Flexigy Smart-grid Architecture

Tiago Fonseca[1][a], Luis Lino Ferreira[1][b], Lurian Klein[2][c], Jorge Landeck[3][d] and Paulo Sousa[1][e]
[1]*School of Engineering of the Polytechnical Institute of Porto, Porto, Portugal*
[2]*Cleanwatts, MIT Portugal Programme, Energy for Sustainability Initiative, Coimbra, Portugal*
[3]*Univ. Coimbra, LIBPhys, Department of Physics, Coimbra, Portugal*

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Abstract: The electricity field is facing major challenges in the implementation of Renewable Energy Sources (RES) at a large scale. End users are taking on the role of electricity producers and consumers simultaneously (prosumers), acting like Distributed Energy Resources (DER), injecting their excess electricity into the grid. This challenges the management of grid load balance, increases running costs, and is later reflected in the tariffs paid by consumers, thus threatening the widespread of RES. The Flexigy project explores a solution to this topic by proposing a smart-grid architecture for day-ahead flexibility scheduling of individual and Renewable Energy Community (REC) resources. Our solution is prepared to allow Transmission System Operators (TSO) to request Demand Response (DR) services in emergency situations. This paper overviews the grid balance problematic, introduces the main concepts of energy flexibility and DR, and focuses its content on explaining the Flexigy architecture.

1 INTRODUCTION

The adoption of Renewable Energy Sources (RES) like wind and solar is growing at a significant rate, with the annual installed capacity growing almost 45% in 2020 (International Energy Agency, 2021). The prices for installing solar photovoltaic (PV) panels keep dropping, household systems are now capable of injecting their self-production surplus into the grid (SEIA, 2021), hence owners become producers and consumers – (prosumers).

The high penetration of RES into power grids results in difficulties maintaining the necessary grid balance. As a result, over the course of the day, the grid energy demand generates a duck-shaped energy consumption curve which highlights the increasingly problematic grid unbalance phenomenon happening with the increase of PV installations (CAISO, 2013).

Figure 1 illustrates the duck-shaped energy consumption curve in California on the 31st of March throughout several years; it represents the total energy consumption minus the energy input from solar generation. The imbalance between peak demand (at 21:00) and its minimum (at 14:00) is due to the peak production from PV panels. This is particularly problematic since conventional power plants require long periods to start or stop producing energy.

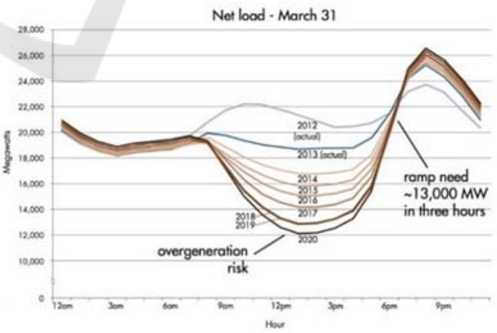

Figure 1: Energy consumption curve (CAISO, 2013).

[a] https://orcid.org/0000-0002-5592-3107
[b] https://orcid.org/0000-0002-5976-8853
[c] https://orcid.org/0000-0003-4666-9722
[d] https://orcid.org/0000-0003-4666-9722
[e] https://orcid.org/0000-0002-4478-1000

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In addition, at certain times of the year, there is also the danger of overgeneration or under generation, which can lead to permanent damage of devices connected to the grid, so grid operators are forced to curtail RES, activating costly Interruptability Contracts or increasing the consumption of energy by activating Regulation Reserves.

One of the problems that we address with the architecture proposed in this paper is to extend this interruptability contract and regulation reserves up to the prosumer, whose consumption/production or storage capability can be aggregated into large loads.

For a healthy grid operation, it is also important to balance consumption throughout the day and avoid, as much as possible, consumption peaks.

Consumers and producers are now capable of organizing themselves into Renewable Energy Communities (RECs) which alongside peer-to-peer (P2P) energy sharing and the aggregation of small-scale demand-side flexibility present a new energy-as-a-service business model as a solution to grid balance. Consequently, the architecture being proposed in this paper tackles these major challenges by using a mix of tactics to smooth and match consumption and productions curves. It does so by assuming that prosumers are associated in RECs, as described in Section 2.3, where a significant percentage of them is capable of producing, storing, as well as, consuming energy. The main idea is to collect information about consumption flexibility, in time and power, from multiple home appliances at prosumer houses, by applying the Flex Offer (FO) concept (Boehm et al., 2012), revised in Section 2.2.

The devices' loads can then be shifted according to electricity prices or other user preferences, balancing the grid and incentivizing user participation. As an example, assume an electric car that arrives home at 16:00 and only has to leave on the following day at 8:00. Consequently, the charging of the car can be made anytime during this period, fulfilling the objectives of the (i) car owner, e.g. by using only green energy or the energy produced in its house; and the (ii) grid, e.g. by scheduling energy consumption in times of lower electricity cost, meaning that the load is shifted to periods of forecasted higher energy availability which ultimately helps with its balancing.

For this purpose, our architecture is composed of a set of IoT devices capable of measuring energy consumption and controlling the home appliances, whose data is aggregated by an in-house smart hub. The data is analyzed in real-time at edge or cloud level, scheduling and optimizing production and consumption at 3 tiers: on the house (or office building), at the REC level, and, if the request cannot be fulfilled at these levels, at the grid.

This paper first overviews the main concepts on energy flexibility in Section 2. Section 3 presents the main architectural components and their rationale. Finally, Section 4 presents the pilot results of the Flexigy project, demonstrating the feasibility of the solution.

2 ENERGY FLEXIBILITY AND RELATED WORKS

This section explores some solutions to the grid balancing problematic such as Demand Response (DR) and energy flexibility through the concept of Flex Offer (FO).

2.1 Demand Response

DR services are a set of methods used by grid Transmission System Operators (TSO) to achieve grid balance between energy supply and demand by shifting and managing consumers' loads. Among the benefits of this solution are the incentive payments and cost savings for participants, increased reliability, reduced volatility, and reduced infrastructure costs for TSOs (Albadi & El-Saadany, 2008).

As an example, in Portugal, only two forms of DR services are legislated: (i) interruptibility contracts; and (ii) regulation reserve services, which are subject to many restrictions as discussed in the next sections. But legislation is evolving all over Europe and is also expected to change in a way that will allow to accommodate our proposal (Government, 2021).

Interruptibility contracts are a method used by TSOs to request the reduction of the electricity consumption of large industrial consumers to maintain grid balance, in exchange for financial compensation.

As an example, in Portugal, this service is not an effective solution for the flexible management of the energy grid as the minimum interruptible power for a consumer to establish an Interruptibility Service Access Agreement contract is 4 MW, and aggregation of loads is not allowed, excluding the participation of small-scale consumers (e.g., domestic end-users) in this process (ERSE, 2020a).

Regulation Reserve Services (RRSs) are an active power reserve that ensures the safe operation of the energy system in case of imbalances between energy supply and demand, after the reserves of primary and secondary regulations have been exhausted (ERSE, 2020a). These services are provided by certified producers who indicate the maximum active power available that can be increased or reduced to maintain the grid stability. Once again, in Portugal, the provision of RRSs is limited as it imposes a minimum load mobilization capacity of 1 MW per consumer and authorizes only the participation of consumers connected to the medium- or high-voltage network (ERSE, 2020a). Despite these limitations that exclude small-scale end-users from taking part in the provision of RRSs some pilots have been conducted to further extend and stimulate the market with aggregation (ERSE, 2020b).

It is expected that all over Europe and the world RRSs and Interruptibility Contracts will evolve allowing the participation of smaller loads, the aggregation of loads, and the participation of end-users (Government, 2021).

2.2 Demand-side Flexibility

Demand-side flexibility can be used as a key contribution to complement a renewable energy-based supply. This state-of-the-art concept is at the basis of this work as it is used to increase grid balance by managing, shifting, and optimizing energy resources based on their schedule and power flexibility. Energy flexibility can be characterized in different ways and formally defined through the Flex Offer concept.

2.2.1 Characterization of Device's Flexibility

In terms of flexibility, devices can be categorized according to two factors while maintaining the user comfort levels unchanged: (i) instantaneous energy consumption and (ii) usage time flexibility. More specifically, three different kinds of devices have been identified with interest to this project:

Fixed Devices: Devices whose energy consumption and the moment of that consumption cannot be modified (e.g., TV, lights).

Shiftable Devices: Devices that allow only to shift the moment of energy consumption in time without modifying the load profile (e.g., washing machine or a dishwasher). These devices offer a possible solution to optimize grid load management.

Elastic Devices: These devices offer the most flexibility, being fully adjustable in terms of usage time and instantaneous power consumption (e.g., HVAC, electric vehicles). Like shiftable devices, these devices provide extended grid load management capabilities, but with higher complexity.

Some studies have been conducted on how to use Elastic Devices, like HVACs as a demand-side flexibility solution (Kohlhepp et al., 2019). In these devices, flexibility can be introduced by changing the temperature of a given space or building while minimizing the impact on user comfort. In (Maasoumy et al., 2014) the authors study how to use the consumption flexibility of buildings' HVAC systems to establish contracts that bring financial rewards to the owners and increase energy flexibility to the utility operator. The algorithm considers forecasted weather conditions, occupancy rates, and other constraints to decide its flexibility for the next contractual period.

Similarly, studies had also been conducted on how to take advantage of Shiftable Devices and how these loads can be aggregated and submitted to a flexibility market. (self-reference)

2.2.2 Flex Offer Concept

The Flex Offer (FO) concept was first proposed by the EU MIRABEL project (Boehm et al., 2012), which defined a standardized model for representing flexible electric loads of both consumption (like the charging electric vehicles, heat pumps, home appliances) and production (like the discharging of batteries and PV panels) devices. The early applications of the concept revolve around energy commercialization in a large flexibility energy market for the overall grid load balancing, distinct from the solution being proposed in this paper where FOs are applied for flexibility management in RECs.

In their simplest form, FOs are generic abstractions expressing an amount of energy, a duration, a price, the earliest start time, and the latest start time.

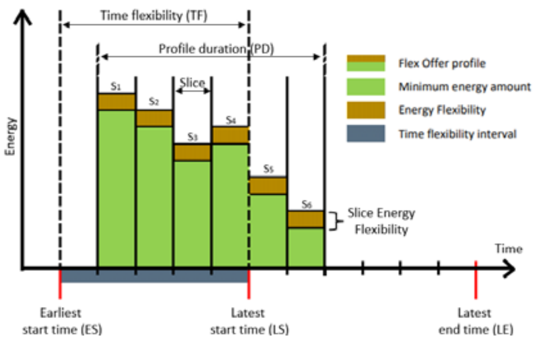

Figure 2: Flex Offer Example.

Figure 2 displays a visual representation of a FO energy profile with the earliest start time (ES) and the latest start time (LS), i.e. the time flexibility for the FO. The energy requirements are expressed in intervals of fixed length (slices). The striped area expresses the flexibility between the maximum and minimum amounts required.

Initially, a FO is an "option" that a prosumer introduces to a flexibility platform, which can be scheduled to optimize energy consumption considering the prosumer preferences, environmental concerns, and the financial motivations of the numerous players involved. In the end, the scheduling is carried out as specified, and the devices are activated according to it.

2.2.3 Flexibility Aggregation

(Boehm et al., 2012) studied the aggregation of energy flexibility, FOs, expressed by market players as the key to balancing energy supply and demand. After their creation and acceptance, the FOs are aggregated into larger loads and submitted to flexibility markets, since these markets do not handle small loads. A response to the bid is returned (for the aggregated FO) and its constituent FOs are disaggregated and returned to the prosumer. Once the execution is carried out, billing is conducted, and incentives are distributed among prosumers.

Similarly, by aggregating loads of building clusters with flexible demand, (Yin et al., 2016) implement an optimization model for the participation of a Distributed Energy Resources (DER) aggregators in the day-ahead market.

2.3 Renewable Energy Communities

The need to encourage the use of new energy technologies and the participation of prosumers in energy market solutions is pivotal to achieve greater levels of RES production, grid resilience, and reliability at lower financial costs.

These prosumers can participate in RECs to obtain environmental and financial benefits. RECs involve groups of geographically close citizens, entrepreneurs, public authorities, and community organizations voluntarily participating by cooperatively investing in, producing, storing, sharing, and selling renewable energy. Moreover, RECs must be autonomous from their members but effectively controlled by them, contingent that: i) the renewable projects are held and developed by the REC; ii) the main objective of the REC is to provide environmental, economic, and social benefits (Hunkin & Krell, 2018).

RECs are also fully responsible for imbalances caused to the energy grid, settling such imbalances, or delegating them to a market participant or its designated representative. In this paper, RECs are described as a group of prosumers buildings/houses under a local transformer capable of transforming from high voltage to 230 V.

To efficiently implement, manage and control RECs new energy projects, models which take advantage of smart home metering systems, sensors, and Internet of Things (IoT) infrastructure are required. For example, the authors in (Oprea & Bâra, 2021) envision an adaptive day-ahead load optimization and control solution for residential homes with an edge and fog IoT architecture.

3 SYSTEM ARCHITECTURE

This section overviews the physical system architecture and its main components. Moreover, it enumerates a set of consumer and producer profiles, focusing on the reasoning and constraints behind the proposed three-tier flexibility scheduling approach. Finally, the design to respond to DR service requests is explained in detail.

3.1 Main Components

The Flexigy architecture (Figure 3) is mainly composed by components distributed among two distinct locations: the End-User Premises and the Cloud Servers. The End-User Premises is where the home appliances, like the washing machine and the fridge, as well as, the smart meters and the smart hub, are located.

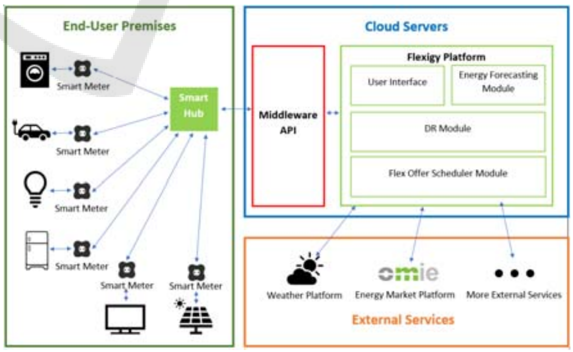

Figure 3: Physical System Architecture.

Smart (energy) meters are devices capable of acquiring energy consumptions and turning on and off home appliances, this is an important requirement in order to execute the scheduled FO. These are connected to the smart hub device through the 802.15 (Zigbee) protocol, but the newer version can also connect to the house Wi-Fi network. The smart hub receives information from all the devices and manages the communication with the Cloud Servers.

The Cloud Servers are where the platform's middleware broker, named Middleware API, and the Flexigy Platform are installed. The middleware API handles the communication with the prosumer's smart hubs.

The External Services include all external systems and platforms responsible for providing data to the Flexigy Platform. The components of this layer are managed and maintained by third parties and are strictly not part of the Flexigy platform, although they are essential to maintain the expected system operation. Some examples of data sources are the Weather Platform and Energy Market Platform.

The Weather Platform refers to an external service that provides real-time and historical weather data and weather forecasts for specific locations.

The Energy Market Platform refers to a system that provides information about prices traded on the wholesale energy market, in our case the OMIE. The OMIE is the Nominated Electricity Market Operator (NEMO) for managing the Iberian Peninsula's day-ahead and intraday electricity markets and prices (*About Us | OMIE*, 2021).

Inside the Flexigy Platform, the most relevant modules are:

User Interface: It is responsible for presenting the data by providing a dashboard where the user can, for example, pick profiles, add devices, specify FOs, and check schedules (Rocha et al., 2018).

Energy Forecasting Module: provides energy consumption and production forecasts. It relies on the Middleware API to fetch devices' historical data to forecast the consumption devices and on the external Weather Platform API to predict the day-ahead PV production.

DR Module: is used to handle interruptibility and regulating reserve requests. It provides a DR API through where TSO's can make these requests. It uses the Middleware API to fetch instantaneous device consumptions and uses the system DB to obtain FO scheduling information.

Flex Offer Scheduler Module: provides optimized Day-Ahead FOs schedules, using the external Energy Market Platform to fetch energy prices and request energy consumption and production values from the Energy Forecasting Module.

The architecture and implementation of this last module are subject to several constraints, which is one of the main topics of this paper and detailed next.

3.2 Energy Scheduling Approach

This section addresses the design concerns and the proposed architecture for the Flex Offer Scheduler Module, assuming the prosumer as part of a REC.

Scheduling FOs plays a crucial role in the management of flexibility. The scheduling is supported by a set of our own proposed heuristics (VPS, ISEP, Ionseed, PH Energia, 2021) that optimize prosumer needs and system constraints. To better incorporate the prosumer requirements, we defined some possible user profiles, considering both the roles of producer and consumer. With these, each prosumer can customize their experience according to what best fits their goals and beliefs:

Bold Profile: the FO scheduling maximizes renewable energy consumption regardless of the electricity price. This profile is designed to answer consumers that prioritize environmentally friendly energy sources.

Cautious Profile: FO of consumers with this profile are always scheduled at the lowest total cost possible. This profile aims to meet the financial needs of consumers.

Local Community Supporter Profile: the FO scheduling of consumers with this profile maximizes community consumption irrespective of its price. This profile allows consumers to support local producers by buying electricity from other community members before grid sources are needed.

Also, an energy producer might choose different profiles:

Go-ahead Profile: The producer wants to sell all is renewable electricity before maximizing self-consumption. This profile is created specifically to the case where the company implementing this solution at a REC supplies the equipment, e.g., smart meters, smart hub, PV panels, to the prosumer in exchange for a contract that requires that prosumer to sell all its production, before optimization, during a finite period (e.g., 6 months).

Tactical Profile: the producer only wants to sell its surplus of renewable generation after optimizing self-consumption. This is the default profile, as it prioritizes self-consumption, minimizing costs for the prosumer, and maximizing RES and REC consumption.

Considering the several kinds of prosumer profiles combined with a large number of prosumers lead to a scheduling approach based on levels. However, before describing such levels we present some of our assumptions.

Self-consumption (i.e., the consumption of energy produced in a house or office building) is considered to have no cost to its owner, which means it is always more beneficial (except for producers with a Go-Ahead profile) to shift the flexible consumptions to periods of peak self-production. This also implies that for FOs with energy needs greater than the self-production available in the FO time interval it is necessary to check forecasted electricity prices, and in a way, that minimizes the total energy cost. For example, scheduling 4 kWh with 3 kWh of self-production and buying 1 kWh for 0.18€ is more expensive than using the maximum 2 kWh of self-production and buying the remaining at a total cost of 0.14€. A consumer with a Bold profile may prefer the first solution, as it maximizes renewable energy consumption, on the other hand, the second solution fits better a consumer with a Cautious profile as it minimizes the total solution cost.

Another constraint is that REC members should be able to fulfil their FOs using the excess self-production of other community members. This requires that all Tactical profile prosumers with self-production must be scheduled first so that their energy surplus can be aggregated and sold to satisfy other community FOs. The details of these algorithms are described in (VPS, ISEP, Ionseed, PH Energia, 2021).

So, for scheduling the day-ahead flexibility of prosumers appliances we envision a three-tier approach. The three levels are as follows:

Level 1: Prosumer level, in this level the scheduling is performed for each individual prosumer, considering the minimization of energy costs and maximization of individual renewable energy self-consumption.

Level 2: REC level, the scheduler tries to minimize overall energy costs and optimize the usage of energy produced at the REC.

Level 3: Grid level, if FO is not fulfilled at Level 1 or Level 2 the scheduler schedules the FO taking into account the market prices and the requirements from different stakeholders. As an alternative, it aggregates several FO into larger ones that can be submitted to flexibility markets.

Figure 4 summarizes the system architecture from a logical point of view. The Level 1 scheduling, depicted in green, is executed for every prosumer building with energy self-production, by collecting each household device's flexibility, generating FOs, and scheduling them according to the user profile.

Depicted in red in Figure 4 are 2 logical Level 2 partitions. Each of these is logically executed at the REC level. The solution presented collects all the FOs generated at the households of the community, including the FOs partially or not totally scheduled at Level 1, and then it schedules them according to each user profile.

Finally, Level 3, represents the more traditional electric grid containing flexibility markets and being able to give different energy prices according to the hour of the day and its source.

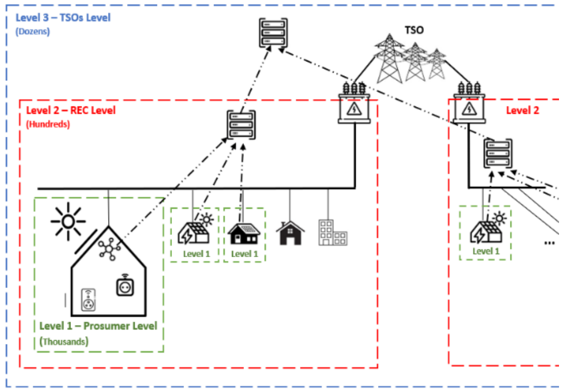

Figure 4: Three-Tier Architecture FO Scheduling Approach.

3.3 DR Module Implementation

The proposed logical architecture also enables the system to respond to DR services. In this architecture the Level 2 communities can aggregate a large set of Level 1 households' appliances, enabling the support of such services, eventually in conjunction with other RECs.

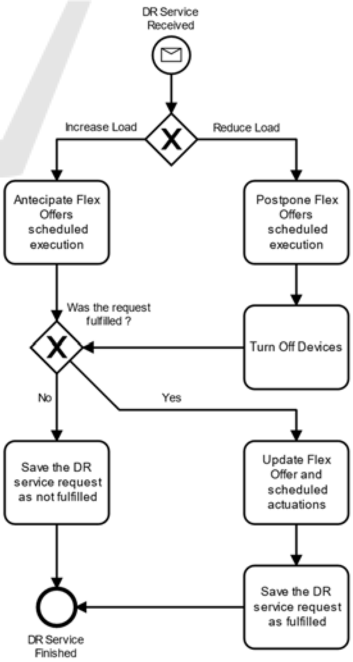

Figure 5: DR services implementation.

Figure 5 shows a flowchart of the process. At its basis, the implemented solution expresses an action, consisting of the increase or decrease by an energy amount, and a duration. If the DR service requested is to reduce the load, the system tries to postpone FOs due to start in the next few minutes while also turning off devices according to user comfort preferences. In the case of a power increase request, our solution tries to anticipate already scheduled flex offers to start consuming in the specified DR service period. In the end, if the request is fulfilled, the corresponding FO schedule and actuations are updated, and the request is saved as fulfilled. Otherwise, the system informs the TSO it cannot fulfil the request.

4 PILOT RESULTS

The results presented in this section are supported by data obtained from the OMIE electricity prices (Subsection 4.1) and from data acquired by the smart meters installed in five different households. After the system collects the data and the prosumer specifies the flexibility parameters to create FO, the scheduling algorithms are executed as described in Subsection 4.2.

4.1 Electricity Prices

To test and evaluate the scheduling algorithms proposed, we obtained the day-ahead electricity prices with 15 minutes granularity from the OMIE market. The price returned by the OMIE API for the day-ahead was used as the reference for RECs electricity prices and the prices used for grid suppliers were simulated. Figure 6 shows the prices from three different energy suppliers. The red line shows the price profile for REC electricity, the orange price profile represents the prices for a renewable energy grid supplier, and the blue price profile illustrates grid suppliers with mixed sources of energy.

Figure 6: OMIE electricity prices.

4.1 Flex-Offer Scheduling

This section presents an example of the pilot results obtained from the scheduling of a Shiftable FO originated from a washing machine and created in the system by a prosumer with a Cautious consumer profile and a producer Tactical profile. The main features of the FO are resumed in Table 1 and Fig. 7.

Table 1: Shiftable FO.

Device	Type	Time Flexibility	Load Profile
Washing machine	Shiftable	ES: 09:30 LS: 13:45	Depicted in blue in Figure 7

Given that the prosumer has self-production (yellow in Fig. 7) and a Tactical supplier profile, it is expected that the Level 1 algorithm should be executed to maximize self-consumption on all its FOs before selling to the community the energy surplus.

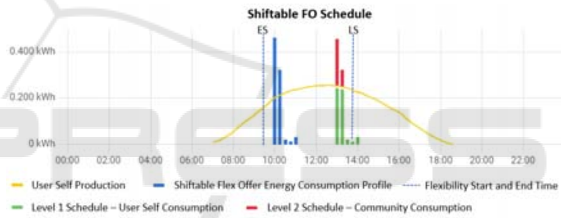

Figure 7: Level 1 scheduling of a Shiftable Flex Offer.

In this case, the scheduling obtained from Level 1 (green bars in Figure 7) is due to start at 13:00, as this solution minimizes the estimated overall cost, the aim of a Cautious consumer. Even though the consumption could have been shifted to match the peak self-production at 12:30, the algorithm schedules it a little forward in time, as some energy prices from 13:00 onwards are lower, thus minimizing the FO total cost. Note that in this instance, the Shiftable device FO is not fully scheduled in Level 1, thus its energy profile is updated for Level 2 scheduling.

In Level 2 scheduling, depicted by the red bars in Figure 7, it is possible to see that the remaining energy was scheduled using community energy as the supplier (the cheapest during both time slices). In the end, combining both the self-consumption from Level 1 and the energy scheduled during Level 2 the FO is totally fulfilled.

5 CONCLUSIONS

This project presents a smart energy optimizing platform architecture that tackles different players' economic and social needs in the energy market value chain. The energy consumers could benefit from the platform's optimized device management based on their energy flexibility. This feature helps lower electricity prices according to each user preference and even provides financial compensations through the fulfilment of DR. If approved by legislation, TSO can use an intelligent module ready to receive and handle DR at the REC level, aiming to minimize the energy imbalance problem and, consequently, the costs of introducing RES in the grid.

Furthermore, the solution proposed in this paper encourages the use of RES, since it helps producers reduce the investment pay-out time by not only maximizing the use of self-produced energy but also by selling the energy surplus to other community members at a profitable price.

Ultimately, society itself could benefit from the solutions provided, as it reduces electricity prices to end-users while promoting the widespread adoption of RES. The objectives tackled in this project are very complex and didn't include a significant size pilot that proves the scalability of the architecture proposed in this paper and the fairness of the scheduling algorithms. We also need to extend the testbed with several RECs and include other kinds of devices, such as cars.

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