point of the intelligent power system, as it facilitates the implementation of DR programs using computational intelligence approaches [103], [114]. Artificial intelligence techniques, such as a generic algorithm, can be used in this context for real-time load management and solve optimization problems in the smart buildings [115]. Furthermore, by combining computational intelligence and blockchain methods, the DR programs can be integrated with various intelligent management approaches on different sectors (i.e., DSO, local markets, and end-users) of smart grids [116].

2.5 Decentralized Energy Management

To control and manage the resources available in a network, two main methods are possible: centralized and distributed control. In the centralized control method, a powerful central control unit is responsible for managing and controlling all network´s resources, where communication between this unit and every single component of the network is required [117]. In the distributed control method, the decisions can take place locally by each network component [118]. Both methods have several advantages and disadvantages. For example, the centralized control requires high initial investments and needs a widespread scheming; however, it provides better efficiency. In the meantime, the centralized method can be implemented step by step from the bottom levels to the top levels [119]. In the centralized management, a central controller engages with solving several mathematical problems mainly focused on an optimal solution for minimizing the operational costs of the entire power system [120]. This is done through the defined objectives for managing the energy resources and controllable loads [121]. The work presented in [117] is an example of centralized management, which provides an optimization algorithm for optimal scheduling in a centralized energy management system of a microgrid.

Currently, the centralized and hierarchical structure of the power system is moving towards decentralized and distributed. Decentralized energy management systems can be a local microgrid or an aggregator, capable of having local control on their electricity consumption and generation resources aiming at self-supply with minimum or no dependence on the main grid [122], [123]. In the decentralized energy management solution, optimization and management are performed fully distributed, meaning that there is no central unit [124]. The level of decentralization is defined by the intelligence of local controller units, which can be utilized just to execute commands and orders from upstream controller units or make their own decisions. This means decentralization of the system is related to the flexible operation, the intelligence level of the local controllers, and the capability of avoiding failures in the entire system when a single point fails [125].

The concepts of decentralized energy management systems are mostly discussed and surveyed in the scope of TE systems. Indeed, the TE system is defined as the economic and control methodologies for managing the rate of consumption and generation resources and the energy trading within a power distribution network based on market mechanisms [126]. TE approaches bring opportunities for aggregators or microgrids to improve their economic performance and aiding the reliability of the entire distribution system [127]. Integrating TE systems into the bulk power systems and DSO network can also enable microgrids and aggregators to improve the mutual benefits, such as financial profits, between themselves and the power system by providing the flexibility of the available resources [128].

In a decentralized TE network, also known as transactive control [129], the management unit relinquishes solving complex optimization formulations. However, it provides optimal operational solutions by involving all network consumption and generation resources in a local energy auction bidding process. In a microgrid or an aggregator using transactive control, energy trading occurs between the consumers and energy resources in the local marketplace [130].

Besides this, layered decentralized optimization is another vision to manage a TE-based network in a distributed and decentralized way. In this approach, the optimization is performed at any layer of the system, and it only involves visibility to the interface points of upstream and downstream layers, and there is no need to be aware of the nature of those layers [131]. In a decentralized management scenario, the failure of one node will affect only a localized part of the system, which can be identified using P2P communications with other sections (e.g., agents), while the entire network will not be affected [132]. In the decentralized energy trading methodologies for both microgrids and aggregators, the system operator may witness the challenge, determining a reasonable pricing scheme for all resources in a way that all participants could take financial benefits. This shows the need for a comprehensive study on designing dynamic pricing approaches to optimize financial benefits for all energy resources (e.g., RERs), as the methodologies presented in [133]. According to the literature review in [28], in the scope of TE systems and decentralized energy management approaches, centralized aggregator methods have been surveyed through some articles. Aggregators using a decentralized TE system for the management of resources are not well investigated, as the issues and challenges should be identified by further research.

2.6 Energy Flexibility in Agriculture Sector

The increasing of the world population has led to more incredible energy and food demands. According to [134], the population will continue to soar, reaching somewhere around 10 billion people by 2050. It is also expected that by 2035, global energy consumption is going to rise by up to 50% of the current rate [135]. The predicted consumption rise is mostly attributed to the agriculture sector and the food supply chain. Food and energy are the basic needs of every society. The growing demand for both makes evident the importance of the agriculture sector [136]. In fact, agriculture is the very backbone of every country. Today's agricultural practices still lack energy optimization measures, leading to high energy consumption [137].

The agriculture industry is considered to be the second-largest emitter of greenhouse gases [138]. This means that the agriculture sector can contribute to reducing total greenhouse gas emissions by adopting a series of measures, such as exchanging fossil fuels for RERs [139]. More specifically, in the agriculture industry, the energy demand for tactical services, namely, irrigation and water pumping, can be supplied by RERs instead of non-renewable sources [140]. The agricultural sector is ideal for implementing all types of solutions involving RERs [141] because farms are located in rural areas where such resources can be easily implemented. Hydro, wind, and solar energy can be used to produce electricity for agricultural purposes, enabling farmers to become mostly independent of the utility grid and to reduce electricity costs.

The use of smart technologies in the agriculture sector has already attracted a lot of attention. In fact, the use of intelligent systems is not only limited to the electrical grid. Smart solutions can be designed exclusively for the agricultural sector, and this line of research has led to the emergence of a new concept, called smart agriculture or smart farming [137]. This concept also involves the application of the IoT in agriculture [142], [143]. The ability to combine IoT and other technological paradigms, namely forecasting services [144], has opened many new possibilities in agriculture.

Another important aspect of agriculture is reducing costs; thus, energy production forecasting [145] and energy demand prediction [146] is also essential to minimize energy costs in smart agriculture models. Such models, in other words, enable electricity consumers and prosumers in the agriculture sector to participate in network management scenarios, such as DR programs [37].

A survey in [147] reveals that much research has been conducted on smart agriculture systems using IoT and wireless sensor networks. Thus, it is an interesting subject undergoing intense study. However, what if there is no internet and mobile network access where the farm is located? Since farms are often situated in remote areas, it is very common for them to lack access to the internet and high-performance computing machines. Therefore, smart agricultural systems should be capable of operating in offline mode without using any external server/machine or internet access. This shows the need for developing an offline agriculture system that can optimally use the available energy resources.

2.7 Conclusions

In this chapter, a brief overview of the DR concepts, aggregator models, and other relevant and related topics was presented. Regarding DR programs, the concepts and programs type, including their specifications and the relation of DR programs with the RERs have been discussed. Also, the aggregator models and the way that they deal with DR programs and resource aggregation have been exposed. A brief view on decentralized energy management approaches, specifically the TE system, has been presented, indicating the main features of decentralized management methods. In the last section, the problems of energy consumption and scheduling in the agriculture sector have been discussed. The potentials of this sector have been identified for making them more efficient in terms of energy consumption.

Furthermore, this chapter provides a perspective on the current trend of each topic to identify the gaps in the current literature by surveying the most relevant references. From the information presented in this chapter, it can be concluded that before implementing a model on a massive scale, an emulation phase is required to test and validate the performance of the model in practice. In fact, the emulation phase makes it possible to discover the technical problems experienced by the system, which mostly remain hidden in the simulation and theoretical phases.

The developed work in this thesis takes the opportunity to overcome the identified gaps. The gaps and their solutions proposed in this work include:

- Need of decision support tool and laboratory testbed to validate the DR programs and aggregator models – which has been addressed through this thesis in [27], [32], and [30], by developing and implementing real-time simulation platforms using several laboratory emulators and real devices;

- Lack of a specific model for ramping of DR programs in aggregator models – which has been discussed in this thesis through [27] and [36] by providing a precise vision to the aggregator´s behavior during the ramp period;

- Decentralized approaches for aggregator or local energy management systems – which have been discussed in [28] and [30] by using decentralized methods to control and manage aggregator and a microgrid laboratory platform;

- Lack of offline energy scheduling approaches in the agriculture sector in the scope of DR programs – which has been addressed by [29], showing energy scheduling in an agriculture irrigation system using RERs.

The proposed solutions for the identified gaps will be discussed in detail in chapters by showing the contribution of the solution demonstrated in each paper to accomplish the core contribution of this thesis.

Chapter 3

Contributions

3 Contributions

This chapter presents the contributions of this Ph.D. work and the role of each published paper used to develop the thesis. In section 3.1, the publications of the thesis are identified. Afterward, in section 3.2, the main contribution is stated. It is followed by a description of the related key contributions (section 3.3 to 3.15). Finally, the main conclusions of the chapter are described in section 3.16.

3.1 Introduction

Nowadays, the role of aggregators in DR implementation is being legalized in several countries. Therefore, technical performance and economic aspects of any business model in this context should be scrutinized before massive implementation.

The contributions of this thesis are related to the following list of 12 scientific papers (Journal – J, Conference proceedings – C), which are the results of the works completed during the Ph.D.:

Core Publications

- [27] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Ramping of Demand Response Event with Deploying Distinct Programs by an Aggregator," Energies, vol. 13, no. 6, p. 1389, Mar. 2020. Doi: 10.3390/en13061389, IF: 2.707 (**J1** in Table 3.1);

- [28] Omid Abrishambaf, Fernando Lezama, Pedro Faria, and Zita Vale, "Towards transactive energy systems: An analysis on current trends," Energy Strategy Review, vol. 26, p. 100418, Nov. 2019. Doi: 10.1016/j.esr.2019.100418, IF: 3.895 (**J2** in Table 3.1);

- [29] Omid Abrishambaf, Pedro Faria, Zita Vale, and Juan Manuel Corchado, "Energy Scheduling Using Decision Trees and Emulation: Agriculture Irrigation with Run-of-the-River Hydroelectricity and a PV

Case Study," Energies, vol. 12, no. 20, p. 3987, Oct. 2019. Doi: 10.3390/en12203987, IF: 2.707 (**J3** in Table 3.1);

- [30] Omid Abrishambaf, Pedro Faria, Luis Gomes, João Spínola, Zita Vale, and Juan Manuel Corchado, "Implementation of a Real-Time Microgrid Simulation Platform Based on Centralized and Distributed Management," Energies, vol. 10, no. 6, p. 806, Jun. 2017. Doi: 10.3390/en10060806, IF: 2.707 (**J4** in Table 3.1);

Other Publications

- [31] Omid Abrishambaf, Pedro Faria, João Spínola, and Zita Vale, "An Aggregation Model for Energy Resources Management and Market Negotiations," Advances in Science, Technology and Engineering Systems Journal, vol. 3, no. 2, pp. 231–237, Mar. 2018. Doi: 10.25046/aj030227 (**J5** in Table 3.1);

- [32] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Application of an optimization-based curtailment service provider in real-time simulation," Energy Informatics, vol. 1, no. 1, p. 3, Dec. 2018. Doi: 10.1186/s42162-018-0006-6 (**J6** in Table 3.1);

- [33] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Laboratory Emulation of Energy Scheduling in an Agriculture System", *2020 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Chicago, USA, 23rd April 2020 (**C1** in Table 3.1);

- [34] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Energy Resource Scheduling in an Agriculture System Using a Decision Tree Approach", *20th International Conference on Intelligent Systems Applications to Power Systems (ISAP)*, New Delhi, India, 2019. Doi: 10.1109/ISAP48318.2019.9065983 (**C2** in Table 3.1);

- [35] Omid Abrishambaf, Pedro Faria, Luis Gomes, and Zita Vale "Agricultural Irrigation Scheduling for a Crop Management System Considering Water and Energy Use Optimization," *ICEER2019 - 6th International Conference on Energy and Environment Research*, Aveiro, Portugal, 2019. Doi: 10.1016/j.egyr.2019.08.031 (**C3** in Table 3.1);

- [36] Omid Abrishambaf, Pedro Faria, Zita Vale, and Juan Corchado "Real-Time Simulation of a Curtailment Service Provider for Demand

Response Participation," *2018 IEEE/PES Transmission and Distribution Conference and Exposition (T&D)*, Denver, CO, USA, 2018. Doi: 10.1109/TDC.2018.8440492 (**C4** in Table 3.1);

- [37] Omid Abrishambaf, Pedro Faria, and Zita Vale, "SCADA Office Building Implementation in the Context of an Aggregator," *2018 IEEE 16th International Conference on Industrial Informatics (INDIN)*, Porto, Portugal, 2018. Doi: 10.1109/INDIN.2018.8471957 (**C5** in Table 3.1);

- [38] Omid Abrishambaf, Pedro Faria, and Zita Vale "Participation of a Smart Community of Consumers in Demand Response Programs" *2018 Power Systems Conference Clemson University (PSC)*, Charleston, SC, 2018. Doi: 10.1109/PSC.2018.8664007 (**C6** in Table 3.1).

The key contributions of each publication are shown in Table 3.1. These contributions are identified from the results of publications developed during this Ph.D. work. Also, "Support" papers listed in Table 3.1 are additional publications and developed during this Ph.D. work.

Table 3.1. Contributions and publications

Scope	**Key contribution**	**Publications**												**Support**
		Core				**Other**								
		J1	J2	J3	J4	J5	J6	C1	C2	C3	C4	C5	C6	
PES	Demand Response Programs Definition	X				x	x					x	X	
	Resources Aggregation	X				X	X				x	X	x	
	Demand Response Gathering	X				X					X		X	
	Distributed Generation and Demand Response Scheduling	X			X	X	x					X	X	
	Renewables Integration			X	X	X	x		x	X	X	X	X	[148]
	Local Markets/ Communities		X									x	x	
	Irrigation Management			X				X	X	X				[149]
CS	Distributed Control		x	X	X							X		[150]
	Intelligent Applications		X	X		X			X				X	[151]
PES and CS	SCADA Systems			X				X				X		[67]
	Real-Time Simulation	X			X		X				X			
	Laboratory Emulation	X		X	X		X	X			X			
	Case Studies	X		X	X	X	X	X	X	X	X	X	X	

3.2 Main Contribution

The work developed in the scope of this thesis is focused on the implementation of DR programs in small and medium scale consumers aggregated by a third-party energy management entity, such as an aggregator or a CSP. In this context, a whole perspective of DR implementation from aggregator models to a single intelligent prosumer has been proposed. The responsibility of the aggregator is to gather all small and medium scale resources and present the flexibility of these resources to electricity market negotiations (or other purposes) as a unique resource. This can include a single consumer intending to participate in DR programs, or a prosumer equipped with RERs intending to be remunerated for the produced energy. It is not obligatory that all consumers or producers in the same geographic area being aggregated.

The aggregator can accept consumers or producers from different network areas, acting as a management platform for the aggregated DR and DG resources. For this purpose, the aggregator has to make contracts with the DR participants as well as the DG resources for remuneration and scheduling. This enables the aggregator to control and monitor the DR and DG resources on the demand side. In fact, the aggregator has a transactional role between the downstream (medium and small-scale DR and DG resources) and upstream (electricity markets and network operators) sides of the power system, as Figure 3.1 illustrates.

In the upper layer, the aggregator is in touch with system operators and electricity markets. While some technical or economic triggers occur, and it is required to reduce consumption, the aggregator will be notified by the upper level players to apply for DR programs. This has been shown on the left side of Figure 3.1 as a flexibility request and offer. Subsequently, in the lower layer, the aggregator communicates with consumers and prosumers (down-right side of Figure 3.1), as they may have several voluntary and mandatory DR programs. In the case of voluntary DR programs, the aggregator is not aware of the response of the customers, as they may accept or reject the event. Therefore, the aggregator dispatches the voluntary DR requests to the end-users, and in response, end-users reply with their preferences, demand bids, reduction capacity, etc. In the case of mandatory DR events, end-users are obligated to respect their contractual commitments with the aggregator during the event. This procedure will be continued in both voluntary and mandatory DR events until the aggregator reaches the needed reduction. In the later step, where the aggregator applies DR bids (requested flexibility) in the electricity markets at a certain price. This should be higher than the market price to gain financial benefits. Regarding the reduction baseline (reduction need a longer time), the aggregator should always consider the reduction rate slightly higher than the forecasted baseline. This is needed to prevent possible failures in the case of some customers opting out during the event.

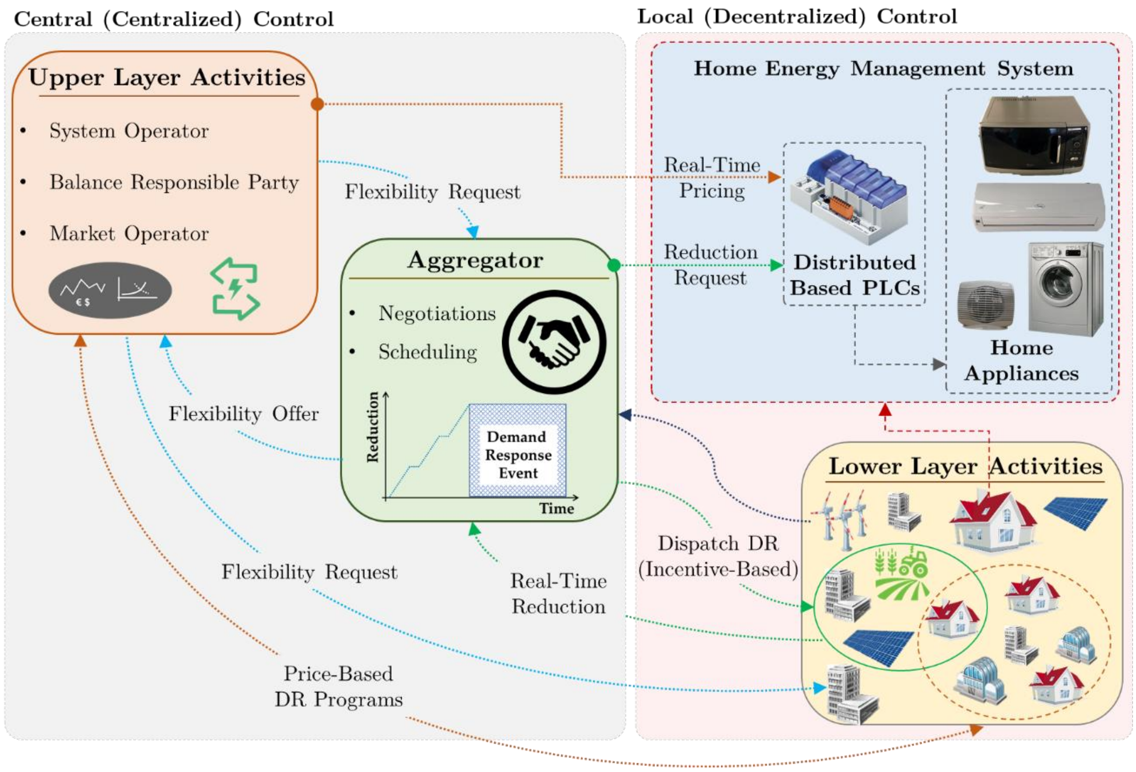

Figure 3.1. Demand response, resource aggregation, and procurement.

In the deployment phase, automation infrastructures are critical as they play the role of a base for network management strategies. All network players must exchange data continuously in real-time, as the aggregator should have real-time information of the DR participants. Therefore, all network players benefit to be equipped with automatic models and decision support tools and systems.

An example of a decision support tool, the concept of a Home Energy Management System (HEMS), is shown on the top-right side of Figure 3.1. Distributed-based Programmable Logic Controller (PLC) as the controllers of

HEMS can be in touch with both upper level network players as well as with the aggregator. In the case of upper level players communications, PLCs can receive market information, such as real-time pricing, to control the home appliances according to the variation of the electricity prices. In the case of aggregator, PLCs can receive a reduction request in the scope of an incentive-based DR program defined by the aggregator, and manage the related appliances based on user preferences. Besides this example, all practical features of these tools and systems should be validated. Accordingly, adequate, realistic models and laboratory platforms are essential to validate the functionalities of any developed model intensively.

The proposed approach in this thesis has considered all perspectives from an aggregator to a single intelligent prosumer. This leads to the design and develops a decision support platform called DEEPDISEM (Demand rEsponse Programs DIstributed control System for intelligent Energy Management), which provides support to the DR program implementation in the context of intelligent energy management. DEEPDISEM aims at validation of DR programs and aggregator aspects using a diversity of actual resources. Figure 3.2 illustrates an overall view of DEEPDISEM architecture.

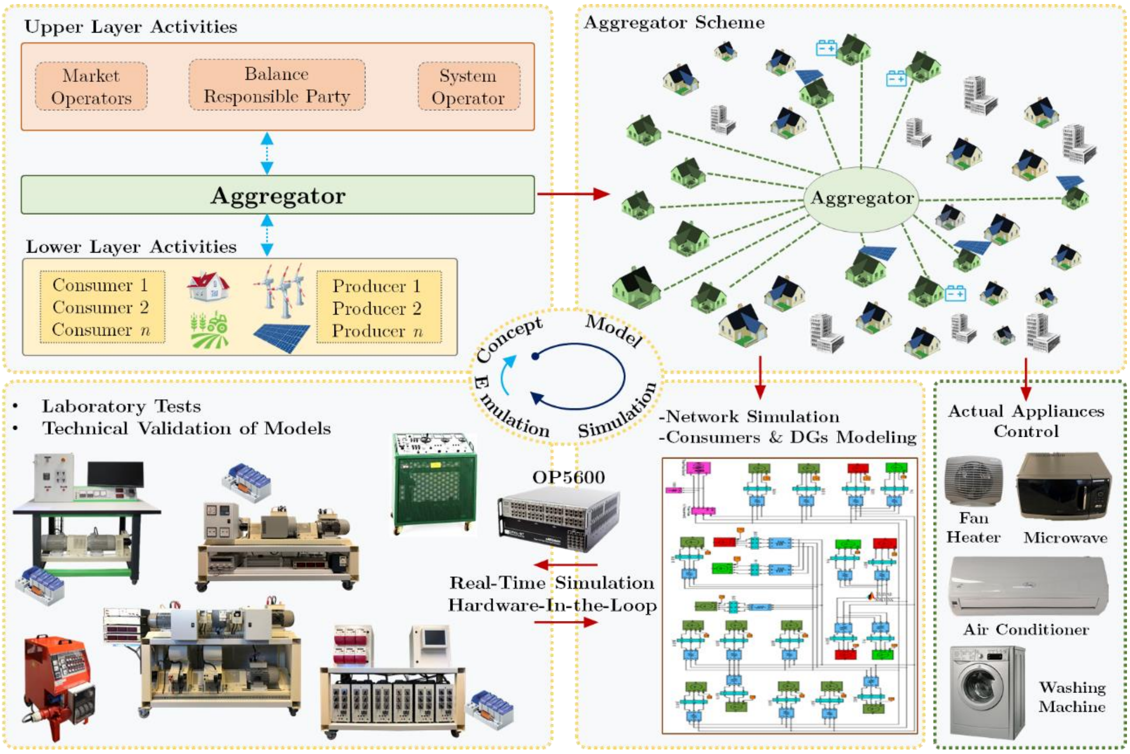

Figure 3.2. DEEPDISEM Architecture.

DEEPDISEM includes four main parts. In the first part (Figure 3.2 top-left), this platform addresses the concept of aggregator and show how aggregator deals with the electricity markets and system operators in the upper layer, and with consumers and producers in the lower layer. Then, the DEEPDISEM platform deals with the network management approaches that are being employed by an aggregator model (Figure 3.2 top-right), including DR program deployment, remunerations, resource scheduling, and clustering. In the third part (Figure 3.2 down-right), DEEPDISEM integrates the network simulation models and consumers, and DG modeling. Also, in this phase, DEEPDISEM provides various controlling solutions for actual appliances to survey the behavior of the consumers in DR events with respect to the optimal results of the aggregator. In the later step (Figure 3.2 down-left) merges a real-time simulator and laboratory resources working as Hardware-In-the-Loop (HIL) to combine both real and simulation environments.

The diversity of capabilities and features of DEEPDISEM make it a powerful tool to assay DR programs and aggregator models through various case studies. Resource aggregation and scheduling distributed control approaches, and real-time simulation are only some of the features of the DEEPDISEM platform, which will be discussed in the following sections.

According to the research question mentioned in section 1.2, the core contribution of this thesis, supported by DEEPDISEM, is approaching an aggregator responsible for DR programs from the concept to the implementation. In this way, aggregator performance in terms of resource scheduling and consumer remuneration and the aggregator interaction with the upper level players of the power system, such as market operators, are addressed using computational intelligence approaches (e.g., K-Means clustering). The focus is given to the ramping period definition, in which the aggregator can choose the DR and DG resources, dealing with the uncertainty of response. Furthermore, through DEEPDISEM, automated load control approaches in the demand side are tackled through computational intelligence methods (e.g., decision tree). This enables the aggregator to implement DR programs in various types of end-users, such as residential, commercial, and agriculture prosumers. The proposed approaches also consider both consumer participation in DR events and the respective appliances used to obtain the required demand reduction. In the later step, the aggregation models and load control approaches are verified through real-time simulation and HIL methodology in a laboratory scale and the scope of various realistic case studies.

In sum, through the DEEPDISEM platform, technical features of DR program implementation supported by the aggregator are verified, and the use of adequate approaches to address the potential of customers for the DR program participation is achieved.

3.3 Demand Response Programs Definition

The definition of DR programs requires an adequate characterization of each program. Supposing that an aggregator intends to define a DR program, several aspects from both consumer and aggregator standpoint should be specified. In most cases, the DR program definition has a strong relationship with the aggregation models and approaches. In the scope of this thesis, six different DR programs have been developed in [38] according to their characteristics, and they have been used by a smart community model. Then, these six DR programs are employed in [27] for validating the ramping of DR implementation. These six DR programs were categorized into two main groups, including direct load control and real-time pricing.

Furthermore, the program type, the remuneration rate, the activation signal, the measure/contract are the parameters considered in the developed DR programs. In [31], more three DR programs have been modeled to be used by an aggregator, such as load shifting, load reduction, and load curtailment. Furthermore, the DR programs defined in [38] have been utilized to verify the implementation of DR programs in [32] using complex real-time simulation and emulation models for a CSP, and in [37] using intelligent office building facility based on aggregator scheduling results.

3.4 Resources Aggregation

An aggregator is an entity normally acting between the electricity market and end-use consumers. This entity aggregates all small and medium scale resources, such as DR and DG, and make them participate as a unique resource in the electricity market negotiations. This topic has been addressed in the scope of this thesis through six publications, namely [27],[32],[31], [36]–[38].

The developed aggregation models in [27],[31], and [37] provide DG and DR program management. In [27], the functionality of the aggregator is categorized into two sections: upper level and bottom-level. In the upper level, the aggregator negotiates with network players, such as market operators, BRP, and system operators. At the bottom level, it deals with demand-side users, namely small and medium scale consumers, and producers. The aggregator model in [31] categorizes the resources in several groups using the K-means approach and specifies a remuneration for each group called group tariff. The maximum price available in each group will be selected for the group tariff. Therefore, the groups are different in remuneration, so the aggregator can select the most economical group and participate in the market negotiations and bids.

In [37], the aggregator controls actual devices in an intelligent office building according to the optimal resources scheduling and DR reduction to minimize the operational costs. In [32] and [36], another type of aggregation model has been presented for a CSP to aggregate DR and DG resources. The CSP is in charge of market negotiations, energy trades, and bids. Also, the CSP model accommodates the uncertainty related to the actual consumption and generation and the actual response of consumers to the DR events. The work presented on [32] has a close look to the complexity of the CSP model using realistic resources, and the work proposed on [36] shows how CSP deals with the uncertainty of the consumers and producers responses during the ramping of DR programs.

In addition, in [38], an aggregation model has been proposed in the scope of a smart community. The main difference between this community model and the aggregation models described in this subsection is that the community model has a smaller number of players and it is not interested on financial profits, as it provides advise for improving the management of the power system. While the proposed aggregation models in this subsection mainly include a significant number of players, and they are profit-based. Furthermore, the community manager is not owning any energy resources, as it only manages the consumption and generation of the entire community by providing strategic planning, such as DR programs or resource scheduling.

3.5 Demand Response Gathering

One of the challenges of aggregator activities that typically are not discussed in the literature is the way that the aggregator deals with DR gathering during the ramp period before the event is started. In short and real-time DR events, DR gathering is more tangible as the aggregator has a small timeline to reach the desired reduction. Incentive calculations and payments between aggregator and DR participants during the ramp period require information exchange between aggregator and network operators.

In this thesis, the performance of an aggregation model during the ramp period has been shown in [36]. In the model presented in [36], the aggregator attempts to reach the required reduction using DR resources as well as the use of RERs. While the ramp period evaluation process is explained in detail and illustrated in [36], it has been further explored and improved in [27] by proposing a precise vision to the DR timeline and ramp period considering remuneration. Figure 3.3 illustrates the timeline developed in [27] for DR implementation. DR announcement deadline, deployment period, assessment period, sustained response, notification time, and actual response time are the time-related parameters considered in the proposed DR implementation timeline.

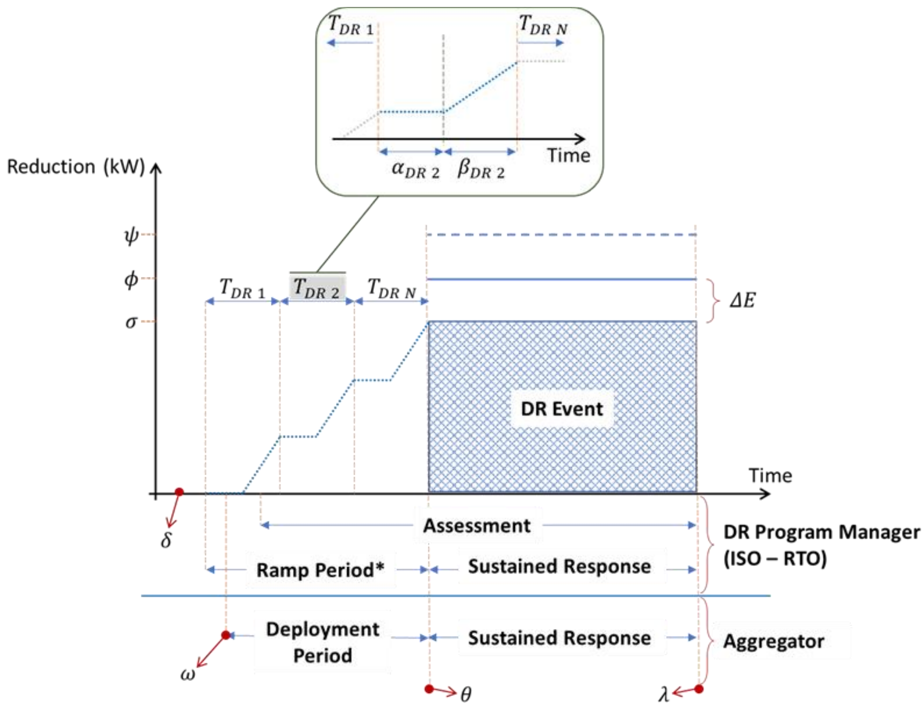

Figure 3.3. Timeline for DR implementation by an aggregator [27].

In [31] and [38], the DR gathering has been performed to reach the network balance in local communities and aggregators with respect to the minimization of operational costs of the network (e.g., CSP) and remuneration costs of DR resources.

3.6 Distributed Generation and Demand Response Scheduling

The implementation of DR programs at the distribution system is one of the main contributions of this thesis. One of the features that are discussed by almost all of the resulting publications ([27],[30]–[32],[37], and [38]) is the DG and DR scheduling, mostly in the scope of an aggregator in a distribution network. In these publications, various constraints and assumptions have been considered in distinct contexts.

The work presented in [27] focuses on the DR scheduling during the ramp period before the DR event to minimize the aggregator´s remuneration costs. The problem of DR and DG scheduling is addressed in [32], [31], [37], and [38], to reduce the operational costs of the aggregator. With a more punctual contribution to the implementation of DR and DG scheduling, in [30] is proposed an actual case study for the DR and DG resource scheduling in the scope of a VPP operation a local microgrid.

3.7 Renewables Integration

Distributed energy resources, mostly focused on renewables, makes power system operation more difficult. It is expected to have a significant growth in the upcoming years as these promise several benefits, such as reducing environmental concerns. However, at the same time, renewable resources can increase the complexity of the distribution network operation as they have a lot of variation in the generation rate. Therefore, the need for reliable management approaches should be tackled to accommodate the massive integration of renewables. In the scope of the work developed in this thesis, the management of renewable energy resources and their integration in different levels of power network has been addressed in [29]–[32] and [34]–[38]. The challenges of keeping network balance that a network controller or an aggregator is facing have been explored in [30], and several optimal approaches have been proposed to overcome those challenges. The effectiveness of renewable-based resources on the aggregator scheduling process considering cost minimization is shown on [31] and [38]. Focusing on laboratory deployment in [32], a set of automatic control approaches for laboratory-based renewable resources is proposed in the context of the aggregator model and DR programs.

In [29], [34], [35], it is shown how RERs (i.e., Photovoltaic–PV and run-of-the-river hydroelectricity) are effective in scheduling of irrigation in an agriculture system to reduce electricity bill and use all the available DG. The role of small-scale renewable-based resources during ramping of DR programs in a CSP model has been validated [36]. Also, in [37], the effect and behavior of a PV system in an office building have been analyzed, and it was shown how PV system could be used as a local resource to supply consumption without making issues in internal network balance.

3.8 Local Markets/Communities

Local markets and energy communities are subject to the most recent works in the power and energy area. TE is a very related topic. Both DR and TE open opportunities to integrate P2P energy trading through local electricity markets and communities.

In this thesis, a discussion on the current trends of TE, P2P local markets, and transactive network management has been presented in [28]. It provides information on how such systems can be implemented in the smart grid paradigm revealing the current gaps in the literature and suggesting the paths forward the actual implementation and required infrastructure. Focusing on the contribution that DR programs can give to the local communities, [37] and [38] have been published. The performance of a community manager is analyzed while it establishes several DR contracts with associated members in the local community.

3.9 Irrigation Management

The agriculture sector is ideal for implementing all types of solutions involving RERs, as the farms are mostly located in rural areas where such resources are largely accessing. However, the potentials of the agriculture sector in terms of DR implementation and energy scheduling remain underexplored. For this reason, in this Ph.D. work, a particular focus is given to prosumer in the agriculture sector for implementing energy scheduling related to DR programs. In this context, four publications have been achieved, namely [29], [33]–[35]. In the first step, [33] presents a set of automation load methodologies that have been implemented in laboratory devices for surveying the performance of energy scheduling in the agriculture context. After that, an offline decision-making methodology using Decision Tree (DT) has been presented in [34] to provide optimal scheduling of energy resources in the agriculture model, including RERs. Thus, all the controlling decisions related to resource scheduling can be made in a local controller unit.

Furthermore, in [35], an autonomous approach is proposed to improve the low efficiency of irrigation by developing a system based on the water requirement of the plantations, using field data. In the later stages, the work presented in [29] is a comprehensive and complete energy scheduling case study for agriculture irrigation system, which is a combination of the models described in [33]–[35], as Figure 3.4 illustrates.

According to Figure 3.4, there are two RERs in this system to ensure agricultural sustainability: PV panels and a river turbine connected to a synchronous generator. The model is intended for scenarios to schedule the energy demand of irrigation and water pump electric motors, to be supplied by the local resources.

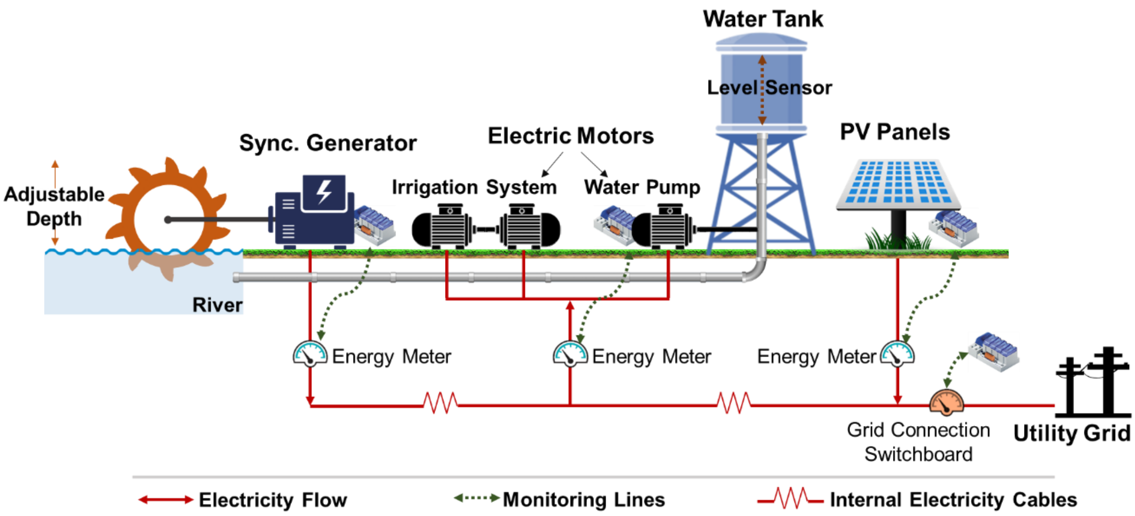

Figure 3.4. Energy scheduling in an agriculture irrigation system [29].

3.10 Distributed Control

Energy management in aggregators or other entities can be tackled in two ways: centralized and distributed control, with respective advantages and disadvantages. In the decentralized approach, the management is performed locally without using centralized control. The level of decentralization is defined by the intelligence of local control units, which can be utilized just to execute a simple command from the upstream controller or make its own decisions. In this thesis, several models and systems consider and perform distributed control approaches, namely in [28],[29],[30], and [37].

A discussion has been presented in [28] regarding the distributed control methods. It explains all the advantages and disadvantages of such methods while they are compared with centralized control methods.

Moving forward to the implementation phase, in [29], a laboratory agriculture irrigation system has been presented for energy scheduling emulation in a farm using a run-of-the-river hydroelectricity emulator and a PV. In the same work, a PLC has been installed in each resource of the system. The PLCs are considered as distributed local controllers. The PLCs continuously exchange messages between each other to fulfill the system goals without the need for a central controller.

The distributed control brings reconfigurability and flexibility features to the overall system. In [30], a laboratory microgrid model has been developed that supports both centralized and distributed control approaches. In this microgrid, the user can choose the system that is being controlled through a central control unit or by several local controllers.

In [37], a distributed SCADA-based system has been implemented for energy management in an office building. Three distributed PLCs are used, each one responsible for a certain number of offices with a set of functionalities. In the proposed SCADA model, the adaptability of the system is improved comparing with centralized control, as the response time to any changes is reduced. As an example, if a fault is detected in one of the PLCs, the other PLCs will cover the tasks of the faulty PLC, so the operation of the main system will not be affected.

3.11 Intelligent Applications

Since the new concepts of the power system, like TE and community, are being implemented in power distribution networks, the use of smart technologies in the demand-side gained importance. End-users can benefit from using intelligence methods, even more than grid operators.

In the scope of this thesis, the application of several intelligent approaches has been addressed in [28],[29],[31],[34], and [38] in different applications. In [28], intelligent decision-making approaches for local electricity markets and P2P optimization algorithms have been shown and discussed. Blockchain technologies, game-theoretic methods, and multi-agent systems are the approaches that have been discussed in [28] for the management of local electricity markets and P2P systems.

In [31], the K-Means clustering algorithm has been used by an aggregation model to perform consumer's clustering for DR remuneration purposes. The methodology presented in [38] employs a DT method to perform optimal energy scheduling in a community of consumers and prosumers. Similarly, in [29] and [34], another DT approach has been presented for energy scheduling in an agriculture irrigation system to minimize electricity costs. The DT methods enable the system to perform decision making in offline mode, without using any external server/machine or internet access nor heavy computational resources.

3.12 SCADA Systems

In the field implementation of DR programs, the end-users should be equipped with means to receive the information regarding DR events from DR managing entities, such as aggregators. Then, end-users should smartly provide the required reduction. Therefore, the necessity of automation infrastructures, like SCADA systems, is evident in this context. Nowadays a significant electricity usage is indeed made in residential buildings. Commercial and office buildings are other options that should be considered. In the scope of this Ph.D. work, [37] presents a SCADA system as a tool for an office building to participate in DR programs. This SCADA and automation infrastructure has been implemented in the GECAD research center building, at ISEP – Polytechnic of Porto, Porto, Portugal, to mainly control and manage building consumption, as Figure 3.5 illustrates.

The proposed SCADA system provides an automated testbed for DR implementation by controlling the air conditioners and lighting system of the building. Optimization algorithms developed in [67] and [152] support building energy management. User preferences have been considered in this optimization algorithm to keep the user´s comfort level. Focusing on other types of end-users, in [29] and [33], several automation mechanisms are presented for an agriculture irrigation system to perform automated decisions energy scheduling. The proposed approaches have been applied in laboratory emulators as parts of the DEEPDISEM platform.

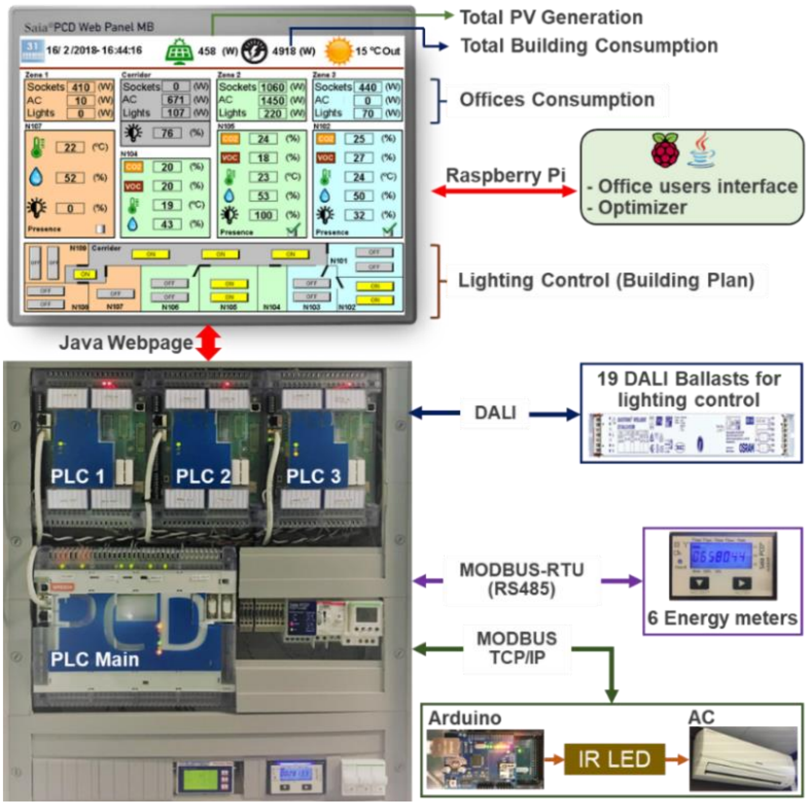

Figure 3.5. SCADA system in an office facility with DR [37].

3.13 Real-Time Simulation

Before implementing new business models, it is recommended to test and validate new models in realistic simulation platforms. For this purpose, fully computational simulation (e.g., an electrical distribution network simulation) can be very difficult and incomplete. Therefore, a real-time simulation strategy is a satisfying solution in several fields for integrating both physical measured and simulation results.

The work related to this thesis considers the use of several real-time simulation approaches using OP5600 equipment and the HIL approach. In [32], a comprehensive description is presented for a real-time simulation methodology in an optimization-based CSP model. It also shows how the real devices and laboratory emulators can be integrated into the simulation via the HIL method. Similarly, in [30], OP5600 has been employed as a central controller to manage a microgrid owned by a VPP. Figure 3.6 presents the centralized microgrid control model proposed in [30].

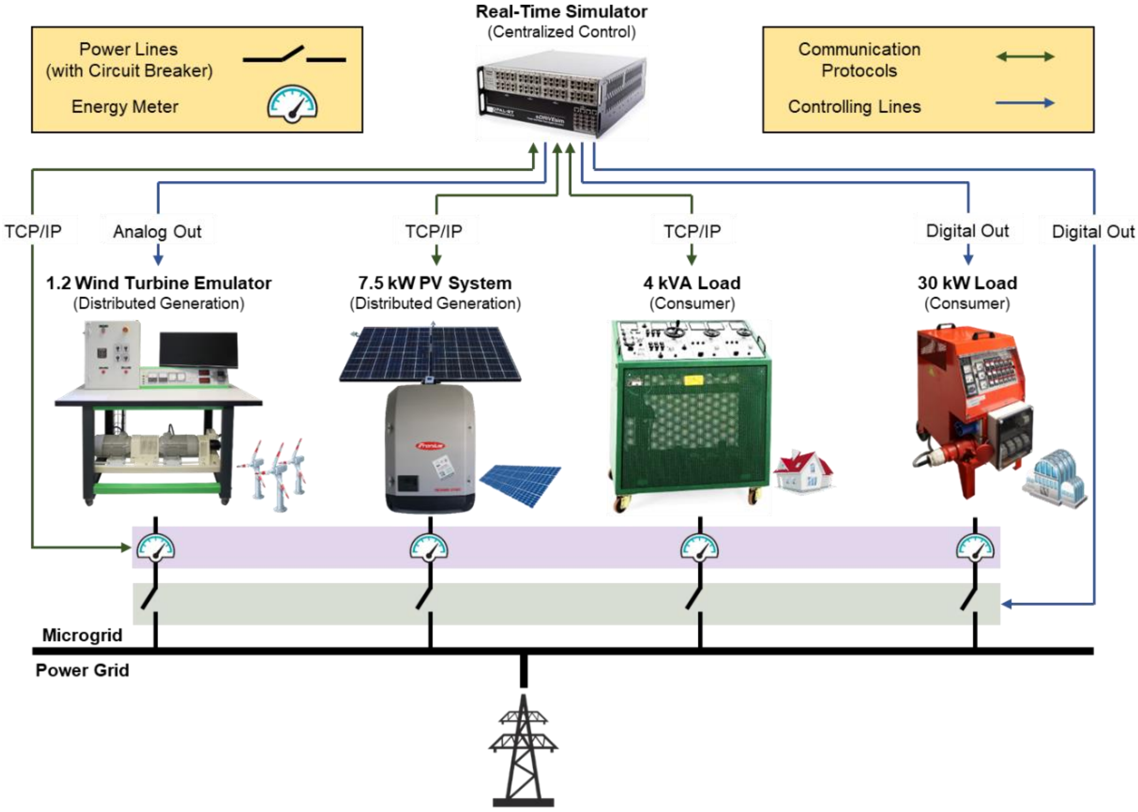

Figure 3.6. Real-time simulation platform [30].

As can be seen, the real-time simulator (OP5600) manages all the laboratory resources as a central controller unit by using the HIL method. OP5600 is responsible for managing the network players and controlling the consumption and generation of the emulated resources. To do this, the OP5600 provides the control of each player through independent communication channels (such as digital and analog input and output signals and Ethernet communication protocol). In [27] and [36], the real-time simulator OP5600 is used in the case studies for validating the performance of an aggregator and a CSP model during the ramp period of the DR event applying the HIL method.

3.14 Laboratory Emulation

In most of the publications produced in the scope of this thesis, there is a laboratory validation to test the proposed models. This is in line with the real-time simulation platforms described in section 3.13. In different publications, decision approaches are different. In [27], a set of six resistive loads are employed to emulate some consumers to validate the actual demand reduction in a DR event. Various real approaches and laboratory emulators have been utilized in [30], [32], and [36] to emulate the consumption and generation profiles of consumers and RERs in an aggregator model. A 4 kVA and a 30 kW load emulate the consumption of two consumers, a 1.2 kW wind turbine emulator is used for wind generation, and a real installation of PV arrays with a rated capacity of 10 kW stands for a PV producer. In the later stage, in [29] and [33], a 2.5 kW synchronous generator and three three-phase induction motors (two with 1.5 kW and one with 2.5 kW rated power) have been used to validate the practical features of energy scheduling in an agriculture irrigation system. The complete network also includes the emulation of cables in the distribution network.

3.15 Case Studies

In this thesis, the challenges of the DR programs implementation mostly by an aggregator have been addressed through a diversity of developed approaches. The illustration and demonstration of each proposed approach aspects have been performed by the implementation of suitable case studies. These case studies have been categorized based on several selected parameters, as organized in Table 3.2. Indeed, the selected parameters, as well as the case studies, are carried out with respect to the key contributions shown in Table 3.1.

As the first parameter, the number of DR programs used in each publication has been identified. This includes both types of incentive-based and price-based. In most cases, incentive-based DR programs have been used, especially Direct Load Control (DLC); however, some others utilize price-based DR programs, including Real-Time Pricing (RTP).

Regarding the accommodation of consumers and DGs, a specific number of units has been considered for each, as in [30] and [36] up to 220 consumers and 68 DG units were used. In [31], [34], [35] and [38], all consumers and DG units have been fully simulated, using a simulation environment (e.g., MATLAB™/Simulink). In [29] and [33], only laboratory emulators have been used to validate the actual demand reduction or generation profiles. In the case of [27], [32], [30], [36], and [37], the case studies reflect the comparison of emulation and simulation.

Table 3.2. Summary of case studies.

Characteristics		Publications											
		Core				Other							
		J1	J2	J3	J4	J5	J6	C1	C2	C3	C4	C5	C6
DR Programs	Quantity	3			2	3	3				2	2	6
	Incentive-Based	3			1	2	2				2	2	5
	Price-Based	-			1	1	1				-	-	1
Consumers	Quantity	27		2	220	20	20	2	2	1	220	20	20
	Simulated	21		-	218	20	19	-	2	1	218	19	20
	Emulated	6		2	2	-	1	2	-	-	2	1	-
DG	Quantity	15		2	68	26	26	2	2	1	68	26	21
	Simulated	15		-	66	26	23	-	2	1	66	25	21
	Emulated	-		2	2	-	3	2	-	-	2	1	-
Controlling Approach	OP5600	X			X		X				X		
	PLC			X	X			X				X	
Decision Technique	Optimization	X			X	X	X					X	
	Decision Tree			X				X	X	X	X		X

In what concerns the decision techniques, several approaches have been considered, namely optimization methods and decision trees. In most publications, decision techniques perform optimal energy scheduling aiming to minimize operational costs.

In [33] and [35], decision techniques are performed using some pre-defined rules; and in [31], decision techniques include mixed integer-linear problems. As the last parameter, the controlling approach/appliance of each proposed model and case study depends on nature and purpose. This parameter is most remarkable in the publications that include the emulation. In [27], [30], [32] and [36], real-time simulator (OP5600) and HIL method have been employed to control the laboratory emulators.

In [29], [30], [33], and [37], PLCs are the main controller of the proposed approach on the case study, where a set of distributed PLCs manage the entire model. While in [31] and [38], the focus of case studies is the concept validation of the DR in the aggregation models by simulation and numerical models, the case studies in [27], [30], [32], [36] and [37], demonstrate a technical validation in the laboratory, to compare the simulation and actual results.

The results of case studies show significant energy savings and cost reductions for both the aggregator and the end-user. Also, the results demonstrate the actual impact of DR implementation through actuation in the actual devices. Thus, the feasibility of field implementation and widespread of innovative DR models, which used to be mostly done by simulation models, disregarding the actual impact in the physical devices, was achieved.

Through this approach, it is possible to show the technical features of DR programs by an aggregator and identify the challenges and gaps that may happen then in the future while the models move forward to the implementation in the field; as claimed in the core contribution of this thesis.

3.16 Conclusions

The work developed in the scope of this Ph.D. thesis has addressed various approaches for DR programs implementation. The proposed DR and aggregator models were surveyed and validated through a diversity of decision tools using real and laboratory equipment. The capabilities and features of each presented model have been validated. Furthermore, it was shown how the key contributions are gathered together to fulfill the core contribution of the thesis.

The DEEPDISEM platform was also presented to support the features and advantages of DR implementation in an energy management system, namely in the presence of aggregator. The key contributions have been supported by implementing adequate case studies, namely in what concerns the economic and technical aspects of using DR by an aggregator. Through the DEEPDISEM platform, it is possible to validate the whole perspective of DR implementation from an aggregation model to a single intelligent prosumer. Beside of the aggregator resources management approaches, such as scheduling and remuneration, the platform provides various controlling solutions for managing actual appliances for realistic implementation of DR programs.

Chapter 4

Conclusions and Future Work

4 Conclusions and Future Work

This chapter finalizes the thesis by providing the main conclusions and contributions of the present Ph.D. work in section 4.1. Section 4.2 identifies several paths for future research worth to be explored.

4.1 Main Conclusions and Contributions

The role of intelligent energy management is gaining importance, namely towards fully decentralized and TE systems. The role of aggregator and DR implementation attracted a lot of attention, as these are being legalized in several countries. Therefore, technical performance and economic aspects of any business model in this context should be validated before field implementation. Many interesting models and research works can be found in the literature focusing on the aggregator concept and other types of energy management approach. Those have been mostly tested through numerical studies. Few of them moved towards testing the model on the real field, namely by piloting.

This thesis contributed to the design and develop Demand rEsponse Programs DIstributed control System for intelligent Energy Management (DEEPDISEM). The main purpose of DEEPDISEM is to develop a decision support platform for technical validation of DR programs and aggregator aspects through a diversity of real devices and laboratory emulators.

As the core contribution of the thesis, supported by DEEPDISEM, is approaching an aggregator responsible for DR programs and respective events implementation. The proposed approach also considers both consumer participation in DR events and the respective appliances used to obtain the required demand reduction. This includes the energy scheduling approaches in the aggregator´s energy management and the decision-making approaches for DR programs in the end-users. In the scope of this thesis, various key contributions have been addressed. The Power and Energy System (PES) contributions include DR programs definition, resource aggregation, DR gathering, DG and DR scheduling, renewables integration, local markets and communities, and irrigation management. Furthermore, the Computer Science (CS) contributions consist of distributed control and intelligent applications. All these contributions are validated through SCADA systems, real-time simulation, laboratory emulation, and case studies. The software and hardware aspects of the work in this thesis are all included in the DEEPDISEM platform. In fact, DEEPDISEM provides aggregation models for DR programs from the concept to the implementation. This is the key feature of this platform to address the research question mentioned in the objective of this thesis. Through DEEPDISEM, it is possible to accommodate DR programs at the consumer level with the support of aggregators considering the uncertainty of consumers response. The platform has a specific look on the ramping of DR programs to cover the uncertainly of the consumers reply and a set of actual loads/appliances controlling approaches to demonstrate the actual demand reduction.

The other important feature of DEEPDISEM is to comprise technical validation of the model using realistic network simulation, mainly real-time simulation. In this way, the platform can overcome the complexity of simulation models that are hard to tune, so these are improved with HIL and emulation methodologies. Therefore, it is possible to improve the functionalities of complex network simulation models using realistic devices. As DEEPDISEM integrates real devices and laboratory emulators in the simulation environment via the HIL method, it can control the real devices from the simulation environment and obtain actual results in the field. The control of real resources in DEEPDISEM is performed by respecting the decision approaches (e.g., aggregation and scheduling) provided by optimization algorithms and other intelligent approaches. Focusing on the case studies, a diversity of scenarios has been implemented in this work to follow two main objectives:

- Concepts validation regarding DR implementation by an aggregator, through simulation and numerical models;
- Technical validation of the models through laboratory platforms and testbeds to assess actual and simulation results.

Through these achieved objectives, it is possible to firstly show a concept proof of DR programs and aggregator models and then validate the technical features and identify the challenges and gaps between the actual and expected results, which is proof of the main contribution of this thesis. This approach is presenting to prevent possible failures while the models move forward to the implementation in real field power systems and electricity markets.

The work conducted in the scope of this thesis has resulted in a total of 12 scientific papers, including six international journals and six conference proceedings, published by the author of this thesis.

4.2 Future Work

The obtained results from work developed in this thesis provide several paths for future research worth to be explored. The following list includes relevant ideas as future research directions:

- Exploring DR information exchange methods and standards, such as Open ADR, for standardizing data exchange between aggregator and DR participants;
- Employing additional methods, namely load optimization, resource aggregation, scheduling, clustering, and remuneration purposes;
- Integrating forecasting methods in energy scheduling and optimization approaches to predict critical parameters and improve efficiency of DR;
- Studying the dynamics of aggregator models using decentralized TE approaches, and surveying aggregator´s role in TE markets for trading flexibility;
- Applying transactive control methods as trigger signals for DR programs;
- Developing P2P energy trading approach for local electricity markets managed by an aggregator;
- Integrating additional laboratory emulators, with the HIL method, and analyzing the network behavior in islanded mode using power amplifier and local energy resources;
- Escalating actual case studies to improve the technical aspects and features of the proposed approaches and models using DEEPDISEM.

The majority of these future research ideas have been included not only for the future advancements of this thesis work but also as a relevant part of several ongoing research projects, to ensure the successful future targets of this thesis, namely the following:

- **DOMINOES** – Smart distribution grid: a market-driven approach for the next generation of advanced operation models and services, H2020, reference no. 771066 – (http://dominoesproject.eu/). Thesis contribution: P2P implementation using transactive energy;
- **COLORS** – Contextual load flexibility remuneration strategies, FCT, reference no. PTDC/EEI-EEE/28967/2017 – (http://www.gecad.isep.ipp.pt/COLORS/), Thesis contribution: additional methods for resource aggregation, scheduling, clustering, and remuneration purposes;
- **TIoCPS** – Trustworthy and Smart Communities of Cyber-Physical Systems, ITEA 3, reference no. 18008 – (https://itea3.org/project/tiocps.html). Thesis contribution: exploring DR information exchange methods and standards in real appliances.

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Annex

Annex A. Published Papers

(According to the list in section 3.1)

[22] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Ramping of Demand Response Event with Deploying Distinct Programs by an Aggregator," Energies, vol. 13, no. 6, p. 1389, Mar. 2020. Doi: 10.3390/en13061389, IF: 2.707 (**J1** in Table 3.1)

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Ramping of Demand Response Event with Deploying Distinct Programs by an Aggregator

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Abstract: System operators have moved towards the integration of renewable resources. However, these resources make network management unstable as they have variations in produced energy. Thus, some strategic plans, like demand response programs, are required to overcome these concerns. This paper develops an aggregator model with a precise vision of the demand response timeline. The model at first discusses the role of an aggregator, and thereafter is presented an innovative approach to how the aggregator deals with short and real-time demand response programs. A case study is developed for the model using real-time simulator and laboratory resources to survey the performance of the model under practical challenges. The real-time simulation uses an OP5600 machine that controls six laboratory resistive loads. Furthermore, the actual consumption profiles are adapted from the loads with a small-time step to precisely survey the behavior of each load. Also, remuneration costs of the event during the case study have been calculated and compared using both actual and simulated demand reduction profiles in the periods prior to event, such as the ramp period.

Keywords: aggregator; demand response; ramp period; real-time simulation

1. Introduction

Electrical energy demand has significantly increased in the last decades. This has led to huge peak of greenhouse gas emissions in order to provide and supply the required demand [1]. In the past decades, fossil fuels were the raw materials for electricity production [2]. However, nowadays several low carbon technologies and renewable energy resources (RERs) have been utilized to produce electricity [3]. Smart grids and microgrids are new some new concepts for the future distribution networks to eliminate the hierarchical structure of the grid and convert them to a fully decentralized and transactive energy system [4]. To do this, the process of energy production should be also placed in the demand side, among all electricity consumers. Therefore, the concept of prosumer (a consumer who also produces electricity) has been raised [5]. However, this makes the network instabilities more tangible than before, as a significant number of small and medium scale consumers and producers will be involved in the network management scenarios [6].

Distributed generation (DG) and RERs are considered as one of the bases of smart grids and microgrids implementation [7]. However, these paradigms would be fully addressed while they have been integrated with demand response (DR) programs [8].

In fact, the DR program is a feature in the upcoming distribution network to connect low carbon technologies without the need for reinforcement [9]. There are various definitions in the literature for

DR program. While each definition has its own strengths and weak points, the most completed one is defined by Federal Energy Regulatory Commission (FERC) [10] as:

"Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."

According to the definition mentioned above, in a simple word, DR can be described as the reaction of electricity consumers to the price signals considered as incentives to reduce/modify the electricity use pattern. There are several types of DR programs: price-based and incentive-based [11]. In Price-based category, there are several programs such as real-time pricing (RTP), time-of-use (TOU), critical peak pricing (CPP), etc. [12]. Also, in the incentive-based DR programs, various strategies are proposed, namely direct load control (DLC), emergency demand response service (EDRS) capacity market programs (CMP), interruptible demand response program (IDRP), etc. [13]. Each program has its own specifications that are applicable depending on technical or economic reasons of the electricity network. As an example, the ERCOT market in Texas utilizes EDRS to maintain network stability in emergency conditions to reduce power outages. In this market, EDRS participants can provide DR reduction within a 10 to 30 min ramp period in advance to the event [14]. However, there is a minimum reduction capacity for the DR event and its participants in order to directly participate in the electricity markets. According to the surveyed references [15–17], this minimum reduction capacity for a consumer who intends to have an active role in the electricity market negotiations, is various depending on the DR type, typically from a few kilowatts to megawatts. In other words, this makes small scale consumers almost incapable to directly participate in electricity markets [18]. To overcome this barrier, an aggregator can be considered as a third-party entity between the upstream and downstream sides of the network [19,20]. In fact, this entity aggregates all small and medium scales DR participants and contribute them as a unique DR resource in the electricity market negotiations [21].

By a simple look on the current trends, a lot of papers and research projects can be found that are focused on the concepts of aggregator, as the role of the aggregator is being legalized in several European countries (e.g., France, Finland, Austria, Denmark, etc.) [22]. However, one of the aspects of aggregator that has not been discussed widely in the literature is the way that aggregator deals with ramp period before the DR event is started. Incentive calculations and payments between aggregator and DR participants during the ramp period, required information exchange between aggregator and network operators (e.g., independent system operator–ISO) during the ramp period, and several other issues need to be discussed before the models move from theoretical phase towards implementation level. Besides this, both scientific and practical features of any model should be scrutinized, learning from past experiences to estimate and prevent probable future issues. To do this, adequate real models and laboratory tools are essential to test and verify the functionalities of any developed model under practical challenges.

To address these issues, this paper proposes an aggregator model with a precise vision of DR timeline and ramp period. The model includes introducing the roles of aggregator in the electricity system as a third party, and how it deals with DR programs implementation and remuneration payments. Furthermore, a case study is developed in this paper to validate the model under practical challenges and technical issues. This has been done by a real-time simulator machine (OP5600) and a set of laboratory equipment as hardware-in-the-loop (HIL). In this way, the behavior of aggregator is surveyed in each moment of DR implementation, especially in the ramp period before the event being started. In the end, the remuneration costs are compared using both experimental and numerical results to reveal the importance of experimental tests and validations.

The rest of the paper is organized as follows: A literature review is presented in Section 2 to identify the challenges and gaps in the current trend of aggregator and DR programs. Section 3 presents the proposed methodology in four different subsections including the role of the aggregator in the power system, DR timeline, and ramp period evaluation, key points of aggregator to define DR programs, and a linear programming optimization for the aggregator to minimize DR remuneration costs. Subsequently, Section 4 proposes a case study and real-time simulation model developed for the aggregator to validate it using practical challenges, and its results are shown in Section 5. Finally, the main conclusions of the work are presented in Section 6.

2. Literature Review and Paper Contributions

There are plenty of research works focused on the context of the aggregator model and DR implementation. In [8], a methodology has been described to use multitype DR programs to smooth the uncertainty of RERs. The method utilizes a multi-objective scheduling algorithm for smoothing the fluctuations in RERs. Several constraints for DR programs have been considered in the same paper in order to maximize the user of RERs and maintain the balance in the network.

A real-time simulation model has been proposed in [12] for an aggregator entity, which uses several real hardware resources to emulate the consumption and generation profiles. Also, an optimization problem has been developed in the same work to optimally schedule the DR resources and RERs aiming at minimizing the aggregator operational costs. Although an actual infrastructure has been proposed in [12] for testing aggregator's concepts, there is no discussion about the ramping of DR programs prior to the event, and how aggregator deals with remunerations in this period. A realistic model of an aggregator in the scope of curtailment service provider has been presented in [17]. The authors proposed a real-time simulation model that supports decision making for DR validation in real-time. Also, a preliminary discussion has been proposed in the paper regarding the ramp period before DR events proposing the use of RERs and DR programs. The presented results proved the performance of the curtailment service provider using real measured data from the laboratory equipment. However, there is no discussion about how curtailment service provider behaves with incentive payments, and also a precise vision to the DR program information received from system operator, such as notification deadline, program duration, etc.

In [23], the authors proposed an assessment of a DR program for consumers who are equipped with a smart meter. A load-serving entity plays the role of the aggregator to offer incentives to the participant relying on near real-time information. Moreover, a timeline has been proposed in the same work regarding the information exchange between the load-serving entity and ISO regarding DR programs. Although the paper presented an interesting model, the authors validated their model through a numerical case study, and there is a lack of an experimental test and validation.

A bottom-up model has been proposed in [24] for an aggregator dealing with DR programs. Load shifting, load recovery, and load curtailment are considered as three types of DR programs available in the aggregator network. Also, through this model, the aggregator participates in the day-ahead markets by trading these DR flexibilities. In the end, the authors validated their model by a numerical case study using Nordic electricity market.

In [25], the authors discussed a short-term decision-making model for an electricity retailer that included RERs. Also, short-term DR trading methodology has been proposed somehow the retailer submits this flexibility to the markets in each hour. Through the simulation performed in the case study, the authors validated that the financial profits of the retailer will be increased if it participates in both real-time market and short-term DR trading mechanism. A short-term self-scheduling model has been developed in [26], which is used by the DR aggregators. It also addressed the uncertainties of the electricity customers participating in the market. Two types of DR programs have been used in this model, which are reward-based DR and time-of-use. The proposed approach has been validated through a case study with realistic data from electricity markets.

Focusing on communication infrastructures in the aggregator network, the work presented in [27] focused on an energy quality aware bandwidth aggregation scheme. The authors firstly modelled the delay-constrained energy quality tradeoff for multipath video communications using wireless networks, and then, they present an approach to merge the rate adaptation. They surveyed the performance of the system using real wireless networks and emulations test beds. In addition to this work, in [28], the authors provided an energy efficient and quality guaranteed video transmission solution. In fact, they proposed an approach to characterize energy distortion tradeoff for video transmission in wireless networks. Furthermore, the authors of the same work developed an algorithm to optimize the energy consumption to achieve video quality target. Their experimental results demonstrated that the developed solution has performance advantages comparing to the schemes in term of energy conversion and video quality.

The main contribution of the present paper, according to the reviews presented above, where only a few of them were focused on the behavior of aggregator during ramp period of DR implementation, is the development of a model that considers short and real-time DR programs ramping, using real-time simulator and laboratory equipment. In fact, most of the previous works considered a simple period prior to the event showing and mainly focusing on the aggregator scheduling process or DR programs itself. Furthermore, a lot of interesting models and research works are available in the literature focusing on the concepts of aggregator under short and real-time DR programs. However, those lack adequate testing on real infrastructures under practical challenges and technical issues.

The following topics are addressed, supporting the main contribution of the paper:

- Evaluating the performance of aggregator during DR implementation timeline, especially the ramp period, in term of scheduling and remuneration;
- Improving aggregator resources management in short and real-time DR;
- Developing a real-time simulation model using a set of laboratory equipment to evaluate the aggregator's performance under practical and technical challenges;
- Remunerating consumers by comparing costs between the actual and simulated demand reduction profiles.

3. Proposed Methodology

This section presents the entire developed model for the aggregator and DR programs. The structure of this section consists of proposing the aggregator model focusing on its role in the electricity systems and wholesale markets. Then, it focuses directly on the DR timeline and the ramp period before the event being started. Later, DR programs specifications presented for the aggregator are demonstrated, and in the last subsection, a linear programming with the objective of DR cost minimization is shown for the aggregator model.

3.1. Aggregator Architecture

This part describes the architecture of the presented aggregator model for DR programs. In fact, the responsibility of the aggregator in this paper is to gather all small and medium scale DR participants located in the same geographical area and present this flexibility to the electricity market negotiation as a unique resource. To do this, the aggregator has to make bidirectional contracts with the electricity consumers who intend to participate in one or more DR programs. This enables the aggregator accordingly to control and monitor the consumption of the end-users. Figure 1 shows the role of aggregator as a network player in electricity systems and smart grid technology.

As Figure 1 illustrates, the aggregator has a transactional role between the downstream (medium and small-scale DR participants) and upstream (electricity markets and network operators) sides of the network. Indeed, the aggregator has two layers, namely communication-based controlling and monitoring sides. In the upper layer, the aggregator is in touch with network operators or electricity market operators. While some technical or economic instabilities occur in the network, and it is required to reduce network consumption, the aggregator will be notified by the upstream level players to apply DR programs. Subsequently, in the lower layer, the aggregator has a multi-round communication with the downstream level of the network (i.e., consumers), as it may have some voluntary DR programs. In other words, the aggregator cannot forecast the response of consumers to each DR event. This leads to having several iterations of DR requests from aggregator to the consumers, and in response, the consumers reply with their preferences, demand bids, reduction capacity, price signal, etc. This procedure will be continued until the aggregator reaches the reduction baseline, which is, in fact, one of the responsibilities of the aggregator during the ramp period. In the last step, the aggregator presents DR bids in the electricity markets with a certain rate based on the real-time price of the market. Generally, the aggregator has day-ahead information of DR bids, such as forecasted reduction rate. Therefore, it should consider the reduction rate a bit higher than the forecasted baseline. This is due to preventing possible failures in the case of some consumers opting out during the event.

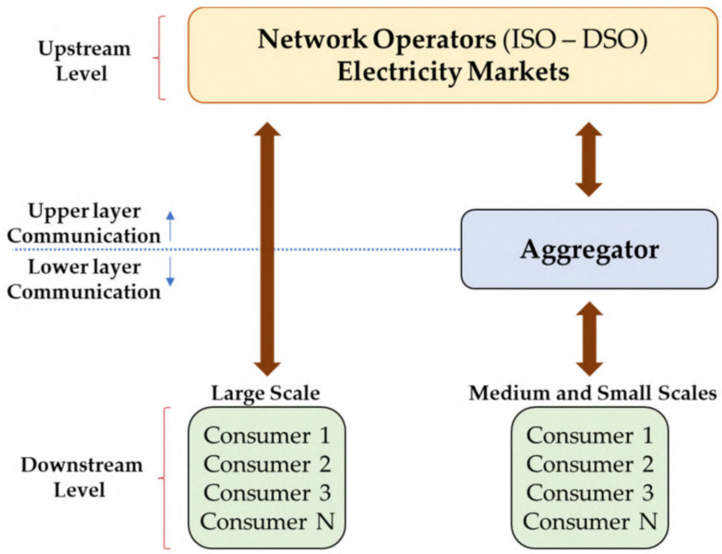

Figure 1. Participation of aggregator in the electricity system as a third-party entity.

In the practical phase, communication infrastructures are very important as they play as a base for the network management strategies, as all network players must exchange data continuously in real-time. This is more visible in critical moments, such as the ramp period, as the aggregator should have real-time information of the DR participants. Furthermore, there are instances during the DR event or ramp period whereby aggregator needs to verify that the consumers have followed the DR programs and contractual reduction correctly, according to the request of the operator (in the case of incentive-based DR). Therefore, all consumers should be equipped with a local energy management system, smart metering, and advanced metering infrastructure (AMI) to monitor real-time data, especially power consumption.

3.2. DR Timeline and Ramp Period

The ramp period is the time that the DR program manager gives to consumers in order to reach the contractual DR event baseline. The duration of the ramp period can be various based on the type of consumers, type of loads, the geographical location of the electricity market and system operator, etc. Also, all consumers will be notified in advance (from several months to 5 min) prior to the ramp period. Consequently, in short, and real-time DR programs, the tasks of aggregator are more complex as it should process the advance notification time, ramp period, and response duration before starting the event.

While the DR program manager specifies a DR event to be implemented by the aggregator, lots of information and setpoints will be dispatched and transmitted between these two entities. Figure 2. illustrates the timeline and information specified for a DR program. In fact, most of the parameters in the following timeline, such as the duration of assessment and ramp period, are defined by the DR program manager and transmitted to the aggregator using the upper communication layer shown in Section 3.1.

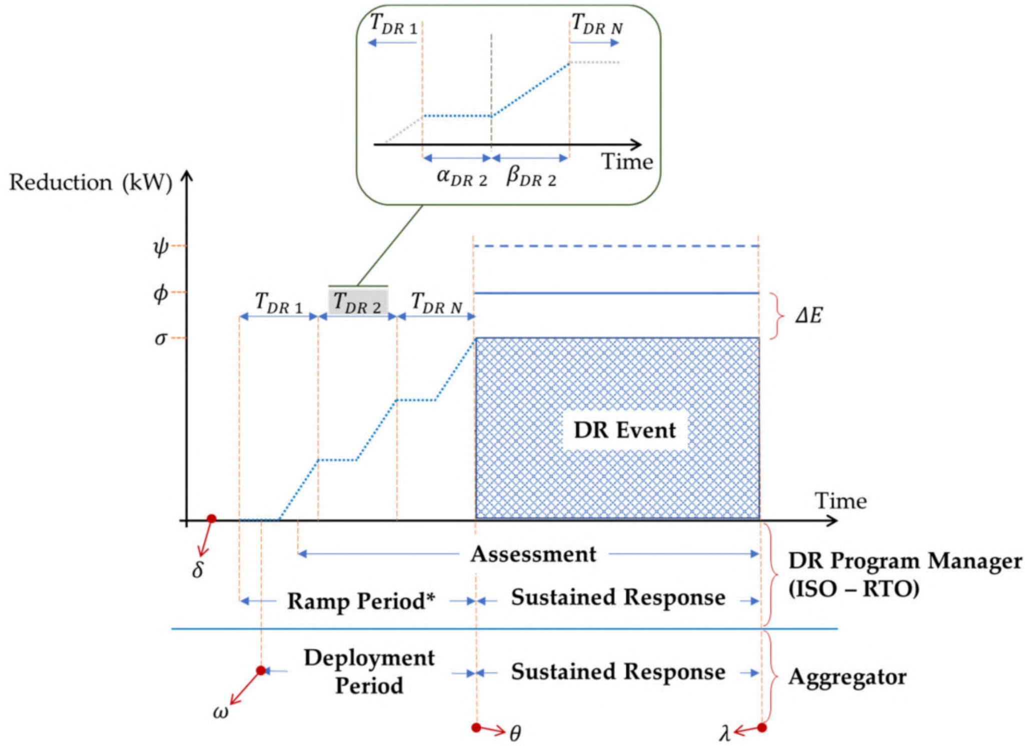

Figure 2. Timeline for demand response implementation by the aggregator.

The first point in the timeline shown in Figure 2 is the announcement deadline (δ), which is the last opportunity for the DR program manager to notify the aggregator for the DR event. After then, there is a ramp period considered as the time that aggregator is allowed to reach the desired amount of reduction. In the meanwhile, the deployment starting point (ω) is a moment during the ramp period that aggregator can take a risk to start the event by relying on forecasting the availability of DR resources. The main difference between deployment and assessment periods is that assessment is a paid period. The deployment period is the period that aggregator collects all the DR amount by different programs. In fact, the aggregator is able to collect all DR amounts within the ramp period, but it is free to start the event a bit later than the starting point of the ramp period. However, the aggregator can operate cautiously and notify DR resources for the event, during the ramp period, and wait for their response. In the last stage, the reduction deadline (θ) is the point at which the aggregator evaluates the available reduction capacity and verifies that their capacity is above the forecasted reduction baseline (ϕ). However, the event could also be started if the available reduction capacity is in the margin of forecast error (ΔE), above the reduction baseline (σ) defined by the DR program manager. While the DR event has been started, the timeline enters a sustained response period, which is the time that DR participants have to maintain their committed level of reduction until the end of the event (λ). During the sustained response period, both communication layers shown in Figure 1 are involved. In the lower layer, consumers transmit the related information to the aggregator, namely real-time consumption, and in the upper layer, aggregator conveys the consumer's information to the DR program manager.

Focusing on the ramp period in the lower communication layer of aggregator, Figure 3 demonstrates a cascade communication process during the ramp period between aggregator and consumers. By comparing Figures 2 and 3, in the first point of the ramp period, aggregator notifies consumers associated with demand response program (DRP) 1. This leads to having an activation notification period, indicated by α_{DR} in the timeline illustrated in Figure 2. After that, consumers reply with OPT IN or OPT OUT, and then if they are OPT IN, they will start the load reduction process. This has been indicated by β_{DR} in the timeline shown in Figure 2 that stands for the actual response period.

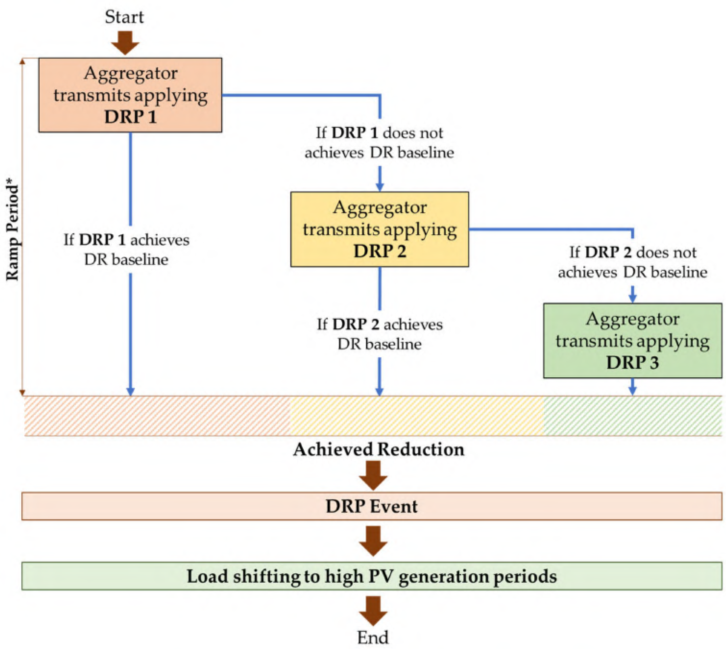

Figure 3. Ramp period evaluation process by the aggregator.

While consumers are replying with the actual reduction, the aggregator assesses the DRP 1 to check if it is sufficient for achieving the reduction baseline. If DRP 1 was insufficient, the aggregator evaluates the use of DRP 2 and notifies the consumers associated with DRP 2. This procedure is continued until the aggregator achieves to the forecasted reduction baseline, so it can inform the DR program manager and start the event.

3.3. Demand Response Programs

The aggregator is able to implement various types of DR programs. However, each program has its specific timescale. Therefore, the aggregator should select the most appropriate program according to the available timescale and objective, from long-term to real-time (Figure 4). In this paper, the main focus is given to short and real-time programs, as the ramp period is more critical in such programs. Therefore, the programs with long-term timescale (months or years planning) will be ignored.

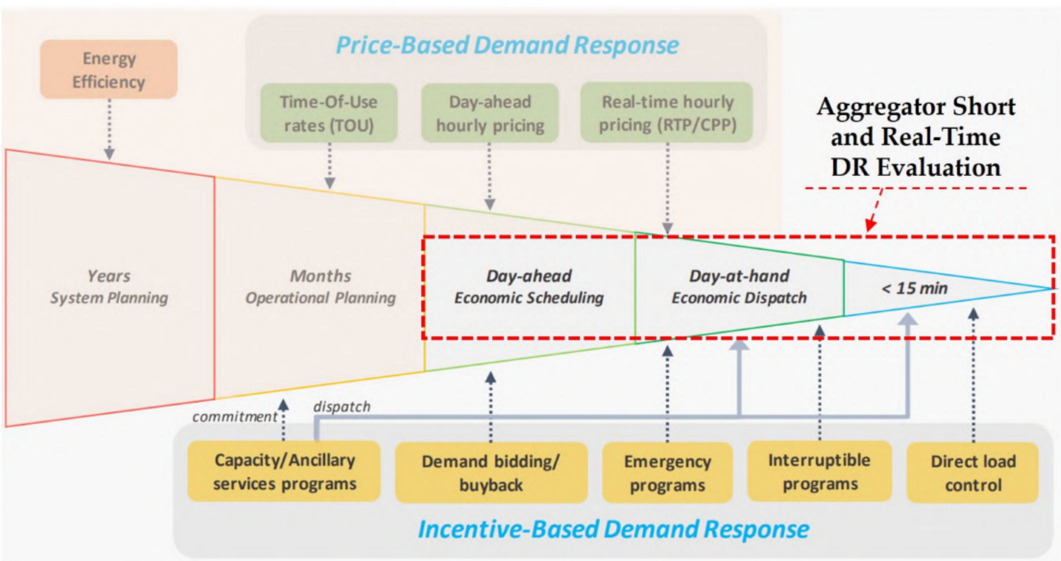

Figure 4. The timescale of demand response implementation. Adapted from [22].

Furthermore, short and real-time DR programs are more applicable comparing to other types of programs. The reason is they are usually implemented for improving or maintaining power quality as well as security of the power distribution network (e.g., voltage and frequency instabilities issues). In this context, incentive-based DR programs are the ones that can be implemented in short-term to real-time timescale, especially less than 15 min. If the aggregator intends to define a DR program, there are plenty of parameters and specifications that have to be considered. In below, there is a list of the most relevant ones to the model proposed in this paper:

- Program Type: Depending on the specification of the market, the DR program can be mandatory or voluntary. In voluntary programs, consumers can decide to participate in the event or not. In mandatory programs (e.g., DLC), the aggregator has full control over the contractual equipment as there is no need for consumer's permission. However, all DR participants will be notified before events whether in mandatory or voluntary programs;
- Remuneration: Most of DR programs has a remuneration rate that can be a power tariff discount, or an incentive paid for reduced kWh. However, some DR programs can be without remuneration as they are price-based;
- Activation signal: The aggregator can activate the event by transmitting a signal to the local controller on the consumer side. This signal can be a reduction notification, actual consumption level, electricity price notification, DLC control signal, etc.;
- Measure/Contract: The aggregator should specify in the program that what kinds of information DR participants must convey to the aggregator during the sustained response period. As an example, it can be the actual kWh reduction or real-time consumption data.

While a lot of DR programs with various specifications and parameters are accessible for the aggregator to implement, a question would be raised that which program is the most economical and optimal solution for the network. Therefore, DR program dispatch can make the use of a linear programming approach as will be explained in the next subsection.

3.4. Optimization

In this part, a set of the mathematical formulation is proposed for the aggregator model to choose the most optimal DR solution. The formulation is related to linear programming with the objective of DR cost minimization from the aggregator standpoint. As mentioned before, all consumers participating in DR programs have a contractual reduction limit as well as a remuneration tariffs associated with each program.

Equation (1) shows the objective function of the proposed linear programming, which aims to minimize the costs related to the DR programs. In this model, technical specifications of the grid, such as load balance, voltage control, etc. are not considered as it is assumed that the network operator is accountable for them. Furthermore, it is presumed aggregator will not sell/buy electricity to/from consumers, and it is only responsible for DR program implementation and provide these flexibilities to the market negotiations. So, the focus of these formulations is only given to economic aspects of DR programs from aggregator standpoint.

$$\begin{aligned} &Minimize \\ &DR\ COST = \sum_{t=\theta}^{\lambda} \sum_{c=1}^{C} \left[P_{DR\ S_{(t,c)}} \times I_{DR_{(t,c)}} \right] \end{aligned} \tag{1}$$

The proposed objective function is modeled as a linear programming optimization problem using Rstudio® tool (www.rstudio.com), using a computer with Intel® Xeon® CPU @2.10 GHz, and 16 GB RAM. The linear and convex problem implemented, which includes in the present case study 4860 variables, can be solved by brute-force, heuristics, and others. There are several constraints that are applied to this objective function. Equation (2) shows the limitation of each DR resource in terms of minimum and the maximum capacity of them. Also, Equation (3) presents that the sum of capacity in available schedulable and non-schedulable DR resources ($P_{DR\ S} - P_{DR\ N}$) during the event should be higher than the reduction baseline in addition to the forecast margin error. This means that aggregator is always counting on an extra reduction capacity higher than the defined baseline to prevent the possible failures if some consumers opted out during the event. However, there is a limit for this extra capacity, and if the reduction goes higher than this limit, the additional capacity is not being paid. This is shown by Equation (4).

$$0 \leq P_{DR_{(t,c)}} \leq P^{max}_{DR_{(t,c)}} \qquad \forall t \in [\theta : \lambda], \ \ \forall c \in \{1, \ldots, C\}, \tag{2}$$

$$\sum_{c=1}^{C} P_{DR\ S_{(t,c)}} + \sum_{c=1}^{C} P_{DR\ N_{(t,c)}} \geq \sigma + \Delta E \qquad \forall t \in [\theta : \lambda] \tag{3}$$

$$\sum_{c=1}^{C} P_{DR\ S_{(t,c)}} + \sum_{c=1}^{C} P_{DR\ N_{(t,c)}} \leq \psi \qquad \forall t \in [\theta : \lambda] \tag{4}$$

In sum, this section presented the developed aggregator model with a focus on the DR timeline and aggregator's responsibility during the ramp period before the DR event is started. In the next section, a case study is proposed in order to validate and survey the functionalities of the presented model using an actual methodology and real infrastructures.

4. Case Study and Real-Time Simulation

This part explains a case study for validating and surveying the performance of the developed model under different challenges. To do this, it is considered that there is a small village with a lot of residential and commercial consumers, and only 27 of the residential consumers have direct DR contract with the aggregator. This means that the aggregator has no interaction with other consumers that are not participating in the DR programs. In the aggregator network, there are 10 consumers equipped with Photovoltaic (PV) panels as RERs, and five consumers with energy storage system (ESS). The use of RERs makes the aggregator capable to shift the load in the high PV generation periods, as the energy produced by this resource is uncontrollable. Figure 5 shows the village and the related aggregator network. In this case study, a part of the DR participants in the aggregator is being emulated by a set of laboratory equipment, so-called resistive loads bench in this paper. In this way, the aggregator's performance can be surveyed in both simulation and experimental aspects.

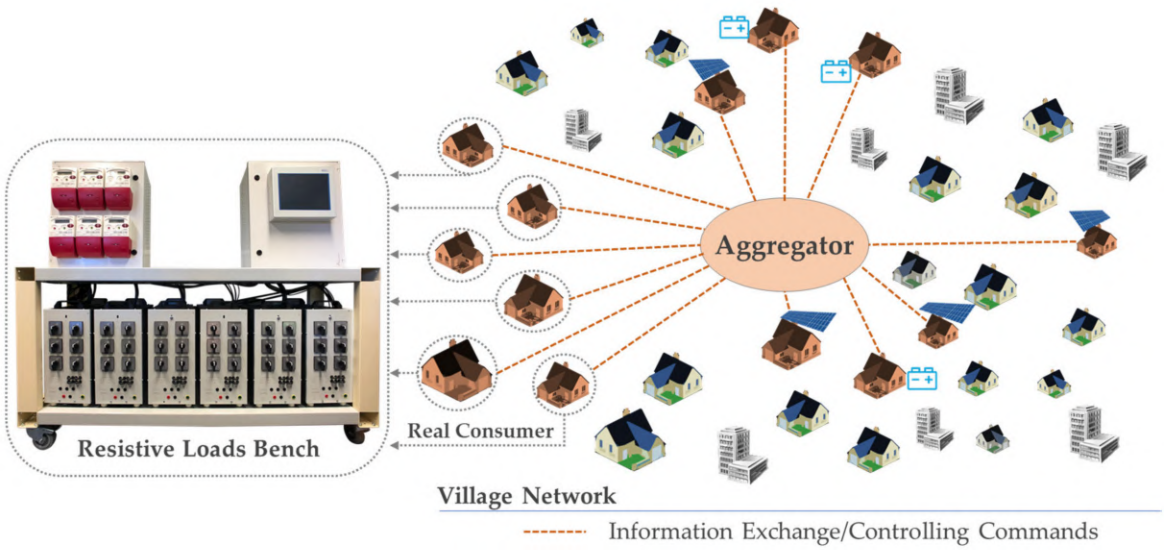

Figure 5. Schematic of the aggregator network in the case study.

The resistive loads bench consists of six resistive consumer loads that each of which has a nominal capacity of 4 kW. The bench is equipped with a set of controlling and monitoring devices, including a programmable logic controller (PLC) as a central controller of the bench, a set of relays to control the rate of consumption in each load, and a set of energy meters and commercial smart meters in order to monitor the real-time consumption of the loads. To survey both numerical and experimental features of the aggregator, a MATLAB™/Simulink model has been developed representing the electrical network of the 27 consumers in the aggregator model, as Figure 6 shows. Moreover, the OP5600 real-time simulator has been utilized to integrate the resistive loads bench in the Simulink model as hardware-in-the-loop (HIL). In fact, OP5600 executes the Simulink model in real-time enabling the user to control and monitor real hardware resources outside of simulation environments. This is done through several communication protocols as well as Digital and Analog slots in OP5600. More information about the performance of OP5600 and HIL methodology are available in [12].

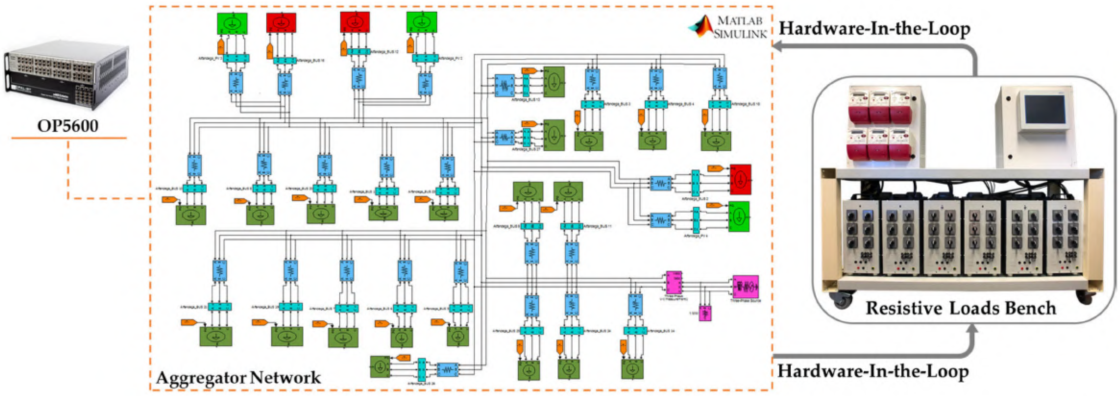

Figure 6. Real-Time simulation model of aggregator integrated with HIL methodology.

Regarding the DR programs, three types of programs are considered that consumers are able to establish with the aggregator, as Table 1 shows. Each program has its own features and specifications, which the aggregator defined according to the instructions and regulations of the upstream network players, such as market operator and DR program manager.

Table 1. DR contracts available for consumers to establish with aggregator.

DR Type	Mandatory/ Voluntary	Activation/ Signal	Remuneration	Measure/ Contract	Associated Device	Notification Time
DLC T1	Mandatory	Directly to the device	0.05 EUR/kWh	Actual kWh reduction	Washing Machine, Dishwasher	5 Min
DLC T2	Mandatory	Directly to the device	0.30 EUR/Event	Actual positive reply	Air Conditioner	5 Min
IDRP	Voluntary	Reduction Notification	0.03 EUR/kWh	Actual kWh reduction	Water Heater, Fan Heater	30 Min

The DR programs and the related remuneration rates shown in Table 1, has been developed by the authors in the scope of their previous works, and only the most relevant description has been mentioned in this part. More detailed information about these DR programs is available in [29]. According to Table 1, if a consumer establishes a contract with the aggregator for DLC T1, it will give permission to the aggregator to directly control its air conditioner, and in exchange, the consumer receives an incentive of 0.05 EUR/kWh for the reduction. In the DLC T2 contract, the aggregator is able to directly control the washing machine and dishwasher of the DR participant for a contractual number of events per month. Consumers who participate in DLC T2 receive an incentive of 0.06 EUR/kWh for the reduction. The last DR contract that consumers can establish with aggregator is IDRP. As this program is voluntary, the consumer can decide to participate or not. Therefore, a longer notification time is considered for this program, so the consumer has an adequate amount of time to make a decision. Table 2 demonstrates the capacity of the associated devices in all 27 consumers related to the aggregator network. The capacities shown on the same table are in kiloWatt (kW). As is clear in Table 2, each consumer has at least one DR contract with the aggregator. This means that the associated devices dedicated in Table 2, are being controlled by aggregator in DLC T1 and T2 programs, and by consumer itself in IDRP. The capacities shown in Table 2 are an average between the minimum and maximum active power consumption of each during an entire day.

Table 2. Controllable devices involved in the DR programs (AC = Air Conditioner, WM = Washing Machine, DW= Dishwasher, WH= Water Heater, FH = Fan Heater).

Consumer ID	DLC T1	DLC T2		IDRP		Consumer ID	DLC T1	DLC T2		IDRP	
	AC (kW)	WM (kW)	DW (kW)	WH (kW)	FH (kW)		AC (kW)	WM (kW)	DW (kW)	WH (kW)	FH (kW)
1	0.54		0.62	0.33		**15**					
2	0.24		0.19	0.29		**16**	0.24				
3	0.39	0.16	0.16	0.20		**17**					0.17
4	0.23	0.18	0.50	0.31		**18**	0.51	0.27	0.45		
5	0.55	0.15	0.50			**19**			0.09	0.19	
6	0.17		0.50			**20**	0.05				
7	0.05		0.07	0.35		**21**	0.39	0.34	0.66	0.46	
8	0.76		0.07	0.23		**22**	0.33	0.25	0.63		
9	0.39	0.19	0.22	0.30		**23**	0.20				
10	0.05					**24**	6.90				0.27
11	0.43					**25**	1.50				0.17
12					0.27	**26**	4.71				0.17
13	0.05		0.19			**27**	0.52				0.12
14	0.02					-	-	-	-	-	-

Furthermore, as Table 2 shows, 85% of consumers are equipped with air conditioner, 26% of them have washing machine, 52% include dish washer, 33% have water heater, and 22% of them have fan heater. Figure 7 illustrates a day-ahead consumption and generation profile of the entire aggregator network as well as available DR capacities presumed for the case study based on Table 2. The data shown in Figure 7 are for a random winter day with a 15-min time interval, and adapted from a research project [30] related to the implementation of an intelligent energy management system in two small cities in Portugal.

The consumption shown in Figure 7 is only related to the aggregator network (27 consumers) and not to the entire village. Moreover, the uncontrollable part of consumption is related to the devices on the consumer side that aggregator has no interaction with them. In this case study, it is considered that the aggregator receives a DR event from the DR program manager with 10 kW as the reduction baseline, starting at 12:00 PM for two hours. Also, the aggregator is notified one hour in advance. The reason for this DR event could be a technical fault or any economic causes in the main grid. Figure 8 shows the DR event applied in the aggregator consumption profile.

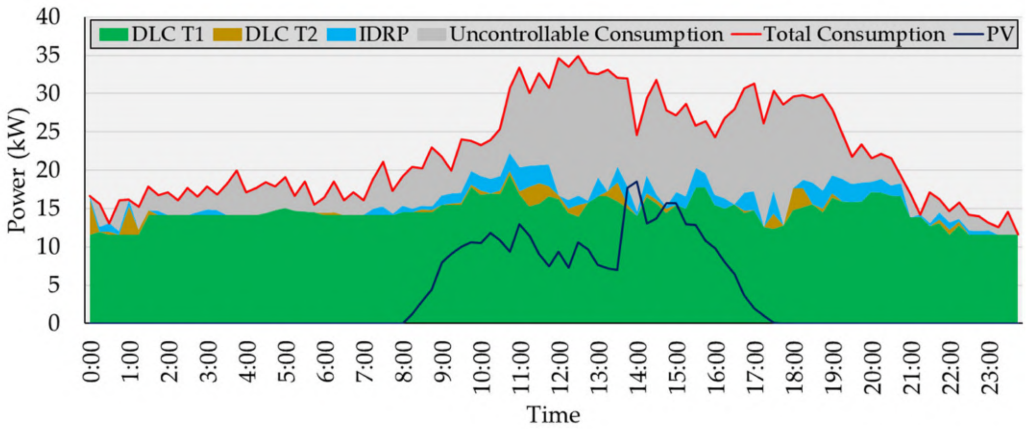

Figure 7. Aggregator consumption profile and stacked available DR capacities.

As Figure 8 shows, the reduced consumption during the DR event has been shifted to some periods after the event that have a high rate of PV generation. This enables the aggregator to use the energy produced by the local resources. Since the notification time of the event is one hour in advance, the aggregator should reach the reduction baseline for one hour (i.e., ramp period). Therefore, the aggregator starts announcing the consumers one by one to participate in the event. In the meantime, if some consumers have delay on replying to the DR announcement, the aggregator is able to use and discharge the available ESS in order to compensate the response time of the consumers. Also, the aggregator adjusts its internal reduction baseline to around 15 kW for keeping the consumption rate at 20 kW. This is due to overcoming the possible issues during the event, namely some consumers opting out.

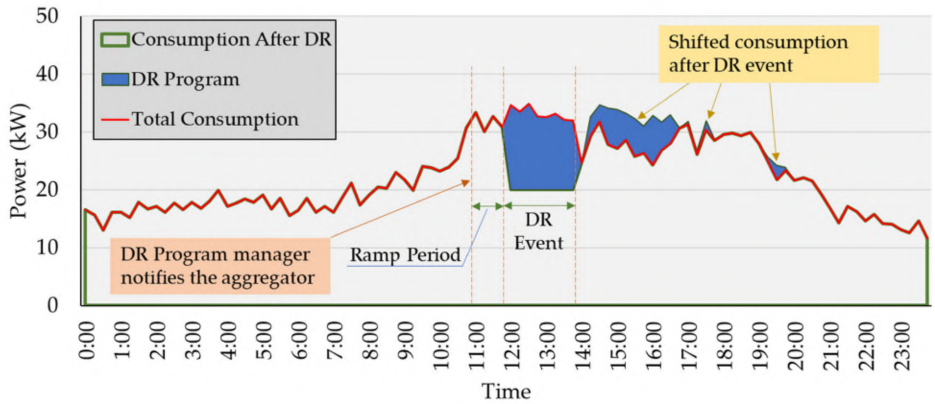

Figure 8. Proposed DR event applied in the aggregator consumption profile.

In practice, a consumption profile with a 15-min time interval is not that applicable for remuneration and scheduling purposes, as a lot of changes could happen during this time. In some cases, it is possible that the DR program manager pays incentives to the aggregator with a 15-min time interval. However, in the downstream side of the network, as the aggregator is dealing with every single consumer, the 15-min time interval is a long period. Consequently, in order to have a clear vision of the consumption profile during the ramp period and DR event, Figure 9 illustrates the aggregator consumption curve between 11:00 to 14:00, with a 1-min time interval. In the same figure, the uncontrollable part of aggregator consumption is not shown as the focus is given to the controllable part of consumption.

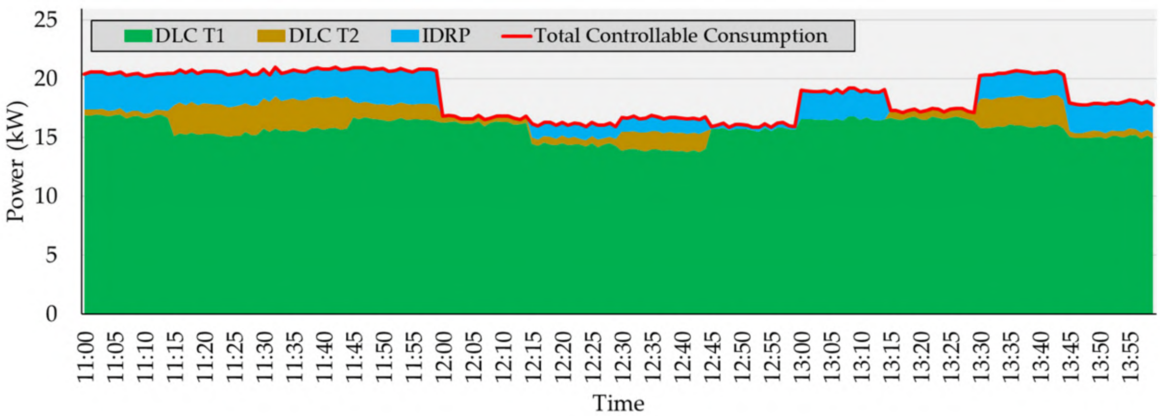

Figure 9. Available Demand response programs during ramp period and event.

As is clear in both Figures 7 and 9, almost half of the consumption during ramp period and the event itself is dedicated to DLC T1 (air conditioner), and only a few parts are devoted to DCL T2 (washing machine and dishwasher) and IDRP (water heater and fan heater). As the fan heaters in the IDRP program are resistive loads, they are a suitable target for emulating by resistive loads bench. Thus, in the next section (results) all fan heaters in the aggregator that are associated in the IDRP program are being emulated by the resistive loads bench and the behavior of each device as well as the aggregator facing an actual profile will be scrutinized.

5. Results

This section presents all the gained results from the aggregator standpoint. All the results provided in this section are for surveying the performance of the aggregator model during the ramp period and the DR event itself. Figure 10 shows the consumption reduction profiles after applying DR programs. The results shown in the same figure are with the one-minute time interval between 11:00 where the DR program manager notified the aggregator for the event, until the end of the event (14:00).

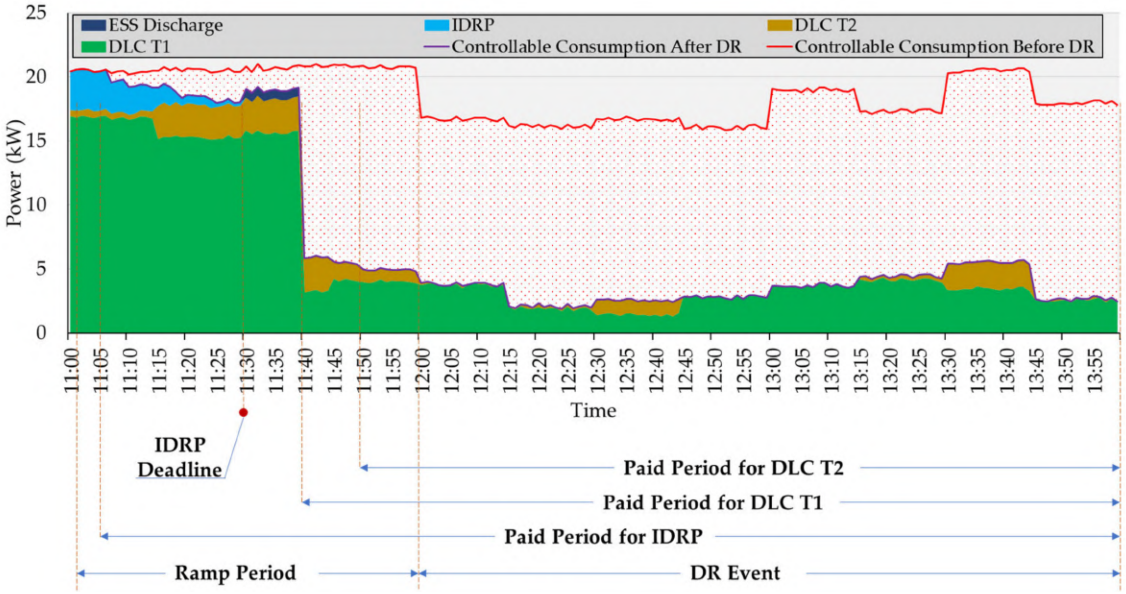

Figure 10. Results of applying demand response programs by the aggregator.

As it is clear in Figure 10, the aggregator firstly started to apply IDRP since it has the lowest remuneration rate from the aggregator point of view. To do this, the aggregator announced all the IDRP resources one by one and waited for their response as the program is voluntary. Then, all IDRP participants replied with their desired responses (OPT IN or OPT OUT) until 11:30 (program deadline). After that, the aggregator evaluates the use of the IDRP program and as it did not reach the reduction baseline, it decided to apply DLC T1 program. Therefore, the aggregator notifies DLC T1 participants 5 min in advance (11:35) to the starting point of the event (11:40). During this 5 min, the aggregator takes advantage of the available ESSs and start discharging them, so there would be a reduction in the consumption. While all resources in DLC T1 have participated in the event and the reduction rate of DLC T1 has been reached, the aggregator stops discharging the ESSs. The same procedure is also applied for DLC T2, and finally, at 11:50, when the aggregator reached the desired reduction baseline and it is ready to start the event at 12:00.

Moreover, as Figure 10 shows, the starting point of the paid period for each program is the moment that the first participant reduced its consumption, so the aggregator has to pay the contractual remuneration according to the reduced power. In other words, the aggregator receives the remuneration from the DR program manager only for event duration (i.e., in this case, two hours between 12:00 to 14:00). However, the aggregator must start paying the remuneration before the event during ramp period as the DR participants started the consumption reduction. That's why aggregator should pay remuneration to the DR participant with a lower rate than the one that it receives from the DR program manager, so it would be able to manage all the paid periods without a financial downturn.

In order to have a more precise and technical vision to the model, Figure 11 illustrates the experimental results adapted from the real-time simulation model and Resistive Loads Bench as HIL. The results shown Figure 11 are related to the 6 DR participants that own Fan Heater and they are involved in the IDRP (indicated in Table 2). In fact, each consumer load in the Resistive Loads Bench emulates a Fan Heater in each DR participant. The results demonstrated in Figure 11 are adapted from MATLAB™/Simulink and OP5600 in 3600 periods of 0.5 s, which is in total 30 min, between 11:00 to 11:30 while all IDRP resources are announced to participate. In other words, the time step of this model in real-time simulation is set at 0.5 s. This means OP5600 conveys the reference signal (power reference in Figure 11) to the resistive load bench with one-minute time interval, and then, it acquires real-time consumption data with 0.5 s time interval. The actual power measurement curve in Figure 11 shows the real behaviors and reactions of resistive consumer loads, and it is only shown until the IDRP deadline, as after this moment all their consumption was cut.

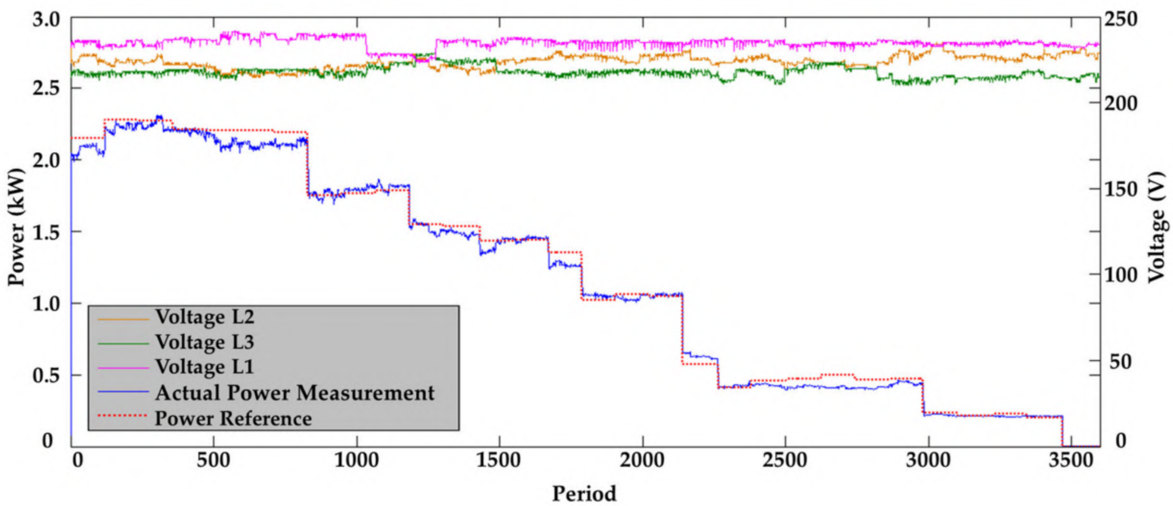

Figure 11. Experimental results adapted from OP5600 and Resistive Loads Bench.

Indeed, employing real-time simulation (OP5600) and laboratory equipment as HIL for emulating consumption profiles have several advantages. One of them is that we validate the actual demand reduction under the technical parameters of the grid, namely voltage variations (as shown in Figure 11). This leads to having a gap between the experimental and simulation results. This gap is clearly visible in Figure 11 between the red dashed line as Power Reference and the blue line as actual power measurement. Consequently, it is interesting to calculate and compare the remuneration costs of aggregator using both experimental and simulation results. Figure 12 shows the accumulated remuneration costs during the ramp period and the event using simulation profiles.

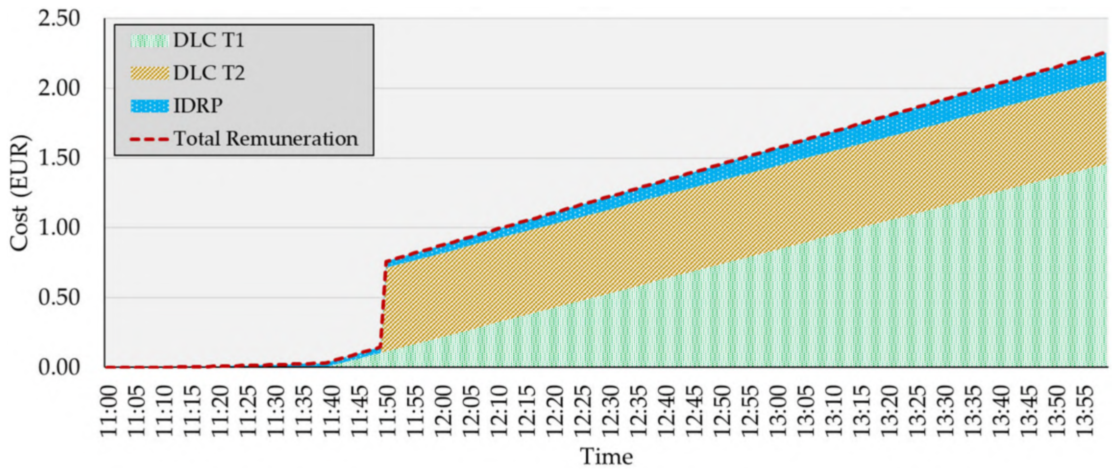

Figure 12. Accumulated remuneration costs of aggregator during the ramp period and the event.

As Figure 12 shows, there are a few remuneration costs for the IDRP program as the remuneration rate and the available capacity were not significant. Also, the costs of DLC T1 has a linear ascending gradient since the available capacity of this program was constant during the event. Finally, as DLC T2 has a fixed remuneration rate per event, it has a constant ratio in the aggregator's remuneration expenses. Table 3 demonstrates the detailed cost calculation for each program. In Table 3, the main focus is given to the first 30 min of the IDRP program as the real-time simulation and HIL methodology have been implemented for this specific program. The actual and simulation profiles are respectively the blue (actual power measurement) and red dashed line (power reference) in Figure 11.

Table 3. Remuneration costs for each program paid by the aggregator to DR participants.

Program Type	**DLC T1**	**DLC T2**	**IDRP**		
Applied Period	11:00 to 14:00	11:00 to 14:00	11:00 to 11:29		11:30 to 14:00
			Actual Profile	Simulation Profile	
Cost (EUR)	1.4583	0.6	0.0083	0.0081	0.1907

Total Cost = 2.2573 EUR (using actual profile); 2.2571 EUR (using simulation profile).

As Table 3 shows, the calculated remuneration cost between 11:00 to 11:29 in IDRP has a difference between the actual and simulation profiles. This cost difference is not significant because in this specific model it is only for six fan heater devices as a part of the IDRP program, which has a little reduction capacity for 30 min. Suppose that the aggregator has a huge number of DR participants, namely 1 million customers with a longer DR event. Therefore, this little difference becomes remarkable in this case as it would mean a huge amount of cost variation between what it is expected and what occurs in actual cases.

6. Conclusions

Using renewable energy resources and distributed generation has an important role to reduce the peak of greenhouse gas emissions. Innovative management strategies, such as integrating demand response programs, are required. This paper presented a precise vision of the demand response timeline in an aggregator model. The proposed aggregator has been considered as a third party between the upstream and downstream sides of the network, to aggregate small scale demand response resources.

The time needed in the short and real-time demand response programs to notify all participants, to wait for their response, and evaluate the available resources is addressed.

For real-time simulation, a set of resistive loads to emulate the actual demand reduction of some demand response participants have been used. The numerical results highlight that the costs related to the periods prior to the event, such as ramp period, should be taken into account as in the most of model, demand response costs are only related to the period between the starting and ending point of the event. It should always be considered that normally the aggregator does not reach the desired reduction level immediately, and it requires some time to reach the desired reduction level. Regarding the remuneration, while the consumption is being reduced, consumers expect to receive remunerations for the related consumption reduction, even if the reduction has occurred prior to the starting of the event.

The experimental results obtained through emulation of loads indicate that there is a gap between the expected and actual results. In this way, laboratory tests play an important role to reveal technical issues of any model under practical challenges, namely voltage variations, frequency instabilities, and other electrical grid conditions.

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Nomenclature

T_{DR}	Required time to achieve demand response baseline
α_{DR}	Notification time specified for each demand response program
β_{DR}	Actual response time of demand response program
ψ	Maximum paid reduction
ϕ	Forecasted reduction baseline
σ	Reduction baseline
δ	Announcement deadline
ω	Deployment deadline
θ	Reduction deadline
λ	The finishing point of the demand response event
ΔE	The forecast error margin of reduction baseline
$\boldsymbol{C}$	Number of consumers
I_{DR}	Incentive paid for each demand response program
$P_{DR\ N}$	The non-schedulable demand response program
$P_{DR\ S}$	The schedulable demand response program

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Towards transactive energy systems: An analysis on current trends

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ABSTRACT

This paper presents a comprehensive analysis on the latest advances in transactive energy systems. The main contribution of this work is centered on the definition of transactive energy concepts and how such systems can be implemented in the smart grid paradigm. The analyzed works have been categorized into three lines of research: (i) transactive network management; (ii) transactive control; and (iii) peer-to-peer markets. It has been found that most of the current approaches for transactive energy are available as a model, lacking the real implementation to have a complete validation. For that purpose, both scientific and practical aspects of transactive energy should be studied in parallel, implementing adequate simulation platforms and tools to scrutiny the results.

1. Introduction

Nowadays, the management of power distribution networks is becoming more difficult than before, mainly due to high electricity demand and large penetration of Distributed Energy Resources (DERs) including renewables. The penetration of renewables as a mean of electricity production is expected to increase in the years to come up to around 30% by 2022 [1] and up to 60% by 2050 [2]. Renewable energy sources (RES) and DERs promise benefits such as the reduction of environmental concerns due to energy production, but at the same time will pose numerous challenges of technological, social, and policy related nature [3,4]. Therefore, the hierarchical and centrally-controlled approach of existing power distribution networks is moving toward a smart power grid paradigm in which the unforeseen peaks of distributed local energy production and uncertainty of renewables can be properly managed [5,6]. Smart grids are intelligent electrical networks employed for enhancing critical features of typical power system, such as flexibility, reliability, sustainability, efficiency, etc., by making the grid controllable, automated and fully integrated [5]. In such a new paradigm, the concepts of Demand Response (DR) programs and Transactive Energy (TE) are widely discussed in the scientific and research societies, with the purpose of balancing the network in term of consumption and generation [7]. In most of the cases, DR programs are only focused on the consumption part of the network, which brings flexibility to the grid by paying incentives to the electricity consumers in exchange of altering their consumption profiles [8–10]. However, only concentrating on the consumption management based on the generation rate might not fully exploit the capabilities of future smart power systems. Due to this, TE is discussed as a mean to not only focus on the consumption part of the network but also to provide solutions to manage the rate of generation in both grid and demand sides [11].

Smart grids, therefore, provide a basis for the implementation of TE systems. To do this, several requirements are essential in this context, such as two-way communication, merge of Information and Communication Technology (ICT) and electricity grid, intelligent and remote supervision, Advanced Meter Infrastructure (AMI) and smart metering [4]. In fact, TE systems expand the current concepts of wholesale transactive power systems into retail markets with end-users equipped with intelligent Energy Management Systems (EMSs) to enable small electricity customers to have active participation in the electricity markets [12]. TE systems can also enable peer-to-peer (P2P) management in smart grids by using intelligent devices in which each device has its own decision and objective.

Both DR and TE open new opportunities in power grids regarding the optimization of power flows, stability of the grid, and energy efficient. At the same time, distributed resources used for DR and TE are intermittent (e.g., in the case of renewables) and nonuniformly deployed, which possess new challenges to be faced in the management of resources [13]. These challenges can be tackled through centralized and decentralized approaches, each of which has its own advantages and disadvantages [14]. Therefore, proposed methodologies should be well tested and validated through several real case studies to identify the strengths and weaknesses on the implementation and preventing future problems.

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This paper presents a comprehensive survey and analysis on the latest advances of TE and their applications in the new paradigm of power systems. The main contributions of this paper are related to:

- TE definition and how TE systems are being integrated in the smart grid context.
- An analysis and comprehensive survey of TE research works, industrial projects and demonstrations.
- A classification of TE research based on the grid level of application into three broad areas: (i) transactive network management (management sector); (ii) transactive control (control sector); (iii) P2P markets (P2P sector).
- Identification of current challenges of TE systems and future work directions.

After reviewing up to 140 works (including articles, scientific reports, projects, and demonstrators) produced between 2006 and2019[1] related to TE, analyzing the keywords from those works, and identifying the grid level of application, the authors propose three areas in which TE concepts can be classified, namely: (i) transactive network management; (ii) transactive control; (iii) P2P markets. Fig. 1 shows the overall view of the identified concepts related to TE and how they can be positioned on the different layers of the power system. Transactive network management is considered as the first category since it is related to management sector of the electricity supply chain. Transactive control is considered as control sector, enabling network operators in the upstream side to control and manage the rate of consumption/generation of the electricity customers in downstream side. Finally, P2P markets are energy exchange methodologies in the P2P sector of electricity system allowing all consumers and prosumers to bid and offer for transacting energy. While this classification is not unique or universal, it can help the reader to positioning the area of study/application, and to devise the interconnection and reaches that a given TE system might have. The details of the topics in this classification are covered in Sections 3, 4, and 5 respectively.

In a complex multidisciplinary paradigm such as TE, both scientific and practical aspects should be considered, learning from past experiences to estimate and prevent probable future issues. Besides, adequate models and tools are essential to address the manners on how TE would be integrated within the current form of power systems. Therefore, this paper aims at surveying TE works to identify gaps and critical aspects in different sectors of the energy chain and to respond and overcome issues that might arise in the coming years.

The paper is organized as follows: After this introduction, Section 2 presents and discusses the main concepts that are used throughout the paper. Section 3 focuses on transactive control methodologies and how they can be integrated into the various kinds of buildings in the demand side. Also, a general overview and a critic analysis of the recent research work in this area is presented. Section 4 presents an overview of P2P markets from both network operator and end-users standpoints. A comprehensive analysis of energy negotiations and contracts for energy trading between customers is also presented. Section 5 surveys centralized and decentralized TE-based network management solutions, covering both models and studies proposed in the literature. Section 6 focuses on the implemented TE research and industrial projects and demonstrations. A classification of projects, differentiating the ones implemented in the United States and the ones in Europe, is also provided with the goals and achievements of each project. The challenges and issues identified through this paper for TE are mentioned in Section 7, along with suggested solutions as future work. Finally, the conclusions provided in Section 8 summarize the relevant points identified throughout the document, including advances and limitations that lead to emerging research paths.

[1] The reviewed work was obtained by searching keywords related to TE into scientific data bases such as: Scopus, IEEE, science direct, and official project websites.

2. Background

At the first stage, it is essential to survey the definitions of TE. There are various definitions proposed for TE in the current literature:

- *"A system of economic and control mechanisms that allows the dynamic balance of supply and demand across the entire electrical infrastructure using value as a key operational parameter."* [15]
- *"A software-defined grid managed* via *market-based incentives to ensure grid reliability and resiliency. This is done with software applications that use economic signals and operational information to coordinate and manage devices' production and/or consumption of electricity in the grid. Transactive energy describes the convergence of technologies, policies, and financial drivers in an active prosumer market where prosumers are buildings, electric vehicles, microgrids, VPPs or other assets."* [16,17]
- *"Techniques for managing the generation, consumption, or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints."* [18].
- *"An internet-enabled free market, where customer devices and grid systems can barter over the proper way to solve their mutual problems, and settle on the proper price for their services, in close to real time."* [19].

Despite variations on the TE definition over different works, one of the most accepted definitions is the first one proposed by the GridWise Architecture Council (GWAC) (see for instance Refs. [13,20,21] in which this definition is used), defining TE as the economic and control methodologies for managing the rate of consumption and generation resources and the energy trading within a power distribution network based on market mechanisms. Other definitions (such as the ones presented above) are variations of this idea depending on differences in the context of application. Therefore, in this paper we adopt the definition from the GWAC to avoid any confusion to the matter. In this regard, a TE system is defined as the electric power systems in which TE concepts have been implemented and deployed across the levels of electricity grid for facilitating the integration of large numbers of Distributed Renewable Energy Resources (DRERs) [22]. To complement key TE related definitions used in this work, TE markets are related to electricity markets in which grid parties, agents, operators, and end-users provide bids and offers for exchanging energy with their own perspective of financial profit maximization [23,24]. Fig. 2 shows a diagram for a separation of the power grid into TE sectors.

The architecture shown on Fig. 2 is based on the infographic proposed by the GWAC in Ref. [25]. In fact, Fig. 2 illustrates how TE applies at all levels of the grid. As it is clear in the same figure, there are four layers in this diagram: residential, microgrid, local grid, and regional. In the residential TE network, all customers can produce and sell their energy surpluses as well as select a specific resource or multiple sources for purchasing energy. In the microgrid layer, advanced control and management of the network players enable the system to provide flexibility to the upstream networks. In the local TE grid, new services and opportunities might be provided to the customers to have active participation in the electricity markets. Finally, in the last layer (regional), interoperability is increased and efficiency and reliability of the network are enhanced [25]. Furthermore, some of the grid players on a comprehensive TE system as the one depicted in Fig. 2 have a crucial role in linking actors from different layers. For instance, Distribution System Operator (DSO) is accountable for the balancing of the electricity demand and supply at the distribution level, and also connecting the retail and wholesale market agents [25]. For this reason, some entities, e.g. the DSO or Transmission System Operator (TSO) in Fig. 2, are placed between two layers making interoperability possible between market participants.

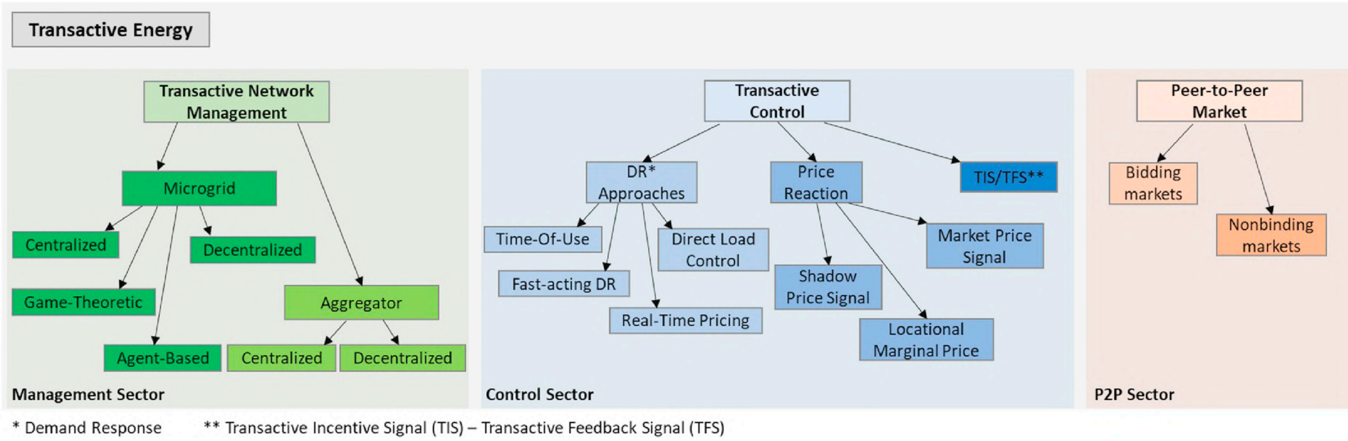

Fig. 1. A taxonomy for categorization of TE related concepts.

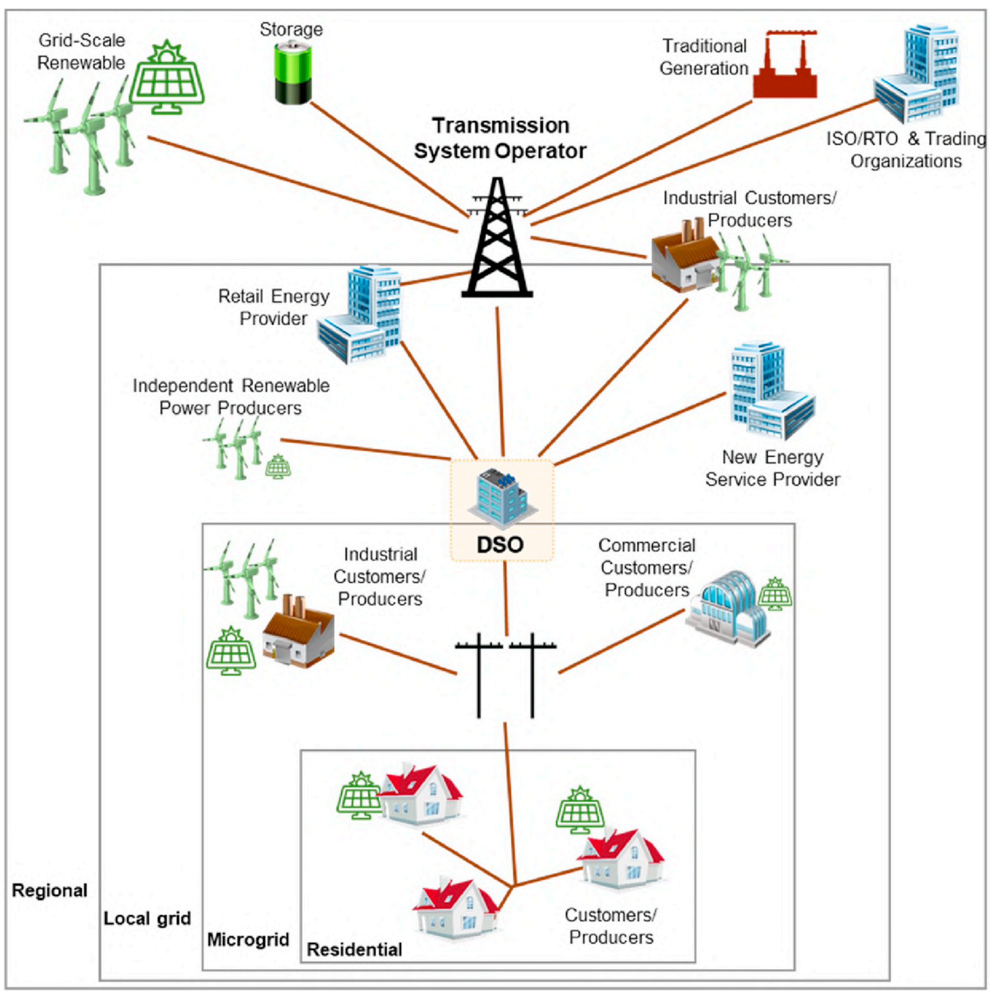

Fig. 2. The GWAC transactive energy diagram (adapted from Ref. [25]).

In a TE market, grid players (e.g., VPP, microgrids or buildings) and grid assets (e.g., storage units, DERs) can be considered financial drivers and active participants [21]. In line with the diagram presented in Fig. 2, using the GWAC TE framework, the costs and benefits of DRERs can be classified as in Ref. [26]:

- TE Products:
  - o Energy: electricity generated by a TE participant in a specific time and place;
  - o Transportation: The produced energy is transferred to another TE participant to be consumed or transferred to another participant;
- TE Markets:
  - o Forward Market: This market operates by relying on future delivery (producers mostly use this market);

  o Spot Market: This market is used for instantly delivery of products;
- TE Participant:
  o Distributed Renewable Energy Resources (DRER): Generating electricity from renewable resources;
  o Utility network: Including generators, consumers, and system operators e.g., DSO for delivering the electricity from producers to consumers;
  o Consumer: Requesting energy for its internal demand;
  o Regulator or Government: An entity for ensuring a safe and efficient transaction in the marketplace.

Following the above classification, in this paper, we consider that energy is a product in a TE system. Therefore, it can be transacted between different TE participants. Fig. 3 shows the process of energy negotiations and transactions in the TE systems. At the beginning of this process, the generated energy belonging to producers/prosumers (e.g., DRERs considered as a product) are located. Also, at the end of the process, consumers in the demand side are placed, where they are always purchasing energy. Based on the reviewed research works in this paper, it was found that energy can be traded on one of the following options depending on the costs and benefits impact into the system [27]: (i) to the TE markets, (ii) to a third-party entity, such as an aggregator, (iii) directly to the consumers. In correspondence consumers can also choose from where they intend to purchase energy. However, those choices for both energy resources and consumers depend on the capacity of production/consumption, since the small-scale resources could not directly participate in the TE markets [18].

One of the interesting points of the TE markets is the ability of multi-interactions with several platforms and markets. According to the definition of TE markets presented previously, it can be seen that TE markets have a feature of interacting with the wholesale markets and third parties, and simultaneously including local and P2P platforms to make the small-scale producers and consumers capable for trading energy directly and locally.

TE systems can also perform self-optimization to keep the stability and reliability of the grid while it controls DERs, especially renewable resources, and transacts power between heterogeneous participants [28]. In order to perform the self-optimization (or distributed-based optimization), price signal plays a key role, since it is a universal language for all type of devices and systems for making a decision and performing the optimal usage of the resources [27]. In the traditional distribution network, customers deal with a retail market, where they are commonly offered simple or double tariffs. However, this simplistic tariff schemes hide multiple components that constitute the consumer price such as use-of-system fees, taxes, retailer margin, among others [29]. Unlocking these components can be used as a basis for TE approaches in which consumers can exploit their flexibility to their benefit and the benefit of the system by taking profit of only the components related to them.

In a TE system, the DERs are integrated into the electricity markets. This can be done by encouraging the customers to invest in small and medium DERs in order to rapidly integrate DERs and take advantage of them in the wholesale markets [30]. In smart grids, the owners of DERs can control the rate of generation based on their own decisions as long as they do not affect the network balance and cause grid congestions. When the TE systems have been integrated in the smart grids, the concept of DR programs could not be limited to only consumers, and might expanded to the generation resources paying financial incentives to them for maintaining the network balance in real-time. This manner would be applied through a decentralized, autonomous and real-time methodology. Furthermore, TE-based power systems allow faster and two-way power flow and communication and utilize the demand-side resources to manage the network and perform energy transactions in the retail markets by employing decentralized intelligent devices and systems. Employing such systems has no time and location restrictions [31], however, such system face the challenge of data privacy and trust between network players and entities. Recently, the European Commission presented a proposal for a directive of the European Parliament focused on common rules for the internal market in electricity [32,33]. In this proposal, data privacy and protection are particularly addressed, and some specific rules have been presented for the privacy of smart metering systems, which are fundamental infrastructures for TE systems.

Based on the presented information, in the downstream level of the TE system, consumers and prosumers, no matter their size, can bid and offer energy. In this regard, the grid operator (i.e. the DSO) has a new minimal set of functional responsibilities, including reliable operation and coordination of employed DRERs (e.g., by the activation of available flexibility from end-users), and scheduling the energy exchanges with the upstream levels of the grid, such as TSO [22]. For instance, based on the universal smart grid energy framework (USEF) [34], the DSO can apply different actions to use the flexibility from the end-users available in the grid, namely reducing peak loads on congestion point, limiting connections when market-based coordination mechanism cannot

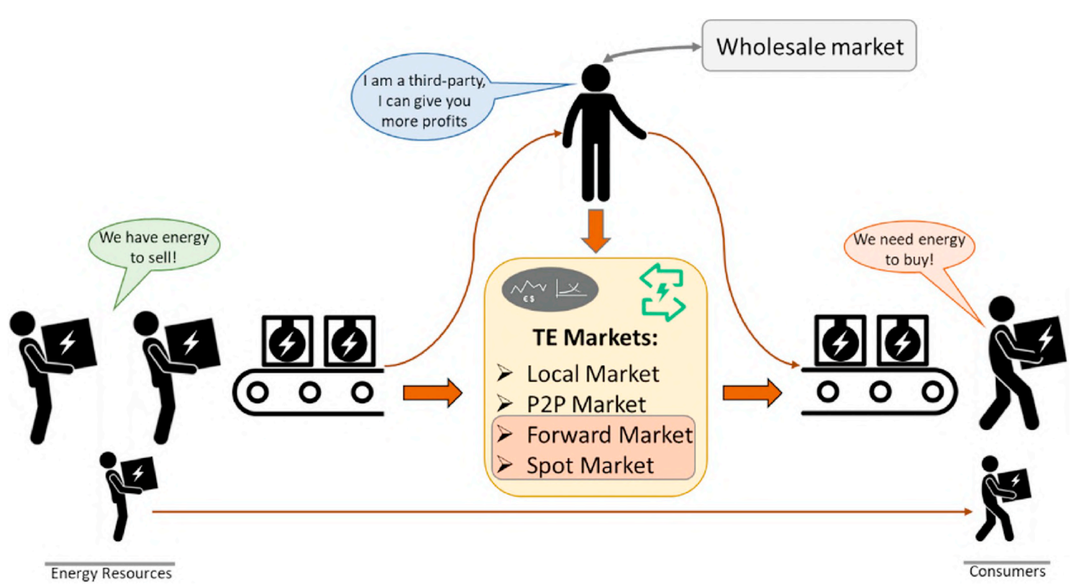

Fig. 3. Energy negotiations and trading process in a TE system.

resolve the congestion, or even activating primary grid protection systems to prevent damage to the grid.

In a TE system, consumer, producers, or prosumers equipped with specialized devices automatically negotiate with each other, and with dispatch systems of energy suppliers through market algorithms. Smart grid energy management approaches using TE system has been classified into four categories in Ref. [35] to discuss the advantages that such approaches can bring to the involved players. The categories are based on the way decision on local issues are made (i.e., centralized or decentralized) and the communication capabilities (i.e., one-way or two-way communication capabilities [35,36]). In the first category (i.e., centralized decision making and one-way communication), top-down switching is considered, where a centralized system makes decisions and transmits the results, such as optimal scheduling outcomes, to the end-users through a one-way communication. As an example, DR programs, in which a DR managing entity makes decisions to turn off/on the devices on the demand-side mainly through the use of Direct Load Control (DLC), are placed in this category. The second category (i.e., centralized decision making and two-way communication) is the centralized optimization methodology. This category includes the methods in which all demand-side customers transmit their information to a high-performance central optimizer unit, such as a VPP [37], and then the optimized output data is transmitted back to the customers. This methodology may have high operational costs as well as less reliability while the number of customers is increased. The third category (i.e., decentralized decision making and one-way communication) concerns price reaction systems. In this methodology, dynamic prices or a price profile for the next hours or next day are transmitted to a local automation system via a one-way communication, and the local system makes decision based on the received price rates and user preferences. The fourth and last category (i.e., decentralized decision making and bidirectional communication) is the most flexible one, referred as transactive control in Refs. [35,37]. This category includes the methods in which all demand-side customers, including residential houses, commercial and industrial buildings, provide a bid in a marketplace and perform energy transactions between each other in distribution level.

Transactive control is introduced as a methodology for managing the rate of consumption and generation of resources in demand-side through a transactive market. Transactive Nodes (TNs) are defined as connection points between different parts of the network for power flow [12]. All TNs constantly exchange information with each other sharing their latest status in order to make decisions locally. Therefore, they operate in a decentralized manner [12]. Distribution Locational Marginal Price (DLMP) is a basis for transactive control via electricity prices. Generally, DSO generates DLMP (based on marginal congestion cost, marginal losses expense, and marginal energy cost [38]) and provides it to the TNs. DSO utilizes DLMP as a control signal for dispatching economic optimization. While TNs received DLMP, they determine Transactive Incentive Signal (TIS) and Transactive Feedback Signal (TFS). Then, they transmit these signals back to the DSO as feedback signals. If TN tends to sell its energy surplus to the neighboring TN, it updates TIS. If this updated TIS is less than DLMP, the energy transaction is performed [24].

In order to exchange information between different levels of TE systems [39,40], proposed Open Automated Demand Response (OpenADR) as a useful tool for DR data transmission. By OpenADR methodology, all pricing and demand-side information can be exchanged between the TNs and upstream levels of TE system with a unique language. Fig. 4 presents the overview of OpenADR technique including Virtual Top Node (VTN), and Virtual End Node (VEN). As it can be seen in Fig. 4, the first layer includes the wholesale markets or ISO associated with VTN, whereas the last layer considers TNs as VEN. In the intermediate level, there are third-party entities, such as an aggregator, VPP, or retail markets considered as VTN/VEN. These entities are a bridge between the end-users (i.e., customers) and the upstream players of the grid (e.g., wholesale markets or ISO). By this way, any demand-side information or any trigger signal, namely price signal, can be transmitted between all infrastructure of the grid through a unique language, therefore, all network players would be able to transmit information.

3. Transactive control

A transactive control refers to the utilization of a fully decentralized methodology based on local information and market data in order to reach the network balance and smoothing network fluctuations [41]. Each TN is a physical point in the electrical network representing consumers/prosumers, substations, and utilities. The required data to be transmitted between each TN and the market or system operator is related to price signals and the desired consumption rate for consumers [42]. Transactive control can also be considered as distributed control method based on local information and preferences of the end-users [43,44]. In other words, if a typical end-user wants to participate in a transactive market, it should be capable of performing the following aspects [45]:

- Modifying its consumption based on market clearing price;
- Calculating the cost that it tends to pay for purchased energy;
- Biding its favorable amount of electricity.

Implementing DR programs in residential and commercial buildings using transactive control is a hot topic of a significant number of research works. Heating, Ventilation, and Air-Conditioning (HVAC) and Thermostatically Controlled Loads (TCLs) are the main targets for transactive control in residential and commercial buildings through DR programs [46–50]. A passive controller model has been designed in Ref. [51] for controlling the HVAC of an office building based on real-time market prices of TE system. Their simulation results demonstrated a significant amount of energy saving could be obtained by using the proposed passive controller model comparing to an office building with typical controlling methods.

A Home Energy Management System (HEMS) has been proposed and designed in Ref. [52], which can participate in the TE markets and modify the schedule of appliances based on price signals and local information defined by home inhabitants. The authors clarified the application of HEMS as TN and also its performance during the scheduling process. Fig. 5 shows the proposed modeling of HEMS for TE systems. The authors also considered the price signal as TIS and the power profile forecast as TFS. The use of this kind of transactive based HEMS brings flexibility to the power system that meets the objectives of both customers and network entities. Furthermore, the authors advanced a methodology for optimal scheduling of home appliances based on multi-objective optimization using a predictive control model. A case study has been presented in the same article, considering each HEMS would participate in the TE markets, and react individually to a price signal, such Time-of-Use (TOU) pricing scheme. Their results showed that there is lack of reliable management and coordination in the power systems when a considerable number of HEMS are applied.

Two transactive control strategies for residential HVAC have been surveyed in Ref. [53]. The first method investigates the cost savings by using transactive control without pre-cooling and in the second method it is considered to have a pre-cooling feature. In the first method, a cooling setpoint rate is defined by respect to the several factors, such as real-time market price, market price statistics, and user preferences and comfort. If a higher cooling setpoint selected due to the market price increment, the controller unit will not allow the cooling set point to go below the favorable temperature rate. In the second method, the controller unit lets the set point goes below the desired temperature rate while the market price is high. In the same article, actual model of a residential house, real market price data, and real weather data have been considered to compare and asses the two transactive control methods. The provided results illustrated that in a typical house under real-time pricing scheme, transactive control without pre-cooling is

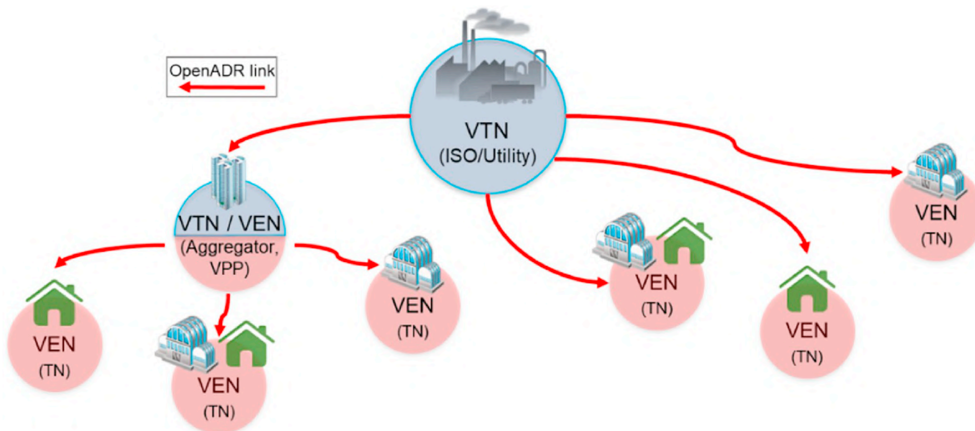

Fig. 4. An OpenADR methodology for TE systems.

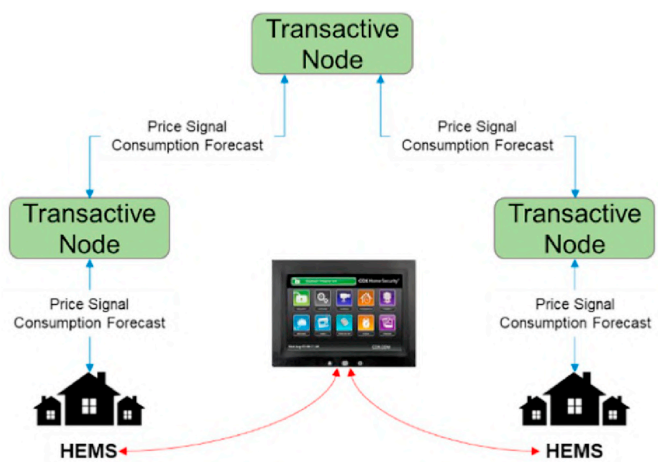

Fig. 5. Application of HEMS in a TE system.

more cost-effective and it can reduce the electricity bill costs.

Transactive control can also be implemented in commercial or industrial buildings with little or no additional development in their typical Building Automation System (BAS) [54–56].

A transactive control methodology has been presented in Ref. [54], which can be employed in a typical BAS. For this purpose, HVAC devices in several commercial buildings have been targeted in order to be controlled and modeled in a transactive control manner by using market data and price signals. In the same article, the authors provided several mathematical formulations regarding the desired temperature defined by users, outside temperature, and market prices. A case study has been presented in the respective article considering a commercial building with several offices and laboratories in Washington to implement, test, and validate the transactive control of HVAC devices based on market data. Although their results confirmed that the model can be implemented in the typical buildings without significant investment on the controlling and automation infrastructures, the authors pointed out that implementation of transactive control requires more investigation and survey since several practical issues, such as technical faults in the hardware devices are needed to be solved first. Similar work was developed in Ref. [55] focusing on experimental analyzes of a green building in Australia with respect to the transactive control over TCLs. Although both [54,55] proposed that transactive control can be implemented in a BAS with little or no capital investment, the experimental results demonstrated the need for a more efficient design and control in BAS since the inefficient operation and unexpected faults in sensors and communication protocols lead to have a gap between the expected and real results.

More focusing on residential transactive control and DR programs, a demonstration project so-called gridSMART [57,58] managed by Pacific Northwest National Laboratory (PNNL) was implemented in Ohio, United State, from 2010 to 2013, to survey the behaviors of residential consumers while they utilize bidding transactions of supply and end-use HVAC devices interfacing with a real-time electricity market. The results of project showed that applying transactive control with a 5-min basis in real-time pricing market, the majority of customers are able to configure their HVACs based on preferences and choices, also the efficiency and reliability of the distribution system can be improved by 30–40%.

Transactive control is also applicable to the EVs in a TE system [59–62]. Based on the work presented in Ref. [63], efficient and optimal charging of EV would be possible using transactive control in TE systems. Suppose that in a fully decentralized TE system, a DSO provides a DLMP for each TN (e.g., a house) in the network. Therefore, the end-users select the most affordable period for charging their EV based on the received price signal, and then, end-users transmit TFS back to the DSO. This will enable the DSO to determine the price signal for the next periods and provide new demand pattern for TN. The presented methodology is useful for DSO since it can manage the local demand by providing desired signal prices to the TN. According to the results of the case study presented in Ref. [63], this method not only is cost-effective for the DSO but also it can decrease the charging bill of EV owner by 60–75%. For reducing the network congestion and to prevent voltage violations due to the high penetration of EVs, the works presented in Refs. [62,64] introduced the transactive control as a solution for this issue. In the presented methodologies, a fleet operator is considered as a supervisory entity on the lower level of the network, which controls the charging schedule of the EV owners. Also, DSO located on the upper level of the network manages the fleet operator in a transactive control manner. By this way, DSO always supervises charging schedule of the fleet operator to check if there are any network operation violations. If violations in operation are encountered, the DSO can propose a shadow price[2] to the fleet operators to alleviate the congestion problem. On the other hand, the scheduling of fleet operator would be approved by DSO when no violations exist.

In order to summarize this section, Table 1 compares the analyzed works underlying their main characteristics and comparing the employed methodologies.

Moreover, Table 2 shows a classification for the articles produced in the scope of transactive control, which have been categorized according to the target control nodes.

[2] Shadow price can be a distribution marginal price from the marginal cost calculation and can be used as a price in the markets.

Table 1
Transactive control at distinct levels of the electric system.

Ref.	Target Loads	Target customers	Controlling Approaches	Purposes/Achievements
[45]	HVACs	Residential	DR	Transactive control in a residential double-auction market
[46]	HVACs	Residential	DR, DLMP	Hierarchical control of DERs and DR for a large-scale integrated transmission system coupled with multiple distribution systems
[53]	HVACs	Residential	Market price signal	The economic impact of transactive control for HVACs with and without pre-cooling considering user comfort and preferences
[57] [58]	HVACs	Residential	DR	Behaviors of residential consumers equipped with HVACs in bidding transactions
[47]	HVACs	Commercial	DR	A double-auction market framework to coordinate HVACs for DR programs
[51]	HVACs	Commercial	Market price signal	Advantages of transactive control for commercial buildings
[54] [56]	HVACs	Commercial	Shadow market signal	A market-based control strategy for typical BAS with little or no additional development to enable the commercial buildings more demand responsive
[55]	HVACs	Commercial	Market price signal	Experimental results of energy efficiency in a commercial building considering DRERs and transactive control over HVACs
[41]	HVACs	All customers	Market price signal	Power fluctuations in microgrids by considering a baseline load for HVACs control
[48]	TCLs	Residential	Fast-acting DR, DLMP	An agent-based method for TCLs to participate in real-time electricity markets
[49]	TCLs	Residential	Real-time pricing	Transactive control-based strategy for residential TCLs supporting real-time pricing
[50]	TCLs	All customers	Market price signal	Transactive coordination mechanism for TCLs considering market coordination signals
[52]	All loads	Residential	TIS/TFS	Transactive-based HEMS for home appliances considering signal prices
[44]	All loads	All customers	DR	Cyber-physical attacks through the transactive control mechanism
[42]	All loads	All customers	TIS/TFS	A simulation platform for evaluating hierarchical transactive control
[43]	All loads	All customers	Fast-acting DR	Balancing network authorities for power regulation in high renewable generation periods
[59]	EV		Real-time pricing	A multi-agent transactive control with high penetration of DRERs and EVs by respect to the customers preferences and voltage regulation constraints
[60] [61]	EV		Real-time pricing	Participation of EV owners in real-time pricing and double auction electricity markets based on transactive control
[62] [64]	EV		Shadow market signal	A multi-period network-constrained transactive control for EVs with respect to the energy inter-temporal features of EVs
[63]	EV		TIS/TFS	A transactive control methodology for optimal charging of EV

According to the information provided in Tables 1 and 2, research on some concepts of transactive control (indicated by gray in Table 2) is still poor. Most of the systems and models developed so far, apart from the type of the building, have chosen TCLs and HVACs as targets in order to implement transactive control. However, focusing only on those types of loads (e.g., TLCs and HVACs) might have an undesired impact in the inhabitants' comfort level. Thus, transactive control should be expanded to consider all types of the loads and devices in the buildings. Also, more attention should be given to residential buildings, as the consumption from those buildings accounts from the %35 of total consumption in the United States [52], making them a good target for transactive control implementation. Furthermore, a significant number of the articles focused on the modeling and theoretical aspects of transactive control. They tested and validated their developed approaches through the simulation platforms. There are a few numbers of research works focused on real demonstrations and testbeds for validating and examining transactive control case studies. Therefore, this bring an opportunity for the research society to cover these gaps and focus on such areas in future.

As a conclusion, transactive control will enable end-users to have active participation in TE markets. In fact, transactive control, especially at residential and commercial level, provides the means for optimal management of consumption and generation by taking advantage of technologies such as blockchain and Internet-of-Things (IoT), and giving network operators accessibility to manage end-users' devices and benefit from local flexibility.

4. Peer-to-peer markets

As it was mentioned in section 2, from DSO standpoint, high penetration of DRERs, especially renewable resources by their intermittent nature, may bring network management issues [65]. However, from electricity customers standpoint, DRERs are interesting since they can reduce the electricity bills by consuming their own generation. In this context, TE was proposed as a control method for integrating high penetration of intermittent DRERs in the grid while operating the system safely and efficiently [27]. However, P2P markets can be envisaged as a complete solution in order to satisfy both sides of the network. While TE is viewed as a control method, a P2P market is defined as energy sharing and trading among all consumers equipped with DRERs, which converts them into active customers (prosumers) in the market by selling/buying energy from each interconnected nodes of the network [66]. Therefore, P2P markets are fully related to TE system by representing one of the most promising paradigms for implementing TE markets. Notice that all these processes should be done at the distribution level of the network [67]. In other words, P2P energy trading allows direct energy sharing among consumers and prosumers in the local electricity grids [68]. Several research and industrial projects have currently surveyed the concepts of the P2P markets, focusing on energy trading on the distribution level to integrate all small and medium scale DRERs [69,70]. In

Table 2
Classification of research articles in the scope of transactive control.

<table>
<tr><th>Target Load</th><th>Transactive Control Method</th><th>Residential</th><th>Commercial</th><th>All customers</th></tr>
<tr><td rowspan="3">HVACs</td><td>DR</td><td>[45] [46] [57] [58]</td><td>[47]</td><td></td></tr>
<tr><td>Price Reaction</td><td>[46] [53]</td><td>[51] [54] [55] [56]</td><td>[41]</td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">TCLs</td><td>DR</td><td>[48] [49]</td><td></td><td></td></tr>
<tr><td>Price Reaction</td><td>[48]</td><td></td><td>[50]</td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">All loads</td><td>DR</td><td></td><td></td><td>[44] [43]</td></tr>
<tr><td>Price Reaction</td><td></td><td></td><td></td></tr>
<tr><td>TIS/TFS</td><td></td><td></td><td>[42]</td></tr>
<tr><td rowspan="3">Home appliances</td><td>DR</td><td></td><td rowspan="3" colspan="2"></td></tr>
<tr><td>Price Reaction</td><td></td></tr>
<tr><td>TIS/TFS</td><td>[52]</td></tr>
<tr><td rowspan="3">EVs</td><td>DR</td><td colspan="3">[59] [60][61]</td></tr>
<tr><td>Price Reaction</td><td colspan="3">[62] [64]</td></tr>
<tr><td>TIS/TFS</td><td colspan="3">[63]</td></tr>
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section 6, the most relevant projects on this topic are briefly presented and compared.

In a P2P market, each prosumer has its local controller leading to have a totally decentralized market, which decisions will be made locally based on users and market information. For instance, the work presented in Ref. [71] considers each prosumer as a TN, and all TNs participate in P2P markets. In the same article, TNs submit a bid to the market and choose the trading partner considering several constraints to obtain the optimal and cost-effective performance.

All consumers in P2P markets become prosumers and they can trade the generation surpluses for the ones that request energy. This energy trading is performed based on several long-term or ad-hoc contracts between all grid players. Two kinds of contracts have been proposed by Ref. [72]: (i) between prosumers (as an example, one prosumer produces electricity and trades it to another prosumer); (ii) between the energy provider and consumers (for instance, one unit only produce electricity and the other one only consumes).

The energy transactions between prosumers in a P2P market are similar to the concept of internet when people share information. On the internet, there are several equivalent nodes that can be considered as “Client” or “Server” at the same time. This means each node of the internet simultaneously is client and server, which enables the network to share information and exchange data among the internet network. This fact is true also for P2P energy markets. All prosumers in a P2P market are simultaneously energy buyer and seller, and they can exchange information and make bids for selling/buying the surplus of generation [73].

Four operation modes in a fully P2P system have been presented in Ref. [23], where each prosumer, retail entities, and other market players are considered as a transactive agent or TN in the system. These four modes include:

1. Operating in autonomous mode where each agent or node makes decisions locally and based on its preferences and comforts;
2. Responding to bidirectional bids and offers presented by each agent or TN;
3. When the network players are operated in response to a trigger signal, such as DLMP;
4. When the system operates based on the instructions provided by a network manager, namely DSO.

In fact, the first two modes have fewer limitations for the agents and TNs in the network, although, they may reduce the reliability of the grid since DSO (or the system operator) is not entirely coordinating agent actions [23]. However, the last two modes are more restricted for the prosumers, but the network reliability and stability may be increased.

According to Ref. [74] and the hierarchical nature of the power distribution grids, P2P energy trading can be performed in three phases, as Fig. 6 illustrates:

- Phase 1: P2P energy trading inside of a local grid (e.g., microgrid);
- Phase 2: P2P energy sharing among several local grids inside of a cell (e.g., multi-microgrids);
- Phase 3: P2P between several cells (e.g., multi-cells).

Different arrangements have been investigated to perform energy trading in local distribution networks, such as the local pool concept in which aggregated distributed generation is used to balance local supply and demand with minimum generation cost [68]. On the other hand, the recently proposed “P2P economy” energy trading arrangement allows peers (e.g., consumers, producers or prosumers) to decide with which peer they want to trade the energy according to their particular objectives (e.g., cost, profits, pollution, reliability, and so on). For instance, to perform energy trading in a P2P market in Ref. [68], energy sellers broadcast messages with the amount of generation surpluses for the next time intervals. After that, all energy buyers make bids with the required energy rates and the favorable prices to buy energy. After the energy sellers receive and collect all the provided bids, orders are either accepted or rejected by suppliers with the intervention of the DSO whose decision is based on network constraints. After the order acceptance or rejection, the winners of the auction are announced and transacts energy between them. Since energy is delivered through the distribution network, all these operations should be done with surveillance of the upstream network entities (e.g., DSO).

Besides the hardware requirements and infrastructures for implementing P2P energy trading systems, a software layer is also necessary to implement. A software platform in the P2P market enables the network operator to control and monitor the energy trading, and also it allows data transitions between all P2P market participants. ELECBAY [68,75] is an example of these software platforms allowing P2P energy trading in a grid-connected microgrid. In this platform, energy sellers list the products for sale (e.g., energy surplus for the next 30 min), and energy buyers look on the listed products by all energy sellers, and then they select the most preferable case and place the order.

Nonbinding TE market can also be considered in the P2P markets. In this market, the energy trading is performed between flexible DRERs,

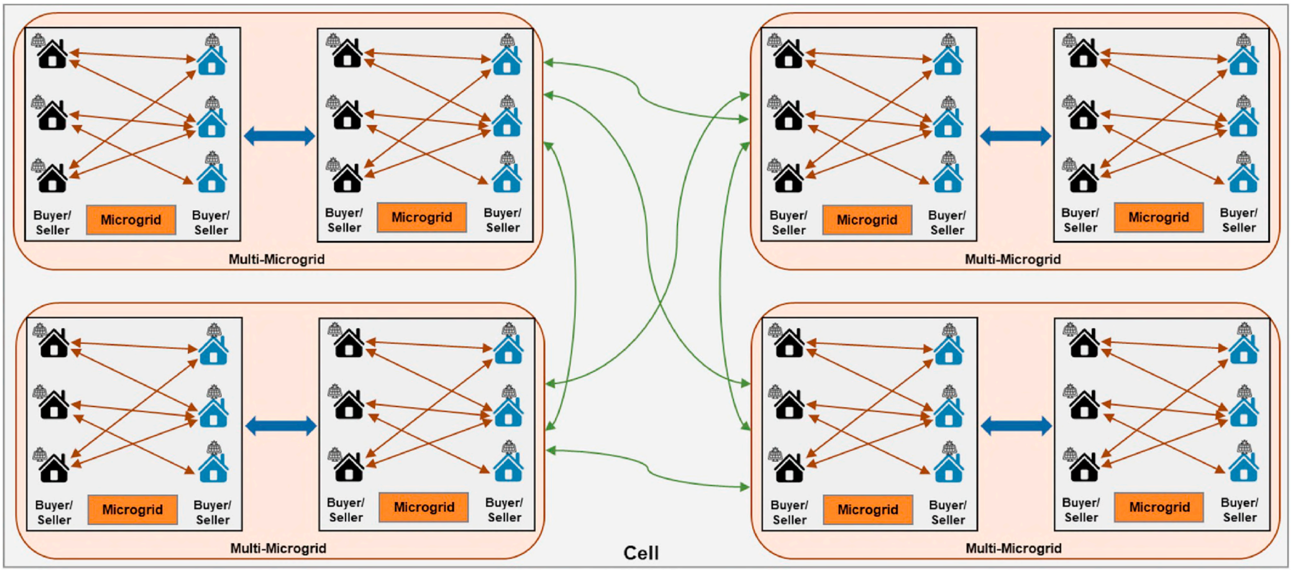

Fig. 6. Different levels of P2P markets.

which are transactive agents and DSO. In this market, the transactive agents publish their intentions for energy transaction and wait for receiving a permission signal from DSO. This means there is no obligation and commitment between the agents and DSO in advance to provide energy, and also, DSO is not obligated to purchase energy from the agents for a specified time [76].

A P2P market can also be combined with a VPP for energy transaction [77]. In fact, a single VPP deals with the demand-side, such as consumers and prosumers, and manages their consumption and generation rates in order to bring flexibility to the wholesale markets and DSO as well. In a P2P market, consumers and prosumers trade energy in demand-side, in order to fully benefit from their DRERs and they are in touch of a retailer as a coalition. The single VPP and the P2P market can be combined and be presented as a Federated Power Plants (FPP). In this way, all consumers and prosumers are in one side of the network as an FPP, which allows them an easy energy trading between each other as well as trading with other groups of prosumers. On the other side of the network, suppliers, large-scale generators, DSOs, and wholesale markets are placed, and a P2P energy transaction platform recognizes flexibilities for the network operator and provides them as contracts to the prosumers to manage the consumption and generation rates with respect to the contracts established for grid services.

With the increment use of aggregators (e.g., VPP) in the electricity markets, DR programs can be applied in the P2P markets as well. This enables the aggregator to react to DR signals by allowing P2P energy sharing between its clients. Several research works focused on the mathematical modeling and decentralized optimization methodologies for P2P markets. A P2P energy sharing model has been proposed in Ref. [78], where the authors developed a framework for the P2P market in three stages: in the first section, the model concerns about the value identification, which maximum available energy for trading in a region should be calculated and evaluated before any specific trading. In the second stage, the overall energy bill for the energy trading is estimated and modeled, and in the last stage, the economic operation index of energy sharing in the P2P market is defined and modeled. Furthermore, a game-theory-based algorithm is used in Ref. [79] for modeling the reactions of prosumers in a P2P trading market, and high penetration of DRERs is considered at the distribution level to calculate DLMP based on the power losses. In Ref. [80], the authors focused on a challenge of P2P markets that the pricing schemes should confirm that all P2P market participants could take financial benefits. For this purpose, they presented a two-stages control method that can overcome the proposed barrier through a constrained non-linear programming optimization to minimize the energy costs of the whole P2P market. The proposed model in the same article utilizes a rule-based control approach, which updates the respective set-points according to the real-time measurement data.

In a full P2P market [66], however, a crucial question that may be addressed is: how the upstream network entities can guarantee that all energy that a typical customer purchases from a peer producing clean energy, comes from a fully clean source? This means that energy buyers may have no information regarding the origin of the purchased energy. To overcome this issue, a power flow tracking algorithm [81] can be merged in the P2P markets for providing more information to the customers, such as the origin of the energy, transportation costs, and power losses. On the other hand, while a significant number of customers are integrated into the P2P markets, the systems may be faced with several challenges, such as the establishment of trust, proposing clearing prices and exchanging money between them after energy transactions. Blockchain technology and smart contracts are possible solutions for overcoming these barriers [82–84]. Implementation of smart contracts in a P2P market with a set of consumers and prosumers equipped with PV systems are demonstrated in Ref. [82]. In the same article, the authors proposed an architecture with respect to the blockchain technology where each energy seller and bidder send/receive a message to the blockchain with an encryption key pair to address the respective prosumer and sending the signed transactions. More focusing on the blockchain P2P markets, the work presented in Ref. [85] provided a smart management system to enable prosumers to trade energy in a fully decentralized market considering local DRERs. In the same work, contract theory has been employed to develop a smart contract for minimizing the necessity of surveillances in a real-time energy trading market.

In sum, P2P markets allow the participants to have energy transactions in the demand side. Most of the works are focused on the concepts of P2P energy trading, presenting several mathematical and optimization models in order to perform P2P energy trading. However, there is a lack of actual pilots for these models, and only a few numbers of works and research projects provide facilities to technically validate the models. There are some research and industrial projects that presented software platforms allowing P2P energy trading and data transitions between all market participants. However, the establishment of trust, proposing clearing prices and exchanging money between them, are still challenges in this context.

5. TE-based network management

This section focuses on the methodologies proposed for the management of TE-based grids, including microgrids and aggregators models. In fact, microgrids are capable to have local control on their electricity consumption and generation resources aiming at self-supply with minimum or no dependence on the main grid [86,87]. TE systems bring opportunities for microgrids to achieve their economic advantages as well as aiding the reliability of the entire distribution system [88]. Integrating TE systems into the bulk power systems and DSO enable microgrids and aggregators to improve the mutual benefits between themselves and the power system by providing the flexibility of the available resources [89].

In a residential microgrid, energy sharing among neighborhoods is an alternative to overcome network congestions and grid stability since the microgrid can supply its demand based on the local resources and independent from the main grid [90,91]. Furthermore, a group of TE microgrids[3] can provide flexibility to the distribution and wholesale markets by bidding transactive services, as Fig. 7 illustrates.

In this structure, load aggregator intends to maximize its benefits by bidding transactive services in the market. Based on the model shown in Fig. 7, the load aggregator is considered as an independent player interacting with distribution and wholesale markets, which has no control over the microgrids players. By this way, the load aggregator can maximize its profit by cooperating with microgrids in order to determine the capacity of energy transaction that can be transferred from a market to the other [92].

Aggregator can directly be in touch with the demand-side, coordinating the enrolled customers, including consumers and prosumers, and assigning the costs and remunerations among the customers [93,94]. To implement this concept, an EMS with several layers should be utilized in the community of enrolled customers. Based on the work presented in Ref. [95], the base layer of this EMS is the measurement devices, which measure the real-time state of the consumptions and generations. In the top layer of EMS, there is a processor in aggregator in order to compute the coordination signals, such as power references or price signals. Also, there is a communication layer between the base and the top layers of EMS, which is responsible for transmitting the measured data from the users to the aggregator as well as moving the coordination signals from the aggregator to the customers. In other related works in this topic, an optimization-based aggregator model has been presented in Ref. [96], which operates as a local market and optimally manages the controlled devices. The aggregation model provided in Ref. [96] allows energy trading between the consumers and producers in a small area, which brings flexibility for meeting the requests of upstream levels of the distribution network, such as DSO. The experimental results of the same article validate the performance of the developed optimization-based aggregator in real-time for controlled devices.

Energy transactions and management in microgrids or aggregators can be tackled in two ways [97]: centralized (optimization-based) and decentralized (transactive control), each with their own advantages and disadvantages. The centralized approach is not referred to a centralized unit control, rather, it refers to a centralized management optimization, in which controlling signals are transmitted to the TNs, however, this approach presents extensive communication infrastructure and huge computational burden. On the other hand, in the decentralized solution, the optimization and management are performed fully distributed, meaning that there is no centralized unit. The level of decentralization is defined by the intelligence of local controller units, which can be utilized just to execute commands and orders from upstream controller units or make their own decisions. This means, decentralization of the system is related to flexible operation, intelligence level of the local controllers and the capability of avoiding failures in the entire system when a single point fails [98]. Both centralized and decentralized methods have their own benefits and drawbacks and the suitability of the application of each is determined based on the type of microgrid or geographic attributes [98]. Table 3 shows the main differences between the two presented network management methodologies.

In the centralized management methodology, also known as optimization based TE microgrid [99–101], a central controller engages with solving several mathematical problems mainly focused on an optimal solution for minimizing the operational costs of the entire microgrid. This is done through the defined objectives for managing the energy resources and controllable loads [99,102]. The work presented in Ref. [101] is an example of centralized management, which provides an optimization algorithm for optimal scheduling in a centralized EMS of the distribution network (e.g., microgrid) based on TE concepts. In the same article, the cost minimization of the network is considered as an objective function by considering real-time pricing scheme. Furthermore, a mixed integer linear problem has been developed in Ref. [103] for co-optimizing microgrid behaviors based on TE concepts, such as reacting to the signal prices, by using Monte Carlo simulation for dynamic price signals computation. Moreover, in Ref. [104] the authors utilized a two-layers optimization method at the aggregator and customer levels, in order to solve two mathematical problems, both aiming at maximizing its own profits. In the same article, after performing the algorithms, aggregator transmits the optimal incentive signals to each consumer and prosumer, which enables them to participate in the TE markets whenever they prefer.

On the other hand, in a decentralized way, sometimes referred as transactive control [105–107], the management unit relinquishes solving complex optimization formulations. However, it provides optimal operational solutions by involving all network consumption and generation resources in a local energy auction bidding process. In a microgrid using transactive control, energy trading occurs between the consumer loads and energy resources in the local microgrid marketplace [108]. Beside this, layered decentralized optimization is another vision to manage a TE-based network in a distributed and decentralized way. In this approach, the optimization is performed at any layer of the system, and it only involves visibility to the interface points of upstream and downstream layers and there is no need to be aware of nature those layers [109]. In a decentralized management scenario, a failure of one node will affect only a localized part of the system, which can be diagnostic using P2P communications with other sections (e.g., agents), while the entire network will not be affected [110].

In the decentralized energy trading methodologies for both microgrids and aggregators, the system operator may witness with a challenge, which is determination of a reasonable pricing scheme for all resources that all participants could take financial benefits. This shows the need for comprehensive study on designing dynamic pricing approaches to optimize financial benefits for all energy resources (e.g., DERs), as the methodologies presented in Ref. [111].

On the other hand, neighborhood energy sharing in a residential microgrid can be considered as a solution instead of injecting the surplus of energy back to the main grid in order to maximize the use of local small-scale energy resources in demand-side [112]. Interconnecting microgrids, with the capability of energy trading between them, provide ancillary services for synchronizing and stabilizing of the power system [113]. This also leads to a reducing of feed-in tariffs in power distribution networks [114].

Several methodologies for energy sharing in TE microgrids are proposed in literature, which most of them aim to maximize the benefits of both energy buyer and seller. However, all proposed methods should be well tested and surveyed before the massive implementation of models. Transactive Energy Market Information Exchange (TeMIX) [115] is a pilot demonstration for live implementation of TE concepts developed by Cazalet Group [116]. In fact, the results obtained from the experimental tests shows the gap between the expected and real results, since

[3] In this work, in a general sense, a TE microgrid is referred to a microgrid that uses TE system to enable the energy sharing.

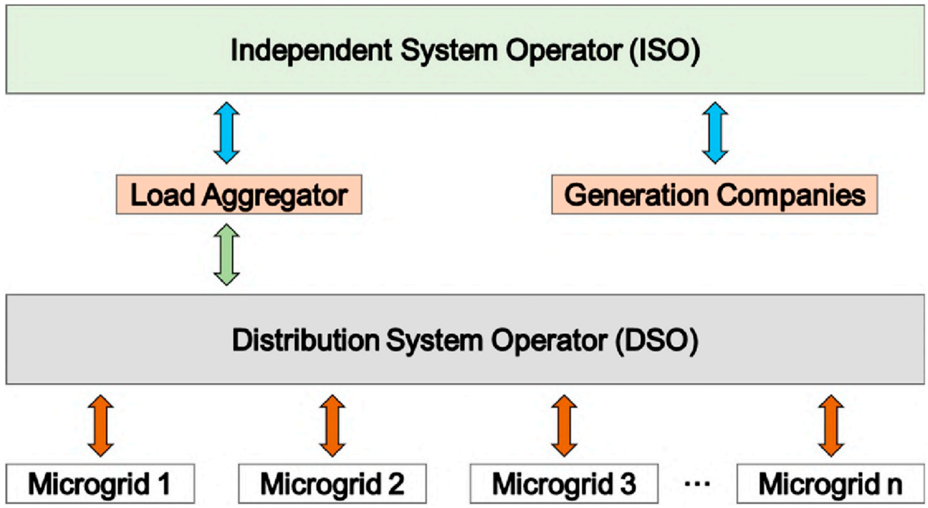

Fig. 7. TE Market structure including TE microgrids.

Table 3
Comparison of centralized and decentralized network management methods [98].

Features	Method	
	Centralized	Decentralized
Flexibility/Expandability (Reconfiguration, adaptability with other systems/agents)	Low	High
Reliability (Single point of failure)	Low	High
Installation Difficulty (Time and cost)	Low	High
Computational Cost (Complexity, space and time)	High	Low
Communication Facilities Cost (High speed control infrastructures)	High	Low

practical issues are typically hidden in simulation tests. Therefore, demonstrations such as TeMIX can be employed by research society to identify the strengths and weaknesses of business models before massive production. Furthermore, VOLTTRON [117] and C2WT-TE [118] are two other platforms that can be applied in this context.

Two approaches for a local TE microgrid have been analyzed in Ref. [119]. In the first approach, a pre-defined strategy is considered for energy exchanging between different nodes of the TE microgrid based on the energy shortage of the consumers and prosumers. The second methodology presents more flexibility to the microgrid players for energy trading by providing an open and competitive local TE market using a game theoretic method with a multi-player game. Based on the results presented in Ref. [119], it can be concluded that the second method brings more flexibility to the microgrids and its participants, while there is no significant difference in cost reduction compared to the first method. Moreover, different methodologies for TE network management in microgrids have been surveyed in Ref. [120] considering the collective and individual interests of microgrid clusters as well as each microgrid itself. In those methods, each microgrid can trade energy with other microgrids of the cluster in order to minimize its operating costs and maximize the energy savings. The proposed methods in Ref. [120] are validated in a local transaction market including 16 microgrids, and the results showed that the energy price can be optimally calculated through the presented models, while the cluster of microgrids can achieve 15% cost saving comparing to the microgrids without clustering.

Multi-agent solutions and islanded TE microgrids are also widely discussed in literatures [121–124]. A rural off-grid microgrid has been modeled in Ref. [122] based on multi-agent transactive scenarios for energy trading between each node of the microgrid. The proposed solution in Ref. [122] focused on multi-priority load clusters with parallel control of typical devices for managing demand/supply of microgrid. Beside this, a multi-agent based Comprehensive Energy Management System (CEMS) has been presented in Ref. [123] for energy transaction in a multi-microgrid market. The CEMS in each microgrid optimally managed the local energy resources available inside of microgrid and allowed microgrid participants to trade energy between each other in an internal auction-based electricity market. Also, the proposed model in Ref. [123] enabled all microgrids to trade energy with the neighboring microgrids in the wholesale markets for maintaining the network balance.

As a result of this section, Table 4 compares all surveyed articles focusing on TE management approaches underlying their main achievements.

Based on the information presented in Table 4, it can be concluded that most of the developed models focused on the centralized management method for residential microgrids and aggregators. This shows the lack of in-depth scientific surveys regarding the commercial and industrial sectors who are merged in the microgrids and aggregators. Therefore, it is required to have more investigations about the commercial and industrial buildings from both mathematical models as well as practical implementations standpoint.

Furthermore, Table 5 demonstrates a classification of analyzed articles and scientific reports, which are categorized based on the management approaches and the related entity. As Table 5 demonstrates, most of the articles considered the implementation of TE concepts on microgrids using different approaches, such as centralized, decentralized, game-theoretic, and multi-agent modeling.

The most important point that can be figured out from Tables 4 and 5 (as highlighted with gray in Table 5) is that there are no references or research articles that specifically address and investigate the aggregator using TE systems through decentralized approaches or other similar methods such as multi-agent modeling. The role of aggregator in the current power system architecture is becoming more important all around the world. For example, several countries are currently accepting the participation of aggregators in several energy markets (e.g., United States, France, Finland, Denmark, and Austria) [127,128]. Furthermore, the centralized and hierarchical structure of the power system is being decentralized and distributed. Consequently, studying the dynamics of TE systems under a decentralized scheme for aggregators provides a path for future research worth to be explored. The integration of TE systems in the current role of aggregators will require different management approaches (e.g., decentralized or multi-agent modeling) in order to comply with the decentralized nature of a TE system and identify barriers that may arise in this scenario.

Table 4
TE sharing approaches.

Ref.	Management Approaches	Manager Entity	Purposes/Achievements
[86] [88]	Centralized/ Decentralized	Microgrid	Identifying practical remarks and restrictions for TE microgrids
[89]	Centralized	Microgrid	TE approaches in microgrids for DRERs at bulk power/transmission operation level
[92]	Centralized	Microgrid	Remarks and challenges of energy transaction between a group of microgrids in distribution networks considering wholesale markets
[99]	Centralized	Microgrid	TE management model for a rural village DC microgrid based on market data and DR programs for multi-priority grouping control of non-smart devices
[100]	Centralized	Microgrid	Two dispatch optimization tools for controlling TE systems
[101]	Centralized	Microgrid	A centralized optimization-based EMS in a distribution network (e.g., microgrid) for optimal resources scheduling based on TE system.
[103]	Centralized	Microgrid	Co-optimizing microgrid behaviors based on TE system, for dynamic price signals
[112]	Centralized	Microgrid	A hierarchical TE network management methodology in a residential microgrid
[120]	Centralized	Microgrid	Various methodologies for TE network management in a cluster of interconnected microgrids
[93]	Centralized	Aggregator	A flexible and scalable TE system for optimization-based multi-energy aggregators
[94]	Centralized	Aggregator	Transactive market modeling with hierarchical optimization levels considering PV and DR
[95] [96]	Centralized	Aggregator	An optimization-based approach for energy sharing in demand-side coordinated by the aggregator
[104]	Centralized	Aggregator	A two-layers optimization method at aggregator and customer levels aiming at maximizing financial profits for both levels
[90] [125]	Decentralized	Microgrid	Blockchain methodology for energy trading in a microgrid
[97]	Decentralized	Microgrid	A distributed optimization technique for TE market of a residential microgrid to optimally charge and discharge the energy storages
[106] [107]	Decentralized	Microgrid	A distributed based energy management solution for energy systems (e.g., microgrids) using energy hub and local autonomous optimization
[108]	Decentralized	Microgrid	The decentralized dynamic market mechanism for microgrids considering the optimal automated transactive procedure
[114] [119]	Game-theoretic	Microgrid	Prioritizing customers for trading energy within a residential microgrid
[126]	Game-theoretic	Microgrid	Event-driven TE system for energy trading between microgrids based on a consumer-oriented and aperiodic market model
[121] [122]	Agent-based	Microgrid	Multi-agent modeling for energy trading among a rural off-grid microgrid
[123]	Agent-based	Microgrid	Multi-agent based TE system for energy sharing in a multi-microgrids market as well as the internal auction-based market.

6. Implemented TE projects

The primary goal of this section is to present and summarize the implemented projects in the United States and Europe regarding TE to have an overall perspective on the developed TE systems so far. Some projects aim at the development of TE system, whereas others focus on the local controls and decentralized methodologies to adequately address the TE concept. Table 6 and Table 7 show a clear comparison and overview on the implemented projects, pilots, and testbeds in the United States and Europe respectively, which have been classified based on the main purposes and the scope of each project.

According to the information shown in Tables 6 and 7, three categories can be proposed for TE projects: (i) projects that only study and survey the trend of TE concepts for future smart grids; (ii) projects that provide testbeds and laboratory facilities for testing and validating TE system; (iii) industrial projects that implement TE concepts in the current form of power system and enable the society to be familiar with those concepts. These advancements in TE systems show the intention of network management entities all around the world to utilize TE in power systems. In the United States, transactive control is the hot topic of TE systems, and most of the presented projects focused on this topic by providing several demonstrations and testbeds for transactive control. Although, in Europe, P2P energy trading attracted the attention, and most of industrial and research projects implemented and surveyed all features of P2P energy trading systems.

7. Trends, identified challenges and future research directions

Most of the research work about TE systems are focused on the mathematical models and formulations, paying almost no attention to the real and practical issues that might arise in the implementation phase. Regarding transactive control, most of the implemented works are focused at the residential and commercial levels by taking advantages of new technologies, such as blockchain and IoT, to have optimal management on consumption and generation rates in demand side. Also, the current trend on P2P market is centered on surveying the P2P energy trading in a theoretical phase, including mathematical and optimization models, and providing software platforms for P2P participants to have management on energy trading through local electricity markets. Furthermore, in TE-Based Network Management, the trend is centered on the optimization methods and application of blockchain in microgrids considering both centralized and decentralized management approaches. Microgrid cost optimization models considering customers reacting to the signal prices is another popular topic in the current trend.

In this regard, adequate simulation platforms and tools are required to scrutiny the practical challenges of the TE system, such as implementation costs, required automation infrastructure, network assets response time, devices and communication failures, physical or cyber-attacks, and also electrical grid conditions, namely voltage and frequency variations. In fact, only a few articles surveyed the implementation of TE systems, which also demonstrates a wide gap between the expected and real results. Therefore, the need of technical verifications of the TE systems by the emulation tools and prototypes is obvious for avoiding the failures in the implementation phase. There are a few industrial and commercial projects that have implemented TE systems in real infrastructures, such as energy trading in some residential microgrids [139]. Furthermore, some of the projects provided emulation-level platforms enabling operators to validate the TE system [132,133]. However, it should be stressed the importance of moving towards TE projects and demonstrations that include a validation phase since different of the mentioned practical issues that might arise during the implementation of TE systems remain hidden in the simulation level (which is the case of many of the articles surveyed in this work).

More specific challenges in TE systems can be identified in the transactive control, such as data security and privacy, speed of financial transactions, resiliency to failures and energy footprint [13]. The current

Table 5
Classification of research articles and reports in the scope of TE management methods.

	Microgrid	Aggregator
Centralized	[89], [92], [99], [100], [101], [103], [112], [120]	[93], [94], [95], [96], [104]
Decentralized	[90], [97], [106], [107], [108], [111], [125]	
Game-theoretic	[114], [126], [119]	
Agent-based	[121], [122], [123]	

Table 6
Implemented TE projects in United States (TC = Transactive Control; TM = Transactive Management).

Ref.	Project Name	Objectives	Outcomes	TE Area		
				P2P	TC	TM
[129,130]	Olympic Peninsula GridWise	Test and validate TE systems experimented with actual energy pricing and smart appliances	Automatic load responding to price variations in a very short time scale		**	
[57,58,99,131]	AEP gridSMART	Controlling residential HVACs in response to 5 min pricing signals	Intelligent software platform for acting in the real-time market		**	
[129,132][133]	Clean Energy and Transactive Campus	TE implementation in large-scale buildings with high penetration of DERs	A multi-campus testbed for transactive control and TE management researches		**	+
[58,129][134–136]	Pacific NorthWest Smart Grid	Evaluation of transactive control approaches in the current state of smart grids	Many key functions for future smart grids including TE concepts		**	
[137]	Connected Homes	The transactive control operation in residential buildings	Integrating IoT devices to automatically adapt them to transactive control		**	
[89][138]	OATI Microgrid Center	Implementing a microgrid center including DERs and renewable sources	A microgrid testbed with sophisticated control and optimization software			+
[139][140]	The Brooklyn microgrid	P2P TE microgrid using the blockchain	A live demonstration of energy trading between prosumers in typical power networks	*		
[115,129][141]	TeMiX	Automated energy transaction and decentralized network management	TeMiX: A cloud-based software platform for energy trading.	*		+
[142]	Kealoha	Implementing P2P markets by considering solar generation	Solar implementation and a software platform for trading the excess of solar generation between houses	*		

Table 7
Implemented TE projects in Europe (TC = Transactive Control; TM = Transactive Management; ICT=Information and Communication Technology).

Ref.	Project Name	Country	Objectives	Outcomes	TE Area		
					P2P	TC	TM
[129][143]	PowerMatcher	Netherlands	Smart grids coordination mechanism by considering DERs and flexible loads	A TE platform as a bridge between network operators and smart devices		**	+
[144][145]	EMPower	Norway	Local electricity market to advance the role of prosumers in smart grids	A trading platform for local energy exchange in local markets	*		
[146]	Couperus Smart Grid	Netherlands	Using PowerMatcher technology for coordinating energy demand and reducing peak load	Around 300 apartments equipped with heat pumps for optimization and participating in TE system		**	
[147]	Powerpeers	Netherlands	Blockchain energy markets for P2P energy sharing among residential buildings	Implementing a P2P market for energy trading in Netherlands based on Blockchain	*		
[148]	Share&Charge	Germany	Blockchain energy markets for EVs	A decentralized protocol for EV charging, transactions, and data sharing	*		+
[149]	Piclo	UK	Selling and buying smart grid flexibility services and P2P energy trading	A software platform for network operators for P2P energy trading	*		
[150]	Vandebron	Netherlands	P2P energy trading from suppliers and customers standpoints	A platform for electricity consumers to select the desirable local sustainable producers	*		
[151]	Peer Energy Cloud	Germany	Local energy sharing by considering local sensors and actuators in demand side	Smart Microgrid Cloud services: A cloud-based platform for local energy trading and smart homes	*	**	
[152]	P2P–smarTest	Finland	Smarter electricity systems by considering ICT and P2P approaches	Demonstration of a smart grid based on TE concepts able to perform P2P energy trading	*		+
[153]	Smart Watts	Germany	Novel methodologies for energy optimization through ICT	A gateway for smart meters to be used on the Internet of energy			+
[154]	Sonnen Community	Germany	P2P energy trading considering solar and storage systems	P2P energy sharing platform considering a virtual energy pool	*		
[155]	Lichtblick Swarm Energy	Germany	An energy management platform for the distribution network	An IT platform for customers to be connected to each other and optimize the use of local DER			+
[156]	ELECTRON	UK	Decentralized solutions for electricity markets based on Blockchain	A flexible system for electricity metering and bills for energy sectors			+

stage of research works on transactive control is limited to HVAC and TCL in the residential and commercial buildings using DR programs as well as price reaction approaches. Cooling and heating processes are vital for all types of the buildings, and controlling the HVAC is directly affecting the inhabitants comfort level, and the reliability of HVACs and TCLs in transactive control may be reduced while the user comforts and preferences are violated. Therefore, focusing only on the implementation of transactive control in HVAC and TCL is not an ideal approach. In fact, transactive control should be dispatched to the all types of the loads and devices in the building. As an example, the lighting systems of the commercial buildings (e.g., office buildings), are an appropriate target for transactive control, since they are much more flexible in term of control comparing to the HVACs and TCLs [157,158]. Surveyed work shows a progress on the combination of TCLs and lighting systems of commercial buildings (e.g., office buildings) as suitable targets for applying transactive control (such as TIS/TFS). Furthermore, more attention should be given to apply transactive control on residential buildings, since they account for a significant part of consumption all around the world (36% of the electricity load in United States are dedicated for the residential building [52]). Moreover, implementation of the transactive control on the home appliances provide flexibility to the network and enable the grid operator to optimize the operational costs by performing the decision making less dependent on communication with web-based energy management optimization [121].

Similar to transactive control challenges, a significant part of articles on TE network management is dedicated to a few specific topics. Through this paper, it has been identified that microgrids and aggregators are two main entities in most of the articles presenting TE network management models. Also, centralized microgrid management method is the hot topic of those articles. Although centralized aggregator approaches have been surveyed through some articles, aggregators using decentralized TE system for management of resources are not well investigated, and the issues and challenges are not yet identified. The role of aggregators is becoming more evident nowadays in electricity markets, and several countries are accepting the participation of the aggregators in the electricity markets [127,128]. Furthermore, the centralized and hierarchical structure of the power system is being decentralized and distributed. Consequently, studying the dynamics of aggregators using decentralized TE system provides a path for future research worth to be explored.

In P2P markets, more prototypes, laboratory platforms, and tools are needed to enable the research society to validate and test the performance of models before implementation in the electricity markets. Moreover, in a near future where it is expected a significant number of customers participating in P2P markets, the system may face challenges such as the establishment of trust between customers and the way of exchanging money between them. Currently, there are some articles providing solutions for overcoming these issues, such as blockchain technology and smart contracts [82–84]. However, the studies and surveys around these approaches still lack maturity and validation in real case studies is required to prevent future problems thoroughly. Another identified issue in P2P markets is to recognize the origin of the transacted energy properly. In a P2P market, the energy buyer may not have any information about the origin of purchased energy, and this is a challenge for the grid entities that should guarantee that the transacted energy has been produced by a fully clean energy source (e.g., a demand-side renewable source). A few numbers of research papers focused on this challenge and provided some solutions, such as tracking algorithm [81], to overcome the particular issue. However, more attention should be paid to P2P markets to identify how the blockchain technologies and smart contracts will operate in a real complex P2P energy trading, while a lot of small-scale prosumers merged into the power distribution network.

8. Final remarks

Transactive energy concept goes forward in the energy transactions with deep concern on the local, distribution level, perspective. In fact, most of the current approaches are available as a model, lacking the real implementation in order to have a complete validation. Before such implementation, however, it is needed to develop and implement adequate simulation platforms and tools to scrutiny the results. Also, it is evident the need for a more efficient design in all TE systems in terms of reliability, flexibility, and accuracy of results.

In this paper, a taxonomy has been provided for the classification of the TE concepts, which can help the reader to positioning the area of study/application, and to devise the interconnection and reaches that a given TE system can have.

On the control technology level, several technologies are available for air conditioning and other appliances, but additional efforts should be made to cover all the consumption appliances, so the full potential of transactive energy is achieved at residential and small buildings level. A restricted focus only on some specific consumption appliances might have an undesired impact in the inhabitants' comfort level. Thus, transactive control should be expanded to consider take advantage of all types of the loads and devices in buildings.

In a more specific business model approach, the management in peer-to-peer markets can bring several challenges, including the trust between customers and the way of exchanging money between them. Blockchain technology and smart contracts are an excellent basis to support the money exchange, but additional work is needed in the trust topic. Finally, the share of information concerning peer-to-peer transactions among the players and entities operating technically and economically the energy system requires discussion, so the relevant information is made available only for the necessary players and entities.

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Declaration of competing interest

The authors declare that they have no competing interests.

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Energy Scheduling Using Decision Trees and Emulation: Agriculture Irrigation with Run-of-the-River Hydroelectricity and a PV Case Study

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Abstract: Agriculture is the very backbone of every country. Unfortunately, agricultural sustainability is threatened by the lack of energy-efficient solutions. The threat becomes more evident with the constantly growing world population. The research community must, therefore, focus on resolving the problem of high energy consumption. This paper proposes a model of energy scheduling in agricultural contexts. Greater energy efficiency is achieved by means of PV (photovoltaics) and hydropower, as demonstrated in the conducted case study. The developed model is intended for contexts where the farm is located near a river, so the farmer can use the flowing water to produce energy. Moreover, the model has been emulated using a variety of state-of-the-art laboratory devices. Optimal energy scheduling is performed via a decision tree approach, optimizing the use of energy resources and reducing electricity costs. Finally, a realistic scenario is presented to show the technical features and the practical behaviors of each emulator when adapting the results of the decision tree. The research outcomes demonstrate the importance of the technical validation of each model. In addition, the results of the emulation reveal practical issues that had not been discovered during the theoretical study or during the simulation.

Keywords: agriculture; decision tree; energy scheduling; hydropower; renewables

1. Introduction

Over the last decades, the world population has been incrementing on a daily basis. This, in turn, has led to greater energy and food demands. According to [1], the population is going to continue to soar, reaching somewhere around 10 billion by 2050. It is also expected that by 2035, global energy consumption is going to rise by up to 50% [2], the predicted consumption rise is largely attributed to the agriculture sector and the food supply chain. Food and energy are intrinsic elements of every society. The growing demand for both makes evident the importance of the agriculture sector [3]. In fact, agriculture is the very backbone of every country. At present, it is necessary to invest in the development of energy management systems [4,5]. Today's agricultural practices still lack energy optimization measures, leading to high energy consumption [6]. It is therefore necessary that the research community address this problem.

The agriculture industry is considered to be the second-largest emitter of greenhouse gases (GHGs) [7], accounting for 21% of the total GHG emissions [8,9]. The reports of the U.S. emission inventory state that methane is the main GHG produced during agricultural practices such as soil management and livestock production. The statistics given in those reports also point to the use of fossil fuels as a significant contributor to GHG emissions in the agriculture sector (between 14% and 30%), where fossil fuels are used in nitrogen-rich fertilizer and to pump water and irrigate crops [10,11]. This means that the agriculture sector can contribute to reducing total GHG emissions by adopting a series of measures, such as exchanging fossil fuels for renewable energy resources (RERs) [8]. More specifically, in the agriculture industry, the energy demand for tactical services, namely, irrigation and water pumping, can be supplied by RERs instead of non-renewable sources [10]. Current agriculture systems should all employ RERs to become environmentally friendly and cost-effective [12,13].

New power system concepts, such as smart grids and microgrids, involve distributed generation (DG) and RERs on the demand side [14]. The agricultural sector is ideal for implementing all types of solutions involving renewable energy resources [15] because farms are located in rural areas where such resources can be easily accessed. Hydro, wind, and solar energy can be used to produce electricity for agricultural purposes, enabling farmers to become largely independent of the utility grid and to reduce electricity costs. The use of smart technologies in the agriculture sector has already attracted a lot of attention. In fact, the use of intelligent systems is not only limited to the electrical grid. Smart solutions can be designed exclusively for the agricultural sector, and this line of research has led to the emergence of a new concept, called smart agriculture or smart farming [6]. This concept also involves the application of the Internet of Things (IoT) in agriculture [16,17]. The ability to combine IoT and other technological paradigms has opened many new possibilities in agriculture, facilitating all types of agricultural practices. An important aspect in agriculture is the weather because crop yields largely depend on it. It is therefore necessary to forecast precipitation probability, air humidity, wind, and solar radiation to enable farmers to take tactical agricultural decisions, namely, field preparation, sowing/planting, irrigation, etc. [18]. For example, forecasting systems have been merged with IoT to gather weather- or field-related data and analyze it to create agriculture-specific classifications and forecast models that are highly accurate [19]. Another important aspect in agriculture is reducing costs, thus, energy production forecasting [20] and energy demand prediction [21] are also essential to minimize energy costs in smart agriculture models. Such models, in other words, enable electricity consumers and prosumers in the agriculture sector to participate in network management scenarios, such as demand response programs [22].

A survey of current literature reveals that much research has been conducted on smart agriculture systems using IoT and wireless sensor networks (WSNs) [23]. Thus, it is an interesting subject undergoing intense study. However, what if there is no internet and mobile network access where the farm is located? Since farms are often situated in remote areas, it is very common for them to lack access to the internet and to high-performance computing machines. Therefore, smart agricultural systems should be capable of operating in offline mode, without using any external server/machine or internet access. This shows the need for developing an offline agriculture system that can optimally use the available energy resources. In this context, the decision tree (DT) approach employs an "if–then" method [24] and can be implemented in any type of controller or programming language [25,26]. However, prior to implementing a model on a massive scale, an emulation phase is required to test and validate the performance of the model in practice. In fact, the emulation phase makes it possible to discover the technical problems experienced by the system, which mostly remain hidden in the simulation and theoretical phases [27].

This paper describes a case study on energy scheduling in agriculture, where PV and hydropower are the available renewable energy resources for energy generation. In the proposed model, it is assumed that the agriculture field is located near a river, so the farmer can benefit from the running water to install a hydropower turbine and produce energy. The model was tested by means of state-of-the-art laboratory devices that emulated energy consumption and energy generation, as well as the typical agricultural tools such as irrigation equipment and water pumping motors. In addition, several automation mechanisms are presented in this paper. These mechanisms were implemented in the emulators to provide a fully automated model for energy scheduling in agriculture. In this model, energy scheduling is performed by a developed DT that considers a series of factors for the optimal use of resources, including real-time generation and consumption rates, as well as electricity markets. Finally, the presented laboratory model was validated in a realistic scenario, and the performance of the DT in real-time energy scheduling is discussed in detail. The emulated model was run for a short period of time in a laboratory, and real results acquired from real resources were used as inputs to test and validate the performance of each emulator.

There are similar research works that focus on this context. In [28], the authors developed and compared three stand-alone models of an agricultural energy management system employing a hybrid wind-photovoltaic (PV) system. The proposed methodology involved the use an energy storage system that maintained the state-of-the-charge at a maximum level and simultaneously kept the water tank full. The results of this research indicated that, in comparison to other energy management strategies, optimal performance was achieved by the strategy that prioritized battery charging. In [29], a coordination framework was presented to optimize energy usage in an agricultural microgrid. A microgrid is capable of interacting with the energy market and involves the use of energy resources (in this case, renewables were used). The proposed model received forecasts of hourly microgrid consumption, wind power, and market prices to optimally schedule the operation of the irrigation system, pumped-storage unit, and energy trading with the utility grid. The numerical results demonstrated that the optimal operation of the pumped-storage unit can reduce the overall electricity costs of the microgrid. An autonomous approach was presented in [30] to achieve optimal and efficient irrigation scheduling in agriculture. This model gathered data for a series of crop-related parameters, making it possible to calculate evapotranspiration without a lysimeter. The proposed irrigation scheduling was performed using electricity market prices; local RERs irrigated the crops in low-cost periods, at time intervals that prevented the crops from reaching the wilting point.

In [31], the authors proposed a forecasting system with the ability to learn from past cases of forecast errors. The learning feature made it possible for the system to improve its forecasting accuracy over time. The system was then used to forecast agriculture price indices, and specifically, the levels of prices for produce and seasonal differences, demonstrating the benefits of applying this forecasting system in the agriculture industry. An energy production forecasting algorithm was presented in [20] and applied to a PV plant. The method utilized transfer function estimation based on the computation of suitable statistical indicators. The experimental results presented in that work showed the efficiency of the method in terms of forecasting quality. In [21], a microforecasting algorithm was proposed for an energy management system employed in small residential or tertiary industry areas eligible for participation in demand response programs. The algorithm provided daily energy consumption estimations to the connected energy management system. Moreover, it was possible to integrate the energy management system with other methods for the forecast of relevant parameters such as weather conditions. The results of the paper showed the practicality of the developed microforecasting module, which provided appropriate and accurate results.

In [32], a prototype of an IoT-based smart off-grid solar system was developed, with voltage and current sensors implemented to monitor the characteristics of the system. Moreover, the model used a battery for the irrigation systems using fog and sprinkler pumps. The results of the work showed that IoT significantly enhanced the functionalities of the developed prototype, offering an alternative for the use of a green energy resource. In [33], the authors proposed a smart community grid model with several consumers and producers. The presented model utilized a DT approach in the developed optimization algorithm, minimizing the operational costs of the community using demand response programs. The numerical results of this work proved that DT, RER scheduling, and demand response programs benefit both sides of the network.

The main contributions of this paper include:

- A realistic case study in which a farm is located near a river with a hydropower generator;
- The scheduling of the energy resources available in such a scenario;
- The development of a DT, within the context of agriculture, for the optimal management of energy resources in offline mode, with no external server/machine or internet access and no complex optimization computations;
- A laboratory emulation of the developed model for the scheduling/distributed control of PV and hydropower energy resources;
- A validation of the performance of DT for optimal energy scheduling in agriculture, under the practical and technical challenges that emerged during the emulation.

This paper is organized into six sections. Following the introduction, Section 2 describes the developed system model. Section 3 presents the laboratory configurations and implemented model for the agriculture emulation. Section 4 details a case study that was conducted to test and validate the performance of the developed system, and its results are shown and discussed in Section 5. Finally, Section 6 outlines the conclusions drawn from the conducted research.

2. Study Description

This section describes the proposed model of an agricultural energy management system. The main objectives of the study are summarized as follows:

(1) Design and implement a suitable architecture;
(2) Develop an optimization algorithm for scheduling the energy resources of the system, conduct a theoretical study, and simulate its performance;
(3) Use the DT methodology to perform energy scheduling;
(4) Conduct a laboratory emulation to test the developed model;
(5) Validate the performance of the DT in an emulated scenario and compare the real energy scheduling results obtained in the emulation with the theoretical results obtained from the optimization algorithm.

Furthermore, the proposed energy management model was developed on a series of assumptions. These assumptions include:

- The farm is located near a river (for hydroelectric power generation and water pumping);
- The planted crops must be irrigated twice a day;
- The water used for the irrigation is supplied from a water tank and not the river.

The abovementioned study objectives are addressed separately throughout this research work. Steps 1, 2, and 3 are described in the next section.

2.1. System Architecture

This paper proposes a model of an energy management system that involves the use of RERs and a river turbine. The main purpose of the system is to supply electricity from local energy resources, minimizing the need to purchase electricity from the utility grid, leading to reduced electricity costs. Figure 1 gives an overview of the proposed system model. There are two renewable energy resources in this system to ensure agricultural sustainability: PV panels and a river turbine connected to a synchronous generator. Thus, the model is intended for scenarios where the farm is located next to a river on which a turbine is placed to rotate the shaft of the synchronous generator. Furthermore, there are three electric motors, two of them responsible for irrigation system and the other one responsible for pumping the water from the river to a water tank. Furthermore, there is a level sensor inside of the water tank indicating the amount of water stored in it. Thanks to this sensor, the water pump motor can be controlled accordingly.

To control the system, several distributed programmable logic controllers (PLCs) and energy meters are employed for the decentralized management of the system. There are four distributed PLCs in this model, one for each system player (i.e., PV, electric motors, synchronous generator, and grid connection switchboard). PLCs enable the system to take decisions locally. Moreover, thanks to the TCP/IP communication protocol, all of the players can communicate and achieve the system goals. In fact, system players must continuously send messages that describe their latest status in the network. In this way, the system's response time to changes is more rapid than in the centralized control approach. Furthermore, distributed control gives greater flexibility and reconfigurability to the system, and it also improves the adaptability of the model.

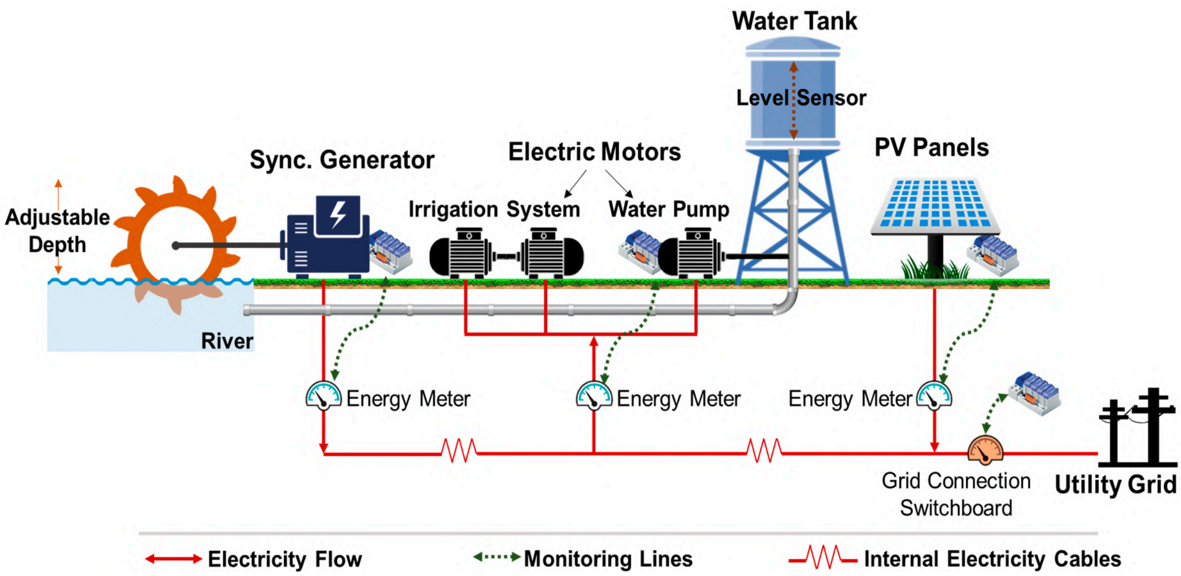

Figure 1. The architecture of the presented model for the scheduling of energy resources in agriculture.

There are two layers in the system that are responsible for performing energy scheduling and managing electricity consumption and generation rates:

- Monitoring layer: There are four energy meters connected to distributed PLCs, one for each resource (as shown in Figure 1) to monitor the system's real-time energy consumption and generation. Furthermore, the level sensor in the water tank indicates whether the tank is full or empty;
- Controlling layer: The system has two tasks in this layer, (1) controlling the status of the water pump motor to turn on or off, depending on whether the tank is empty or full; (2) controlling the depth of the turbine in the river to regulate the speed of the synchronous generator's shaft.

In fact, the deeper the turbine is submerged in the river, the greater the rotation speed and the production rate of the synchronous generator. This means that the distributed PLC installed on the synchronous generator can adjust the production rate of the turbine by controlling the depth to which it is submerged in the river.

Moreover, the PLC in the grid connection switchboard is responsible for dispatching information about electricity market tariffs among the other players, so the system is aware of current market prices and can perform optimal decision-making in terms of electricity costs.

2.2. Decision-Making Approaches

As mentioned in Section 2.1, the main goal of the system is to supply electricity from local energy resources to minimize electricity costs (ECs). Therefore, to ensure optimal system operation, it is essential to implement a decision algorithm. The system's objective function for minimizing the EC is shown in Equation (1). In this objective function, P_{Buy} is the power that the system purchases from the utility grid, and P_{Sell} is the surplus of the generation that is injected in the utility grid. These are shown in Equations (2) and (3), respectively.

In Equations (1) to (3), P_{PV} is the PV production, P_{Sync} is the power produced by the synchronous generator, and P_{Motors} stands for the consumption of the electric motors. In addition, T is the time period, and C is the weight of cost for each resource, which is scaled between 0 and 1. The resources whose weight of cost is small (near to 0) are prioritized by the system because they are the low-cost resources that can be used to supply energy.

Minimize

$$EC = \sum_{t=1}^{T}\left[\left(P_{PV(t)} \times C_{PV(t)}\right) + \left(P_{Sync(t)} \times C_{Sync(t)}\right) + \left(P_{Buy(t)} \times C_{Buy(t)}\right) - \left(P_{Sell(t)} \times C_{Sell(t)}\right)\right] \tag{1}$$

$$P_{Buy(t)} = P_{Motors(t)} - \left(P_{PV(t)} + P_{Sync(t)}\right)\ \forall t \in \{1, \ldots, T\} \tag{2}$$

$$P_{Sell(t)} = \left(P_{PV(t)} + P_{Sync(t)}\right) - P_{Motors(t)}\ \forall t \in \{1, \ldots, T\} \tag{3}$$

Equations (4) to (8) show the technical limitations of each resource in terms of its minimum and maximum capacity (P^{max}).

$$0 \le P_{PV(t)} \le P^{max}_{PV(t)}\ \forall t \in \{1, \ldots, T\} \tag{4}$$

$$0 \le P_{Sync(t)} \le P^{max}_{Sync(t)}\ \forall t \in \{1, \ldots, T\} \tag{5}$$

$$0 \le P_{Motors(t)} \le P^{max}_{Motors(t)}\ \forall t \in \{1, \ldots, T\} \tag{6}$$

$$0 \le P_{Buy(t)} \le P^{max}_{Buy(t)}\ \forall t \in \{1, \ldots, T\} \tag{7}$$

$$0 \le P_{Sell(t)} \le P^{max}_{Sell(t)}\ \forall t \in \{1, \ldots, T\} \tag{8}$$

The present mathematical problem was solved as a linear programming optimization problem using the "OMPR" package of RStudio® tools (www.rstudio.com). In this work, a high-performance computer was employed to solve the optimization problem and provide the results. However, it is not advisable to use a computer or a server to implement this decision-making approach because farms are normally located in remote areas that lack access to computers and external servers. Therefore, a methodology should be employed that would enable the system to perform decision making locally in the distributed PLCs.

The DT approach is considered to be a suitable solution since it can easily be implemented in the PLCs or any other controllers. Therefore, a DT was developed to model the proposed objective function using the RPART package of RStudio® tools. RPART is an abbreviation for recursive partitioning, defined as a statistical approach for multivariable analysis [34]. When RPART starts building a DT, it chooses the most effective variable that divides the data into two parts. Afterwards, this method is used separately for every single subsection. This process is continued until the subsections are reduced to a minimum size or no more improvements can be made. The RPART consists of various methods ("anova", "poisson", "class", and "exp") that can be optionally selected by the user [34]. In this paper, the authors selected the "class" method to build the DT, whose operation is based on the classification of data.

It should be noted that linear programming solvers (e.g., OMPR) are not considered to be a suitable solution for this system since the system is to perform energy scheduling autonomously and in real time using real data. To do this, linear programming solvers would have to be executed every single time a parameter of the system changes. The RPART package provides a set of complementary decisions using "if–then" rules that can be implemented in any type of controller, such as a PLC. Therefore, the system can rely on those predefined rules, implemented in each distributed PLC, to perform energy scheduling autonomously. Moreover, the optimization algorithm may be executed, and it is not necessary for the system to communicate with a server or external entities during its execution. Then, the optimization solution provided by "OMPR" is compared with the solution provided by DT to demonstrate the superiority of DT and the accuracy of its outputs.

3. Laboratory Implementation

In this section, the developed laboratory model of the agricultural energy management system is illustrated. All of the practical features and automation approaches of real devices and laboratory emulators are described. The automation mechanisms for the monitoring and control of the emulators were developed and implemented by the authors of this paper. Before implementing these automation approaches, the emulators had to be controlled manually by a user. Each emulator in this model is controlled and managed by the distributed PLC installed locally in the emulator. Figure 2 illustrates the two laboratory emulators and their automation mechanisms.

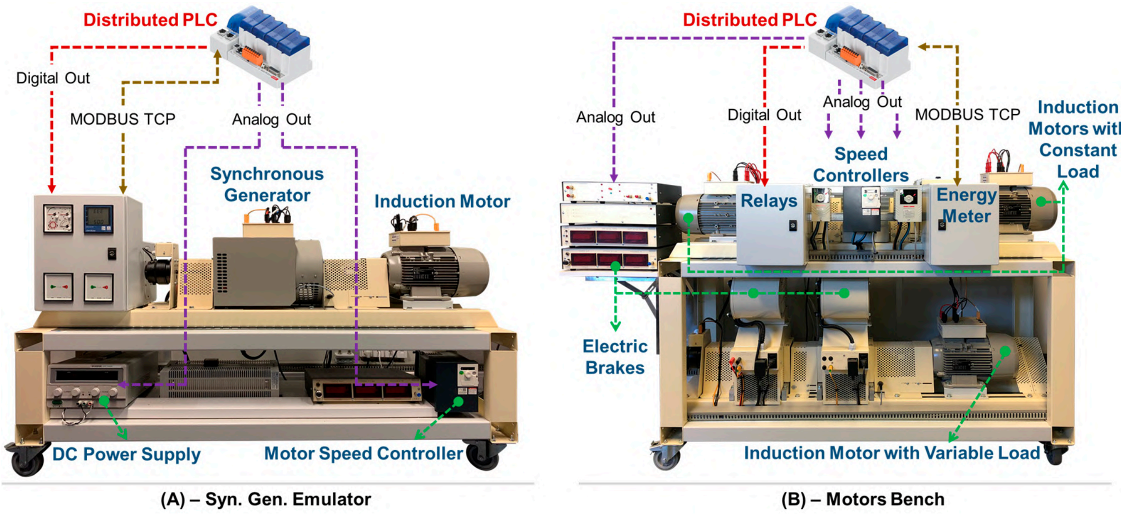

Figure 2. Automation approaches implemented in laboratory synchronous generator and electric motor emulators for experimenting case studies.

The first emulator used in this model is the synchronous generator, hereinafter syn. gen. emulator (Figure 2A). The second emulator is a group of induction motors, hereinafter motor bench (Figure 2B), to emulate the irrigation system and the water pumping motor.

The syn. gen. emulator includes a 3-kW synchronous generator coupled with a three-phase induction motor. In this model, the induction motor emulates the river turbine described in Section 2.1, which rotates the shaft of the synchronous generator. Thus, controlling the speed of the induction motor in the syn. gen. emulator is a process that corresponds to adjusting the depth to which the turbine is submerged in the river. The speed of the synchronous generator affects its energy generation level. As illustrated in Figure 2A, the PLC installed in the syn. gen. emulator controls the speed of the induction motor as well as the amount of direct current (DC) power provided to the generator. For this purpose, the syn. gen. emulator uses two independent analog output channels. Furthermore, there are three relays in the syn. gen. emulator controlled through the PLC's three digital output channels: (1) motor relay, which is responsible for turning the induction motor on/off and the related speed controller unit; (2) DC relay, which is accountable for connecting/disconnecting the DC power supply to/from the synchronous generator; (3) grid relay, which is responsible for the islanded-mode or the grid-connected mode of the emulator (in this paper, the emulator is used only in grid-connected mode). In addition, there are two energy meters installed in the syn. gen. emulator, one in the generator side to measure the produced power, and one in the grid side to monitor the utility grid parameters. The PLC acquires the data from these two energy meters using an Ethernet interface, with the MODBUS TCP/IP protocol.

When the system intends to produce energy by means of the syn. gen. emulator, the induction motor begins to rotate the shaft of the generator at a specific speed to achieve a frequency rate (in this case, close to 50 Hz) in the generator. Thereafter, the PLC triggers the DC relay and connects the DC power supply to the rotor of the generator with a nominal value of DC voltage and current specified in the plate of the emulator. This process leads to alternating voltage (AC) in the stator side of the generator. To connect the generator´s stator to the utility grid, the frequency of the AC voltage in the stator should be exactly equal to the frequency of the grid. This frequency synchronization is performed by the PLC since it is aware of the frequency rate in both sides (generator and grid sides). For this purpose, the PLC increases or decreases the frequency of the generator by regulating the speed of the induction motor. When the frequency has been synched in both sides, the difference in AC voltage between the stator of the generator and the utility grid becomes minimal, that is, near to zero. At this point, the PLC triggers the grid relay and connects the utility grid to the stator of the generator. Henceforth, the frequency of the generator´s stator is exactly equal to the frequency of the network (in this study, 50 Hz). While the frequency of the generator is higher than the frequency of the network, the generator produces energy and injects the power to the utility grid with the frequency of the network.

The second emulator utilized in this model is motor bench, as illustrated in Figure 2B). In this emulator, there are two 1.5-kW three-phase induction motors with a constant load and one 3-kW three-phase induction motor with variable load. The motors with constant load always have a constant rate of electricity consumption since a load is already fixed and applied to the shaft of each motor. However, in a 3-kW motor there is an electric brake system applied to the shaft of the motor that enables the system to have a variable rate of loads on its shaft, so the electricity consumed by the motor would vary. The distributed PLC installed in this emulator controls the speed of each motor separately, as well as the electric brake ranging from 0% to 100%, using analog output channels.

In this paper, it is considered that the two induction motors with constant load model the irrigation system of the model, and the induction motor with variable load models the water pump motor. These assumptions have been made considering that the user is able to adjust the flow rate of the water pumped from the river to the tank, so the electricity consumed by the water pump motor varies. It should be noted that these assumptions are only for this specific agricultural energy management system, and that they could vary in different models.

Regarding the RERs used in the developed system, 7.5-kW rooftop PV arrays are employed. This PV system is not an emulator, and in fact, it is already installed in the GECAD research center building in Porto, Portugal, where the developed system model was implemented. To merge this PV system in the model, an energy meter was installed in the AC side of the inverter to measure the real-time PV production and transmit the data to a local distributed PLC assigned to the PV system. Figure 3 shows the methodology implemented for monitoring real-time PV production.

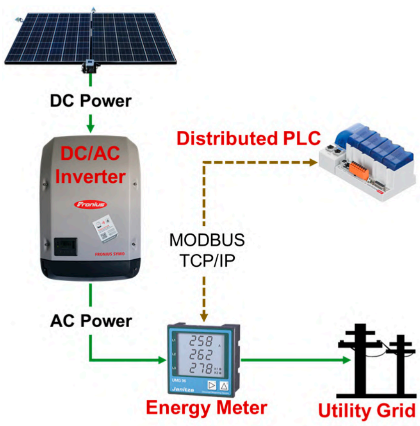

Figure 3. Monitoring mechanism of the PV system to be integrated in the proposed model.

The PV system, as well as the two emulators shown in this section, are all connected together through an internal electricity network as shown in Figure 4. This internal electricity network consists of three power lines, one for each resource of the system. The grid connection switchboard shown in Figure 4 is the connection point of the power lines to the utility grid. In addition, there is a console implemented in the switchboard showing a web-based graphical interface for monitoring the system parameters, such as electricity market tariffs, the status of each emulator, and real-time consumption and generation.

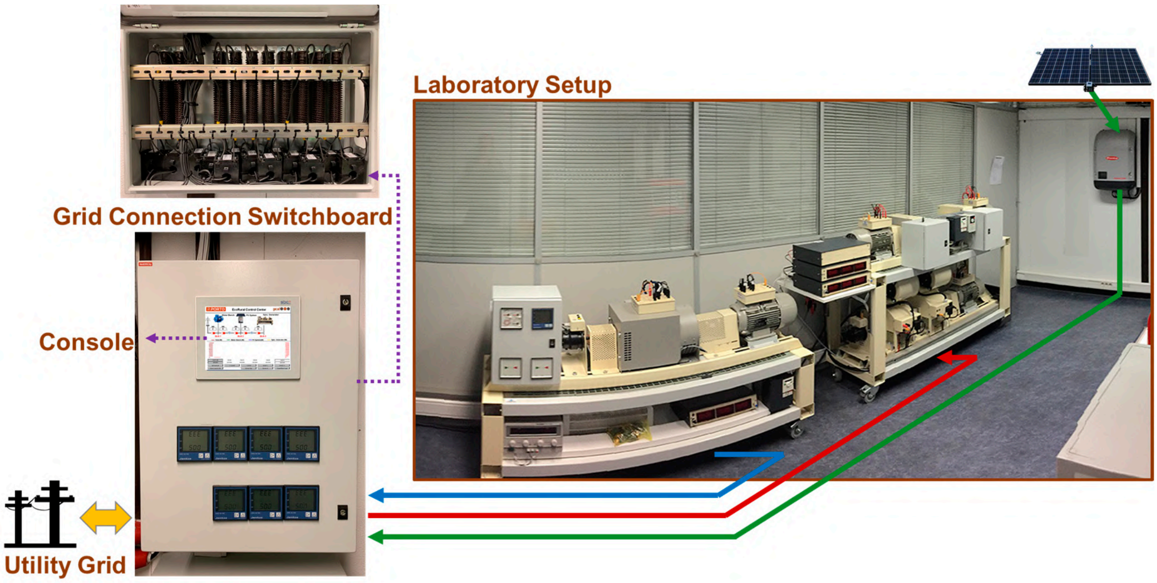

Figure 4. Internal electricity network of the presented system.

In sum, this section provided the laboratory model developed for the agriculture system. Practical features of all the equipment and emulators have been illustrated, and the implemented automation mechanisms have been described.

4. Case Study

This section details the case study that was conducted to validate and survey the performance of the developed model and the energy scheduling algorithms. Figure 5 shows the electricity price data used as input in this case study. All the profiles shown in this case study are for a complete day (24 hours) with a 1-minute time interval (1440 periods).

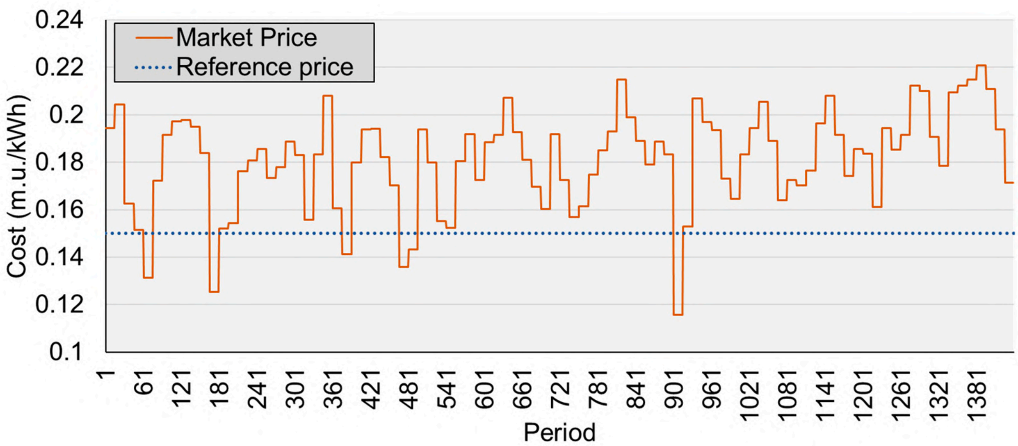

Figure 5. Electricity market and reference prices considered in the case study.

The profile shown in Figure 5 was created on the basis of the records given in the Portuguese section of the Iberian Electricity Market (www.omie.es). In the proposed agricultural energy management system, the electricity grid is considered as an external supplier, which supports the system whenever the local energy resources cannot supply the electricity demand. In this case study, it is considered that the user can also define reference price (as shown in Figure 5), so that when the electricity market prices are cheaper than the maintenance and technical costs of the local energy resources, the system is allowed to use electricity from the grid instead of using local resources (e.g., synchronous generator).

In addition, Figure 6A shows the total consumption and generation profiles considered in the system, and Figure 6B illustrates the detailed consumption profiles of the irrigation motors as well as the water pump motor. Furthermore, the level of water stored in the tank ranged from 0 to 100%, as shown in Figure 6B. In this case study, the initial tank level was considered to be 50%. The PV production profile shown in Figure 6A is a real profile adapted from the GECAD research center database.

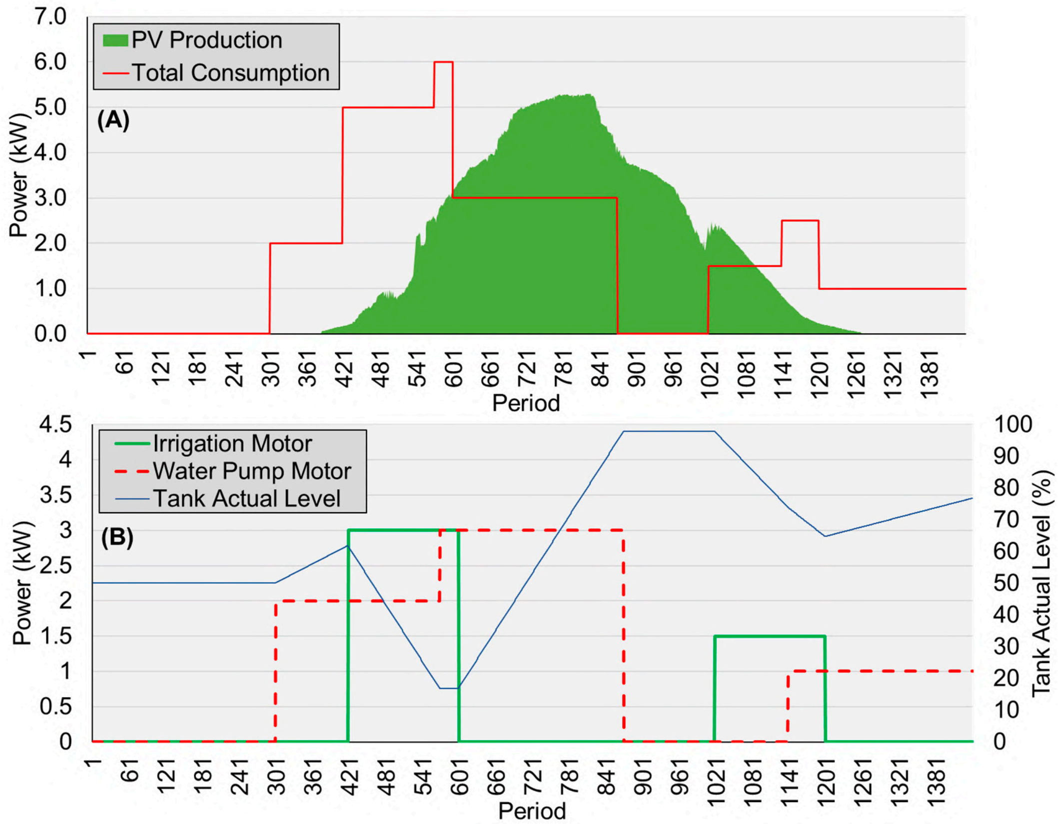

Figure 6. Consumption and generation profiles of the system for 24 hours: (**A**) total consumption and generation of the system; (**B**) energy consumed by the employed equipment.

According to the information provided by Food and Agriculture Organization (FAO) [35], the best time to irrigate crops is early in the morning and evening when the transpiration of water on the soil surface is minimal. Therefore, in this case study it was considered that the system irrigates the crops twice a day (as Figure 6B demonstrated), at full capacity in the morning (between 07:00 and 10:00) and at half-capacity in the evening between (17:00 and 20:00). The water used for the irrigation is supplied by the water tank, and the intention of the system is to maintain the tank full. Therefore, the water pump motor is responsible for supplying the tank with water from the river at different water pumping rates defined by the user. Table 1 shows the relation between the electricity consumption of the water pump and the three levels of pumping capacity.

In this case study, the dashed line in Figure 6B indicates the electricity consumption profile of the water pump motor, which depends on the pumping capacity level chosen by the user. Furthermore, the energy consumption of all of the irrigation and water pump motors in the system is shown in Figure 6A, and the generation profile is the energy generated by the PV. At some periods in Figure 6A, the energy produced by the PV can supply the demand fully. At other points, surplus energy is generated, which will be injected into the grid. However, there are some periods during which the system consumes more than it generates. In such periods, the use of synchronous generation, as well as the electricity grid, should be optimized and scheduled in order to minimize the electricity costs of the system.

Table 1. Water pump motor consumption and capacity levels (CA = capacity).

Pumping Level	Electricity Consumption	Water Pumping Rate
1	1 kW	$\frac{1}{3}\times$ CA
2	2 kW	$\frac{2}{3}\times$ CA
3	3 kW	$\frac{3}{3}\times$ CA (full capacity)

In this model, DT is responsible for the optimal scheduling of the energy resources. In fact, all of the profiles shown in Figures 5 and 6 are used as input data during the building of the DT. A large amount of data on the different conditions within the system had to be provided to the "RPART" package of RStudio® as a dataset in order to begin the building of the DT. For this purpose, 5 groups of data were considered. Table 2 shows the dataset for DT.

Table 2. Characteristics of the dataset created for decision tree (DT).

	Group 1 (Base)	Group 2	Group 3	Group 4	Group 5
Total Consumption	Figure 6A	Base × 1.2	Base × 1.1	Base × 0.9	Base × 0.8
PV Generation	Figure 6A	Base × 1.2	Base × 1.1	Base × 0.9	Base × 0.8
Market Prices	Figure 5	Base × 1.2	Base × 1.1	Base × 0.9	Base × 0.8
Tank Level	Figure 6B (tank actual level profile)				

Using the data shown in Table 2, a dataset was created giving numerous possibilities for different conditions within the system. The dataset was used by "RPART" to build the DT. The output of the DT was a set of rules specifying the amount of energy that should be produced by the synchronous generator to supply the electricity demand.

After the DT had been configured, the data shown in Figures 5 and 6 were used to solve the optimization problem discussed previously in Section 2.2. These data were delivered as inputs to the "OMPR" package of RStudio®. In the next section, the optimization solution provided by "OMPR" is compared with the solution provided by DT to demonstrate the superiority of DT and the accuracy of its outputs.

5. Results

This section presents all of the results obtained by the DT and the optimization problem. Furthermore, the functionalities of the system are discussed. Thus, first the DT created by the "RPART" package of RStudio® will be presented, and the accuracy of the tree will be discussed. Then, the DT's scheduling results will be compared with the optimization results of the "OMPR" package of RStudio®, so that the performance of the DT is validated. In the final stage, the DT itself was implemented in laboratory emulators and energy scheduling was performed for real resources, yielding real results.

5.1. Decision Tree Accuracy

The accuracy of the results of a DT is dependent on a series of factors, such as the nature of the input data, the vastness of the dataset, the calculation methods, etc. In fact, whenever the number of splits in a DT increases, the DT becomes more complex and precise. Figure 7 illustrates the created DT using the dataset shown in Table 2. The consumption and the PV values represented on the DT are in kW, market prices are in EUR/kWh, and the tank level ranges between 0 and 100%.

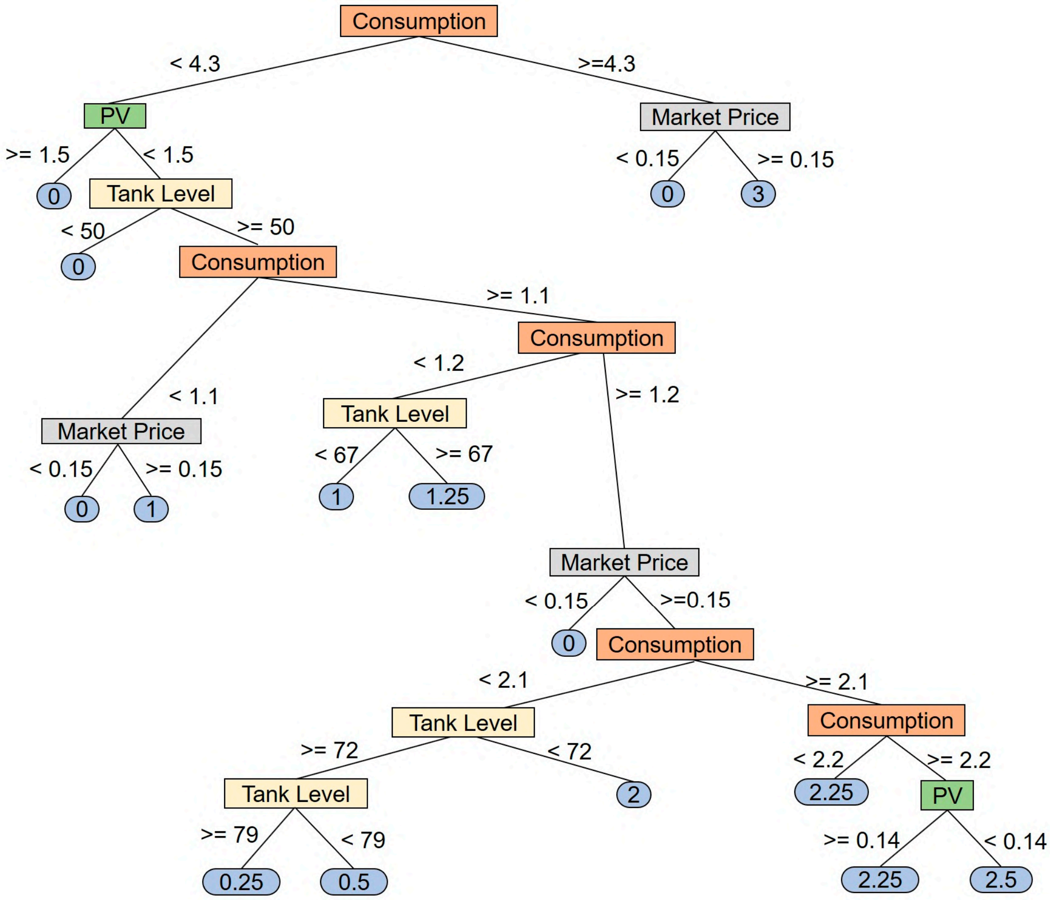

Figure 7. Developed DT for energy scheduling of the agriculture system.

The type of DT shown in Figure 7 is a classification tree (CART—classification and regression tree) that is employed to predict a qualitative response. In the classification tree, the training dataset is broken down into smaller subsets until the DT reaches an optimal level with a low error rate. Furthermore, the classification tree provides several decision paths based on the provided training data. The system employs these paths to predict that each piece of data can be placed in the most related category. Each node of the DT shows the utilized variables and thresholds employed for classification. The terminal nodes include the predicted solution in that node. In this system, the final result of the DT (terminal nodes) is the amount of power (in kW) that should be produced by the synchronous generator. The decision rules employed in this DT are presented in Table 3.

All the variables used in the DT have an importance rate, and as shown in Table 3, consumption is the most important variable. More specifically, Figure 8 illustrates the importance of each predictor variable in the DT, scaled to sum to 100%.

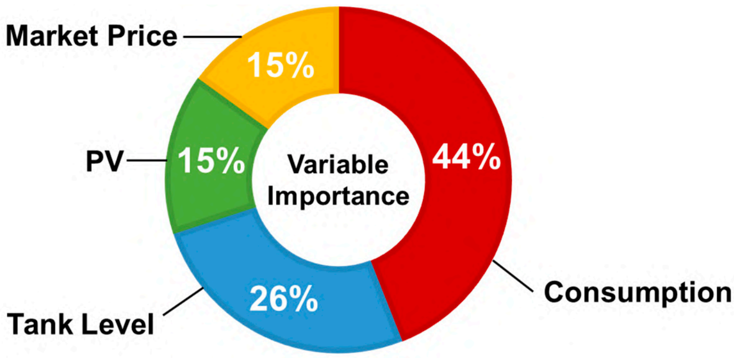

Figure 8. Importance of the variables in the developed DT (scaled to 100%).

Table 3. Employed decision rules to produce the DT.

	Decision Rules	Sync. Gen. Emulator
(1)	IF Consumption < 4.3 AND PV >= 1.50	0
(2)	IF Consumption < 4.3 AND PV < 1.50 AND Tank Level < 50	0
(3)	IF Consumption < 1.1 AND PV < 1.50 AND Tank Level >= 50 AND Market Price < 0.15	0
(4)	IF Consumption is 1.2 to 4.3 AND PV < 1.50 AND Tank Level >= 50 AND Market Price < 0.15	0
(5)	IF Consumption >= 4.3 AND Market Price < 0.15	0
(6)	IF Consumption is 1.2 to 2.1 AND PV < 1.50 AND Tank Level >= 79 AND Market Price >= 0.15	0.25
(7)	IF Consumption is 1.2 to 2.1 AND PV < 1.50 AND Tank Level is 72 to 79 AND Market Price >= 0.15	0.5
(8)	IF Consumption is 1.1 to 1.2 AND PV < 1.50 AND Tank Level is 50 to 67	1
(9)	IF Consumption < 1.1 AND PV < 1.50 AND Tank Level >= 50 AND Market Price >= 0.15	1
(10)	IF Consumption is 1.1 to 1.2 AND PV < 1.50 AND Tank Level >= 67	1.25
(11)	IF Consumption is 1.2 to 2.1 AND PV < 1.50 AND Tank Level is 50 to 72 AND Market Price >= 0.15	2
(12)	IF Consumption is 2.2 to 4.3 AND PV is 0.14 to 1.50 AND Tank Level >= 50 AND Market Price >= 0.15	2.25
(13)	IF Consumption is 2.1 to 2.2 AND PV < 1.50 AND Tank Level >= 50 AND Market Price >= 0.15	2.25
(14)	IF Consumption is 2.2 to 4.3 AND PV < 0.14 AND Tank Level >= 50 AND Market Price >= 0.15	2.5
(15)	IF Consumption >= 4.3 AND Market Price >= 0.15	3

Table 4 shows the pruning from the "RPART" algorithm for the developed DT. In this table, each row specifies the depth of the tree and the calculations that correspond to that level. In fact, the number of splits in each level is increased until the algorithm reaches an optimal level with a low error rate. Moreover, in Table 4, the relative error indicates the prediction error of the data that was used to make the tree, and the cross-validation error is the amount of error produced by the "RPART" built-in cross-validation. In addition, CP stands for complexity parameter, which is a value in each depth of the tree used to perform divisions in the nodes until the relative error decreases to a desired rate.

In other words, CP controls the size of the tree and chooses the optimal tree size. Moreover, CP α determines how the cost of a tree $R(T)$ is affected by the number of terminal nodes $|T|$, which results in a standardized cost $R_\alpha(T)$ [36]. In Equation (9), a larger amount of α results in small trees and potential underfitting, and small α results in larger trees and potential overfitting. The process of CP calculation is clearly illustrated in Figure 9.

$$R_\alpha(T) = R(T) + \alpha|T| \quad (9)$$

In fact, Figure 9 shows a summary of the computation process based on the relative error and CP in order to calculate the most optimal size of the tree. The dashed line in Figure 9 is a certain rate of relative error that the algorithm should reach to compute the most optimal results. More simply, the point at which the two lines in Figure 9 have crossed each other is the most optimal size of the tree, which in this case is 15 terminal nodes.

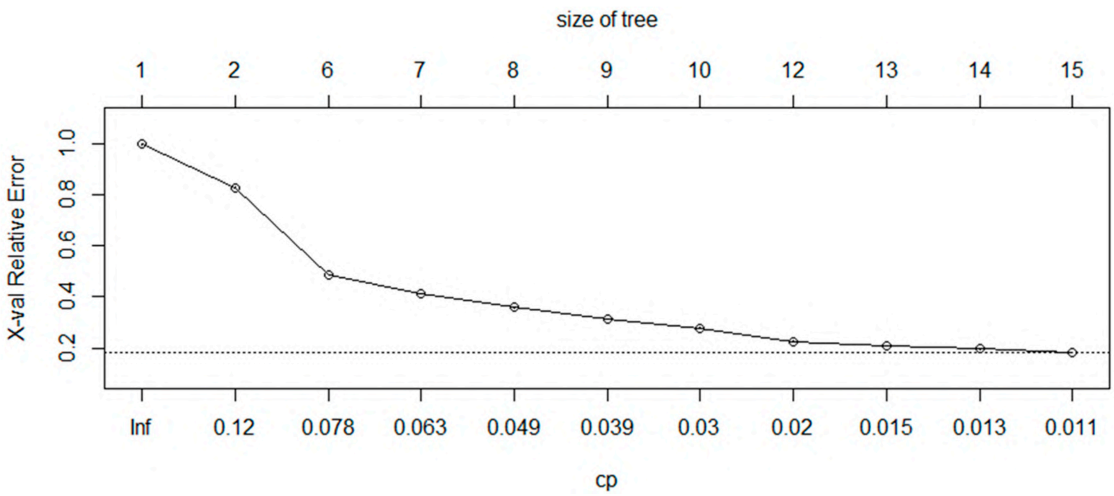

Figure 9. Pruning plot of the DT and its computational process based on relative error and the complexity parameter (CP).

Table 4. Pruning table of DT to indicate the errors in each level of the tree.

Level	Complexity Parameter	Number of Splits	Relative Error	Cross-validation Error	Standard Deviation Error
(1)	0.169397	0	1.0000	1.0000	0.001366
(2)	0.081906	1	0.8306	0.8306	0.001307
(3)	0.075205	5	0.4866	0.4867	0.001089
(4)	0.053611	6	0.41139	0.41171	0.001019
(5)	0.045048	7	0.35778	0.3581	0.000961
(6)	0.034624	8	0.31273	0.31305	0.000907
(7)	0.026061	9	0.27811	0.27832	0.000862
(8)	0.015637	11	0.22599	0.22614	0.000785
(9)	0.014892	12	0.21035	0.20908	0.000758
(10)	0.011914	13	0.19546	0.19559	0.000735
(11)	0.01	14	0.18354	0.18368	0.000714

To summarize, the process of building a DT has been outlined, and detailed information has been given regarding its errors. In this section, we explored how it is possible to increase the accuracy of the results obtained by the DT. The output results of the DT (terminal nodes) will be compared with another optimization method to validate its performance.

5.2. Energy Scheduling Results

In this section, the energy scheduling results of the optimization algorithm as well as the developed DT are outlined and compared. The mathematical formulations shown in Section 2.2 were used to present the optimization problem, which was then solved by means of linear programming with the "OMPR" package of RStudio®. The energy scheduling results using the optimization algorithm are shown in Figure 10A. Furthermore, the DT and its decision rules shown in Section 5.1 were also implemented in RStudio®, and the energy scheduling results using DT were acquired, as illustrated in Figure 10B.

By comparing Figure 10A,B, it can be concluded that the developed DT results are very similar to the scheduling results of the optimization algorithm. This can prove the performance of the DT and its decision rules since the system can operate in an optimal way using the developed DT. In both scheduling results shown in Figure 10, PV production is the first source of energy for the supply of the demand, and then the system regulates the output of the synchronous generator to supply the remaining energy needs. In periods of high consumption, the energy supplied by the PV and the synchronous generator is not enough and the system purchases energy from the electricity grid. However, there are several periods in which the PV generation is higher than the consumption rate, so the system injects the surplus energy into the electricity grid. It should be noted that the DT is only applied in the system when the consumption and generation rates are higher than zero since there is no need to apply the scheduling when these two rates are equal to zero.

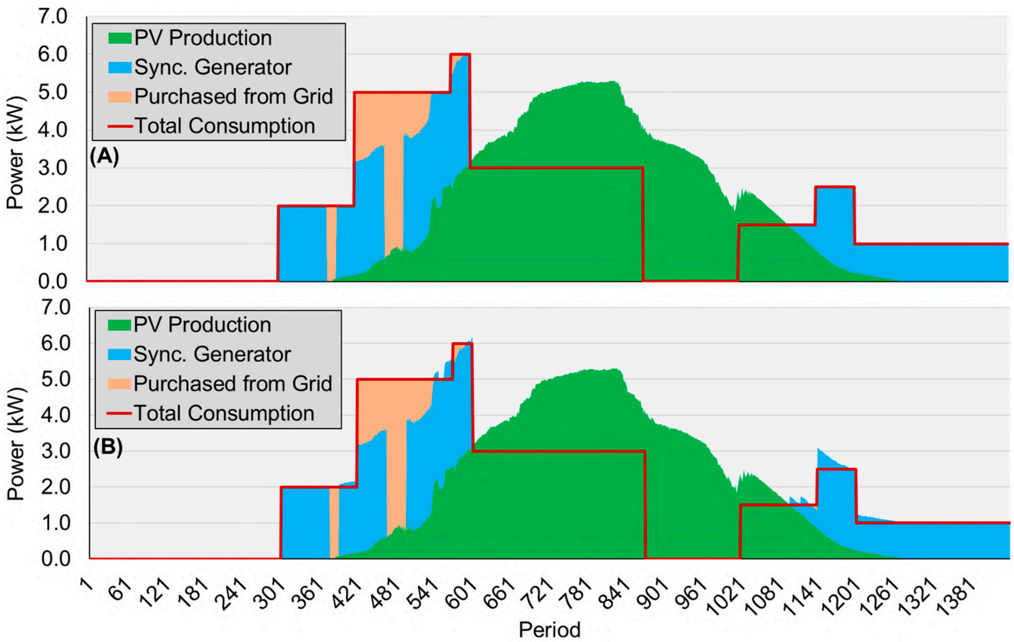

Figure 10. Energy scheduling results using (**A**) an optimization algorithm; (**B**) DT.

In some periods of the scheduling shown in Figure 10, the system purchases energy from the utility grid instead of using a synchronous generator. This is because in these specific periods, the electricity market prices are cheaper than the reference price defined by the system user. This reference price is calculated according to the service and maintenance costs of the synchronous generator and its river turbine. In other words, if the system recognizes that the market price in a period is cheaper than the maintenance costs of the synchronous generator, it purchases energy from the utility grid and stops the synchronous generator. The same is not true for the PV resource because PV arrays are always able to produce electricity with little or no maintenance cost. To compare the scheduling results in more detail, Figure 11 shows the energy scheduling results for the synchronous generator. In most of the periods in Figure 11, the differences between the two profiles are not significant. Therefore, it is concluded that the system can rely on the DT to perform the optimal scheduling of the resources.

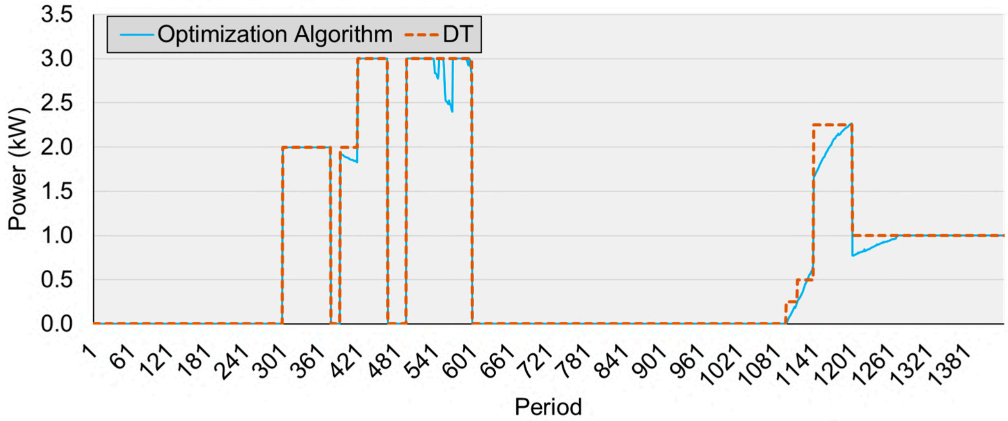

Figure 11. Scheduled generation profile for the synchronous generator during the entire case study.

5.3. *Actual Measurements*

This section demonstrates the performance of the agriculture system in the laboratory. All the equipment presented in Section 3 was employed to implement energy scheduling, acquire real results, and test the behavior of each laboratory emulator. In this regard, a 10 minute-cycle was selected between period #300 and #600 of the case study, each period having a duration of 2 seconds in real time. In some experimental results shown in this section, the cycle lasted more than 10 minutes due to the emulator's technical features.

Figure 12 shows the first experimental results of the syn. gen. emulator. In Figure 12, the setpoints are the scheduled values that the PLC specified to be produced by the synchronous generator to supply the consumption of the system. The real measurement profile consists of the information acquired from the emulator (absolute amount of generated energy), which is measured by the energy meter of the emulator and monitored by the local PLC.

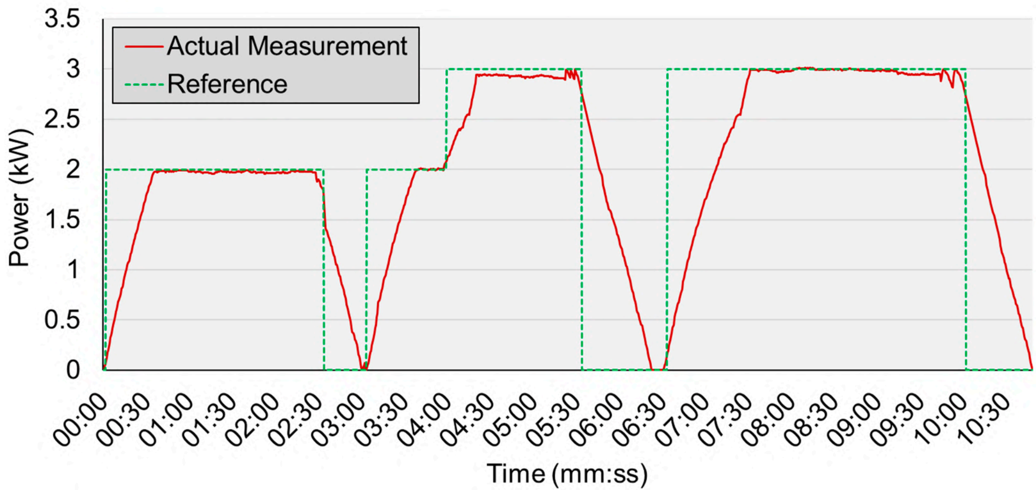

Figure 12. Generation profile of the syn. gen. emulator.

The instabilities of the emulated profile demonstrated in Figure 12 are because of the technical and practical features of the system, such as electrical grid conditions and voltage variations. The PLC is responsible, in this regard, for the control of the rate of generation and for ensuring it is stable and close to the setpoint. Furthermore, the slow response time of the sync. gen. emulator creates a gap between the expected and real results. In fact, this is one of the most important aspects of emulation and laboratory experiments; they reveal the practical features and technical issues of each model.

Regarding the consumption emulation of the agriculture system, Figure 13 illustrates the consumption profiles emulated by the motor bench. As shown in Figure 13, the critical moments in this emulation are those where the irrigation motors start operating. In these moments, the motors lead to some instabilities in the system for a short period of time. By comparing Figure 13A,B, it can be concluded that the emulated consumption profile of the two irrigation-related motors is smoother than the water pump motor. This is due to the constant loads applied to the shafts of the irrigation motors in the emulator. In the water pump motor, the PLC should adjust the rate of load applied to the motor shaft, and this causes some variations in consumption rate.

Furthermore, Figure 14 shows the whole consumption profile produced during the emulation of the system as well as the power that was supplied by the utility grid during the emulation. All resources were operated in a grid-connected mode in this laboratory experiment, and the electricity network was considered as an external supplier that supports the system when the local energy resources cannot supply the electricity demand.

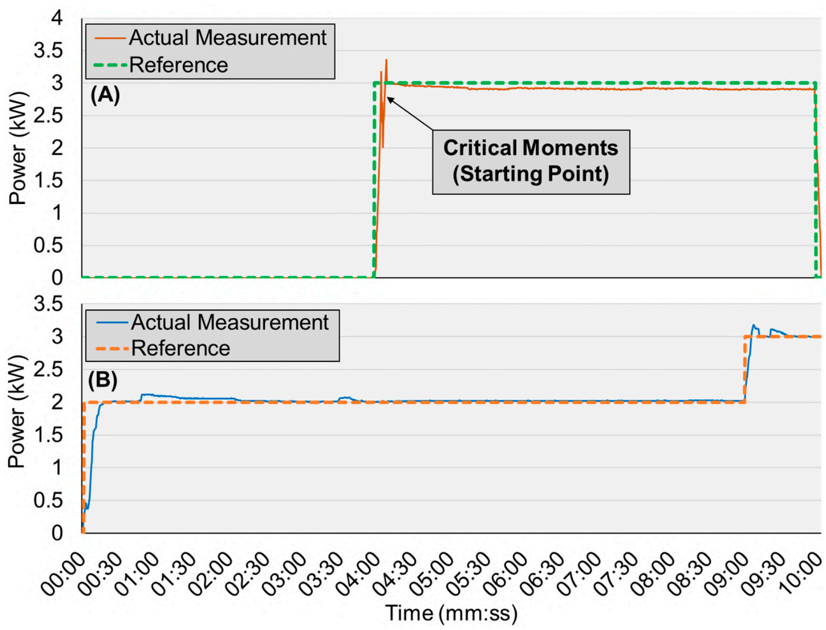

Figure 13. Emulated consumption profile of the system by the motor bench: (**A**) irrigation motors; (**B**) water pumping motor.

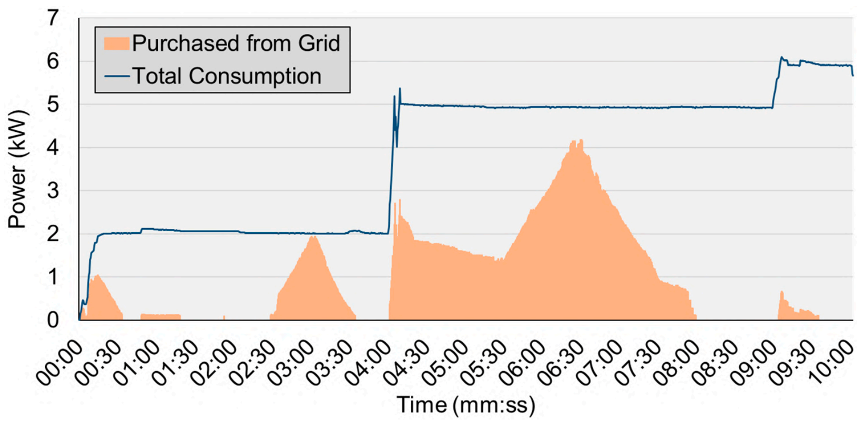

Figure 14. Power purchased from the utility grid in comparison to total consumption during the laboratory experiment.

As Figure 14 shows, while all the electrical motors of the system (irrigation and water pumping) operate at full capacity, the local energy resources (PV and synchronous generator) are not able to supply the demand, so the rest of consumption is supplied by the electricity network.

5.4. Cost Comparison

The final results involve the comparison of cost. For this purpose, the overall costs of the system were calculated for three different scenarios: (1) without using any RERs and decision making; (2) using RERs and the optimization algorithm for decision making; (3) using RERs and the developed DT. The market prices shown in Figure 5 were considered as the cost of purchasing energy from the utility grid. The cost of selling energy (injecting generation surplus) to the main grid is considered to be 0.0522 EUR/kWh according to the Portuguese regulations—Article 24 of [37,38]. The results of the cost calculations are shown in Table 5.

Table 5. Cost calculation during the proposed case study.

Scenarios	Features	Daily Cost (EUR)
(1)	No RERs No Decision Making	5.752
(2)	With RERs With Optimization Algorithm	–0.085
(3)	With RERs With DT	–0.117

As can be seen in Table 5, the use of RERs contributes significantly to the reduction of daily electricity costs. The system profits from the surplus energy injected into the utility grid. Thanks to employing RERs on the demand side, electricity consumers take on the role of prosumers who also produce electricity. Furthermore, the use of the DT approach leads to slightly greater cost reductions than those achieved by the optimization algorithm. This is because the DT's scheduling was more optimal than that of the optimization algorithm.

The profit obtained in scenario (2) comes from the surplus PV energy generation; since the tank was already full, the energy was injected into the grid. In scenario (3), additionally, the DT's scheduling decisions involve some error. Some energy from the synchronous generator was sent to the grid when this was not optimal.

6. Conclusions and Future Lines of Research

The world's population is increasing on a daily basis, as a result ensuring agricultural sustainability is more important than before. It is essential to improve energy efficiency in this sector, and we need more automation mechanisms that are compatible with the new concepts of the power system, such as smart grids and demand response programs. In addition, renewable energy resources are easy to access in rural areas and have minimal environmental consequences.

In this paper, an energy-scheduling model was proposed and a case study was conducted to test its viability. Hydropower and renewable energy resources were considered in the model to supply the electricity demand of the farm. Some automation mechanisms were proposed and described in this paper, which were been implemented in real laboratory devices and machines for modelling the consumption and generation of the proposed agriculture system. Furthermore, a decision tree was presented for optimal energy scheduling in the system. The DT was also implemented in a laboratory model to test its performance. In this way, the system was able to minimize its dependence on the utility grid since it could supply the electricity demand with the locally produced energy using a photovoltaic unit and a hydropower turbine.

The system was tested and validated in a realistic scenario, with its energy scheduling performance examined as well as the technical and practical capabilities of the developed model. Real data were used for some of the system aspects; real data on energy resources were used in the development of the decision tree. Furthermore, the precision errors of the system were calculated. In the final stage, the technical behaviors of the emulated agricultural energy scheduling model were discussed.

The results of this paper show that the operation of the decision tree approach is acceptable since it can schedule the use of energy resources in an automated offline mode with no need for an external server or machine for the complex computational algorithm. This is a very important factor in practice since most farms are located in remote areas that lack access to the internet or any high-performance computing machines. Moreover, the practical results of the paper showed a gap between the expected and the real results. This is the main advantage of laboratory experiments—they make it possible to identify practical features and reveal the technical issues of each model, which mostly remain hidden during the phases of theoretical study and simulation. Therefore, laboratory implementation and experiments are essential when validating the performance of any system under practical challenges, such as device response time and electricity network conditions, namely voltage variations and frequency instabilities.

In a future work, it is intended to develop and integrate an autonomous approach to determine optimal irrigation periods using field data, such as soil moisture level, evapotranspiration of crops, precipitation, etc. In this way, the system will not only be able to optimize the use of water in the irrigation process, but it will also be able to optimize and reduce the overall operational costs associated with energy consumption. Forecasting will also be utilized to predict critical parameters (i.e., energy consumption and generation, solar radiation, precipitation, etc.), improving the efficiency of the model. Further lines of research can go beyond model emulations, focusing on the implementation of the model in real scenarios and testing other optimization techniques, such as particle swarm optimization.

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Implementation of a Real-Time Microgrid Simulation Platform Based on Centralized and Distributed Management

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Abstract: Demand response and distributed generation are key components of power systems. Several challenges are raised at both technical and business model levels for integration of those resources in smart grids and microgrids. The implementation of a distribution network as a test bed can be difficult and not cost-effective; using computational modeling is not sufficient for producing realistic results. Real-time simulation allows us to validate the business model's impact at the technical level. This paper comprises a platform supporting the real-time simulation of a microgrid connected to a larger distribution network. The implemented platform allows us to use both centralized and distributed energy resource management. Using an optimization model for the energy resource operation, a virtual power player manages all the available resources. Then, the simulation platform allows us to technically validate the actual implementation of the requested demand reduction in the scope of demand response programs. The case study has 33 buses, 220 consumers, and 68 distributed generators. It demonstrates the impact of demand response events, also performing resource management in the presence of an energy shortage.

Keywords: demand response; distributed generation; microgrid; real-time simulation

1. Introduction

The increment on the penetration of the distributed generation (DG) resources encounters the current power grid with management and reliability challenges [1]. For overcoming these issues, the entire power network can be distributed into several small power grids, which are the sub set of the main power network. This solution is attainable via the concepts defined in smart grids, such as microgrids [2]. The microgrid refers to a group of DG units, renewable energy resources (RERs), and the local loads that can rely upon the main distribution network [3]. Basically, the RERs consist of photovoltaic (PV) systems and wind turbines [4].

The real-time measurements of different nodes of a microgrid are an essential issue for managing and controlling the grid through both the centralized and distributed methods. This can be released by phasor measurement units (PMU). The PMU are synchronized time based instruments, which collects highly precise phasor data of the power system [5]. The PMU plays a key role in the real-time monitoring of the smartgrids and microgrids that utilizes the global positioning system (GPS) to provide the concurrent measurements [6]. Typical PMU devices are able to provide 30 samples per second [7]. This enables the grid operator to be informed from the synchronized time based voltage and current phasor measurements in different nodes of the grid, in order to control and manage the power stability and delivery [8].

Additionally, if the DG resources are integrated with demand response (DR) programs, the microgrid conceptions can be fully addressed. DR programs are defined as altering the electricity consumption profiles based on the incentives payment provided by the network operator due to technical reasons or economic purposes. Incentive-based and price-based are two major classifications of DR programs [9]. In this context, virtual power players (VPPs) play a key role for aggregating the DG and DR small size resources, in order to be used in electricity markets as a large scale resource [10].

In order to control and manage the resources available in the microgrid, two main methods can be proposed: centralized and distributed control. In the centralized control method, a powerful central controller unit is responsible to manage and control the microgrid, where communication between this unit and each single component of the network is required [11]. However, in the distributed control method, the decisions take place locally and are based on the real-time information exchanged by the network components [12]. Both methods have several advantages and disadvantages. For example, the centralized control requires high initial cost and needs a widespread scheming; however, it provides better efficiency. In the meantime, the centralized network can be implemented step by step from the bottom levels to the top levels [13].

This paper presents the development and implementation of a real-time microgrid simulation platform managed by centralized and distributed controlling decision support. In this platform it is attempted to provide a realistic microgrid implementation using real and laboratorial hardware equipment. The microgrid players included in this platform consist of two renewable DG units (PV and wind turbine), and a low and a medium consumer load (laboratorial equipment), which are connected to each other as well as the main power grid through four power lines. The local demand of the microgrid can be supplied from the energy provided by the DG and the grid as well. For the centralized control method, a real-time simulator model has been employed in order to manage the system, and for the distributed control manner, a local controller is associated for each player in order to perform the decision making locally and achieve the microgrid goals.

There are several related research works, which implemented and surveyed the microgrid models based on centralized or distributed decision support. In [13], the authors examined two implemented microgrid topologies, one centralized and one distributed model, which combine solar panels and batteries for 20 residential houses. In [14], the authors provided an optimal solution for dispatching of the local resources in the medium voltage (MV) microgrids that temporary or permanently operate in islanded mode. In the optimization problem, they considered that all the power produced by renewable generators (PV and wind) is used, in order to minimize the microgrid operation costs as well as the pollutant emissions of the programmable generators. In [15], a new distributed controlling method was proposed for secondary frequency and voltage control and stability in a microgrid while it is operating in islanded mode. In this method, the authors utilized localized data as well as nearest-neighbor communication to implement the secondary control operations while there is no necessity of information about the loads and microgrid methodology. In [16], a unified controlling method is addressed for the cooperation of distributed energy resources (DERs) and the DR to support the voltage and frequency of an islanded microgrid in which it minimized the overall operation costs of the grid through an optimization problem. In the proposed algorithm, the frequency deviation was considered as a new state variable in the model. In this way, the model enables us to calculate the required set points for the DERs and the amount of power that should be curtailed by the controllable loads available in the grid. In [17], a simulation based analysis of dynamical behavior of a residential DC microgrid laboratory setup in distributed and centralized voltage control configurations is presented. In [18], the authors described the control algorithm of a utility connected microgrid, based on independent control of active and reactive power and operating in centralized and distributed operation mode. In addition to these works, a significant number of published works have been focused on the multi-agent based and distributed control models for the energy management of the microgrids [19–21].

There are a lot of laboratories and test beds implemented for development and validation of the capabilities of smartgrids and microgrids by utilizing the real-time simulation facilities [22]. Austrian Institute of Technology (AIT), Vienna, Austria, includes three configurable three-phase low-voltage grids and the real-time simulation with hardware-in-the-loop (HIL) setups in order to experiment with the real-time simulation platform for advanced power-HIL and controller-HIL analysis, and the validation of energy management systems and distribution supervisory control and data acquisition (SCADA). OFFIS—Institute for Information Technology, Oldenburg, Germany has an automation laboratory, which includes OPAL-RT simulator for executing a highly detailed and dynamic power grid. The OFFIS utilizes this laboratory for centralized and decentralized controlling methods and parallel simulation. Laboratoire de Genie Electrique de Grenoble, Grenoble, France, includes a real-time power-HIL simulation laboratory equipped with two real-time multiprocessors digital simulators. This enables them to focus on power system protection relays, testing different types of equipment, namely wind turbine emulator and hydro turbine, and testing the industrial converters for PV systems. Commissariat A L'energie Atomique et AUX Energies Alternatives, France, has a microgrid platform including several renewable and conventional generators, energy storage systems, controllable loads, and electrical vehicles. The main core of this platform is a HIL simulator, which enabled the facility to validate and examine the microgrid operation and protection, voltage and frequency control, energy storage systems management etc. Distribution Network and Protection Laboratory, Glasgow, UK, consists of a three-phase power grid including several multiple controllable voltage supplies, flexible and controllable loads. There are several real-time simulators in this laboratory, which are utilized for surveying protection concepts, automation equipment, and new solutions for distributed power system control.

The main objective of the present paper is to develop and implement a real-time microgrid simulation platform using several real and laboratorial hardware equipment. Such a platform supports real-time simulation skills and HIL means in order to address the validation of demand response and distributed generation optimization. A microgrid accommodates such resources and is managed by a VPP that aims at minimizing the operation costs, using both distributed and centralized control methods. An upstream network is modeled in MATLAB/Simulink, using mathematical and non-physical models. The use of real-time simulation and HIL scenarios brings the ability of controlling and managing the real resources from the simulation environment with non-real management scenarios, such as optimization models.

The problem statement is related to how a microgrid business model can be examined and validated in terms of management and control, before massive implementation. Implementing a completely realistic microgrid model only for testing and validating, would not be a cost-effective solution. Furthermore, it would not be available for everyone, since only a limited number of companies or research institutes could be equipped with that type of test bed. The microgrid platform designed in this paper is flexible in terms of controlling methods and is up to the operator to choose.

In this way, namely when comparing with [23], the contribution of the present paper relies on the presented approach that integrates all the above referred aspects of the work, namely with improved aspects as the optimization of resource use.

In both centralized and distributed control methods, the different nodes of the microgrid (accommodating consumers and generators) will be measured through the several energy meters mounted on the various locations of the grid. The sampling period of these energy meters are one sample per second, which have enough accuracy for optimization problems and DR program applications, and the high precision measurement devices, such as PMUs, may not be required for these kinds of applications. This microgrid is also able to be configured in islanded or grid-connected mode. Since the energy transaction between the microgrid and the main grid is considered, the autonomous mode is out of the focus of the paper. Another topic out of the present work focus is the market congestion in the connection of the microgrid with the upstream network. It is not included on the economic model since the main focus is given to minimize microgrid operation costs. The considered VPP is selling electricity in the market and the network has enough capacity for the energy transactions.

This paper is structured as follows: after this introductory section, the development and implementation of the proposed microgrid simulation platform is described on Section 2. Then, a case study is defined and executed with the presented model in Section 3 and its results are described in Section 4. Finally, Section 5 clarifies the main conclusions of the work.

2. Real-Time Microgrid Simulation Platform

This section describes the real-time implementation of a microgrid simulation platform based on two controlling methods: centralized and distributed. This system has been implemented in GECAD laboratory [24]. In this model, several laboratorial hardware resources have been employed in order to simulate a realistic microgrid. The present model is designed and implemented in a way that the controlling methods can be selected by the user/operator. This enables the operator to choose the centralized or distributed control method, depending on its application.

Since the proposed system employs the real-time simulator as well as several real hardware equipment, it enables the systems or platforms that include network simulation models to use the real data in their simulation models. Therefore, the present microgrid model will be used as a part of a network simulation model used by DR program simulation platform developed in [25], called SPIDER—simulation platform for the integration of demand response. This platform has been designed to widely support the decision-making for different types of network players, which are involved in the DR programs. As a general description of SPIDER, it surveys and specifies the data-mining methods, which are appropriate for the consumers who intend to participate in DR programs. Data-mining algorithms are applied in the module "model optimization" (with orange highlights in Figure 1). In fact, this module includes several types of algorithms for DR implementation, such as the energy resource optimization, data-mining for aggregation of resources, forecasting online tools, etc. For example, if data-mining is applied, whenever a new scenario is computed in the simulation, the system automatically includes the scheduling of resource results as input to the aggregation of the resources. After the data-mining is computed, the simulation proceeds to step "4" (as can be seen in Figure 1). A data-mining algorithm used for energy resource aggregation and remuneration can be found in [26].

SPIDER is an essential instrument for validating and analyzing the business and economic aspects of the DR programs, and surveying their influence in the electricity network. For this purpose, SPIDER uses MATLAB/Simulink [27] tools in order to simulate the basis platform for the grid simulation. Figure 1 illustrates the overall view of the SPIDER simulation platform with the proposed microgrid simulation configuration using the centralized control method. In this system, several softwares have been employed in order to exchange data between different sections.

The platform starts the process from network simulation in Simulink; afterward, JAVA application programming interface (API) is used in order to transmit the information of the network simulation to the optimization block. Then, TOMLAB [28] tool is used for the optimization in the SPIDER, and its optimization results transfer to the network simulation block using JAVA API as well. Full details about the SPIDER and its infrastructures can be found in [25].

The microgrid model proposed in this paper has been demonstrated in the top of the Figure 1, as depicted by green color. The model includes four nodes; two nodes dedicated for the consumers, and the other two devoted to renewable DG units. This microgrid has the capability of supplying the local loads by its own DG units, and transacts energy with the main grid in order to feed the loads in the moments that there is not enough generation from the energy resources. In addition, it can inject the excess of the produced power to the main gird.

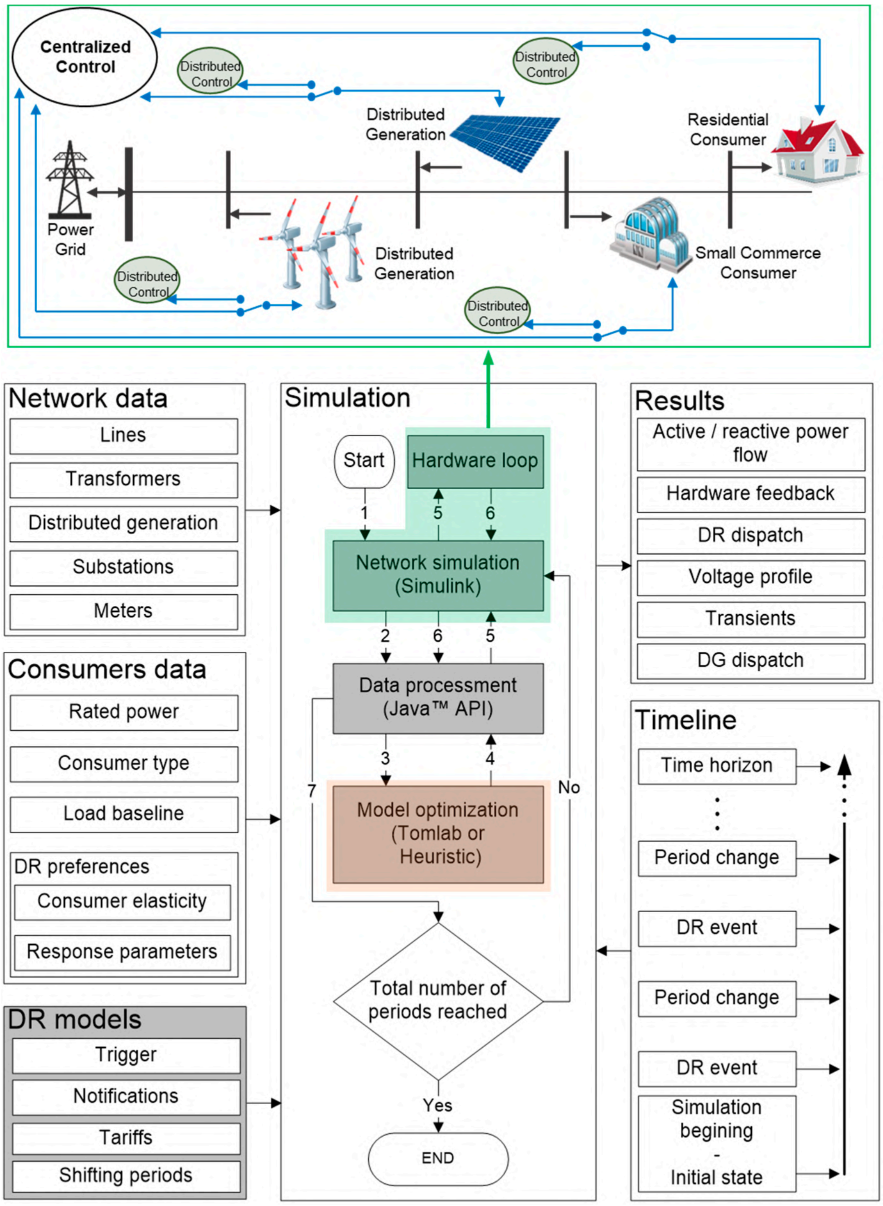

Figure 1. Proposed microgrid configuration for the simulation platform for the integration of demand response (SPIDER) simulation platform implementation.

As can be seen in the top of Figure 1, there are four switches; one for each player, which enables the microgrid operator to select the controlling method. If the centralized controlling method is selected, the central controller unit is responsible for managing the network players and controlling the consumption and generation of the resources. For this purpose, the central controller transmits the controlling commands to each player by using independent communication channels line. However, if distributed control method is selected, the central control unit is eliminated and the local controllers manage the network by transmitting and sharing information between each other. It should be noted that the status of all switches should be equal (all centralized or all distributed). The following sub sections describe how the microgrid is controlled by the centralized and the distributed methods.

2.1. Centralized Control Model

In this section, the central controller unit, network players, and the controlling methods, will be explained. The microgrid model proposed in this section is an improved and reformed version of the model proposed in [23]. In the previous work, there were low and medium consumer units playing the role of residential and small commerce facility consumers, and a wind turbine emulator playing the role of a home-scale wind turbine. However, in this paper, a 7.5 kW PV system and four power lines have been added to the system in order to implement a comprehensive laboratorial microgrid model.

Figure 2 presents the centralized microgrid control model proposed in this paper. As can be seen, the central controller unit is located at the top of the model and the other network players are connected to this unit. This unit is OP5600, the real-time simulator machine [29], a powerful instrument to produce real-time simulations even with a high complexity degree while enabling HIL. OP5600 is based on the MATLAB/Simulink and indeed it runs the Simulink models in real-time. Additionally, there are several Digital/Analog I/O slots embedded on the OP5600, which enable the user to control real hardware devices from Simulink models and also receive feedback. This is how HIL integrates the real data with the Simulink models.

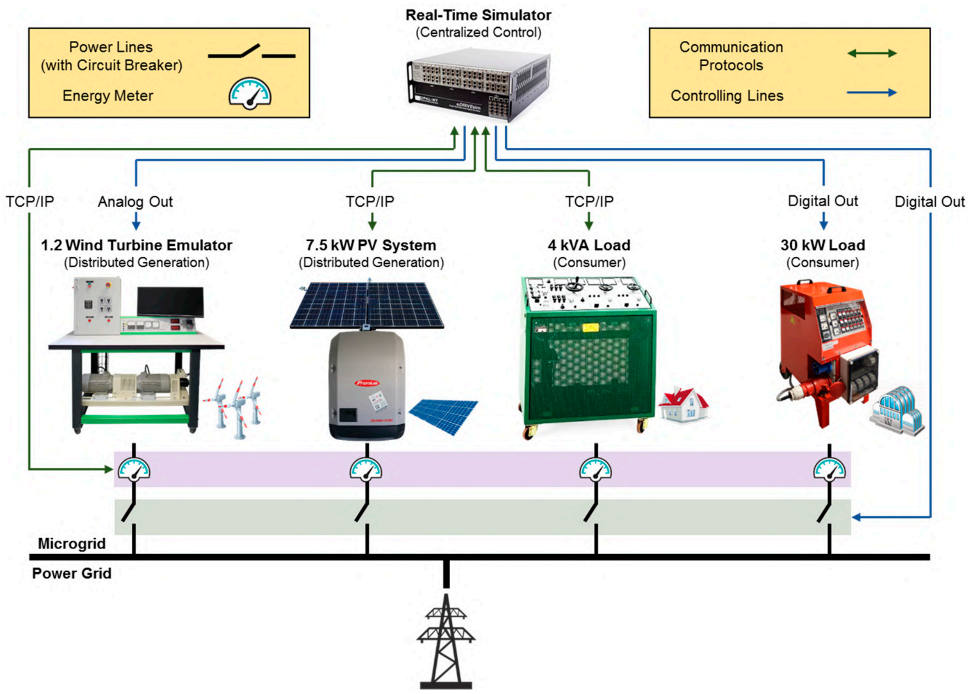

Figure 2. Centralized microgrid model architecture.

The other network players consist of a 4 kVA and a 30 kW load playing the role of low and medium consumer units, and a 1.2 kW wind turbine emulator and a 7.5 kW PV system as DG units in the microgrid. All of these network players were not operating automatically in their factory configuration. However, several automation projects have been implemented on them, in order to control and manage them remotely and automatically [23,30]. For concentrating on the innovative perspectives of the model, only the most related sections of the system are described here.

As shown in Figure 2, the first DG unit is referred to the 1.2 kW wind turbine emulator. This emulator consists of an inductive three-phase generator coupled with a three phase asynchronous motor with variable speed. The speed controller unit allows the variation of the wind speed and consequently the speed variation of the wind turbine rotor. This emulator is controlled through the analog outputs of the OP5600 (Simulink).

The second DG unit is a 7.5 kW PV system, which is already installed on the GECAD laboratory and currently is producing energy. For acquiring and monitoring the real-time generation data in OP5600 and Simulink model, Modbus/TCP (transmission control protocol) protocol has been used.

The third node is related to the 4 kVA load, the low consumer player of the microgrid, which plays the role of a domestic consumer in the microgrid. This load includes three independent sections of resistive, inductive, and capacitive. The automation process was focused on the resistive part. In the factory setting, it had a steering connected to a gauge in the resistive section, which enables the user to increase or decrease the consumption of the load. Currently, a programmable logic controller (PLC) connected to a 12 V DC motor controls the resistive gauge. This enables the 4 kVA load to receive the desired amount of consumption from OP5600 through Modbus/TCP communication protocol, and to adjust its consumption based on the received value.

The last node is connected to the 30 kW load, the medium consumer player of the microgrid that represents the consumption of a small commerce. By default, it had an integral control panel equipped with several selector switches, which enables the user to control the consumption. However, in order to control this unit automatically, four relays have been mounted on the load and are connected to the digital output of the OP5600. Therefore, the central controller unit is able to control the consumption of this resource through the Simulink model.

The power lines is the section that is not included in the previous microgrid model, and is proposed in this paper. As can be seen in Figure 2, there are four power lines that connects each node of the microgrid to the main power network. In each line, there is a circuit breaker and an energy meter. The circuit breakers are connected via digital output channels of the OP5600, and it enables the user to interrupt the line and disconnect the resource from the main grid through the Simulink model. Furthermore, the energy meters measure the power flow in the lines and transmit the real-time active power data to the Simulink model using Modbus/TCP protocol.

The existing platform can be improved in order to accommodate transient and stability studies which would require the use of PMUs instead of energy meters. In fact, the existing meters in the platform provide acceptable accuracy and sampling per second; however, it doesn't allow the synchronizing of measurements by GPS.

2.2. Distributed Control Fashion

As it was shown in Figure 1, there are four switches for the microgrid players where the user can choose how the microgrid be controlled. Figure 3 illustrates the microgrid distributed control method. In this condition, the central controller unit (OP5600) will be excluded from the microgrid point of view, and the local controllers manage the network.

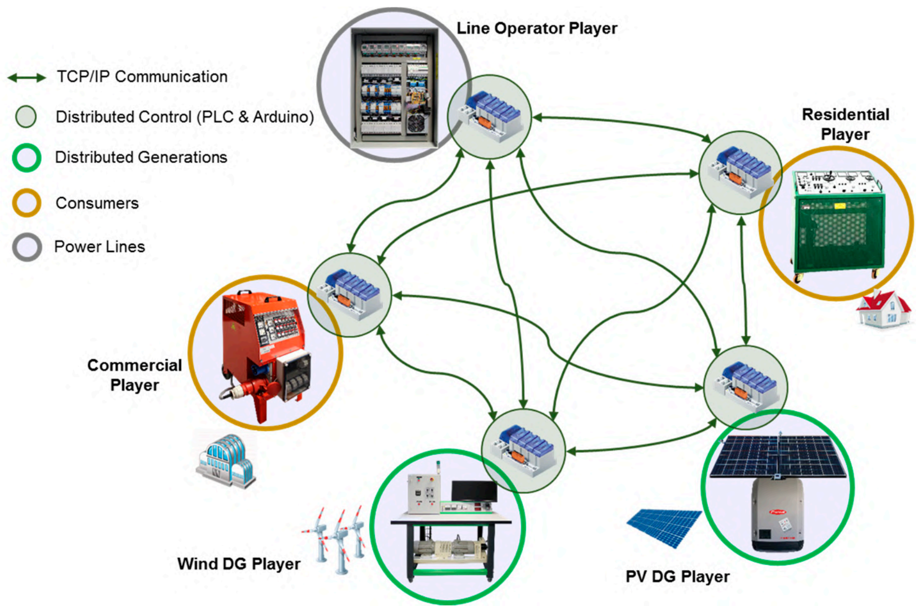

Figure 3. The distributed control based microgrid model.

In distributed control, there are five main players: a residential player, using a 4 kVA controllable load; a commercial player, using a 30 kW controllable load; a line operator player, that controls the power lines; a PV DG player; and wind DG player. A PLC is dedicated for each player. This enables the microgrid to accomplish decision making locally and communicate with other microgrid players, through TCP/IP (internet protocol) communication protocol, to achieve the microgrid's goals. The players are responsible for constantly exchanging messages in order to report their latest status in the network.

The microgrid players have dedicated PLCs with several Digital/Analog I/O slots used for their control and management. Residential player uses digital output slot to control the load motor. The commercial player is equipped with digital output slot in order to control the relays, and wind DG player employs an analog output slot for controlling the speed variation of the wind turbine rotor, and finally the line operator player uses the digital output slot to control the status of the circuit breakers of the lines.

The main task of the residential and commercial players are to control and adjust their consumption based on the overall system's goals. Furthermore, the PV DG player contains the data regarding the PV production and is accountable for informing the other agents with the latest value of the PV generation. Meanwhile, the wind DG player undertakes requesting the wind speed data from an external resource, such as a local weather station, and generates power depending on the received wind speed value. Finally, there are two main objectives for the line operator player since it contains all of the energy meters and the circuit breakers employed in the power lines. As mentioned, the first goal of the line operator player is to supervise the circuit breakers in the power lines. The second purpose is to request the real-time amount of the active power measured by the energy meter of each power line and transmit them to the other players. In this way, the other players, namely residential player, commercial player, and wind DG player, will be aware of their real-time amount of consumption or generation.

In the distributed control method, adaptability of the system is improved compared with the centralized control, since the response time to any changes is reduced. Furthermore, the distributed control method brings reconfigurability and flexibility features to the overall microgrid. Suppose that, in a simple way, the PV DG player transmits a signal to the other players saying that its instant amount of generation changed to 4500 W. The wind DG player also broadcasts a message saying that there is wind generating energy. Therefore, the line operator player responds to the wind DG player that their current output generation is supposedly 500 W. In the meantime, the residential and commercial player reply that they are consuming energy with a certain value, and the line operator player broadcasts their total amount of consumption, which is, supposedly 9500 W. Therefore, the microgrid supplies the rest of the required power from the power grid; hence, there is not enough energy production by DG units.

3. Case Study

In this section, a case study is presented and implemented by the microgrid model provided in this paper in order to test and validate the system capabilities. In this case study, it is considered that the user intends to use the centralized microgrid control model.

Figure 4 represents a 33 bus distribution network, including 220 consumers and 68 DG units. The distribution network was implemented MATLAB/Simulink, being compatible with OP5600. The microgrid model is a node connected to bus #10 of this network. Furthermore, the Simulink model developed in OP5600 for real-time controlling of the microgrid players is shown in Figure 4.

In this case study, we consider that a VPP owns the microgrid and its resources containing the consumers (with or without DR programs), and the energy generators. Therefore, the VPP aggregates the DG and DR resources since in the proposed microgrid they are considered as small size resources. Additionally, the VPP is capable to transact energy to the main grid, which means it can absorb energy while it has high demand and low generation, or inject power to the grid while it has more generation than consumption. This enables the VPP to have active participation in the electricity markets.

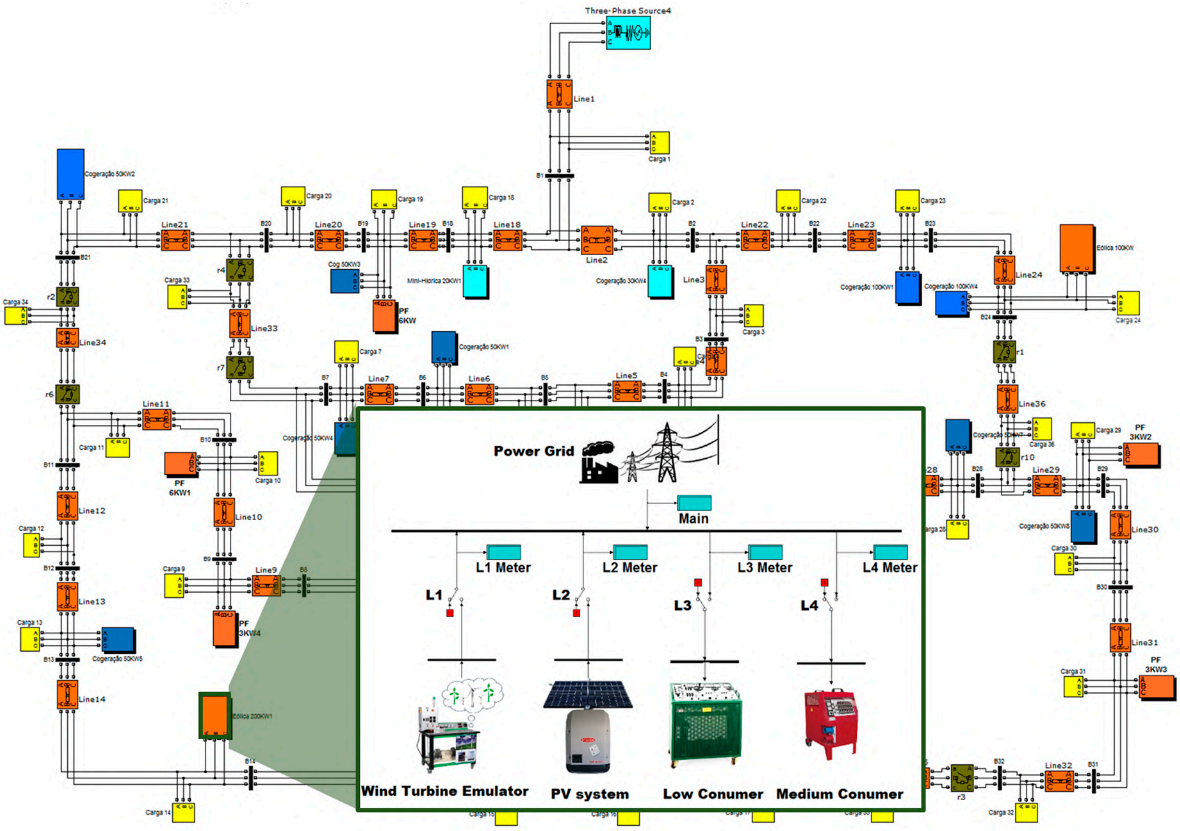

Figure 4. The microgrid model used in the 33 bus network.

VPP also can define several DR programs for the microgrid consumers in order to reduce or shift the consumption to one or more specific periods based on incentives and/or the prices offered to them. Technical or economic reasons can also be the motivation for the VPP to define DR programs. While the DR programs defined reduction or shifting, the VPP can use an optimization for the generation and demand resources in order to economically make a decision and execute the load shifting scenarios. The number of DR programs that VPP executed is a fundamental matter, which should be taken into account.

The shifting periods in this model are the amount of power that can be shifted from a period to other periods. Additionally, the number of periods that the shifted consumption will be entered, and also the amount of load reduction, which will not be shifted, should be considered.

The optimization problem used in this paper for the VPP has been adapted from [31], and only the most applicable information has been mentioned in this part. The objective function of this optimization is to minimize the operation costs of the VPP, considering the generation and shifting costs in each period t for all periods in the defined time horizon T. Equation (1) demonstrates the objective function of the optimization problem. The constraints of the model include:

- Balance equation containing the DR balance in each period of t, the energy production, and the consumption demand, which contains the shifted load from period t to period i, and the incoming consumption in period t shifted from period i. This is represented in Equation (2);
- The maximum DR capacity considering the consumption reduction executed in period t, which can be shifted to period i after or before t, presented in Equation (3).
- The maximum generation capacity limit in each period t, performed by Equation (4).

$$\text{Minimize} \quad OC = \sum_{t=1}^{T}\left[P_{DG(t)} \times C_{DG(t)} + \sum_{t-I\leq i}^{i\leq t+I} P_{DR(t,i)} \times C_{DR(t,i)}\right] \tag{1}$$

$$\begin{gathered} Load_{(b,t)} - \sum_{t-I\leq i}^{i\leq t+I} P_{DR(b,t,i)} + \sum_{t-I\leq i}^{i\leq t+I} P_{DR(b,i,t)} - P_{DG(b,t)} = \\ \sum_{j=1}^{B} V_{(b,t)} \cdot V_{(j,t)} \cdot \left[G_{(b,j)} \cdot \cos\left(\theta_{(b,t)} - \theta_{(j,t)}\right) + G_{(b,j)} \cdot \sin\left(\theta_{(b,t)} - \theta_{(j,t)}\right)\right] \\ \forall 1 \leq t \leq T, \forall 1 \leq b \leq B \end{gathered} \tag{2}$$

$$P_{DR(b,t,i)} \leq P_{DR(b,t,i)}^{\max}; \forall 1 \leq t \leq T, \forall - I \leq i \leq I, \forall 1 \leq b \leq B \tag{3}$$

$$P_{DG(b,t)} \leq P_{DG(b,t)}^{\max}; \forall 1 \leq t \leq T, \forall 1 \leq b \leq B \tag{4}$$

$$V_{(b,t)}^{\min} \leq V_{(b,t)} \leq V_{(b,t)}^{\max}; \forall 1 \leq t \leq T, \forall 1 \leq b \leq B \tag{5}$$

$$\theta_{(b,t)}^{\min} \leq \theta_{(b,t)} \leq \theta_{(b,t)}^{\max}; \forall 1 \leq t \leq T, \forall 1 \leq b \leq B \tag{6}$$

TOMLAB, which is based on MATLAB, are used in order to solve the proposed optimization problem. Therefore, the optimized results can be easily provided to the microgrid central controller unit (OP5600) as inputs, and consequently, it controls the real hardware equipment in real-time based on these inputs. The output of the economic energy resource scheduling optimization model is a requested amount of power for each consumer to reduce its demand in a certain period. However, the actual implementation of this demand reduction request in a real load will depend on the electrical grid conditions. This is in fact one of the advantages of using real-time simulation (in this paper OP5600) and laboratorial equipment for consumption modeling. In this way, we validate the actual demand reduction in order to be included in the simulation results, namely for remuneration purposes.

4. Results

In this section, the results of the proposed methodology will be executed using the microgrid model and its results illustrated. We consider that the case study consists of 10 periods with a one minute time interval. The consumption and generation profiles of the microgrid aggregated by the VPP during this 10 min is shown in Figure 5. As can be seen, the blue area is the total power aggregated by the VPP during the 10 periods, and the red line indicates the total consumption. The aggregated power supply includes the PV generation, wind production, and the incoming power from the main network to the microgrid.

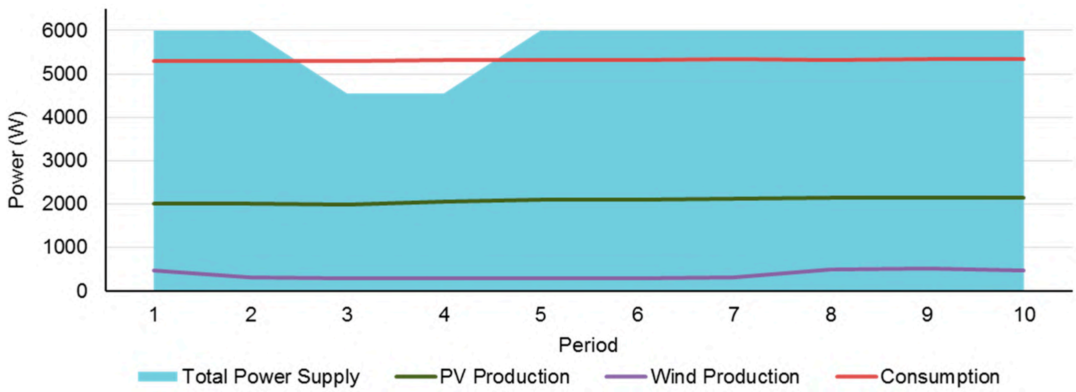

Figure 5. The microgrid model used in the 33 bus network.

The data used in the case study is for the day 13 January 2017 (Friday), between 11:30 AM to 11:40 AM. The PV curve is the real-time generation profile adopted from GECAD database. The wind generation is the simulated profile by the wind turbine emulator based on the real-time wind speed data, acquired from [32], and the consumption curve is also the real-time consumption of the GECAD building, emulated by the 4 kVA and 30 kW load.

As Figure 5 demonstrates, the microgrid meets a drop on generation in the periods 3 and 4. The reason for this lack of generation is considered to be a fault or any other cause in the main grid. Therefore, this is an opportunity for the VPP to start the optimization problem in order to optimally schedule the consumption shifting of the resources. The results of the optimization problem is depicted in Figure 6. The shifted periods have been scheduled in order to minimize the operation costs of the VPP.

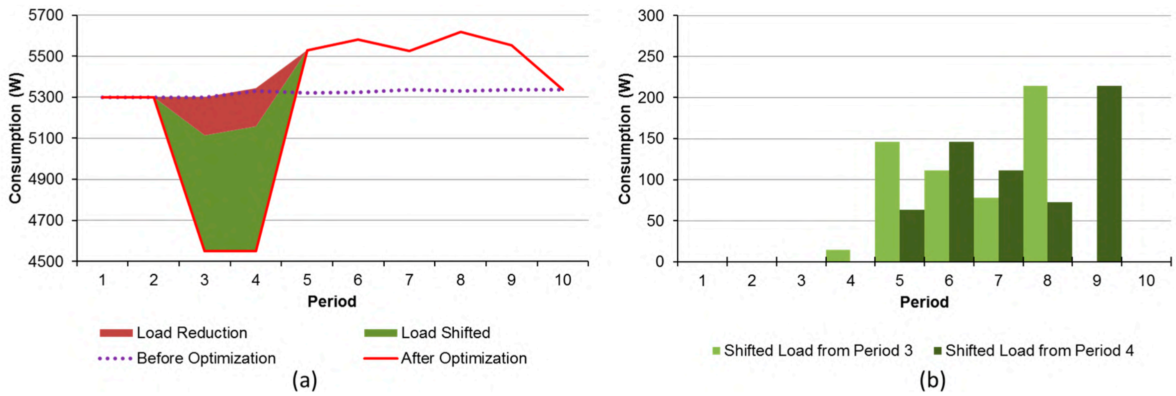

Figure 6. The optimization results for the consumption resources.

Figure 6a illustrates the load reduction and shifting that have occurred during the periods 3 and 4, where the VPP faced a lack of generation and shifted to the periods after period 4. The red area is the reduced consumption by the consumers, and the green area is the shifted consumption to the other periods. Also, as can be seen in Figure 6b, the incoming consumption in the periods of 8 and 9 are much higher compared with the other periods. This can be because of the DR programs and the economic advantages.

While TOMLAB outputted the results of optimization, they will be provided to the OP5600 real-time simulator as inputs. Consequently, the real-time simulator starts to control and manage the HIL equipment in order to implement the optimization results in real-time. Figures 7–9 show the final results of the real-time simulation during 10 min. All of the results illustrated in these figures are adapted from OP5600 and MATLAB/Simulink.

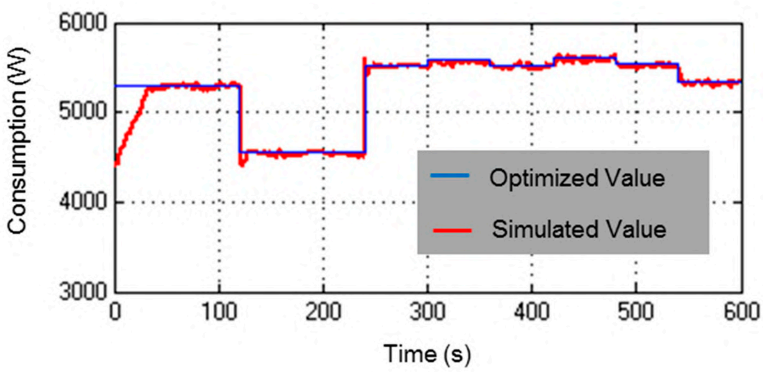

Figure 7. Real-time simulation of the consumption profile using the consumers of the microgrid.

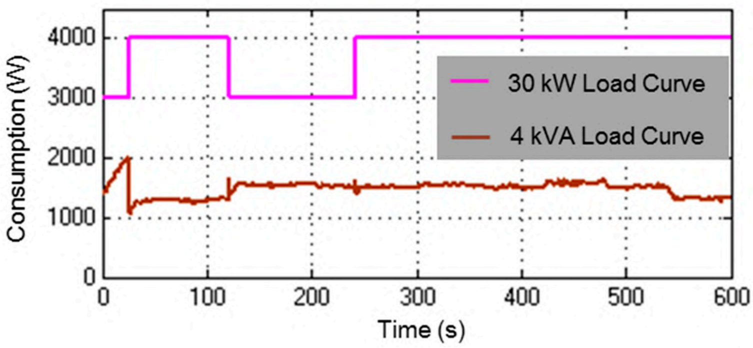

Figure 8. The separated consumption curve of each player of the microgrid.

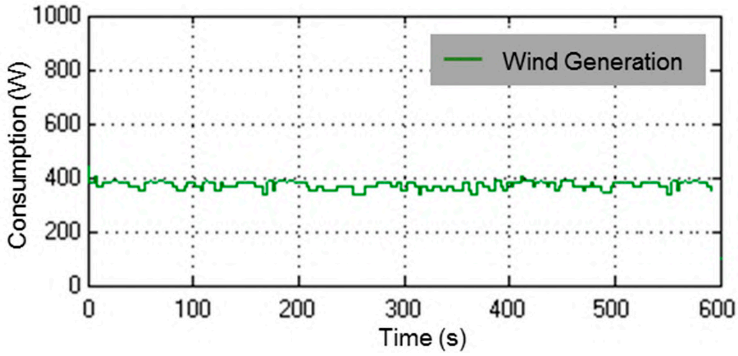

Figure 9. Real-time simulation of wind production curve.

As Figure 7 illustrates, the total amount of consumption of the microgrid has been reduced and shifted to other periods based on the optimization results, which occurred between the second of 120 to 240 (periods 3 and 4). Also, the denotative consumption profiles of the microgrid have been illustrated in Figure 8. It is obvious that the residential player shifted its consumption; however, the commercial player reduced consumption based on the data received from the OP5600 real-time simulator. Furthermore, Figure 9 represents the wind production simulated by the wind DG player. This generation curve has been simulated based on the real-time wind speed data provided to the emulator from the OP5600 real-time simulator.

5. Conclusions

Microgrids are a particular case of distribution networks, namely in the context of smartgrids. Demand response and distributed generation are very relevant resources in the scope of microgrids and smartgrids. As discussed in the present paper, the realistic simulation of the impact of these resources is very important in order to validate the technical and business model's impact in smartgrids management.

In this paper, important improvements have been added to SPIDER, a simulation platform that accommodates real-time simulation skills adequate for demand response and distributed generation. The innovative content provides details on the integration of both centralized and distributed control approaches, and also includes the emulation of generation and load components which allowed us to more realistically simulate the microgrid and validate the computational models.

The case study presented here has briefly demonstrated the platform skills in order to validate a business model for optimal resource scheduling in the microgrid, and its connection to the upstream distribution network. A VPP managed the resources aiming at minimizing the operation costs. It has been shown that the results obtained by the scheduling algorithm benefit with the integration in the real-time simulation platform in order to check the actual simulated consumption and generation values which include the variability of these resources. Moreover, the presented results are the ones actually measured in the load, and generation emulation devices which are shown to have relevant information that was not given by the electrical network simulation model. The main one is that when the load schedule is changed, the actual consumption devices take some time in order to reach the desired consumption.

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Author Contributions: Omid Abrishambaf wrote and organized the paper, and discussed the work with the rest of authors; Pedro Faria adapted the SPIDER platform and the network model used for the developed approach; Luis Gomes implemented the simulation components interoperability and JAVA API; João Spínola developed the energy resources optimization model; Zita Vale raised and developed the overall concept; Juan M. Corchado contributed for the distributed control nature.

Conflicts of Interest: The authors declare no conflict of interest.

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An Aggregation Model for Energy Resources Management and Market Negotiations

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Currently the use of distributed energy resources, especially renewable generation, and demand response programs are widely discussed in scientific contexts, since they are a reality in nowadays electricity markets and distribution networks. In order to benefit from these concepts, an efficient energy management system is needed to prevent energy wasting and increase profits. In this paper, an optimization based aggregation model is presented for distributed energy resources and demand response program management. This aggregation model allows different types of customers to participate in electricity market through several tariffs based demand response programs. The optimization algorithm is a mixed-integer linear problem, which focuses on minimizing operational costs of the aggregator. Moreover, the aggregation process has been done via K-Means clustering algorithm, which obtains the aggregated costs and energy of resources for remuneration. By this way, the aggregator is aware of energy available and minimum selling price in order to participate in the market with profit. A realistic low voltage distribution network has been proposed as a case study in order to test and validate the proposed methodology. This distribution network consists of 25 distributed generation units, including photovoltaic, wind and biomass generation, and 20 consumers, including residential, commercial, and industrial buildings.

1. Introduction

The present paper is an extension of work originally proposed in *2017 IEEE Manchester PowerTech* [1]. The generation variation in Distributed Renewable Energy Resources (DRER) is a topic of introduction in a lot of research works, since they have a key role in nowadays power system [2], [3]. By appropriate management on the consumption in demand side, energy efficiency and optimal energy usage should be addressed [4]. Curtailment Service Provider (CSP), Virtual Power Player (VPP), and aggregator are entities that can provide reliable solutions for the management of consumption and generation resources, since these can be aggregated and represented as a unique resource in electricity markets [5-7].

In this context, an aggregator is responsible to optimally manage a certain number of resources in a region, and aggregate them as one resource. This simplifies the process of energy negotiation in electricity markets [8]. Moreover, if other players, such as Balance Responsible Parties (BRPs), exist in the network, the role of aggregator would be more efficient and important [9].

Nowadays, there are several European countries that employ the aggregator concept for electricity consumers [10]. As an example, France is one of these countries that accepted aggregated loads in every ancillary service program, and BRPs and aggregators have been reorganized based on [11], [12]:

- Performing electricity market negotiations, to calculate compensation costs by aggregator for BRP;
- Aggregator has no direct interaction with BRP, however, it establishes contract with an electricity supplier in order to have flexibility services.

In fact, an aggregator is accountable not only for DRERs, but also is responsible for Demand Response (DR) programs [12]. According to the Federal Energy Regulatory Commission (FERC) [13], DR program is referred as "Changes in electric use by demand-side resources from their normal consumption patterns in response to changes in the price of electricity, or to

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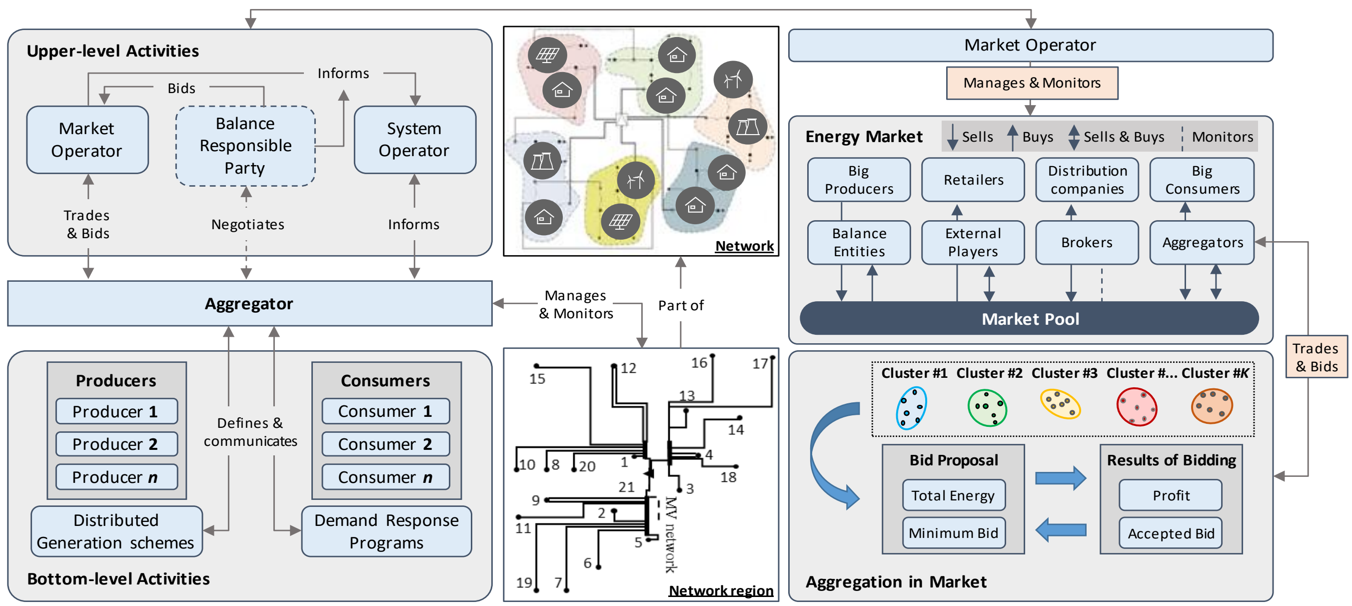

Figure 1. Overal architecture of the aggregation model.

incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized". The role of an aggregator in terms of DR programs is to gather all electricity consumer who can participate in DR programs, and present them as one. Therefore, it can be considered as a flexible player [14]. For this purpose, the aggregator can establish bidirectional contracts with end-users for DR programs to manage consumption resources, and consequently, to have flexibility in electricity market negotiations. In order to manage the generation of end-users, which are considered as prosumer (a consumer who is able to produce electricity), the aggregator can play the role of VPP, as [15-17] demonstrated before. It is clear that the generation capacity of these prosumers is not significant, thus, the network management would be difficult for system operators. Therefore, the need of a third party, namely an aggregator, is evident to gather all these small-scale consumption and generation resources, and participate in electricity market.

This paper represents an optimization based aggregation model for DRERs and DR programs managements, which enables small and medium resources to have active participation in the electricity markets. The aggregator controls demand-side customers by providing them several tariffs based DR programs, which brings flexibility in the electricity market negotiations. Moreover, this aggregator model gathers energy of resources and aggregated costs to be aware of available energy and minimum selling cost for defining remunerations, and also participate in the market with profit.

The rest of the paper is organized as follow. Section 2 details the aggregator model architecture considered for the aggregation. Section 3 describes the mathematical formulation considered for the optimization problem and aggregation process. Section 4 explains a case study that will test and validate the proposed method, and its results are expressed in Section 5. Finally, main conclusions of the work are proposed in Section 6.

2. Aggregator Model Architecture

This section focuses on how the presented aggregation model performs scheduling, aggregating and remuneration. The overall view of the presented model is illustrated by Figure 1. In this aggregation model, the consumption and generation resources are classified in several groups, where the output of the aggregation process will be the energy and cost of each group. As one can see in Figure 1 and also proposed in [18], the functionality of the aggregator is categorized in two sections of upper-level and bottom-level. In the upper level, the aggregator negotiates with players, such as market operator, BRP, and system operator; however, in the bottom level, it deals with demand-side users, namely small and medium scale consumers and producers.

The aggregator performs the scheduling process relying on external suppliers, Distributed Generation (DG) especially renewable resources, and DR programs. The customers who can execute DR programs would be able to establish contract with aggregator in three programs: load shifting, load reduction, and load curtailment. The load shifting model has been adapted from [19], and in this aggregation model it is considered as a free DR program. Load reduction and curtailment are the programs that aggregator takes them into account for scheduling and participating in the market. The aggregator considers a linear cost function for all external suppliers, DGs, load reduction and load curtailment. In this model, the aggregation process is done by K-Means Clustering algorithm by respect to the scheduled energy and its costs. In the aggregation process, only the resources that have been selected form the scheduling, are considered, and the rest that have no interaction in scheduling process, will not be considered. The aggregator categorizes the resources in several groups, and specifies a remuneration for each group, which called group tariff. This means the remuneration process should be calculated after the aggregation. The resources that are classified in a group, will be remunerated with same price. For this reason, the maximum price available in each group will be selected for group tariff. Therefore, the cheapest resource in the group will be motivated to participate in aggregation, since the group tariff is greater than the price initially defined, and also the most expensive resource will be satisfied, since the group tariff is as same as the price that it proposed.

In this way, the aggregator is able to participate in the market with a bid for each group. In each bid, the aggregator deliberates the gathered energy from the resources and also the group tariff as the minimum rate. The energy in each group is related to the aggregation of scheduled resources of that related group, therefore, the aggregator can easily manage its activities. On the other hand, the aggregator will be able to have negotiation in the market by biding the available energy of each group with a certain price, where this price should be greater or equal to the group tariff for the aggregator to gain profits or at least obtain the amount expended for the resources.

3. Optimization problem

The mathematical formulation regarding the presented aggregation model, especially resource scheduling, will be presented in this section. The optimization problem developed for the aggregator scheduling contains several continuous and discrete variables, therefore, the problem is considered as a mixed-integer linear problem (MILP). The objective function considered for the aggregation model is to minimize its Operational Cost (OC) and is shown by (1). It should be noted that in this model it is supposed the technical verification of the network is the obligation of the network operator, and the aggregator is not responsible for this matter.

$$MinOC = \sum_{s=1}^{S} P_{(s,t)}^{Sup} \cdot C_{(s,t)}^{Sup} + \sum_{p=1}^{P} P_{(p,t)}^{DG} \cdot C_{(p,t)}^{DG} + \sum_{c=1}^{Cs} \begin{bmatrix} P_{(c,t)}^{Red} \cdot C_{(c,t)}^{Red} + P_{(c,t)}^{Cut} \cdot C_{(c,t)}^{Cut} \\ + \sum_{d=1}^{T} P_{(c,t,d)}^{Shift} \cdot C_{(c,t,d)}^{Shift} \end{bmatrix} \quad \forall t \in \{1,...,T\} \tag{1}$$

In this objective function, $P_{(s,t)}^{Sup}$ is purchased energy from external supplier, $P_{(p,t)}^{DG}$ denotes the attained energy from DG, $P_{(c,t)}^{Red}$ stands for DR load reduction, $P_{(c,t)}^{Cut}$ is for DR load curtailment, and $P_{(c,t,d)}^{Shift}$ represents DR load shifting.

There are several constraints that should be considered in the objective function. The first constraint stands for load balance, as (2) shows. In this equation, $P_{(c,t)}^{Load}$ presents the required demand of consumers.

Also, the technical limitations of all resources available in the proposed methodology should be considered. Therefore, (3) represents the generation limitations of external supplier in term of minimum and maximum ($P_{(s,t)}^{Sup\min}$, $P_{(s,t)}^{Sup\max}$), and (4) considers DG limitations ($P_{(p,t)}^{DG\min}$, $P_{(p,t)}^{DG\max}$).

$$\sum_{c=1}^{Cs} \begin{bmatrix} P_{(c,t)}^{Load} - P_{(c,t)}^{Red} - P_{(c,t)}^{Cut} \\ -\sum_{d=1}^{T} \left(P_{(c,t,d)}^{Shift} - P_{(c,d,t)}^{Shift} \right) \end{bmatrix} - \sum_{s=1}^{S} P_{(s,t)}^{Sup} - \sum_{p=1}^{P} P_{(p,t)}^{DG} = 0 \quad \forall t \in \{1,...,T\} \tag{2}$$

$$P_{(s,t)}^{Sup\min} \le P_{(s,t)}^{Sup} \le P_{(s,t)}^{Sup\max} \quad \forall s \in \{1,...,S\}, \forall t \in \{1,...,T\} \tag{3}$$

$$P_{(p,t)}^{DG\min} \le P_{(p,t)}^{DG} \le P_{(p,t)}^{DG\max} \quad \forall p \in \{1,...,P\}, \forall t \in \{1,...,T\} \tag{4}$$

DR technical limitations, including load reduction, curtailment, shifting, are presented by (5)-(8).

$$P_{(c,t)}^{Red\min} \le P_{(c,t)}^{Red} \le P_{(c,t)}^{Red\max} \tag{5}$$

$$P_{(c,t)}^{Cut\min} \le P_{(c,t)}^{Cut} \le P_{(c,t)}^{Cut\max} \tag{6}$$

$$P_{(c,t)}^{Cut} = P_{(c,t)}^{Cut\max} \cdot X_{(c,t)}^{Cut} \quad X_{(c,t)}^{Cut} \in \{0,1\} \quad \forall c \in \{1,...,C\}, \forall t \in \{1,...,T\} \tag{7}$$

$$P_{(c,t,d)}^{Shift\min} \le P_{(c,t,d)}^{Shift} \le P_{(c,t,d)}^{Shift\max} \tag{8}$$

Although load shifting may not be pleasant for end-users, it is an appropriate and practical tool for aggregator. Load shifting process may limit consumers use of devices in a certain period, however, it enables the aggregator to manage the consumption based on the offered generation capacity. For this purpose, the limitations of maximum energy that will be shifted out from a period ($P_{(c,t)}^{Shift\_out}$), and enters to another period ($P_{(c,t)}^{Shift\_in}$) are proposed in (9) and (10).

$$\sum_{d=1}^{T} P_{(c,t,d)}^{Shift} \le P_{(c,t)}^{Shift\_out} \tag{9}$$

$$\sum_{d=1}^{T} P_{(c,d,t)}^{Shift} \le P_{(c,t)}^{Shift\_in} \quad \forall c \in \{1,...,C\}, \forall t,d \in \{1,...,T\} \tag{10}$$

Moreover, (11) demonstrates the constraint regarding the groups tariff and their remuneration, which is the maximum price of group. The groups are separated based on the type of available resources (DG or DR).

$$G_{(k,t)}^{DG} = max(C_{(p,t)}^{DG}) \quad G_{(k,t)}^{DR} = max(C_{(c,t)}^{Red}, C_{(c,t)}^{Cut}), \forall c \in \{1,...,C\} \quad \forall p \in \{1,...,P\}, \forall k \in \{1,...,K\}, \forall t \in \{1,...,T\} \tag{11}$$

As a summary, the mathematical formulation for resources scheduling and their remuneration performed by the aggregator have been explained in this part. The methodology presented in this section will be employed in a case study in the next section.

4. Case Study

In order to examine the model represented in this paper, a case study is proposed. For this purpose, an low voltage distribution network of a university campus, in Porto, Portugal, is considered for the aggregator, which has been adapted from [20]. This distribution network is shown in the bottom of Figure 1 (Network region) and is considered as a part of main network. The network consists of underground electrical lines with 21 buses, where a MV/LV transformer in BUS #21, connects the campus network to the main network.

For this case study, we considered that there are 20 consumers, and 26 producers in the network. The consumers include 8 Residential (RE) buildings, 10 Commercial buildings in three scales of small (C-S), medium (C-M), and large (C-L), and 2 Industrial (IN) units, which are classified based on average daily consumption. Moreover, producers consist of renewable resources including 20 Photovoltaic (PV) units and 4 wind generators, 1 biomass, and external suppliers. The generation and consumption profiles of whole network considered for day-ahead scheduling in a winter day are shown on Figure 2.

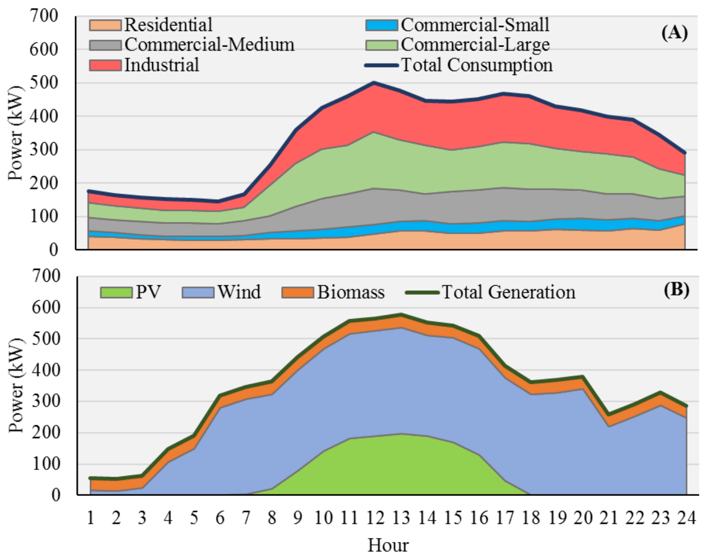

Figure 2. Day-ahead profiles of the network considered for case study: (A) Consumption, (B) Production.

As it can be seen in Figure 2 – (A), large commercial buildings and industrial units have occupied a huge part of consumption, and peak periods start from period #10 to #23. In this case study, it is presumed that the biomass production, and external suppliers have maximum capacity of 40 and 500 kW respectively. The external suppliers profile is not illustrated in Figure 2 – (B), since it is out of scope of figure and is a constant value during all periods. Moreover, it is considered that all producers would be able to contribute in the aggregation process, except external suppliers. Additionally, as you can see in Figure 2 – (B), since a winter day selected for the case study, PV producers have no significant generation, therefore, the aggregator should rely on wind, biomass, external suppliers and DR programs to prevent purchasing energy from the market. However, by comparing both parts of Figure 2, it is obvious that there are some periods that aggregator has more generation than consumption, therefore, it would be able to sell energy to the market and gain profits.

Regarding DR programs, Figure 3 demonstrates linear costs considered for each consumer based on its type. These costs are for load reduction and load curtailment, where 20% of the initial consumption is considered as maximum load reduction, and 15% for maximum load curtailment.

Furthermore, the linear costs considered for energy resources are shown on Figure 4. Each point in Figure 4 is the individual cost of each resource, where resource #1 to #20 are all PV, #21 to #24 are wind generators, #25 is biomass unit, and #26 illustrates external suppliers. It is should be mentioned that the costs demonstrated in Figure 4, are constant in all periods.

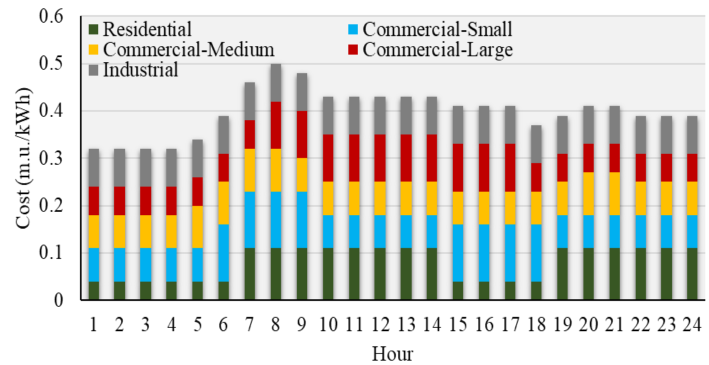

Figure 3. DR program costs for consumers.

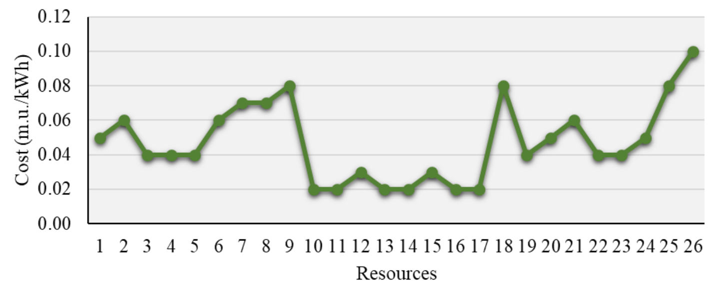

Figure 4. Individual cost for each energy resource.

Additionally, Figure 5 represents the day-ahead market prices considered for the aggregator in order to participate in market negotiations.

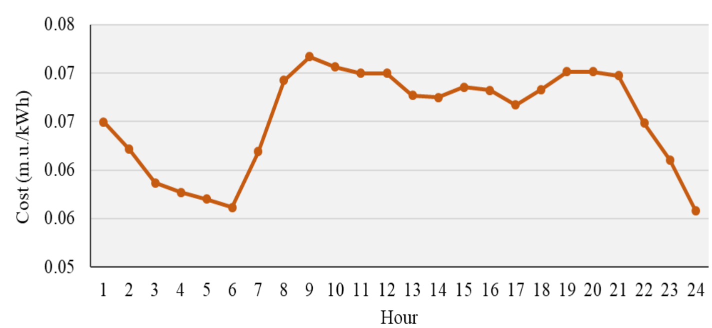

Figure 5. MIBEL market price for Portugues section in a winter day.

These prices are for a winter day in 2017 and have been adapted from Portuguese sector of Iberian Electricity Markets (MIBEL) [21]. In order to model the participation of the aggregator in the electricity markets, a market place should be taken into account, to guaranty its contribution in the competition. For this purpose, a market pool is an appropriate solution to ensure that third parties, such as aggregator, would be able to present energy bids.

5. Results

This section concerns the aggregation and scheduling results of the case study presented in the previous section. The optimization problem of aggregation and scheduling presented in this paper, has been solved through TOMLAB [22]. Additionally, the market negotiation results are represented, which shows how the aggregator utilizes these results for providing a bid. In the case study, we considered that the aggregator meets a drop from external suppliers in first four periods that can supply only 10% of their capacity. The reason of this lack of energy is considered as a fault or any other causes in the external suppliers. Figure 6 shows the network consumption before and after the scheduling of aggregator.

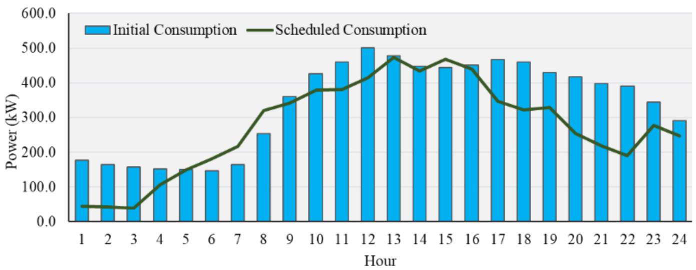

Figure 6. Total consumption of the network.

The scheduling results shown in Figure 6 are based on DG and available energy during each period. Additionally, there are several periods that scheduled consumption profile are greater or smaller than the initial profile. This is due to the utilization of DR programs by aggregator. With this in mind, Figure 7 illustrates more information regarding the generation and DR scheduling.

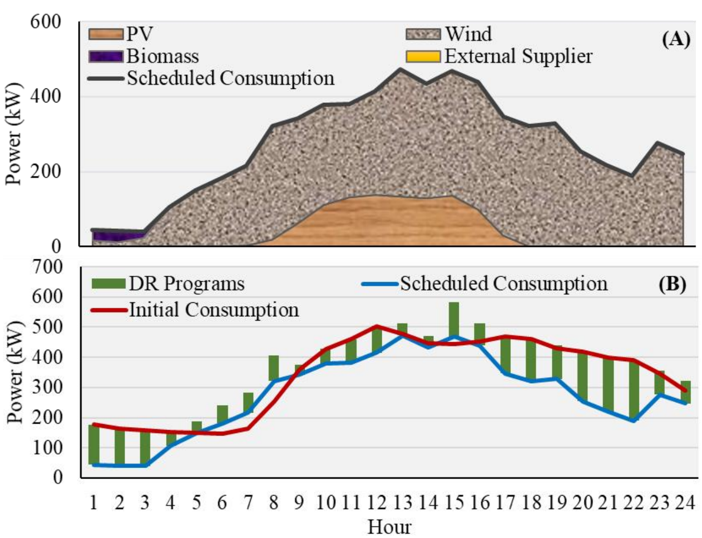

Figure 7. Detailed scheduling results of aggregator: (A) Generation scheduling, (B) DR scheduling.

As one can see in Figure 7 – (A), since the DG suppliers are considered as cheapest resources comparing with external suppliers, the aggregator utilizes the available DG energy, especially PV and wind, to supply the demand, and in the first four periods, it employs biomass generation to supply the loads. In other words, the aggregator reduced the consumption to the available DG energy in order to prevent purchasing energy from market for minimizing the costs. This means, in the periods that the DG generation is not adequate for the demand, aggregator applies DR programs to regulate the difference between the consumption and generation, as illustrated in Figure 7 – (B). The DR programs that aggregator employed to balance the network for each single period, are shown on Figure 8. The utilized DR programs include load reduction, load curtailment, and load shifting.

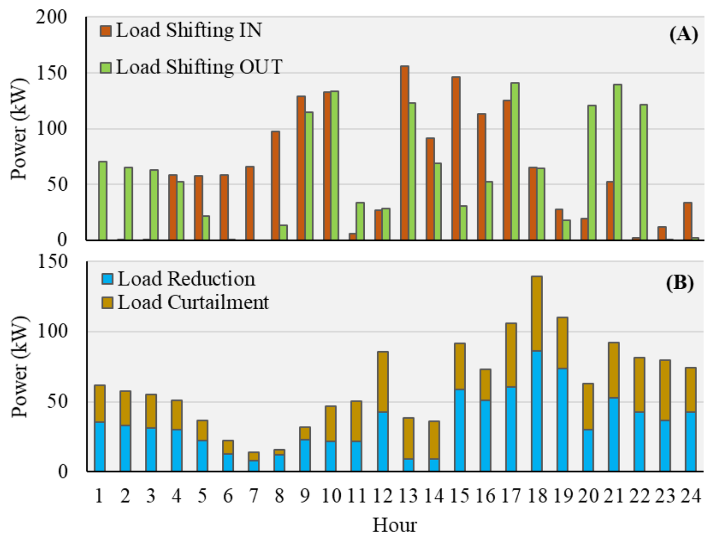

Figure 8. DR programs used by aggregator for network balancing: (A) Load shifting, (B) Load reduction and curtailment.

The incoming and outcoming consumption of each period during load shifting are shown on Figure 8 – (A), which occurred during low generation periods, and shifted to high generation periods. The load shifting enables the aggregator to manage the consumption and shift it to desired periods to prevent purchasing energy from the market, since it is more expensive comparing with DG resources.

Additionally, Table 1 shows the results of aggregation and remuneration processes for period number 12.

Table 1. Remuneration and aggregation results for a single period.

Group		1	2	3	4	5
DG	PV (kW)	0	36.23	19.64	37.54	43.86
	Wind (kW)	250.58	0	0	0	26.88
	Biomass (kW)	0	0	0	0	0
	tariff (m.u./kWh)	0.05	0.02	0.05	0.06	0.06
DR	Residential (kW)	0	0	0	0	0
	Commercial Small (kW)	0	0	0	0	10.09
	Commercial Medium (kW)	0	0	11.07	20.05	7.11
	Commercial Large (kW)	0	0	0	0	0
	Industrial (kW)	26.21	10.94	0	0	0
	tariff (m.u./kWh)	0.06	0.06	0.05	0.05	0.05
Total (kW)		500.18				

In Table 1, the total energy as well as the number of resources in each group have been calculated by aggregation computation, however, the group tariff has been indicated by remuneration calculation. Moreover, in order to calculate the profit of the aggregator after paying all resources, including DG and incentives for DR participation, (12) is proposed. This profit is the monetary benefit that aggregator gained after its operations.

$$Profit = C_{(t)}^{mcp} \cdot \left[\sum_{p \in k}^{P} P_{(p,t)}^{DG} + \sum_{c \in k}^{C} (P_{(c,t)}^{Red} + P_{(c,t)}^{Cut}) \right] - \left[G_{(k,t)}^{DG} \cdot \sum_{p \in k}^{P} P_{(p,t)}^{DG} + G_{(k,t)}^{DR} \cdot \sum_{c \in k}^{C} (P_{(c,t)}^{Red} + P_{(c,t)}^{Cut}) \right] \quad (12)$$
$$\forall k \in \{1,...,K\}, \forall t \in \{1,...,T\}$$

In (12), the $C_{(t)}^{mcp}$ denotes market clearing price, which is considered in this case study is equal to the market prices provided in Figure 5. The classification of the resources in the several groups enables the aggregator to provide lower group tariffs, comparing with the situation that all resources are in the same group. It is true that with classification of resources in several groups, high group tariff will be still remained, however, the chance of aggregator to reach some group tariff with lower rates will be increased. The financial profit gained by aggregator during period number 12, is shown on Table 2. In this single period, the aggregator has total energy of 500.18 kW, which has incoming of 35 monetary unit from the energy that sold to the market. However, it also paid 22.84 monetary unit for all resources, including DG units and DR incentives, and in total, 12.17 monetary unit will be the final profit of aggregator during period number 12.

Table 2. Gained profit by aggregator during market negotiations for one period.

Parameter	Value
Costs paid to all resources (m.u.)	22.84
Market clearing price (m.u./kWh)	0,0700
Income from market sell (m.u.)	35.00
Total aggregator profit (m.u.)	12.17

The profit of aggregator shown on Table 2, is for a single period (considered as one hour in a day in this case study), and even with a few number of consumers and generators, it could gain profit from market negotiations. This means that if the aggregator is responsible for a larger network He will be able to aggregate more energy capacity for clustering, and therefore, with great participation in market, which leads to obtain a satisfying amount of financial benefits. However, this profitability depends on the capabilities and offers of aggregator in market negotiations and existing competitions. Figure 9 demonstrates the financial results concerning the participation of aggregator in the electricity market for all periods of case study. These results are obtained after the scheduling and remuneration processes. It should be noted that only the resources that participated in these processes, are considered. The costs of each period in Figure 9 follows the same process represented in Table 2, which the gained profit is a subtract of costs paid to all resources and the income from market participation.

The last results of this section are related to a comparison that shows the impact of load shifting method for aggregator. For this purpose, it is considered that the aggregator is not capable to employ load shifting during scheduling process. The scheduling results, without load shifting, are illustrated in Figure 10. The results shown in Figure 10 (without load shifting) can be compared with the scheduling results demonstrated in Figure 7 (with load shifting).

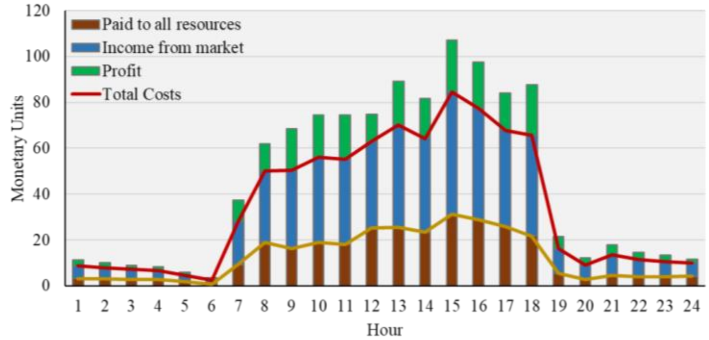

Figure 9. Detailed aggregator costs after scheduling and remuneration process for all periods.

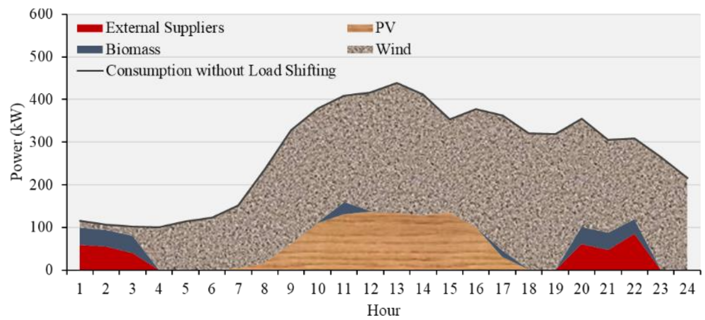

Figure 10. DG scheduling results without load shifting.

As one can see in Figure 10, in some periods the aggregator not only utilizes all available DG resources to supply the demand, but also, it is forced to use energy from external suppliers to feed all demand. By this way, since the electricity price of external suppliers are more expensive than the DG resources, the total costs of aggregator will be increased, and therefore, the gained profit will be decreased. However, as Figure 7 demonstrated, if the aggregator utilized load shifting scenario, and shift the load from the moments that there is no adequate DG energy, to the periods with high DG energy, its operational costs will be reduced, and obtained financial benefits will be increased.

6. Conclusions

This paper presented an aggregator model for distributed energy resource and demand response program management. The presented model considered the resources able to participate in electricity market negotiations through the aggregator. The aggregator has capability of demand-side flexibility by establishing several demand response contracts with consumers.

The main focus of the paper was given to a business model that aggregator utilized it to gather energy of resources and their costs, to define a fair remuneration tariff for all resources, as well as an affordable price for market participation. By this way, the aggregator guarantees that the small-scale resources, including distributed generation and demand response programs, will participate in the electricity market, and therefore, getting profits.

The results of case study demonstrate that the aggregator model is able to perform an optimal scheduling for distributed resources, in order to minimize the operational costs of the aggregator. This is done through implementing several DR programs. The final outcomes of aggregation and remuneration processes validated the proposed method, and proved that the aggregator can gain financial benefits from market negotiations, even by paying a fair tariff to all available resources.

Conflict of Interest

The authors declare no conflict of interest.

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Application of an optimization-based curtailment service provider in real-time simulation

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Abstract

The use of demand response programs and distributed renewable energy resources are intensively discussed. These concepts play a key role in the distribution network, especially smart grids and microgrids. Nowadays, most of the implemented demand response programs are considered for large-scale resources, which make small and medium resources unable to participate in electricity market negotiations. In order to overcome this barrier, a third-party entity, namely an aggregator, can be considered as an intermediate player between the demand side and grid side. For this purpose, curtailment service provider is considered as an aggregator, which aggregates small and medium-scale resources, who do not have adequate capacity of reduction or generation and allow them to participate in wholesale electricity markets as a unique resource. However, before massive implementation of business models, the performance of the curtailment service provider should be adequately surveyed and validated in order to prevent future problems. This paper proposes a real-time simulation model of a curtailment service provider, which employs several real and laboratory hardware equipment considered as hardware-in-the-loop in the real-time simulator. Furthermore, an optimization problem is developed for a curtailment service provider in order to optimally schedule the available resources including several demand response programs and distributed renewable resources, aiming at minimizing its operation costs. The implemented case study considers a distribution network with 20 consumers and prosumers, and 26 renewable-based producers including wind and photovoltaic generation, where the developed model is performed in real-time for 12 min and behaviors of small and medium prosumers and producers is surveyed.

Keywords: Demand response, Curtailment service provider, Real-time simulation, Hardware-in-the-loop, Optimization

Background

The daily increment of electrical energy usage impels the network operator to provide efficient solutions regarding energy resources. Demand Response (DR) programs and Distributed Generation (DG) are two major concepts, which play a key role in this context (Aghaei and Alizadeh 2013). DR programs can be defined as the modification of the consumption in demand side, according to the price variations or financial incentive paid by DR managing entity to the consumers (Hurtado et al. 2018). In fact, by promoting DR programs, all the players can benefit. The demand side will be encouraged to utilize DR programs for reducing their electricity bills, and the grid side will benefit from that by reducing congestion of the grid and lowering the consumption in the peak periods (Falvo et al. 2014). DR programs are categorized into two main groups (Mortaji et al. 2017; Shariatzadeh et al. 2015):

- Price-based: in which the end-users modify their consumption based on the electricity price variations. Real-Time Pricing (RTP) is an example of this group;
- Incentive-based: in which the grid operator pays a remuneration to the end-users in exchange for modifying their consumption pattern. Direct Load Control (DLC) is an example of this group.

If the use of DR programs is merged with Distributed Renewable Energy Resources (DRERs), the grid operator would be able to fully benefit from these concepts and participate in market negotiations (Wang et al. 2015). However, both DR and DRERs should have enough capacity of reduction and generation in order to participate in the market negotiations. Based on several surveyed references (Bakr and Cranefield 2015; Khezeli et al. 2017; Paterakis et al. 2017), the minimum reduction capacity of customers for participating in DR programs in several electricity markets is 100 kW. This means that in such markets it is not possible for small and medium consumers, such as typical residential customers, to contribute to market negotiation individually (Gkatzikis et al. 2013). In order to overcome this barrier, a third party entity can be considered as a solution in order to aggregate small and medium scale resources and represent them as a unique resource in the energy market negotiations with adequate capacity (Siano 2017; Reddy 2016). Curtailment Service Provider (CSP) is a concept that can be considered as a third party in the electrical network operation (Hillman 2011; Faria and Vale 2013). However, before the implementation of business models, it is required to test and validate the model concepts in reliable and physical simulation platforms, which are capable to provide actual measurement and control in order to identify future problems (Mao et al. 2018). For this purpose, the use of fully computational resources to simulate an electrical distribution network can be very difficult and unaffordable, and perhaps the produced results will be far from the reality (Olivares et al. 2014). Therefore, a real-time simulation strategy would be a satisfying solution for integrating both reality and simulation results (Alvarez-Gonzalez et al. 2017).

There are few research works concerning the real-time simulation of a CSP model; this was a motivation for the present work. This paper provides a real-time simulation model for a CSP by using several real and laboratory hardware equipment considered as Hardware-In-the-Loop (HIL). The CSP aggregated resources include consumers, producers, and prosumers who do not have adequate capacity of generation and DR reduction in order to participate in the wholesale market negotiation, therefore, they establish a contract with CSP in order to be aggregated and managed by this third party. Moreover, an optimization problem is developed in this paper in order to be used by CSP for optimal resources scheduling, which aims at minimizing its operation costs. The HIL equipment employed for CSP resources contain two small and medium scale laboratory loads, laboratory wind turbine and Photovoltaic (PV) emulators, and a real PV producer, which are controlled and managed by a real-time simulation machine (OP5600) through MATLAB/Simulink environment. In this way, the main purpose of the paper is to demonstrate that the hybrid simulation platform is also capable to implement optimal scheduling results and DR programs.

The rest of paper is organized as follows: Section 2 presents the related works and clarifies the main contribution of this paper. Section 3 explains the presented CSP model including all DR programs and mathematical formulation regarding the optimization problem. Section 4 presents the real-time simulation model considered for the CSP, where all HIL infrastructures and MATLAB/Simulink models implemented in the OP5600 are denoted. Section 5 discusses a case study implemented using the presented model in order to test and validate the system capabilities, and its results are presented in Section 6. Finally, the main conclusions of the work are presented in section 7.

Related works

There are several research works related to this topic. In (Bottaccioli et al. 2017a) the authors presented a hybrid simulation platform, including a PV simulator and a real-time network simulation model. The PV simulator models the real PV systems and calculates the energy generation based on the input data such as the solar radiation. For the network model, it has been used the OP5600 real-time simulator, in order to verify the PV model in the real conditions, such as real electricity network configurations. It has been presented a case study for testing the platform on the actual electricity network conditions in Turin, Italy, and the results demonstrated that the current configuration of the network cannot handle the integration of a significant number of PV installation, therefore, an improvement is necessary for preventing future problems. Although the authors in (Bottaccioli et al. 2017a) used OP5600 for a hybrid platform, they did not focus on the aggregation level and optimal resource scheduling, and also, there was not real or laboratory consumer loads in order to emulate the consumption profile in real-time.

In (Bottaccioli et al. 2017b), a novel and flexible platform has been developed in real-time simulator OP5600. In this work, the authors integrated load simulation and physical devices by employing an Internet of Things (IoT) adaptor. The proposed simulation platform contains PV and storage integration; it can be used for testing and validating the smart grids concepts. They also presented a case study that utilizes the developed platform in the real conditions of the network in northern Italy, and they confirmed the performance of the system. However, in this work, the authors did not include any optimization algorithm integrated with OP5600 regarding the aggregator concepts.

Reference (Marulanda et al. 2014) utilized a realistic methodology by considering CSP as a load aggregator in order to evaluate the impact of DR programs in the day-ahead Colombian electricity market. They considered that CSP can bid in the wholesale market by using the demand-bidding program. They also presented a tool for the market operator in order to quantify the impact of DR programs on the system. Realistic values from Colombian market have been used in order to perform numerical tests. The numerical results shown that the penetration of demand-bidding program changes the dispatch for different generation units. Although they utilized real input data for the model, the final results are totally numerical without any experimental test and validation.

Reference (Rotger-Griful et al. 2016) introduced a co-simulation platform, called virtual integration laboratory (VirGIL) with HIL devices in order to evaluate DR programs in a residential building located in Denmark. This platform is able to control the ventilation system of the building, as well as to integrate power system simulation, communication, and control. In the case study, the authors surveyed the impacts of a DR program defined by the CSP on the controlling of the ventilation system in the building using VirGIL. The results demonstrated the capabilities of the developed model, in which the ventilation systems can track the changes with 1-min time interval in order to perform the decisions at the certain time. However, they focused on a particular consumer on the CSP network, and they do not describe how the CSP perform the optimization and the day-ahead scheduling of the resources in order to define DR programs.

In (Li et al. 2017), the authors presented a real-time operation scheme for thermostatically controlled loads aggregation in electricity markets, which is considered as biding resource contributing in the day-ahead market negotiations. Moreover, they utilized an optimization model in order to maximize the profit of the aggregator in the regulation market. They performed several experimental tests with the proposed load aggregation simulator as a load shedding service provider, which validated the system. Although, they provided only the numerical results, and they did not use any real-time simulator or any HIL equipment in order to validate their system with actual measurements and control for gaining realistic results.

The main focus of the present paper is to implement a real-time simulation platform for an optimization-based CSP model considering several real and laboratory HIL infrastructures, which are controlled based on the optimal resource scheduling of a CSP and DR programs implementation. The HIL equipment enables the system to validate the developed methodology by using real data and enables actual measurements and control of hardware devices that are outside the simulation environment. The scientific contribution of this paper is to address an optimization based CSP model to the small and medium scale consumers and producers by employing a hybrid simulation platform, including real systems, laboratory emulators, and mathematical models.

CSP model

This section concerns the presented CSP model applying DR programs to its consumers, and the optimization formulations utilized by the CSP in order to optimally schedule the consumption and generation resources.

Model description

As it was mentioned before, in order to implement a DR program in a network, there is a minimum capacity for load reduction, which should be reached by the customers in order to be able to participate in the DR event. In this context, if a consumer has enough capacity of reduction, He can directly establish a contract with the system operator or DR managing entity. However, for small and medium consumers, who do not have adequate capacity of reduction, a third party entity (CSP in this paper) should aggregate these consumers, and allow them to participate in DR event as one. This means that the small and medium consumers can establish a DR contract with a CSP in order to be able to utilize DR programs, and participate in the wholesale market negotiations. The overall concept of the proposed CSP model is illustrated in Fig. 1.

As it can be seen in Fig. 1, the CSP is an intermediate entity between the demand side and grid side. In the demand side there are several small and medium scale consumers, producers, and prosumers (a consumer who can also produce); the CSP will be responsible for aggregation, scheduling and remuneration of DR events. In the grid side, the CSP will be in charge of market negotiations, energy trades, and bids with grid players, such as market or system operator. Also, the CSP should be able to accommodate the uncertainty that is related to the actual consumption and generation and to the actual response of consumers to DR events. In some cases, the CSP can make Direct Load Control (DLC) in the consumers loads but in other cases, without control hardware, the forecasting tools are very relevant in order to take full potential of the DR event. Such aspects should be considered in the scheduling and remuneration phases of the method since it doesn't imply with the HIL simulation model, only with the parameters of each simulation.

The network considered for the CSP model (right side of Fig. 1) is an internal low voltage distribution network of a university campus in Porto, Portugal (Silva et al. 2015). The CSP grid includes 21 bus with underground cables, where a MV/LV transformer in BUS #21 connects the CSP grid to the main network. This CSP network is considered as a part of the main network containing 220 consumers, and 68 DG units (left side of Fig. 1), which has been developed by the authors in the scope of previous works (Abrishambaf et al. 2017).

The CSP is able to perform the resources scheduling considering external suppliers, DG units (especially renewable producers and surplus of prosumer generation), and also DR programs. For this purpose, the customers that intend to participate in DR events can establish a contract with the CSP in three different programs: Direct Load Control (DLC), Load Reduction (Red.), and Real-Time Pricing (RTP). The characteristics of these DR programs are shown in Table 1. The load shifting program is an

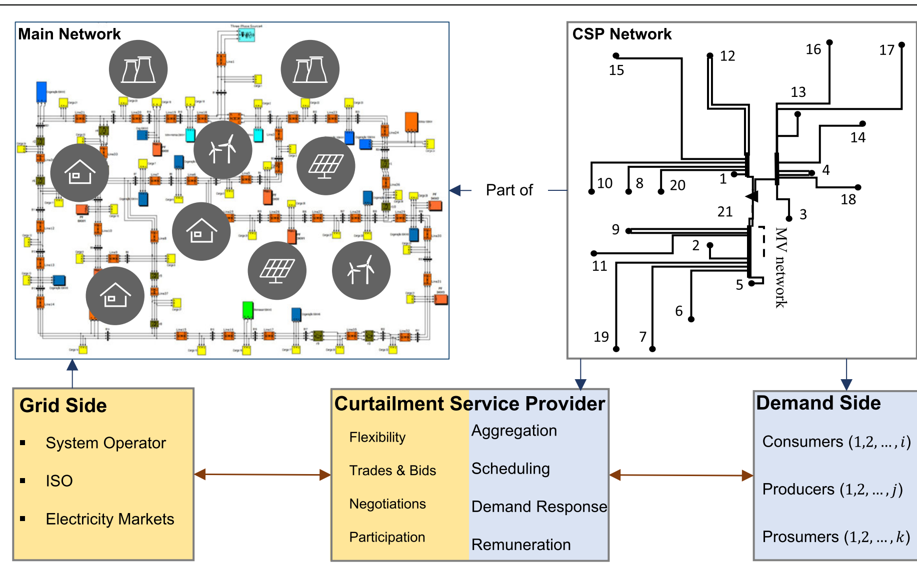

Fig. 1 The overall architecture of CSP model

Table 1 DR Programs proposed by the CSP to customers

DR Type	Mandatory/Voluntary	Remuneration	Activation/Signal	Measure/Contract
DLC	Mandatory	Cost/kWh reduced	DLC per equipment	Actual kWh reduction
Red.	Voluntary	Cost/kWh reduced	Reduction notification	Actual kWh reduction
RTP	Voluntary	N/A	Electricity price notification	N/A

important tool for the CSP since it can manage the consumption and shift it based on the available rate of generation. A load shifting model has been developed by the authors in the scope of their previous work (Faria et al. 2015), and since the purpose is to show that the developed model can also implement DR programs, three different programs have been presented in this paper and load shifting is not considered.

If a customer establishes a contract with the CSP for DLC, He will give permission to the CSP to directly control the devices whenever it witnesses with critical periods, for instance, while He faces a technical or economic reason. For this purpose, the customer will be notified about the event, and receive remuneration based on the actual kWh reduction. If a customer makes a contract with CSP for Red. program, while the CSP decides to apply DR event, the customer will be notified for consumption reduction, and if it is accepted, he receives remuneration based on kWh reduction. Finally, if a customer has a RTP contract, it specifies a value of electricity price somehow that if the electricity price raises and is greater than that specific value, He will decrease the consumption as much as it is specified in the contract. This means that the customer will be notified about the real-time electricity price, and if He agrees to participate, He will reduce the consumption. In the RTP program, the customer will not earn remuneration for the consumption reduction, which means RTP program has no cost from CSP standpoint.

In total, the CSP can perform resource scheduling and aggregation processes considering DG units, external suppliers, and DR resources. In this context, the CSP should utilize an optimization problem in order to optimally manage the resources, which will be demonstrated in the next sub-section.

Optimization problem

The CSP always tends to supply the demand using the local resources. Renewable resources are the first ones that CSP utilizes for scheduling since these have a lower price from the CSP standpoint. After that, DR resources, especially RTP program, are the next options for CSP scheduling, and external suppliers would be the last choices for the CSP since it is considered as the most expensive resources from the CSP standpoint. Therefore, an optimization problem is required for the CSP in order to provide an optimal resource scheduling. However, as previously stated, the optimization problem is not a core contribution of the paper since the main focus of the paper relies on demonstrating that the hybrid simulation platform is also capable to implement optimal scheduling results and DR programs.

The objective function presented for CSP to minimize his Operation Cost (OC) is shown by Eq. (1). In this model, it is considered that technical verification of network is the responsibility of the network operator, and the CSP is not accountable for such matters.

Minimize

$$OC = \sum_{i=1}^{I}\left(\sum_{s=1}^{S}\left(P_{Ext(s,i)} \times C_{Ext(s,i)}\right) + \sum_{c=1}^{Cs}\left[P_{DG(c,i)} \times C_{DG(c,i)} + P_{DLC(c,i)} \times C_{DLC(c,i)} + P_{Red(c,i)} \times C_{Red(c,i)} + P_{RTP(c,i)} \times C_{RTP(c,i)}\right]\right) \quad (1)$$

There are several constraints considered for this optimization problem. The first constraint stands for load balance, as shown in Eq. (2). The second constraint, in eq. (3), concerns DG units and prosumers, where indicates if the customer is a prosumer, its DG generation supplies the local demand first, and then, if there is any generation surplus, it will be injected to the CSP network.

$$\sum_{s=1}^{S} P_{Ext(s,i)} + \sum_{c=1}^{Cs}\left(P_{DG(c,i)} + P_{DLC(c,i)} + P_{Red(c,i)} + P_{RTP(c,i)}\right) = P_{Load(\ i)} \forall i \in \{1, \ldots, I\} \quad (2)$$

$$P_{DG(c,i)} = \begin{cases} P_{DG(c,i)} - P_{Cons(c,i)} & P_{DG(c,i)} > P_{Cons(c,i)} \\ 0 & P_{DG(c,i)} \leq P_{Cons(c,i)} \end{cases} \forall c \in \{1, \ldots, Cs\}, \forall i \in \{1, \ldots, I\} \quad (3)$$

Additionally, the technical limitation of each resource should be considered in the optimization problem. For this purpose, eq. (4) and eq. (5) demonstrate the limitation regarding external suppliers and DG units, respectively.

$$0 \leq P_{Ext(s,i)} \leq P_{Ext(s,i)}^{max} \quad \forall s \in \{1, \ldots, S\}, \forall i \in \{1, \ldots, I\} \quad (4)$$

$$0 \leq P_{DG(c,i)} \leq P_{DG(c,i)}^{max} \quad \forall c \in \{1, \ldots, Cs\}, \forall i \in \{1, \ldots, I\} \quad (5)$$

The technical limitation regarding DR programs, including DLC, Red., and RTP programs, is shown by eq.(6–8), respectively.

$$0 \leq P_{DLC(c,i)} \leq P_{DLC(c,i)}^{max} \quad \forall c \in \{1, \ldots, Cs\}, \forall i \in \{1, \ldots, I\} \quad (6)$$

$$0 \leq P_{Red(c,i)} \leq P_{Red(c,i)}^{max} \quad \forall c \in \{1, \ldots, Cs\}, \forall i \in \{1, \ldots, I\} \quad (7)$$

$$0 \leq P_{RTP(c,i)} \leq P_{RTP(c,i)}^{max} \quad \forall c \in \{1, \ldots, Cs\}, \forall i \in \{1, \ldots, I\} \quad (8)$$

In sum, the mathematical formulation of the CSP model for resource scheduling with the objective of minimizing the operation costs, are shown in this section. In the next section, this formulation will be implemented in the real-time simulation model considered for the CSP.

Real-time simulation

In this section, the real-time simulation model considered for the CSP is presented. Several real and laboratory hardware equipment is employed in order to simulate the model in real-time considering the HIL methodology.

The real-time simulation model implemented for the CSP is shown in Fig. 2. In this model, it is considered that there are 20 consumers and prosumers, and 26 producers.

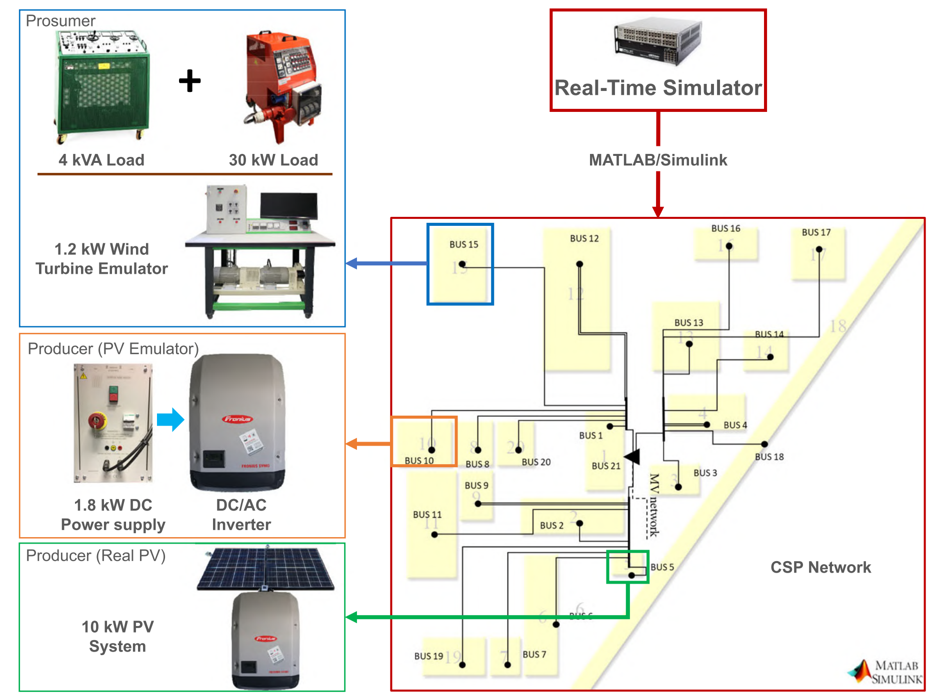

Fig. 2 Real and laboratory HIL equipment in MATLAB/Simulink CSP model

The consumers are 12 residential buildings, 6 commercial buildings, and 2 industrial units. Also, the producers are all renewable resources including 22 PV systems and 4 wind generators. Moreover, external suppliers are considered.

As Fig. 2 shows, the CSP network has been modeled in MATLAB/Simulink in OP5600. In this network, several real and laboratory equipment has been employed in order to emulate the consumption and generation profiles of the CSP players via the HIL methodology. BUS #15 is considered as a prosumer, BUS #10 is dedicated to a 1.8 kW PV emulator, and BUS #5 includes a real 10 kW PV producer.

For the prosumer in BUS #15, a 4 kVA and a 30 kW load emulate the consumption, and a 1.2 kW wind turbine emulator is responsible for wind generation. Moreover, for the two PV producers, in BUS #10, a 1.8 kW DC power supply connected to a DC/AC inverter emulates a PV producer, and in BUS #5, a real installation of PV system with a maximum capacity of 10 kW stands for another PV producer. All this equipment is controlled and monitored via OP5600 in MATLAB/Simulink.

Regarding the equipment connected to BUS #15 (prosumer), in a 30 kW load, there are four relays that increase or decrease the rated consumption, and in a 4 kVA load, there is an Arduino® (www.arduino.cc), which manages the amount of consumption. The relays in 30 kW load are connected to Digital Output board of OP5600, and Arduino® has been connected to OP5600 via Ethernet interface, with MODBUS TCP/IP protocol. Also, in wind turbine emulator, there is an induction motor coupled with the generator, in which the motor emulates the wind turbine. The motor has a speed controller unit, which manages the speed of the wind, and therefore, the output power generation of the machine. The speed controller unit of this machine is connected to the Analog Output of OP5600. More information about these resources is available in

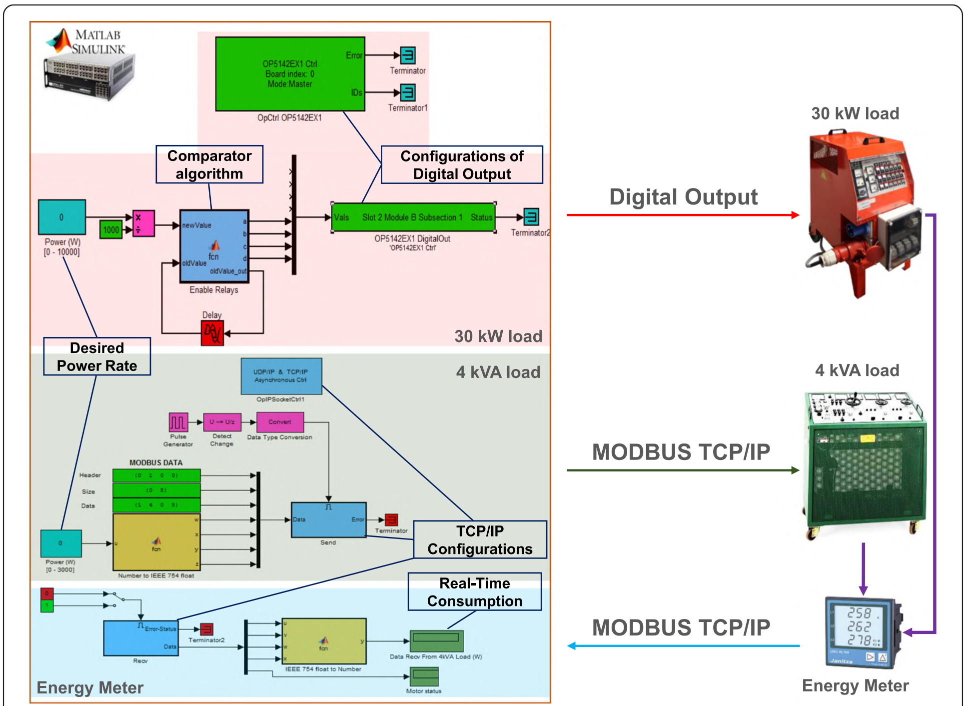

Fig. 3 Simulink HIL models for consumption of prosumer in BUS #15

(Abrishambaf et al. 2015). Figures 3 and 4 present the Simulink models, implemented in OP5600 for controlling these resources via HIL.

As it can be seen in Fig. 3, two Constant blocks in Simulink indicate the desired consumption to be consumed by the 30 kW and the 4 kVA loads. In the case of 30 kW load, the output of Constant block will be divided into the four binary outputs through a comparator algorithm in order to be provided to the Digital Output board. In the case of 4 kVA load, the output of Constant block will be converted to MODBUS TCP/IP format with IEEE 754 standard, which is four hexadecimal numbers. Furthermore, there is an energy meter for these two loads, which measures the consumed active power and transmit it to OP5600 in real-time via MODUS TCP/IP. By this way, OP5600 is able to transmit the favorable amount of power to the loads and simultaneously receives the real-time consumption of them.

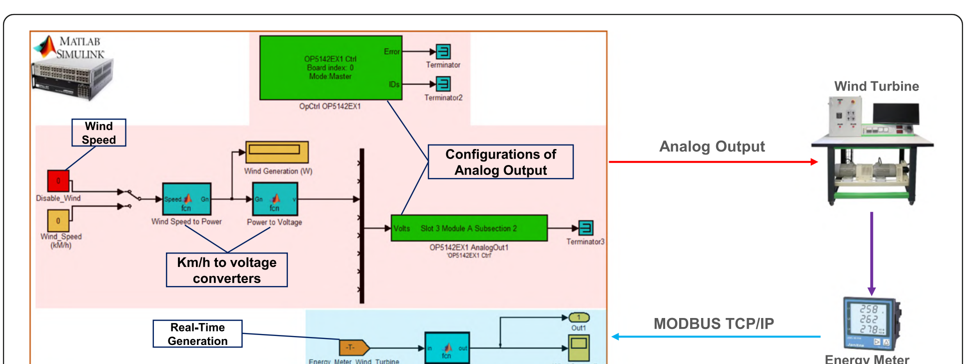

Fig. 4 Simulink HIL models for wind generation of prosumer in BUS #15

The Simulink model regarding the wind turbine emulator is shown in Fig. 4. In this model, since the wind turbine is controlled by Analog Output of OP5600, the wind speed data should be converted to a 0 to + 10 V signal. The output of a Constant block, which is favorable wind speed value, is converted to 0 to + 10 V voltage range through two developed algorithms implemented in two MATLAB Function blocks, and therefore, OP5600 controls the emulator based on the provided voltage. Simultaneously, an energy meter measures the generation of the emulator and transmit it to the OP5600 in real-time via MODBUS TCP/IP. The TCP/IP configurations blocks regarding the energy meter are not shown in Fig. 4 since these are similar to the ones in Fig. 3.

Regarding the 1.8 kW PV emulator located in BUS #10, an Arduino® has been utilized in the DC power supply in order to manage the output power between 0 and 100% of capacity. In fact, the DC power source simulates the PV arrays, which provides DC voltage, and the DC/AC inverter is a usual model that is utilized in real PV installations. The Simulink model for controlling and monitoring the equipment in BUS #10 is shown in Fig. 5. In this model, two groups of TCP/IP blocks have been employed, one for the DC power source (Arduino®), and the other for the DC/AC inverter. By this way, the OP5600 transmits the desired value of PV generation to an Arduino via a MODBUS TCP/IP request and receives the real-time AC power generation from the DC/AC inverter.

The Simulink model considered for real 10 kW PV producer in BUS #5 is the same as the model presented in Fig. 5, however, the difference is that there is no DC power source, and therefore, OP5600 has no control over the PV generation and is only able to monitor the real-time AC power generation of the unit. This has been implemented via a group of TCP/IP blocks that request the real-time AC power generation from the DC/AC inverter.

In sum, the Simulink models implemented in the real-time simulator (OP5600) have been demonstrated in this section. All Simulink models have been designed by relying on the HIL methodology in order to control real hardware resources and utilize real data in Simulink.

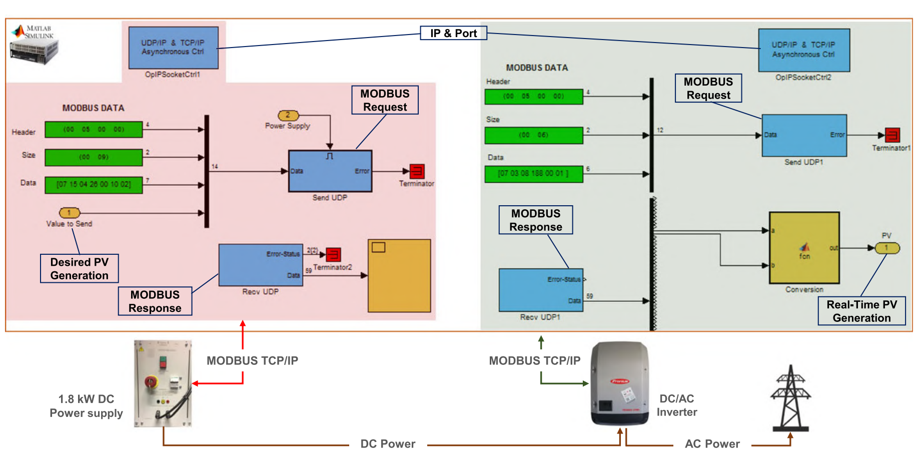

Fig. 5 Simulink HIL model for PV emulator in BUS #10

Case study

In this section, a case study tests and validates the developed Simulink models in OP5600. For this purpose, 24 periods of 30 s (12 min in total) are considered for running the model in real-time and obtain the results. The 12 min period, which is a rather short one, has been selected in order to provide deeper focus on the results analysis. Longer periods can be easily implemented using this hybrid platform. The consumption and generation profiles considered for the day-ahead scheduling of the CSP are shown in Fig. 6.

As Fig. 6a illustrates, in some periods the CSP is able to manage the consumption relying on local DG and DR resources, however, in other periods CSP is forced to purchase energy from external suppliers. The aggregated profiles shown in Fig. 6b, are related to the prosumer in BUS #15, and to two PV producers in BUS #10 and #5, which are real data of GECAD research center in Porto, Portugal, adapted from GECAD database. The profiles shown in Fig. 6 are day-ahead profiles, which enable the CSP to manage and schedule the consumption and the generation of the network for the next day. By this way, the customers will be notified of the scheduled events for next day, and therefore, they have adequate time in order to negotiate and response their availability for the next day events.

In this case study, DG units are considered as the cheapest resource for CSP so these will be the first resource to be utilized by CSP to supply the demand. In the meantime, the price of buying energy from external suppliers is considered as the most expensive resource of the CSP. This means that, in high consumption periods, it is affordable for CSP to perform DR programs to reduce the consumption in order to avoid purchasing energy from the external suppliers. In this context, it is considered that the prosumer in BUS #15 has established a DR contract with the CSP for 2.5 kW reduction between periods #8 to #19.

With this in mind, it is obvious that the CSP should perform the proposed optimization algorithm, in order to optimally schedule the resources for minimizing its operation costs. In this model, the real-time simulation starts from the OP5600 and Simulink model. Then, JAVA Application Programming Interface (API) is employed in order to transmit the Simulink data to the R Studio tools (www.rstudio.com), where the optimization algorithm has been implemented. Therefore, the optimization algorithm is performed, and afterward the optimized data including optimal resource scheduling results is transferred to the OP5600 and Simulink model using JAVA API. Full details regarding this process are available in (Abrishambaf et al. 2017), which has been developed by the authors in the scope of their previous works.

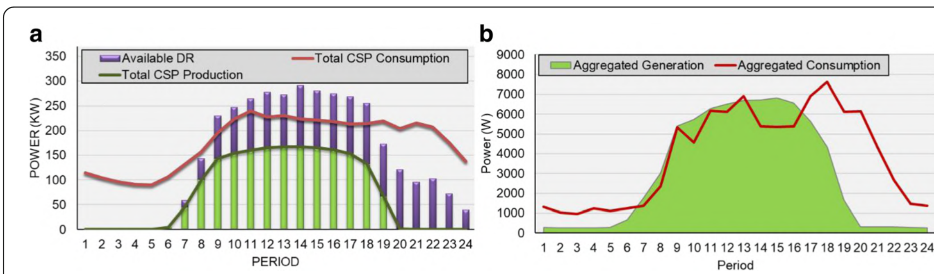

Fig. 6 Day-ahead consumption and generation profiles considered for case study: **a** Total CSP network, **b** Aggregated profiles from BUS #15, #10, and #5 by CSP

The optimization problem developed in this paper is a linear problem and is solved using R Studio. Since R studio tools play the role of mathematical problem solver and are separate from the real-time simulator, OP5600 is able to manage HIL devices according to the acquired results of any optimization model supported by R Studio, such as linear or nonlinear problems.

In other words, the outcomes of the optimization process, which is the economic resource scheduling, is the rate of power that has been requested from each consumer and generator in the CSP network. In order to implement these optimal scheduling results on the real resources, the conditions of the electrical network are important. The OP5600 real-time simulator used in this paper enables us to address this fact; we can validate the actual amount of reduction in the consumers and actual generation of energy resources and obtain the actual measurement results in order to be employed in the remuneration phase.

Results

In this section, at first, the results obtained from optimization problem are provided, and then, the real-time data acquired by OP5600 from Simulink is presented. The optimization results belong to all the CSP network, however, the main focus is given to the prosumer in BUS #15, and to the two producers in BUS #10 and #5. Figure 7 illustrates the optimal resource scheduling results of the CSP for network players in BUS #15, #10, and #5.

As it can be seen in Fig. 7a, all DG units are responsible to provide the maximum generation to the CSP network since it is the cheapest resource of the grid. Additionally, Fig. 7b shows the load reduction in the scope of Red. DR program, which CSP utilized for prosumer in BUS #15, for reducing the consumption in order to avoid purchasing energy from external suppliers.

When these optimization results are obtained, they are provided to the OP5600 real-time simulator as inputs. Consequently, the real-time simulator starts to control and manage the HIL equipment in order to implement the optimization results in real-time. The consumption profiles shown in Fig. 7b will be emulated by the 4 kVA and the 30 kW loads; the wind production curve shown in Fig. 7a will be provided to the 1.2 kW wind turbine emulator; the PV profile in BUS #10 will be modeled by the 1.8 kW PV emulator; and the PV curve in BUS #5 will be the real profile of GECAD PV production. The output of the optimal energy resource scheduling model is a requested amount of power for each resource to manage its demand or generation in a

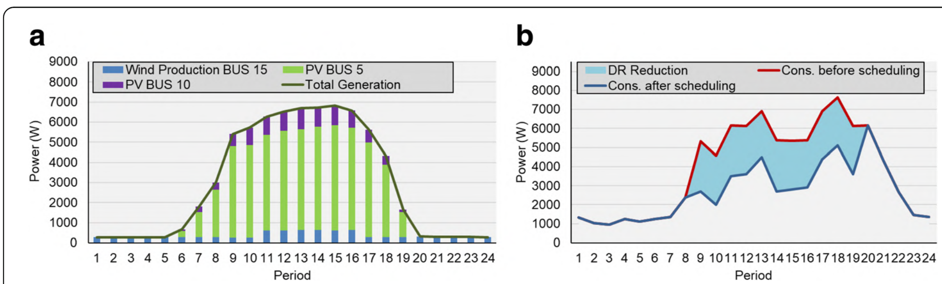

Fig. 7 Optimization results for CSP resource scheduling: **a** generation scheduling for BUS #15, #10, and #5; **b** consumption scheduling for BUS #15

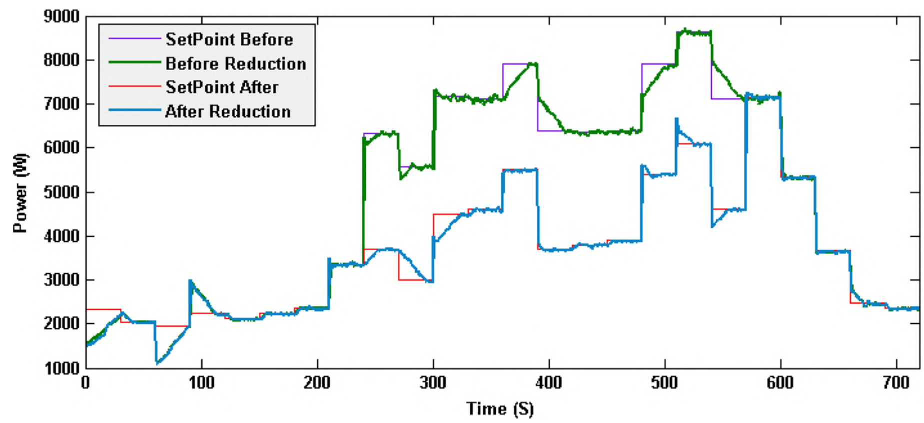

Fig. 8 Real-time simulation of consumption in BUS #15 before and after DR reduction

certain period. However, the actual implementation of the demand reduction and the DG production requested for each real resource will depend on the electrical grid conditions. In fact, this is one of the advantages of using real-time simulation (OP5600) and laboratory equipment, as HIL, for modeling consumption and generation profiles. With this method, we validate the actual demand reduction, and the actual DG production in order to be used in the simulation results, namely for remuneration and aggregation goals.

Figures 8, 9, 10, 11 and 12 show the final results of the real-time simulation for 12 min. All the results illustrated in these figures are adapted from OP5600 and MATLAB/Simulink. In this model, the time step for real-time simulation is configured as 0.5 s. This means that OP5600 transmits the optimization results to HIL devices with 30 s time interval (one value for each period), and then, it acquires the real-time data with a 0.5 s time interval. The results shown in Figs. 8, 9, 10, 11 and 12 are the behaviors and reactions of customers during the scheduled events; they accepted their availability for these events in the day before.

In Fig. 8, the set point values are the ones that OP5600 transmitted to the 4 kVA and to the 30 kW loads in order to simulate the consumption of the prosumer in BUS #15. The green and blue lines are the responsibility of the loads in real-time. The DR event has applied between the instant of 240 s (period #8) to 570 (period #19), which leads to reducing the consumption. As it can be seen in Fig. 8, whenever the rate of

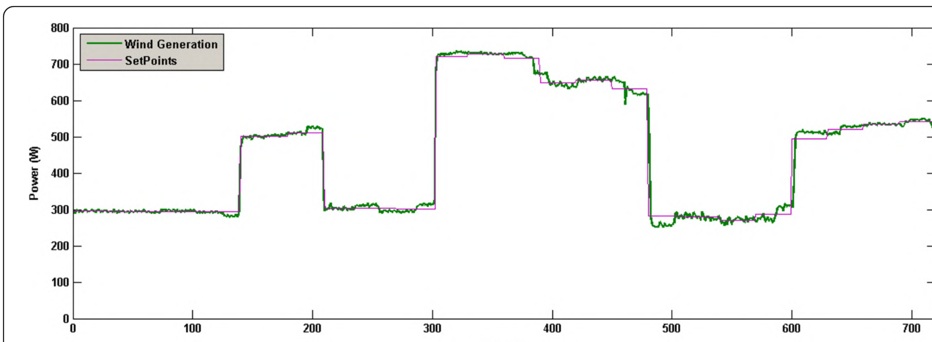

Fig. 9 Real-time results of wind turbine emulator in BUS #15

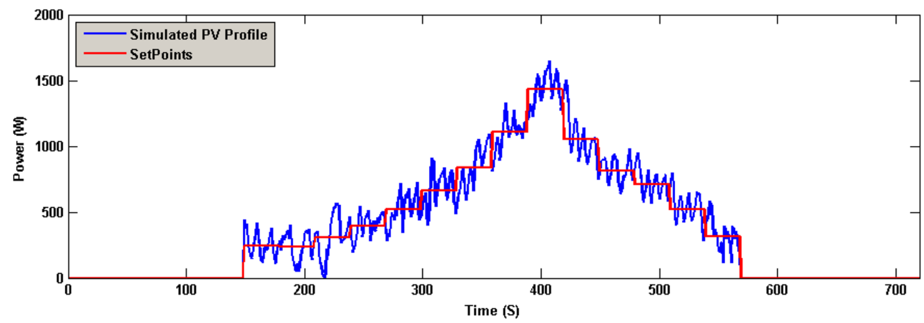

Fig. 10 Real-time results of PV emulator in BUS #10

consumption changed, the loads require some time to reach the desired consumption level. This is one of the main differences between the experimental works and simulation works; in simulation environment the consumption rate changes immediately, however, consumers modeled by HIL devices employed in this platform require some time to meet the desired rate of consumption since it accommodates analog control in AC Loads.

Moreover, Fig. 9 illustrates the real-time wind generation of the prosumer in BUS #15, which has been simulated by the 1.2 kW wind turbine emulator. The wind speed data provided by OP5600 to the wind turbine emulator has been acquired from (Meteo 2017).

As it can be seen in Fig. 9, the set points are the scheduled values that have been requested from the wind turbine to be emulated. Consequently, the emulator produces power and transmits the actual measurements of active power generation (green line in Fig. 9) to the OP5600. By this way, the system is able to emulate a scheduled wind generation profile based on the electrical grid conditions, such as voltage variations.

Figure 10 shows the real-time results of the PV emulator considered in BUS #10. As it is clear in Fig. 10, the set points are the scheduled amount of power to be generated by PV emulator, and the simulated PV profile (blue line) is the real generated profile by the PV emulator, which has been transmitted to OP5600 in real-time. Also, as Fig. 10 illustrates, there are a lot of variations in generation curve, which is due to the voltage variations in the AC side of the inverter. In this condition, the controller section of the DC power supply attempted to keep the generation level on the desired generation level.

Additionally, Fig. 11 demonstrates the PV generation results of BUS #5 in the CSP network. The results shown in this figure are the real production data of GECAD PV system with 10 kW capacity of generation. The considered generation profile is for an

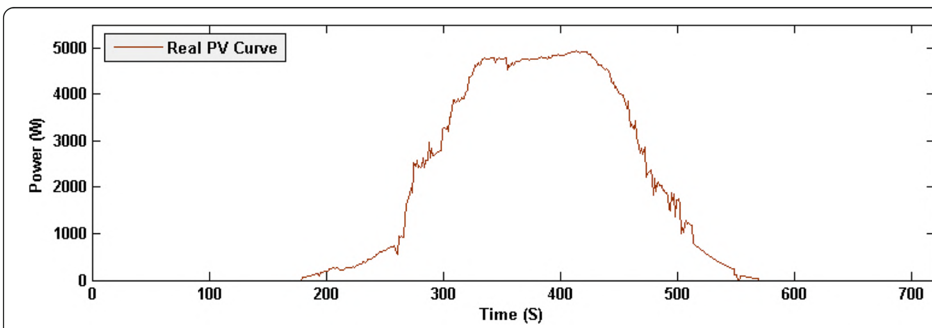

Fig. 11 Acquired results for real 10 kW PV producer considered in BUS #5

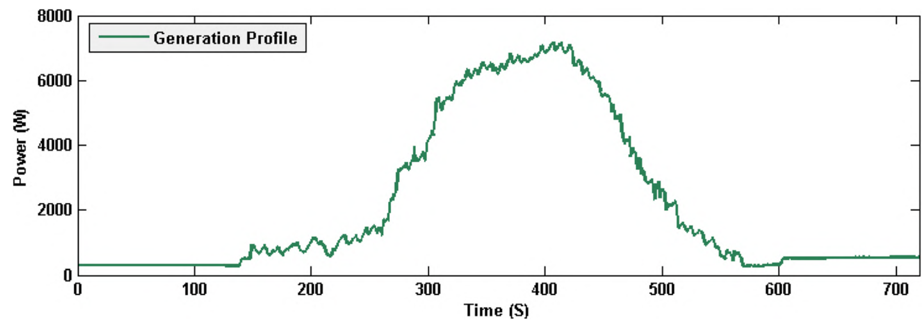

Fig. 12 Real-time profile of aggregated generation from BUS #15, #10, and #5

entire day with 1 min time interval (1440 periods of 1 min, for 24 h) available in GECAD database, and the profile shown in Fig. 11 is the same profile; however, OP5600 acquires the data with 0.5 s time interval (1440 periods of 0.5 s, in total 720 s).

As a final result, Fig. 12 shows the total aggregated generation from BUS #15, #10, and #5 in the CSP network in real-time, which is the sum of generation profiles shown in Figs. 9, 10 and 11.

The results shown in Fig. 12 are the actual measurements from the generation resources, which OP5600 acquired in real-time from different resources with different time intervals and merged into a unique profile. Since this is a real aggregated generation profile, it can be used by a CSP for several simulation purposes, such as remuneration processes or electricity market negotiations.

In sum, the results regarding the real-time simulation model of the CSP are illustrated in this section. These results prove the platform skills in order to validate a business model for optimal resource scheduling using several real and laboratory hardware resources and the real-time simulator.

Conclusions

The use of demand response programs and distributed energy resources, especially renewable generation, are a key role of nowadays distribution network. Moreover, in order to have an efficient solution for these resources management, third-party entities, namely curtailment service providers, are very relevant in this scope. The model presented in this paper concerns the real-time simulation of a curtailment service provider by utilizing several real and laboratory hardware resources. All the equipment presented in this paper has been employed in the real-time simulator as hardware-in-the-loop in order to take advantage of realistic results inside of the simulation environment. Moreover, an optimization problem is developed in this paper, which enables the curtailment service provider to have an optimal solution for the resource scheduling with the aim of minimizing the operation costs.

The presented case study tested and validated the system capabilities in terms of controlling and monitoring the real resources from the simulation environment by using a real-time simulator. The results of the case study are the ones actually measured from the real and laboratory loads and generators. These results demonstrate that the real implementation of management scenarios, namely demand response programs or resources scheduling, electrical grid conditions play a key role since voltage variations affect the consumption and generation profiles. Moreover, it is shown that the results obtained from the optimization have a little difference compared to the real-time simulation results. This is because of the reaction of the real resources outside of simulation environment; real resources take some time in order to fulfill the system goal and reach the desired consumption or generation level. In fact, this issue validates the need for a real-time simulation and hardware-in-the-loop methodology using real hardware resources, before massive implementation of business models.

Nomenclature

Parameters

OCOperational Costs of CSP
P_{Ext}Incoming power from external suppliers
P_{DG}Produced power of DG
P_{DLC}Power reduction in scope of DLC DR program
P_{Red}Power reduction in scope of Red. DR program
P_{RTP}Power reduction in scope of RTP DR program
C_{Ext}Cost of purchased power from external suppliers
C_{DG}Cost of produced DG power
C_{DLC}Cost of remuneration for DLC DR program
C_{Red}Cost of remuneration for Red. DR program
C_{RTP}Cost of remuneration for RTP DR program
P_{Load}The total power consumption of CSP
P_{Cons}Consumption of each CSP player
P_{Ext}^{max}Maximum capacity of incoming power from external suppliers
P_{DG}^{max}Maximum generation capacity of DG
P_{DLC}^{max}Maximum reduction for DLC program
P_{Red}^{max}Maximum reduction for Red. Program
P_{RTP}^{max}Maximum reduction for RTP program

Indexes

INumber of time periods
SNumber of external suppliers
CsNumber of CSP customers

Abbreviations

CSP: Curtailment service provider; DG: Distributed Generation; DLC: Direct Load Control; DR: Demand response; DRER: Distributed renewable energy resources; HIL: Hardware-in-the-loop; PV: Photovoltaic; RTP: Real-Time Pricing; VPP: Virtual power player

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Availability of data and materials

Please contact author for data requests.

Authors' contributions

OA organized the real-time simulation models and optimization problems and drafted the manuscript. PF carried out the overall concepts of CSP and demand response programs designing. ZV raised and developed the overall idea of the work. All authors read and approved the final manuscript.

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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[29] Omid Abrishambaf, Pedro Faria, and Zita Vale, "Energy Resource Scheduling in an Agriculture System Using a Decision Tree Approach", *20th International Conference on Intelligent Systems Applications to Power Systems (ISAP)*, New Delhi, India, 2019 (**C2** in Table 3.1)

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Agricultural irrigation scheduling for a crop management system considering water and energy use optimization

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Abstract

Center pivot systems are widely used to overcome the irrigation needs of agricultural fields. In this paper, an autonomous approach is proposed in order to improve the low efficiency of irrigation by developing a system based on the water requirement of the plantations, through field data. The data are local temperature, local wind, soil moisture, precipitation forecast, and soil evapotranspiration calculation. This information enables the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures. By this way, the system schedules the irrigation for the lower cost periods, considering the produced energy by the local resources, and the price of energy purchased from the utility grid. Also, it is considered that the irrigation must be carried out within the time interval in which the plantations do not reach the wilding point, so it will be carried out at the periods with the lowest cost. This will optimize the overall operational costs of the irrigation.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Energy and Environment Research, ICEER 2019.

Keywords: Smart farming; Water resource scheduling; Agricultural irrigation; Energy optimization

1. Introduction

The need for irrigation management has become relevant in many regions, especially in Mediterranean areas. This leads to having a limitation on the water resources, changes in the climatic conditions and the negative effect of human behavior on the environment. The purpose of the irrigation is to give the proper amount of water to the plants in order to guarantee their necessity. The amount of water used in the irrigation system is also important, somehow the new irrigation methods implemented in such a manner that consume less water comparing to the previous and old technologies. Smart irrigation methods also can be implemented, which means not only they

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should consider consuming less water, but also, they should limit the water supply to optimize crop production. For optimum operation, soil water in the crop root-zone must be maintained between a desirable range with upper and lower limits of available water for the plant. Proper irrigation management will prevent economic losses (yield quantity and quality) caused by over or under irrigation. The objective of irrigation management is to establish a proper timing and amount of irrigation for greatest effectiveness [1].

In agricultural fields, the main intention is to reach the maximum yield of the crop with the minimum operational costs. One of the developed methods in this area, which improves the efficiency of the use of water and the use of energy as well, is the irrigation by sprinkler with a system of the center pivot. In this method, the device rotates around a pivot, in a circular path, and crops are watered with sprinklers as the machine moves. Also, this method can be integrated with multi-depth sensors for measuring and monitoring the conditions of the soil. Therefore, an optimal solution can be reached through these approaches for minimizing the use of energy and water. Soil moisture sensors and Photovoltaic (PV) arrays are also useful for the water pumping, while the minimum moisture level is reached. However, more deep studies and surveys are essential in this context in order to have an efficient use of those systems [2].

This paper proposes an autonomous approach for improving the low efficiency of irrigation by developing a system based on the water requirement of the plantations, through the field data. The data are local temperature, local wind, soil moisture, precipitation forecast, and soil evapotranspiration calculation. This information enables the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures. By this way, the system schedules the irrigation for the lower cost periods, considering the produced energy by a PV system, and the price of energy purchased from the utility grid. Also, it is considered that the irrigation must be carried out within the time interval in which the plantations do not reach the wilding point, so it will be carried out at periods with the lowest cost.

There are several similar works focused on this topic. Dong et al. [3] presented an autonomous precision irrigation model based on a center pivot irrigation system that uses wireless underground sensor networks. In the same work, the system provided autonomous irrigation management through monitoring the soil parameters in real-time. In Boobalan et al. [4], and Pernapati [5] the authors developed an automatic Internet of Things (IoT) based irrigation system in order to monitor the soil and weather conditions and afford with auto irrigation to the crops by employing microcontroller and cloud server. Debauche et al. [6] provided a center pivot irrigation method for optimizing the crop water necessity by using multi-depth sensors for monitoring the soil moisture. Also, Wang et al. [7] proposed a dynamic irrigation low limit method, which considers the crop growth and development time and water supply to settle the irrigation while the water source is limited. In Brajovic et al. [8], the authors explained four solutions to smart irrigation software, where the explored data obtained from various kinds of sensors. However, the main focus of this paper is given to optimizing the overall operational costs of a smart irrigation system equipped with a renewable energy resource, and it is aware of the real-time electricity market prices. Therefore, the irrigation can take place at the most economic moments considering the soil moisture, PV generation and electricity price.

The rest of this paper is organized as follows: Section 2 explains the proposed model including mathematical calculation and optimization algorithm. Section 3 demonstrates two scenario calculations for testing and validating the system performance, and the results are shown in the same section. Finally, Section 4 presents the main conclusions.

2. System description

In the agriculture fields, the main intention is to reach the maximum yield of the crop with the minimum operational costs as well as water consumption. The proposed model in this paper is based on the Center Pivot (CP) irrigation, which improves the efficiency of water usage and energy consumption. Fig. 1 illustrates the typical architecture of a CP irrigation system.

As Fig. 1 shows, the CP system rotates around a pivot, in a circular path somehow the crops are watered with sprinklers as the machine moves.

The irrigation method presented in this paper considers multiple zones of the agricultural field that allows having different plantations or planting the same type but in different stages of growth. Fig. 2 demonstrates the proposed irrigation method. The system considers the irrigation requirements for each zone and regulates the speed of the electrical motor, related to the rotation of the infrastructure, and the valve motor related to the water pumping, based on the plant's requirements in each zone.

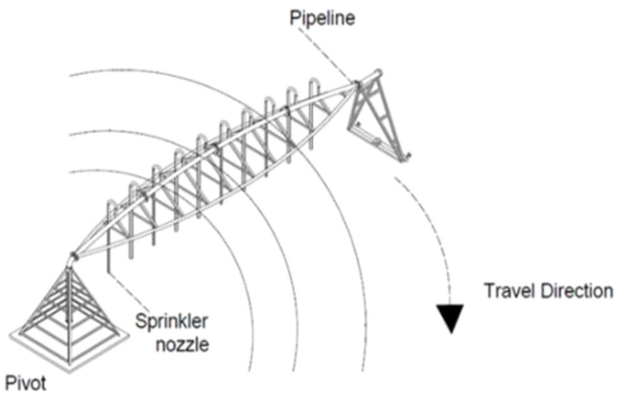

Fig. 1. The CP irrigation system.

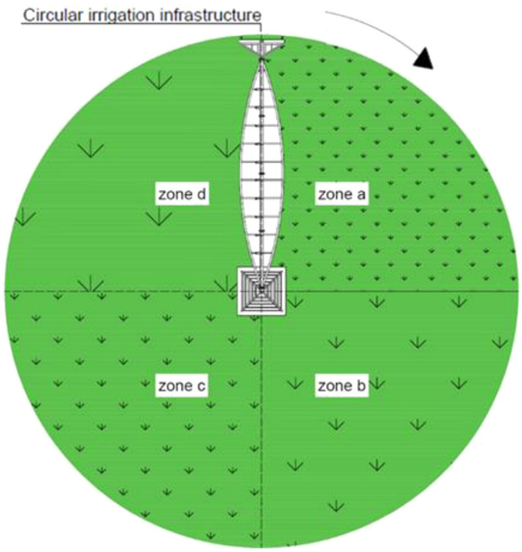

Fig. 2. Multiple zones CP irrigation system.

The system calculates the time remaining until the level of soil moisture goes below a desired limit for the plantations of the different zones considering the evapotranspiration of each zone and the precipitation forecast. Furthermore, the system obtains the local PV production and the electricity market price, in order to propose the most optimized scheduling for the irrigation of each zone. The priority of the system is set to use the local energy generation for the electricity demand of the devices. The presented optimization algorithm for the system is shown in Fig. 3, where the output would be the optimal irrigation scheduling. There are several sensors in the system, which enables the scheduling process to have real-time data, such as soil moisture, solar radiation, temperature, humidity etc.

The system is also able to perform precipitation and sun forecasting, which are used by the irrigation scheduling process. The algorithm checks the PV generation, electricity price, precipitation and sun forecast for the next three periods, and selects the best and optimal period that the irrigation can be performed with the minimum operational cost.

In order to estimate the period and the adequate amount to irrigate the field, it is necessary to calculate the evapotranspiration of the plantations. For this purpose, the FAO Penman-Monteith method [9] is utilized to estimate the potential evapotranspiration (ET_0) and the evapotranspiration of the crop (ET_c). Eq. (1) shows the calculation of the potential evapotranspiration considering the stage of vegetative growth of the crop by weighting the potential

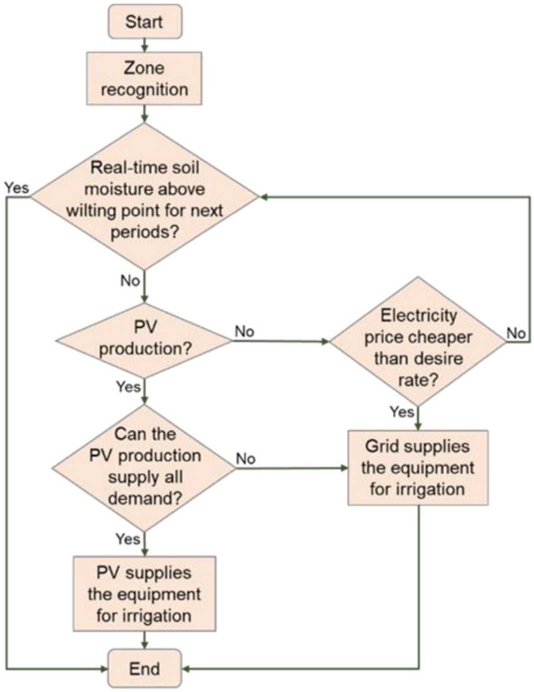

Fig. 3. Flowchart of the irrigation scheduling process.

evapotranspiration (K_c).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \tag{1}$$

where:

ET_0	Reference evapotranspiration [mm day^{-1}];
R_n	Net radiation at the crop surface [MJ m^{-2} day^{-1}];
G	Soil heat flux density [MJ m^{-2} day^{-1}];
T	Air temperature at 2 m height [°C];
U_2	Wind speed at 2 m height [m s^{-1}];
e_s	Actual vapour pressure [kPa];
e_a	Actual vapour pressure [kPa];
e_s-e_a	Saturation vapour pressure deficit [kPa];
Δ	Slope vapour pressure curve [kPa °C^{-1}];
γ	Psychrometric constant [kPa °C^{-1}].

The calculation of ET_c (as Eq. (2) shows) is the product of ET_0 and K_C, which K_C is determined from the type, growth length of the crop and chooses the corresponding coefficients K_C.

$$ET_c = ET_0 * K_c \tag{2}$$

where:

ET_c	Crop evapotranspiration [mm day^{-1}];
ET_0	Reference evapotranspiration [mm day^{-1}];
K_c	Single crop coefficient.

As a summary, this section demonstrated the proposed model for optimal irrigation by considering several real-time data and forecast information. The performance of the system would be validated through two scenario calculations presented in the next section.

3. Scenario calculations

In this part, two scenarios are presented for testing and validating the performance of the irrigation system. For this purpose, it is considered that the system is equipped with a 5 kW PV arrays, which can supply a part of irrigation system consumption. Therefore, a real production profile adapted from GECAD research center database, is provided to the algorithm, as Fig. 4-(A) shows. For the electricity market prices, a random day has been selected from the Iberian Electricity Market (www.omie.es), and the prices are provided to algorithm by considering a coefficient (Fig. 4 -(B)).

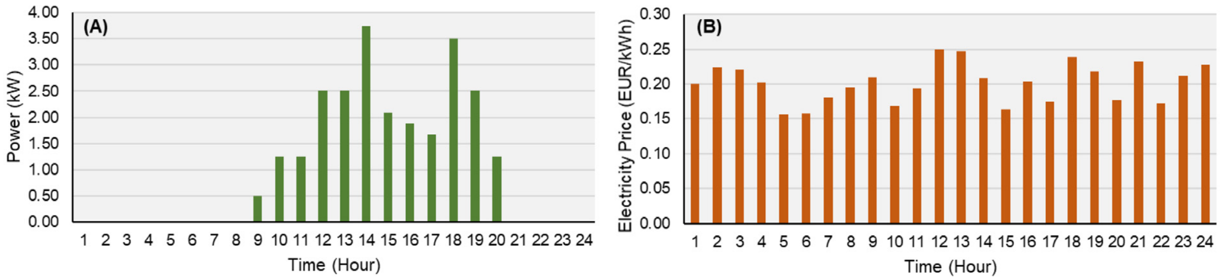

Fig. 4. Input data for the irrigation algorithm: (A) PV production profile; (B) Electricity market prices.

In addition to the production profile and the electricity prices, the precipitation and sun forecasts are calculated and provided to the irrigation algorithm as inputs.

As it was mentioned in the previous section, the system is equipped with several types of sensors in order to monitor the environmental and soil conditions in real-time. Therefore, two scenarios with 24 h duration (24 periods) are presented in this section by considering different input parameters, and the algorithm will calculate the most economic period to perform the irrigation. Table 1 demonstrates the parameters considered for the two proposed scenarios. In fact, the input data shown on Fig. 4 are equal for both scenarios, and only some critical parameters and irrigation devices characteristics are changed in order to survey the performance of the model.

Table 1. Input parameters for the two proposed scenarios.

Scenario 1		Scenario 2	
Soil moisture level [mm]	800	Soil moisture level [mm]	1500
Evapotranspiration crop [mm]	100	Evapotranspiration crop [mm]	100
Wilting point plantation [mm]	450	Wilting point plantation [mm]	800
Motor power [kW]	75	Motor power [kW]	100
Irrigation capacity [mm/min]	20	Irrigation capacity [mm/min]	30
Desired soil moisture level [mm]	1500	Desired soil moisture level [mm]	3000
PV panel capacity [kW]	5	PV panel capacity [kW]	5
Precipitation Forecast [mm]	50	Precipitation Forecast [mm]	0

Furthermore, the precipitation forecast is considered in scenario 1, which happens in the first four periods (between 12:00 AM to 04:00 AM) with 50 mm in each period. In fact, the precipitation increases the soil moisture, and therefore, the irrigation would be occurred shorter in order to reach the desired level. The gained outputs of algorithm are shown in Table 2. The results shown in Table 2 are the irrigation scheduling with the cost in each period, somehow the green is the most economic period for the irrigation and the red is the most expensive period. The costs are calculated by respect to the market prices considering the consumption of the devices and duration of the irrigation in each period.

The duration of irrigation in each period is based on the real-time and desired soil moisture level and the irrigation capacity. As it is clear in Table 2, the irrigation scheduling is shown until one period before the soil moisture is reduced to the wilting point. If the soil moisture becomes equal to the wilting point, the irrigation should be performed in any condition, and therefore, no algorithm is required for scheduling of the irrigation. Moreover, since there are precipitations in the first four periods of scenario 1 (50 mm in each period), and also the evapotranspiration rate is considered as 100 mm in each period, the soil moisture level would be compensated in the rainy periods

Table 2. The results of the irrigation scheduling algorithm.

Time	Scenario 1			Scenario 2		
	Soil moisture level [mm]	Irrigation duration [min]	Irrigation price [EUR]	Soil moisture level [mm]	Irrigation duration [min]	Irrigation price [EUR]
12:00:00 AM	800.00	35.00	2.34	1500.00	16.67	1.67
1:00:00 AM	750.00	37.50	2.81	1400.00	20.00	2.25
2:00:00 AM	700.00	40.00	2.94	1300.00	23.33	2.57
3:00:00 AM	650.00	42.50	2.86	1200.00	26.67	2.70
4:00:00 AM	550.00	47.50	2.47	1100.00	30.00	3.15
5:00:00 AM	-	-	-	1000.00	33.33	3.33
6:00:00 AM	-	-	-	900.00	36.67	3.31

(first four periods). Therefore, the most economic periods for irrigating in scenario 1 are firstly on 12:00 AM, and then on 4:00 PM. However, in scenario 2, the only economic period for irrigation is 12:00 AM.

The results and performances of the proposed irrigation scheduling algorithm have been shown and discussed in this section. Using this algorithm would enable the farmers to have smart management on the operational costs in the irrigation process. However, the proposed optimization approach should be implemented in a real pilot case in order to survey all functionalities of the model and identify the practical gaps for overcoming them in the future works

4. Conclusion

An autonomous approach was proposed in this paper to provide an optimal and efficient irrigation system. The model utilized the field data, in order to meet the requirements of the plantations. These data enable the system to calculate the real evapotranspiration for not being necessary to restrict to lysimetric measures and schedule the irrigation for the affordable periods. The electricity market prices, and a local renewable energy source are also considered in the scheduling algorithm. The important functionality of the presented scheduling algorithm is considered that the irrigation must be carried out within the time interval in which the plantation does not reach the wilting point, so it will be carried out at the periods with the lowest cost.

Two scenario calculation were demonstrated to validate the performance of the irrigation scheduling process. Precipitation and sun forecasts were also considered, which affected the soil moisture and therefore, it reduced the irrigation duration. From the results shown on the scenarios, it can be concluded that using the proposed irrigation scheduling approach enables the farmers to have affordable irrigation and smart management with a significant reduction in the operational costs.

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