Graphical Abstract

Coordination of Specialised Energy Aggregators for Balancing Service Provision

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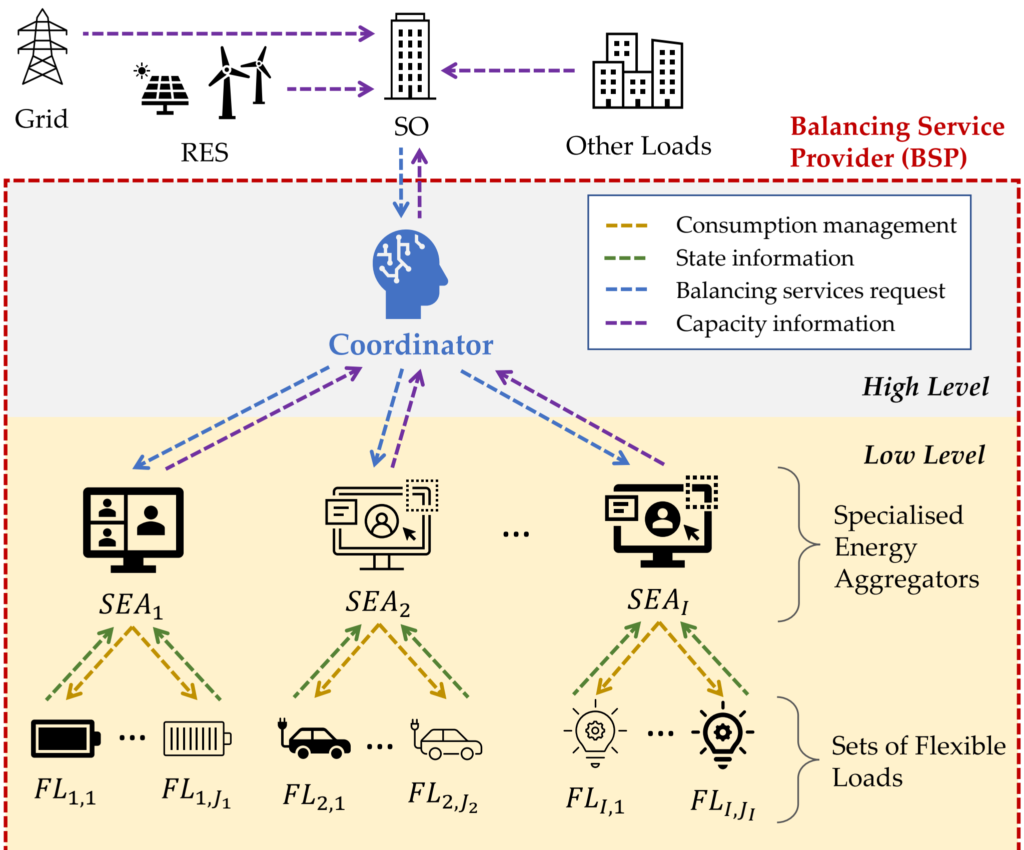

Highlights

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- Specialised Energy Aggregators (SEAs) are proposed for different types of loads.
- The SEAs interact with a Coordinator for providing balancing services.
- The information exchange between the Coordinator and the other entities is defined.
- The control algorithm developed for the Coordinator is described.
- The multiple SEA effectiveness to provide coordinated balancing services is assessed.

Coordination of Specialised Energy Aggregators for Balancing Service Provision

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Abstract

In the present context of evolution of the power and energy systems, more flexibility is required on the generation and demand side, to cope with the increasing uncertainty mostly introduced by variable renewable energy resources. This paper presents a conceptual framework that encompasses different types of aggregators, including local network aggregators, demand-side general aggregators, specialised energy aggregators (SEAs), and energy community aggregators. In this framework, this paper focuses on the coordination of SEAs to provide balancing services to the system operator. Each SEA manages a specific type of load, so that these loads can be managed by exploiting their control capabilities in a detailed way considering response time, dynamics and available flexibility. Moreover, the presence of the SEAs increases the privacy protection of the users, as only the information on a specific type of user's load is sent to the SEA. The SEA Coordinator interacts with the Balancing Service Provider aimed at procuring frequency containment, frequency restoration and replacement reserve services. This paper contains the SEA Coordinator formulation, information exchange and control operation strategies. Case study applications are presented by using SEAs for three specific types of loads (thermoelectric refrigerator, water booster pressure systems and electric vehicle charging stations). The results show how the control algorithm of the SEA Coordinator is effective in providing balancing services at different timings with the different types of loads. Various scenarios are considered, comparing an ideal situation without command propagation delays with realistic situations that take into account the

command propagation delays.

Keywords: Aggregator, Balancing Service, Flexibility, Electric Vehicle Charger, Thermoelectric Refrigerator, Water Booster Pressure System.

1. Introduction

Power and energy system flexibility is one of the most debated topics in today's research. In general terms, the flexibility of the power and energy system concerns the system *operation*. Different definitions and characterisations of flexibility from a technical point of view have been given on the generation side, the grid side, and the demand side [1]. In a context with resources and reserves, operational flexibility is defined as the "Technical ability of a power system unit to modulate electrical power feed-in to the grid and/or power out-feed from the grid over time" [2]. Specific indicators are based on maximum capacity, minimum stable generation and up/down ramp rates of conventional generators [3], determining the aggregated maximum flexibility through Minkowski sums on polytopes [2]. In addition, the available operational flexibility depends on time-variable constraints [4].

On the generation side, many approaches used to represent flexibility are inspired by unit commitment and economic dispatch [5], using appropriate approaches to incorporate uncertainty [6]. On the grid side, flexibility considers the ability of the power system to use flexible resources to cope with fluctuating changes during operation, which could increase the risk of congestion [7]. On the demand side, flexibility can be obtained by using an aggregation of components capable to adapt their consumption over time, also considering local production in case of prosumers. The various components of the demand side have been the subject of specific studies for determining their potential for flexibility. Specific results have been reported for aggregate loads with thermostatic control [8] also represented with a virtual battery model [9], water booster pressure systems [10], building space heating [11], multi-energy systems [12], energy conversion technologies [13], electric vehicles [14], aggregation of residential loads [15], and the contribution of buildings to energy flexibility [16]. Virtual battery models have emerged as interesting tools for representing different situations [17]. The examples reported above highlight the main concepts and issues, while a comprehensive review of the literature is beyond the scope of this paper.

Further considerations have been introduced for the characterisation of flexibility on the economic side. In this case, relevant aspects are the introduction of flexibility products and contracts [18], the emergence of concepts linked to the representation of the average power patterns for determining new contract structures [19], and the definition of economic and commercial flexibility through the mapping of iso-cost regions [4].

1.1. The Role of the Aggregators

Starting from the characterisation of the technical and economic features related to flexibility, a significant aspect is the deployment of the resources in energy markets based on price signals or incentives to participate in the provisioning of system services through flexibility. This can occur in the context of demand response (DR) programmes, which offer the opportunity to exploit the flexibility potential of small end-users by modifying their consumption. DR programmes can be classified into two categories: incentive-based programmes and price-based programmes [20]. In this respect, groups of users can be conveniently represented by an *aggregator* that manages a portfolio of end-users and interacts with the DR manager [21].

The presence of the aggregator has multiple advantages. For example, small end-users may be unable to implement and manage the infrastructure needed to access DR options and, in general, have no specific knowledge on the market mechanisms involved in the provision of DR. Hence, the aggregator acts as an intermediate operator that avoids sending private information on the individual end users to the DR manager, in particular on costs [22]. Moreover, the aggregator benefits from managing a group of end-users which can together offer a smoother average power curve. In the DR programmes, the aggregator can offer specific ancillary services [23] in the balancing market such as upward or downward flexibility over day-ahead or intra-day time horizons, to provide these services in real time. In this framework, there is room for the development of local flexibility markets [24].

Most strategies for controlling aggregators focus on price-based programmes, in which the offered flexibility capacity depends on the price signal defined by an overall managing entity such as the Distribution System Operator (DSO) [25]. The DSO aims at achieving the optimal scheduling of the power consumption or production of the individual aggregators by determining the energy and ancillary service prices [26]. Each aggregator determines how to operate the controlled assets in response to the price signal, adopting local coordinating mechanisms in a strategic way [27], or game-theoretical models [28]. Each aggregator acts as a price taker with respect to the wholesale market, and as a price designer for billing the aggregate assets [29].

On the other hand, in incentive-based programmes the aggregators are coordinated by the DSO, typically under the objective of minimising the energy losses and costs in the network, while the local aggregators minimise their own energy consumption cost or maximise their profits. In this kind of models, the optimisation problems of the DSO and of the local aggregators are solved independently, for example considering battery energy storage as the flexible asset [30], or controlling clusters of residential assets (thermostatically-controlled loads, electric vehicles, and water booster pressure systems) with an aggregator that provides energy regulation services at hourly intervals. After the determination of the strategy for controlling the assets, the aggregator can report to the DSO the optimal power profile [31] or some load boundaries only [32].

1.2. Coordinated Management of Multiple Aggregators

In the presence of multiple aggregators, a coordination is needed. In this case, multi-layer aggregation schemes can be defined, in which each entity on a given layer interacts with the entities located in the layer at the lower level, and there is an overall coordinator that has no direct access to the final users. The development of multi-layer schemes needs the creation of dedicated aggregators that act as interfaces between the "master" operator (e.g., the distribution network operator, DNO) and the users. One of the main advantages of the development of dedicated aggregators is privacy protection, such that the "master" operator has no access to information on the users managed by the dedicated aggregators [25]. The dedicated aggregators connected to the "master" operator (or more generally to a higher-level aggregator) can be set up considering different prospects, as:

1. Local network aggregators (LNAs): needed to consider the operational constraints of the local network and to construct a portfolio of different types of generation or demand [33]. An example is a virtual power plant [34] considered as the "master" operator with multiple distributed energy resource aggregators. The aggregation can include local energy systems that are aggregated individually [35] or interact under the coordination of a multi-energy player that acts as the "master" operator [36].
2. Demand-side general aggregators (DGAs): manage different types of demand without considering the grid operation. Typical examples are

aggregators that interact with the DNO and coordinate demand response in a low voltage network [37] or demand-side flexible resources [38]. Multiple load aggregators can be coordinated to provide frequency regulation services [39].

3. Specialised energy aggregators (SEAs): exploit the specific knowledge on different types of assets (generation or demand), to provide effective interactions with each type of asset, and using dedicated communication channels (specific information timing) for each set of resources. Each SEA is dedicated to a specific type of asset and is able to apply strategies (e.g., generation curtailment, load shedding, or flexibility services) selectively to the given asset [40]. Distinct SEAs can be defined for dispatchable distributed generation, renewable energy with storage [41], various types of equipment used for DR [42] including consumer responsiveness [43], electric vehicles [44] and charging stations [45]. Each SEA can handle the specific asset by considering more details in the models and control strategies [46], avoiding the need of designing overall strategies for many assets together.
4. Energy community aggregators (ECAs): energy communities do not necessarily include a local network. The ECA can be seen as an aggregator of multiple sources (generation and demand) of various kinds, located at different points in the network, or moving in the community such as electric buses [47]. The ECAs consider self-consumption and self-sufficiency of the energy community, as well as synergies between a building manager and an aggregator of electric vehicles to solve a scheduling problem in a coordinated way [48]. The aggregation of energy communities is a timely topic that needs to find appropriate business models [49].

Each DGA or SEA does not carry out network modelling, network monitoring, or assessment of the network operation. These tasks are assigned to the "master" operator (higher-level aggregator or coordinator).

About the existence or emergence of the specialised aggregators, a reference is the classification of the aggregator types provided in [50]. The main classification makes a distinction between the integrated aggregator, which is a commercial aggregator that supplies energy to the prosumer, and the independent aggregator, which does not supply energy to the prosumer, and may need to assign a Balance Responsible Party (BRP) as a contractual aggregator. For the independent aggregator, three sub-categories are defined, among which the "aggregator as service provider" does not sell flexibility services at its own risk, but activates the service to third parties, for example, to the supplier. The SEAs considered in our paper belong to the latter sub-category and are proposed with the focus set on balancing services to the grid. However, the novel aspect introduced in our paper is that each SEA addresses an individual type of loads, rather than a set of loads belonging to the same local energy system or microgrid.

The use of aggregators dedicated to specific technologies to provide grid services has been already considered for some specific technologies [51]. For example, there is a vast literature on Electric Vehicle (EV) aggregators, with numerous solutions already proposed for addressing the management of EV fleets in various conditions with a specialised aggregator. The EV aggregators range from the ones dedicated to technical aspects to other ones that manage the whole interaction with the market operators [52]. Another example considers an aggregation of thermostatically-controlled loads to provide grid services, already developed in the last years [53, 54]. Many contributions have highlighted different ways to interact with the power system and the markets.

The trend towards the consideration of specialised aggregators has been envisioned in our paper as a viable opportunity. Some recent publications indicate various reasons that support this trend, namely:

a) Different business models are emerging to support various solutions for managing multiple aggregators (e.g., centralised, decentralised, hierarchical, etc) [55].

b) The SEAs exploits dedicated tools to achieve high level of controllability of the type of resources to manage [56]. The technologies needed to implement the control actions may be more effective if the specific aspects of a given type of technology can be addressed together. In our paper, the SEAs are proposed with the focus set on balancing services to the grid, with different timings and characteristics (e.g., ramp rates).

c) The objectives of the individual types of demand and their mode of participation in providing ancillary services to the grid are different and sometimes conflicting. Mixing up a large number of heterogeneous units could not be the most efficient solution in practical cases.

d) General aggregators could be useful when there is a low number of demand and local generation units, while SEAs could address the presence of massive amounts of units.

e) The SEA operates with no need for knowing the grid conditions, with a kind of decentralised solution with respect to the upper centralised level that appears in a utility-based DER management [56]. In addition, the presence of the SEA Coordinator enables the management of the resources for providing the grid services without the need of explicitly modelling the grid.

f) Reaching a multitude of loads of different types by providing all kinds of commands to be used for their control is less practical than reaching similar types of loads for providing dedicated commands in a selective way.

g) User privacy concerns are addressed effectively by a SEA. In fact, the SEA has access only to the user's information that refers to the specific type of load and for the purpose of addressing the grid service under consideration. In this way, no SEA has visibility on the whole electrical behaviour of any user.

1.3. Behaviour of Aggregators in Markets

The introduction of distributed energy resources has prompted the emergence of new actors and policies in the electrical market. A stochastic optimisation problem is designed as a strategy of an aggregator that participates in the day-ahead market with demand flexibility in [57, 58]. For aggregator operation, a network-constrained transactive energy paradigm is proposed to integrate prosumers with the spot and balancing markets in [59].

Further approaches consider the aggregator as a price-maker in the wholesale electricity market and use a bilevel programming model of the interaction between the aggregator and the independent system operator that manages the market. In this case, the upper-level problem represents the cost minimisation [60] or profit maximisation of the aggregator of a microgrid [61] or virtual power plant [62], and the lower-level problem represents the market clearing problem of the independent system operator.

Moreover, in [63], a bi-level optimisation technique is used to design the involvement of a renewable energy-based aggregator in a real-time market. Furthermore, Nash bargaining theory is used in [64] to create an aggregator and a price scheme that clusters small energy storage devices, demonstrating long-term cooperation between players and avoiding market power abuse by an aggregator that plays in the wholesale market. Owing to the aggregator's function in the day-ahead market and its price volatility, a mechanism design is created in [65] to limit the aggregator's risk of financial loss due to spot price unpredictability. Furthermore, an optimal portfolio allocation for a demand response aggregator is provided in [66], considering its participation in day-ahead electricity prices and load contract types. The incorporation of aggregators into the electricity markets is still a hot topic of debate.

1.4. Contributions and Organisation

None of the above-mentioned models that deal with the coordination of aggregators consider the provision of many ancillary services from specialised aggregators. An initial conceptual framework for the coordinator of aggregators with heterogeneous flexible loads has been outlined in [67]. Flexible loads are considered with both continuous and discrete models. Each aggregator is specialised for a given type of flexible load, and uses predictive-optimal controllers and classical Proportional-Integral (PI) controllers to manage the loads flexibility.

According to ENTSO-E [68], a Balancing Service Provider (BSP) is an agent (e.g., generator, demand response and storage operator) that can offer balancing services to the System Operator (SO). In this paper, an entity, denoted as Coordinator, interacts with the BSP and is responsible of providing flexibility services for the coordination of the distributed flexible loads aggregated by the Specialised Aggregators. In particular, Water Booster Pressure Systems (WBPS), ThermoElectric Refrigeration (TER) units, and Electric Vehicle Charging Stations (EVCS) are considered as flexible loads in this paper. These types of flexible loads have the potential to provide various balancing services in the context of smart grids.

This paper is the extension of [67], with the following additional novelties:

a) The categorisation of the energy aggregators presented in Section 1.2.

b) The formulation of the SEA Coordinator with the development of the operation functions for planning and tuning the SEAs power demand.

c) The definition of the main parameters for information exchange between the SEA Coordinator and the SO as well as between the SEA Coordinator and the SEAs.

d) The development of the control algorithm used by the SEA Coordinator to follow the SO requests, taking into account the previously constructed power baseline.

e) The extension of the case study application, including the propagation delay of the commands and the possibility of offering higher capacity for the reserve service thanks to an improved management of the interactions among multiple SEAs in the longer term.

In the proposed framework the task of the Coordinator is to manage the aggregated services based on purely technical considerations, without economic considerations, i.e., no market participation [24] or price formation model is assessed. Instead, it is considered that prices are defined a priori through bilateral contracts between the BSP and the aggregators, and also between the aggregators and the customers. Therefore, the economics are assumed to be covered by the presence of bilateral contracts. In these contracts, the user will receive from the SEA an availability revenue to cover availability to provide the grid service if requested, plus an exercise revenue depending on the actual grid service provided following the request. Both terms concur in forming the possible profit of the user. On the other side, if the user will not be able to provide the service as agreed, the user will have to pay to the SEA a penalty established in the contractual rules. Likewise, the profit of SEAs comes from the bilateral contract structure. Then, the SEA will receive from the SEA Coordinator an availability revenue to cover availability to provide the grid service if requested, plus an exercise revenue depending on the actual grid service provided following the request. Both terms concur in forming the possible profit of the SEA. The possible penalties paid by the users if the service has not been provided is a further revenue for the SEA. On the other side, if the SEA will not provide the service as agreed, the SEA will have to pay to the SEA Coordinator a penalty established in the contractual rules.

The next sections of the paper are organised as follows. Section 2 recalls the characteristics of the balancing energy services used to maintain or restore the system frequency within its normal operating range. Section 3 describes the hierarchical coordination of a set of specialised aggregators. Section 4 evaluates the BSP operation based on simulation campaigns. Section 5 contains the conclusions and points out some notes on future works.

2. Provision of Balancing Services

In the past, the power systems exhibited as the main uncertainty source the variability of the loads. Hence, the continuous equilibrium between loads and generation was guaranteed through successive power injections or reductions by acting on the generation control system, which led to modify the power produced by every generator. Today, new forms of frequency support are required, because the uncertainty is affecting also the generation, due to the variability of the energy sources. The challenge of maintaining the system stability has to be faced by all the system operators, that hence must rely on common definitions and markets. With this aim, the European Commission Regulation 2017/1485 of 2 August 2017 [69] introduced the different products that can be offered for frequency regulation, as well as the requirements for the technical parameters to facilitate the exchange of balancing energy across borders.

The standard products offered on the balancing service market are the following:

- Frequency Containment Reserves (FCR) [69]: this reserve aims intervening after the unbalance to contain the frequency and start the recovery towards the nominal frequency value;

- Frequency Restoration Reserves (FRR) that can be activated automatically (aFRR) [70] or manually (mFRR) [71]: the role of this reserve is to provide the active power resources to restore the frequency at its nominal value.

- Replacement Reserves (RR), aiming to restore the proper level of FRR, in a way that the reserves can be able to face further imbalance.

Table 1 presents the full activation time and delivery periods of the balancing energy services.

Figure 1 shows a schematic representation of the timing of the intervention and deployment of every frequency reserve after a power imbalance happening at the time step t_0. Within 30 s the FCR of the system must be entirely deployed, followed by the aFRR (completely active within 5 minutes), which allows the restoration of both the FCR reserve (which results again available to face possible successive power imbalance) and the nominal value of the frequency. Then, the mFRR substitutes the aFRR (that is then released to face further imbalance), being completely deployed after

Table 1: Balancing energy services [69, 70, 71, 72].

Service	Full activation time	Delivery Period
FCR	15 s (50%) - 30 s (100%)	15 min
aFRR	5 min	15 min
mFRR	12.5 min	15 min
RR	0 - 30 min	15 min - 60 min

12.5 minutes. Finally, the RR activation is performed after 30 minutes, to release the mFRR and bring the system to a new operation point, after having adjusted the set points of the traditional generation.

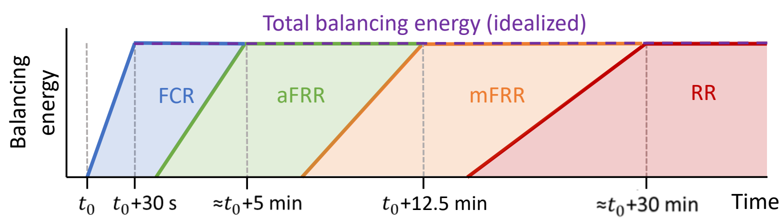


Figure 1: Balancing processes for frequency restoration.

Moreover, the European Commission Regulation 2017/2195 of 23 November 2017 [73] introduced common principles for both the procurement and the settlement of the reserve products among the different European countries. This led to create pilot platforms to test the provision of the products among the partners, i.e. [74]:

- FCR platform [75], involving up to now eight European Transmission System Operators.
- Platform for the International Coordination of Automated Frequency Restoration and Stable System Operation (PICASSO) [76], which is the European platform for the exchange of balancing energy from aFRR. It counts 26 members and four observers;
- Manually Activated Reserves Initiative (MARI) [77], aiming to build a common market platform for the mFRR deployment. It counts 30 members and four observers;

- Trans European Replacement Reserves Exchange (TERRE) [78], representing the RR Platform where the European RR balancing energy market is set up. It counts 8 members and four observers.

Besides the standardisation of the frequency reserve products, the innovations included within the European framework continued thanks to the *Electricity Regulation* 2019/943 [79] and the *Electricity Directive* 2019/944 [80], issued as part of the *Clean Energy for all the Europeans* package [81]. Here, the role of the customers and of the aggregators is stressed as fundamental for the proper operation of the system. In particular, the Electricity Regulation 2019/943 improved the possibility of participation in the ancillary service market (where the frequency reserve products are actually exchanged) for aggregation of distributed resources. Two different players are defined, i.e.:

- the Balancing Service Provider (BSP)
- the Balancing Responsible party (BRP)

The BSP is the entity that presents the offers/bids on the market, as an aggregator of distributed energy facilities. Once the offer/bid is accepted, this must be handled by the distributed resources owners/managers, i.e., the BRP. It is worth noting that the contractual relation between BSP and BRP are not specified by the regulation and hence is open to the discussion about the two entities.

The operation of the BSP, with the contribution of the Coordinator, is driven by the SO for ensuring the balance between demand and generation in the real-time dispatch, by activating the flexibility services. The balancing market normally considers the SO, the BSP, and the BRP, and consists of two phases:

1. *Balancing planning phase*: performed in a day-ahead market. The BRP reports the scheduled demand and generation per time step, computes the energy imbalances and sends them to the SO. The BSP informs the SO about the power demand baseline, defined as the sum of all the aggregator power demand. This can be based on forecast or historical data. The BSP offers to the SO upward and downward flexibility capacities, based on the sum of all the aggregator flexibility. Each aggregator is responsible for its own flexibility forecast and baseline.

2. *Balance settlement phase*: performed in real-time market. The SO guides the BSP for activating the balancing service based on the BRP imbalances information. The coordination within the BSP allocates the SO energy request among the aggregators. Each aggregator manages its loads and generation resources providing upward or downward power variations to follow the coordination requests.

3. Hierarchical Structure for a Balancing Service Provider

In this section, a hierarchical structure for a BSP is proposed, considering a two-level structure. Figure 2 presents the BSP structure taking into account:

i) the Coordinator at the higher level,

ii) several Specialised Energy Aggregator (SEAs) at the middle level, and

iii) a large sets of flexible loads (FLs) at the lower level.

The BSP is capable of offering a portfolio of balancing energy services to the SO, based on the optimal management of the aggregated capacity of the complete set of heterogeneous flexible loads. This task is split into two different types of control entities. The higher-level entity (i.e., the Coordinator) is responsible of the interaction with the SO, reporting baseline consumption and capacity, also receiving and dispatching balancing service requests. The low-level entities (SEAs) are responsible of managing the energy consumption of a (possibly large) set of flexible loads, according to the requests transmitted by the Coordinator.

The existence of the Coordinator allows to simplify the operation of the balancing services, reducing the number of agents interacting with the SO and the amount of information exchanged. In fact, the data transfer is limited to the power consumption and capacity, going upward, and the balancing services requests (FRC, FRR, and RR) moving downward. In the same way, the internal interaction between the higher level and lower level layers considers a few parameters. More importantly, it is independent of the type of load being managed.

Each SEA is responsible for managing the energy consumption of a large set of flexible loads of the same type but with heterogeneous characteristics, e.g., a set of electric vehicles with different battery capacities and charging

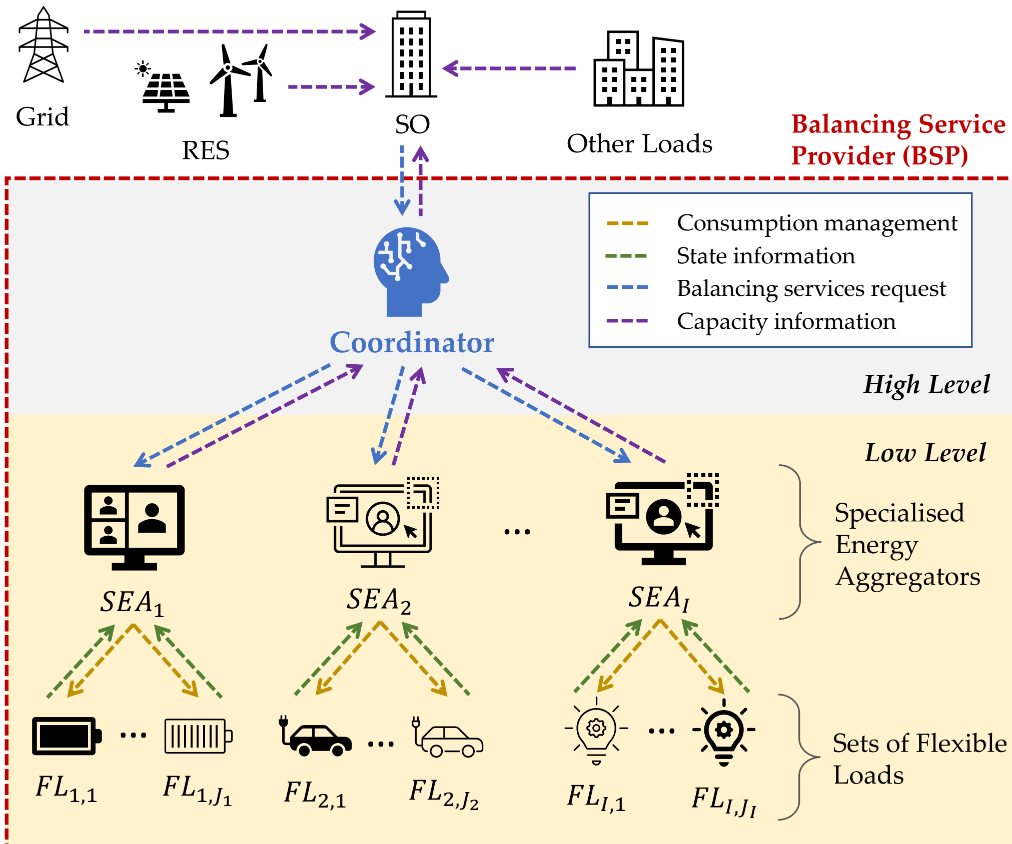


Figure 2: Two-level BSP general structure.

power. Therefore, the challenge of the Coordinator is to integrate several SEAs that operate loads with different parameters, response and recovery times, while offering a balancing service that complies with existing regulations on timing and quality.

From the Coordinator side, a generic behaviour of the SEA is assumed. Each SEA periodically reports the actual power demand and flexibility capacity of its set of loads. In addition, it must manage the loads in order to follow any power deviation request received from the Coordinator, applying scheduling policies based, for example, in closed-loop control strategies that allow reducing the uncertainty in the service provision.

Note that the hierarchical structure is scalable by varying number and characteristics of the SEAs. As more SEAs participate in the framework, better performance of the balancing service can be reached, as the Coordinator gets more degrees of freedom to satisfy the requests arriving from the SO.

The presence of the SEAs increases the privacy protection of the users. In fact, each user sends to a given SEA information on the relevant type of user's load only. The work hypothesis is that all SEAs and the coordinator are trustable, but are in any case third parties, and the users must be somehow guaranteed that their data are not disclosed. On the one hand, the data that the users send to the SEA refer only to the specific type of load and for the purpose of addressing the grid service under consideration. In this way, no SEA has visibility on the whole electrical behaviour of any user. Moreover, the aggregation of the data must follow the security protocols, such as the Local Differential Privacy (LDP) applied as in [82] and [83], for residential and industrial users, respectively. Hence, privacy-preserving data aggregation schemes are useful even in presence of smart meters characterised by limited computation ability, and with the possibility to operate in absence of a trusted third party. The same considerations apply for the interaction between the coordinator and every single SEA: in this case, the aggregation level is even wider, with no possibility to identify the single user's behaviour. The Coordinator, at the top of the BSP, interacts with the SO by sending information on the aggregate demand of all the managed types of load. No entity manages the overall demand of any user during the provision of balancing services.

3.1. Coordinator of Specialised Energy Aggregators

The Coordinator is developed by considering the SO requirements and the availability of flexible resources provided by each SEA, in order to procure balance services such as FCR, aFRR, mFRR, and RR. Then, the main responsibilities of the Coordinator are to:

- Understand the capacity and response time of each SEA.
- Offer a portfolio of balancing energy services based on the complete flexibility of the structure to the SO.
- Assign the balancing services that each SEA must provide.
- Manage the provision of SO requests, i.e., if any SEA deviates from the assigned power service, the Coordinator must regulate the overall service activating/modifying the requests to other SEAs.

The operation of the BSP is performed around a baseline power consumption, prepared in the day ahead, and during the real-time execution is split in two phases, a *Planning phase* and a *Tuning phase*.

The decision of the service provision starts with the baseline computation, i.e., the power demand and the flexibility capacity for the next day. This baseline is built upon the information provided by each SEA. Then, in real time, the Coordinator evaluates and calculates the services to offer to the SO.

The *Planning phase* aims to schedule the energy consumption of the flexible loads for the next dispatch time interval (e.g., 15 min). Therefore, in this phase, the Coordinator seeks to follow the baseline demand when no service is requested by the SO, and to assign adequate power deviations to each SEA to comply with any balancing service request. The criteria to select which SEAs should react to a request are the response speed, availability and capacity reported by each aggregator. Notice that this phase is executed at every dispatch time interval, not only at the arrival of a SO request.

The *Tuning phase* aims to correct any unexpected consumption variation of the aggregated loads caused by the uncertainty in the load behaviour. In order to compensate these variations, the Coordinator operates on a time interval smaller than in the planning phase. In the tuning phase, the Coordinator sends requests of slight modifications with respect to the power consumption defined in the planning phase, to a subset of aggregators that have reached their steady-state operation and have flexibility margins available.

3.2. Coordinator Formulation

In this subsection, the Coordinator formulation is introduced by presenting its interactions and the algorithm logic that the Coordinator follows in the operation (planning and tuning phases) to define the SEA requested powers.

Given the BSP general structure presented in Figure 2, let us assume that there are I aggregators, whose power demand profiles are programmed through the Coordinator. Then, each aggregator SEA_i can be called or not to activate its flexibility, i.e., to modify its power consumption profile for a defined period of time.

Figure 3 depicts the response of different aggregators to the Coordinator request. The figure shows the activation time, the delivery period, and the ramp-down period of a balancing service requested by the SO. In this example, it is supposed that for fulfilling the entire SO request, only the SEA_1,

SEA_2, SEA_{I-1}, and SEA_I are called to modify their power demand. The response times and the sample time (grey vertical rows) of the aggregators are different between them. In the figure, the blue lines on the SEA_i are the power modifications requests (signal to follow) sent by the Coordinator in the planning phase, while the red dashed lines are the expected power demands on the planning phase. In addition, the yellow dashed lines are the actual power demands of the SEAs after operating the tuning phase. The orange vertical arrows indicate the time steps for running the planning phase, whereas the green vertical arrows mark the time steps for executing the tuning phase.

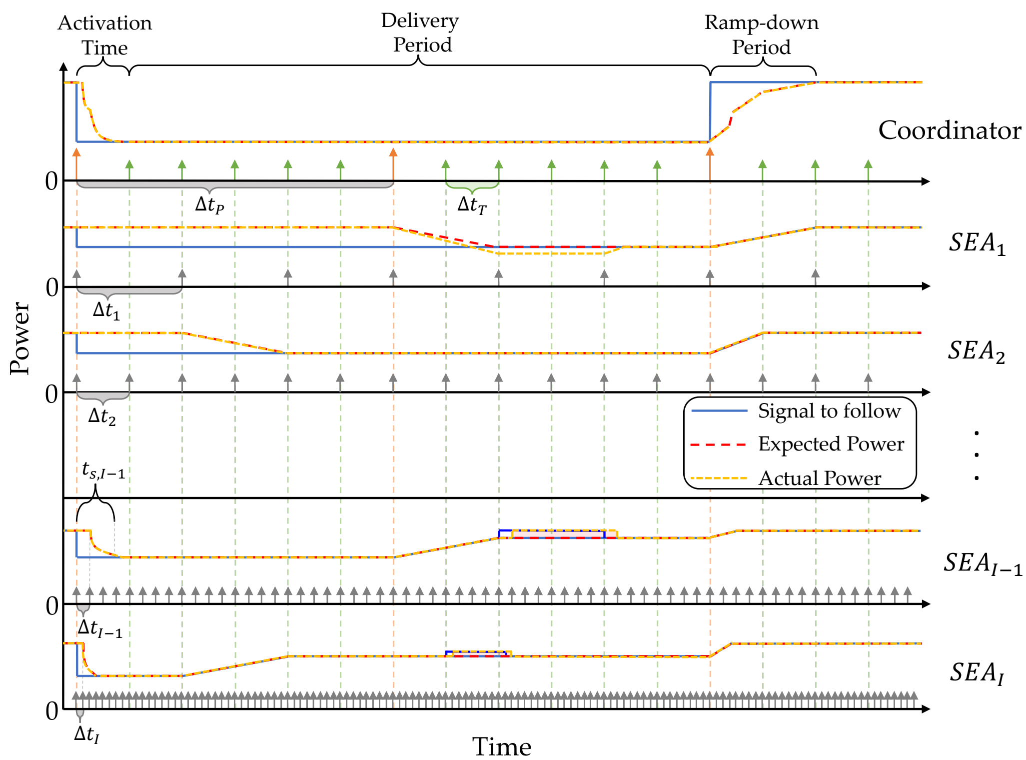


Figure 3: Specialised Energy Aggregators responding to the Coordinator requests.

The Coordinator operation time in the planning phase is divided into K_P discrete time intervals with equal length, being a discrete time slot $k_P = 1, 2, \ldots, K_P$, with sampling time Δt_P defined as the BSP dispatch time. Therefore, at every k_P the Coordinator recalculates the aggregators' schedules and possibly defines new power command signals.

The Coordinator operation time slot in the tuning phase is defined as $k_T = 1, 2, \ldots, K_T$, with sampling time Δt_T, where $\Delta t_T < \Delta t_P$. The tuning phase sampling time Δt_T is limited by the speed of the aggregators that have *very short duration* time response (aggregators capable to respond between seconds and 5 minutes, capable to provide FCR and aFRR services according to [84]). Then, given a set of aggregators, the relevant parameter to identify is the longest stabilisation time in front of a power command modification, which is not computed by the Coordinator but reported by each aggregator. This stabilisation time provides the minimum possible Δt_T time to have the opportunity to operate the aggregators already in a steady-state. In Figure 3, the available aggregators for providing fast services are SEA_{I-1} and SEA_I in which the longer stabilisation time is $t_{s,I-1}$. Therefore, in this example, the tuning sample time is $\Delta t_T > t_{s,I-1}$.

On the other hand, each SEA operates with a time period $\Delta t_i < \Delta t_T$. The operation time is divided into K_i discrete time intervals with equal length. The SEA_i time slot is $k_i = 1, 2, \ldots, K_i$, with sampling time Δt_i, $\forall i = 1, 2, \ldots, I$.

For simplicity, Δt_T is considered as the nearest Δt_i of the aggregators. Therefore, the general operation of the Coordinator will be executed with time period Δt_T. However, the tuning phase is not considered at each iteration when the planning phase is executed.

3.2.1. Information Exchange

The Coordinator interaction is carried out with two main stakeholders, the SO and the SEAs (see Figure 2). The exchanged information is summarised as follows:

- Coordinator exchanged information with the system operator:
  - From SO to Coordinator at the beginning of the balancing service event:
$$\Gamma_C = \{\vartheta_C, \overline{\gamma_C}, \underline{\gamma_C}, r_C\} \tag{1}$$
  - From Coordinator to SO at each time slot k_P:
$$\Phi_{C,k_P} = \{P_{C,k_P},\ \phi_{C,k_P}\} \tag{2}$$
- Coordinator exchanged information with the aggregators at each time slot k_T:

– From Coordinator to $SEA_i,\ \forall i = 1, 2, \dots, I$:

$$\Gamma_{i,k_T} = \begin{cases} \{\vartheta_i, \overline{\gamma_i}, \underline{\gamma_i}, r_i\} & \text{if} \quad \text{Planning phase,} \\ \{r_i \pm \Delta r_i\} & \text{if} \quad \text{Tuning phase;} \end{cases} \tag{3}$$

– From the $SEA_i,\ \forall i = 1, 2, \dots, I$ to the Coordinator:

$$\Phi_{i,k_T} = \{P_{i,k_T}, \phi_{i,k_T}\}. \tag{4}$$

In the previous definitions Γ is the information sent from an upper level during an energy request, either from the SO (Γ_C) or the Coordinator (Γ_{i,k_T}). The request considers the balancing energy service type (i.e., FCR, aFRR, mFRR, or RR) in ϑ_C and ϑ_i, the service starting time in $\overline{\gamma_C}$ and $\overline{\gamma_i}$, the ending service time in $\underline{\gamma_C}$ and $\underline{\gamma_i}$, and the balancing energy in r_C and r_i. Note that, the full request Γ_{i,k_T} from the Coordinator is employed in the Planning phase, while in the Tuning phase, only the balancing energy $r_i \pm \Delta r_i$ is updated, where Δr_i is a fine tuning value.

The information flowing upwards from the lower levels is Φ, either from the coordinator to the SO (Φ_{C,k_P}) or from each SEA to the coordinator (Φ_{i,k_T}). The reported information contains the actual power consumption, where P_{i,k_T} is measured by the SEAs, and the coordinator evaluates the net power P_{C,k_P} at each time slot k_P as:

$$P_{C,k_P} = \sum_{i=1}^{I} P_{i,k_P}, \tag{5}$$

Φ also contains information about the available flexibility for the following Planning interval. ϕ_{C,k_P} reports to the SO the aggregated flexibility of all the BSP for an horizon Ψ, i.e.,:

$$\phi_{C,k_P} = \left[\sum_{i=1}^{I} \phi_{i,k_P+1},\ \ \sum_{i=1}^{I} \phi_{i,k_P+2},\ \ \dots,\ \ \sum_{i=1}^{I} \phi_{i,k_P+\Psi} \right], \tag{6}$$

while the flexibility capacity reported by each SEAs at the time slot k_T, for an horizon $\Delta t_P = \Psi \Delta t_T$ is:

$$\phi_{i,k_T} = \left[\phi_{i,k_T+1},\ \phi_{i,k_T+2},\ \ \dots,\ \phi_{i,k_T+\Psi\psi} \right]. \tag{7}$$

3.2.2. Hierarchical Control Strategy

As described before, the coordinator is in charge of managing the activation of the flexibility of each SEA, in order to comply with the requests of the SO. The proposed Coordinator is developed considering a feedback control strategy, where the nominal operation condition is the tracking of the baseline power $P_{Baseline,k_P}$. When a balancing service request arrives at the BSP, the target power is modified with the SO request r_C.

The Coordinator divides the request r_C into the I SEAs, fulfilling:

$$r_C = \sum_{i=1}^{I} r_i. \tag{8}$$

This is performed in the planning phase through an optimization problem in which the coordinator schedules the activation the flexibility made available by each SEA, minimizing the tracking error of the energy request. The Coordinator decides the energy service each SEA must provide taking into account that all SEAs have different response times. To sum up, the Coordinator deals with the following optimisation problem at each time slot k_P:

$$\min_{P_{i,k_P},\ \forall i=1,2,\dots,I} \quad \sum_{i=1}^{I} P_{i,k_P} - P_{Baseline,k_P} + r_C \tag{9a}$$

$$\text{s.t.} \quad 0 \leq P_{i,k_P} \leq f(\phi_{i,k_P}) \tag{9b}$$

$$\forall i = 1, 2, \dots, I$$

The solution to the previous problem is the set of power commands P_{i,k_P} that each SEA must follow. The problem constraints are the SEAs power bounds, in which $f(*)$ is a function that depends on the effective power flexibility reported by the SEAs. Note that the capacity vector ϕ_{i,k_T} in Eq. (7) is used to build the net flexibility at time slot k_P. Problem (9) is always feasible under the assumption that the capacity information is accurately reported at the planning phase.

At the lower level each SEA must solve a regulation problem in order to follow the power consumption P_{i,k_P} commanded by the coordinator. This can be performed with several strategies. For example, the SEA can have a predefined set of rules that links the power request with the amount of flexible loads that must be activated, or a feedback strategy, as illustrated in the case study of Section 4.

To summarise the Coordinator operation in both phases, the logic presented in Algorithm 1 is proposed. The first step of the algorithm is to identify the set L of aggregators able to provide fast services and acquire their stabilisation times $t_{s,i}$ for computing Δt_T. Then, the total number of time slots K_T in the tuning phase is calculated based on the operation horizon H. The feedback control strategy starts in Step 5. On the one side, in the planning phase (Step 6), the Coordinator solves the problem presented in Eq. (9). On the other hand, in the tuning phase (Step 11), the algorithm assesses if the power tracking error is higher than the acceptable tolerance D for each SEA. Then, if for the SEA i the error is higher, the algorithm searches among the SEAs already activated and in steady-state, the one with maximum flexibility and request a slight modification Δr_i to its current demand in order to compensate the power deviations of SEA_i.

4. Unified Aggregation Framework: Case Study

In this section, a case study of a hierarchical structure for a BSP is presented, taking into account the Coordinator and three SEAs with different flexible load models (see Figure 4). Later, simulation results of the BSP operation are presented.

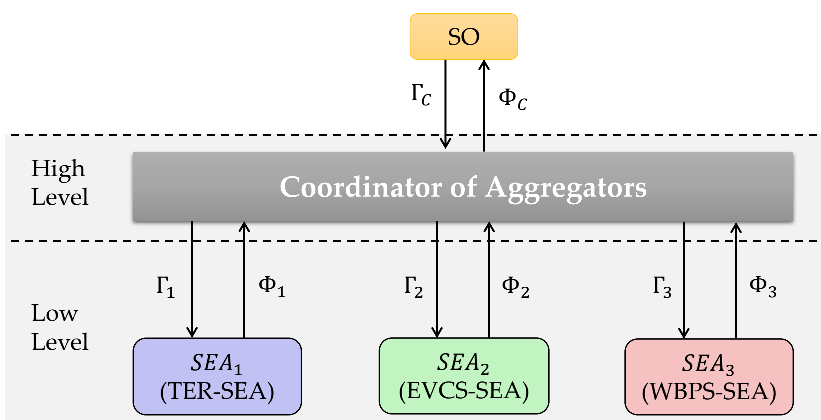


Figure 4: Two-level BSP structure: case study.

Algorithm 1 Coordinator Logic

Input: $P_{Baseline,k_P}$, Γ_C, Φ_{i,k_T} $\forall i = 1, 2, \ldots, I$
Output: Φ_{C,k_P}, Γ_{i,k_T} $\forall i = 1, 2, \ldots, I$
Identify the set $L = \{SEA_i \mid SEA_i \text{ with fast response}\}$
Acquire $t_{s,i} \in L$
$\Delta t_T > \max\{t_{s,i} \in L\}$
$K_T = H/\Delta t_T$
for $k_T \leftarrow 1$ to K_T **do** ▷ Coordinator loop
  if k_T is in Planning phase **then**
    Solve Problem in Eq. (9) ▷ Set-point re-computation
    $r_i \leftarrow P_{i,k_P}$
    return Φ_C
  else ▷ Tuning phase
    for $i \leftarrow 1$ to I **do**
      $\Delta r_i = |r_i - P_{i,k_T}|$
      if $\Delta r_i > D$ **then**
        Identify the $SEA_m \in L$ in steady-state and with $\max\{\phi\}$
        $P_m \leftarrow r_m + \Delta r_i$
      end if
    end for
    return Γ_{i,k_P} $\forall i = 1, 2, \ldots, I$
  end if
end for

4.1. Specialised Energy Aggregators

The SEAs considered in the BSP low level are presented below. Three types of load with different characteristics and aggregation strategies are included for illustrative purposes. However, the framework can be applied to any other flexible load, provided that an automatic control strategy for power regulation is available and the response time of the closed-loop system fits into any of the services described in Section 2.

4.1.1. ThermoElectric Refrigeration SEA

A ThermoElectric Refrigeration (TER) is a solid-state energy-conversion technology that exploits the Peltier effect to convert electricity into thermal energy for heating or cooling. Reference [85] proposes an aggregator for large populations of TERs, providing both upward and downward power deviations. The flexibility is achieved by changing the temperature set-point to the highest or lowest limit of each TER. The aggregated dynamic response can be represented by linear transfer functions. The interaction between TER-SEA and TER is depicted in the purple blocks of Figure 5.

The aggregator (TER-SEA) is a proportional-integral (PI) feedback controller. The TER-SEA decides the amount of TER systems that must modify the temperature set-point between nominal, high, or low (signal β_{TER} in Figure 5) based on the high-level coordination request Γ_1 and the TER-SEA capacity Φ_1. It is designed to avoid any rebound effect after providing a balancing service. In addition, due to the fast response of the TERs, instantaneous changes after the activation of a service can be considered.

4.1.2. Electric Vehicle Charging Station SEA

An Electric Vehicle Charging Station (EVCS) is composed of various chargers, to which electric vehicles (EVs) connect for being charged. Reference [86] proposes an aggregator to manage the charging profiles of the EVs served by the EVCS. The model considers a switching behaviour of the chargers, caused by the arrival and departure of EVs. The EV charger flexibility is defined as the maximum power deviations, given a nominal charging profile, that guarantee proper charge level at the end of the charging period. The green blocks of Figure 5 shows the interaction between EVCS-SEA and EVCS.

The aggregator (EVCS-SEA) is based on a Model Predictive Control (MPC) strategy that aims following the aggregated power scheduled in the baseline plus the Coordinator requests Γ_2, i.e., looking for minimising the baseline tracking error considering a penalty cost. The decision variables are the power delivered by each charger (β_{EVCS}) and the flexibility capacity. Moreover, the SEA has the capability to schedule a day-ahead power demand based on the expected EV chargers request. The baseline is formulated as an optimal control problem to minimise the operation cost while maximising the flexibility capacity, subject to battery dynamics and technical limits. This aggregator can provide upward and downward flexibility.

4.1.3. Water Booster Pressure Systems SEA

Water Booster Pressure Systems (WBPS) are responsible of supplying water and maintaining adequate pressure levels in a building pipeline. Reference [10] proposes an aggregator for large populations of WBPS, providing downward power deviations. The flexibility is achieved by changing the pressure set-point for each pressure tank. The aggregated dynamics can be represented as a discrete time model with sampling time of 3 min. The interaction between WBPS-SEA and the WBPSs is shown in the red blocks of Figure 5.

The aggregator (WBPS-SEA) is a discrete-time PI controller with gain-scheduling. The WBPS-SEA decides the amount of WBPS whose pressure set-point must be modified (signal β_{WBPS} in Figure 5), based on the high-level coordination request Γ_3 and the WBPS-SEA capacity Φ_3.

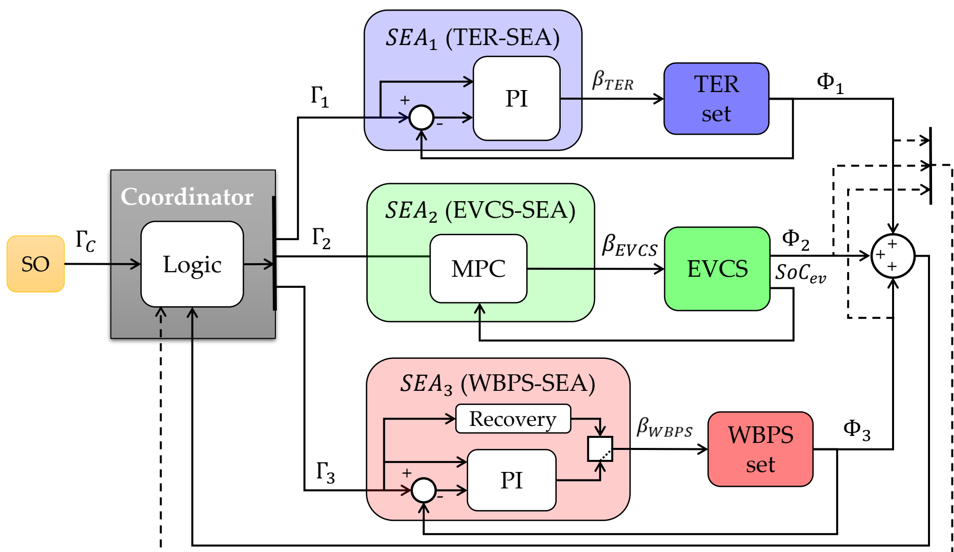


Figure 5: BSP operation scheme.

To summarise, Table 2 presents the main characteristics of the SEAs. In fact, the TER-SEA and WBPS-SEA information is acquired from [85] and [10], respectively. In addition, according to [86] the EVCS-SEA response time is limited by-few minutes, then, for sake of simplicity, a 3 minutes response time and a 1 minute Δt are defined. The flexibility reported in the table refers to the percentage that can be shifted from the power baseline.

4.2. Simulations of the Balancing Service Provider Operation

Simulation campaigns were performed to evaluate the capability to provide FCR, FRR, and RR services. The results compare the baseline power schedule with the actual power consumption considering the balancing services provision.

Table 2: SEA main characteristics

SEA	Response time	Δt	Downward Flexibility	Upward Flexibility
1. TER-SEA	20 s	1 s	63% (FCR) or 53%	123% (FCR) or 85%
2. EVCS-SEA	3 min	1 min	Based on definition of reference [86]	
3. WBPS-SEA	9 min	3 min	27%	0

The SEA baseline power schedules are defined as: i) nominal power consumption for the TER-SEA and the WBPS-SEA, considering residential TERs and WBPS; and ii) the day-ahead scheduling for the EVCS, taking into account a station with 25 chargers, each one capable of injecting 8 kW. More information related with the simulation parameters can be found in Table 3. In fact, the tuning phase operation sample time is $\Delta t_T = 3$ min, i.e., the Coordinator operation sample time. This time is obtained by analysing the very short duration time response aggregators, in which the TER-SEA and EVCS-SEA are suitable (see Table 2). Then, being $\Delta t_T \geq 1$ min and considering the WBPS-SEA sampling time, a 3 minutes sampling time is defined for the tuning phase. Moreover, the planning operation phase is defined as $\Delta t_P = 15$ min, considering it as the dispatch time.

Table 3: Simulation parameters

Parameter	Value
Number of TERs	4000
Number of WBPS	1000
Number of EV chargers	25
Δt_T	3 min
Δt_P	15 min

Based on Table 2, the flexibility offered by each SEA is fixed as the capacity found by the proposers of the aggregators:

- TER-SEA: considering the flexibility for RR service, the upward and downward capacities are 85% and 53% of the baseline, respectively.
- WBPS-SEA: the downward flexibility capacity of 27% of the baseline is considered.
- EVCS-SEA: upward and downward flexibility capacities based on the chargers flexibility definition provided in [86] are considered.

Figure 6 presents the flexibility offered by each aggregator, as well as the aggregated capacity offered by the BSP to the SO. The total flexibility is always higher than ± 100 kW. However, the flexibility usage will depend on the service provision, e.g., with the purpose of providing all the balancing services in the same frequency restoration process, i.e., FCR, FRR, and RR, it is not possible to offer 100% of the capacity. In fact, only the TER-SEA can provide fast services such as FCR. Then, following the frequency restoration process presented in Figure 1, the maximum capacity is defined by the aggregator with the fastest response, i.e., TER-SEA. Moreover, for long-lasting services such as mFRR and RR, the flexibility offered by the BSP can be the complete capacity depicted in Figure 6.

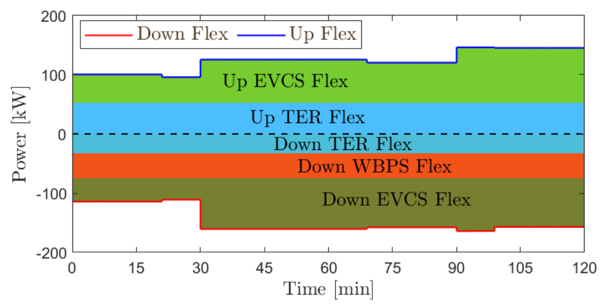


Figure 6: Flexibility of the BSP.

The BSP performance in a frequency restoration operation is evaluated for two different energy balancing service provisions:

- *Case 1*: Providing all the balancing services. Therefore, the maximum capacity provision is constrained by the TER-SEA (the one with a fast response). Moreover, this case follows an idealistic scenario because no command propagation delay is supposed, i.e., the information exchange between all the participants is instantaneous. Then, two approaches are evaluated:
  - *Case 1.a*: Each SEA provides a specific service every 15 minutes. Nevertheless, the RR service is provided by all the SEA.
  - *Case 1.b*: The services are provided by overlapping the SEA power requests, following an idealised provision case (see Figure 1).
- *Case 2*: Providing the mFRR and RR services. Then, the capacity provision is much higher than in *Case 1*. Moreover, this case follows a

realistic scenario because the commands propagation delays are taken into account.

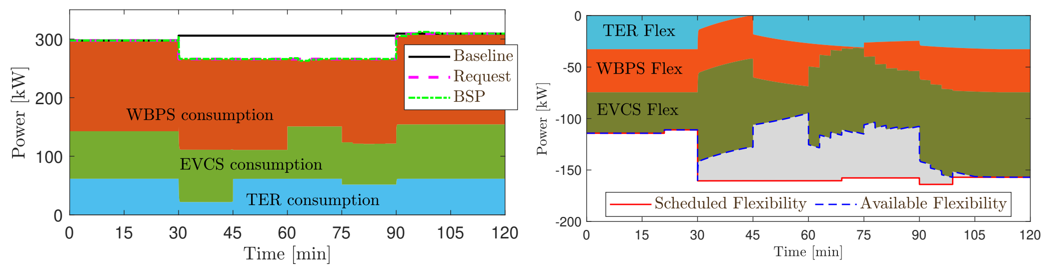
Both cases 1 and 2 are evaluated in MATLAB/Simulink simulations. These cases provide different power capacities due to the maximum power the TER (fast service) can provide to the grid in the *Case 1*, and the total flexibility all the SEAs can provide in the *Case 2*. The Coordinator defines and reports to the SEAs the power deviation they should follow. Moreover, in the simulations, only reduction power requests by the SO are analysed due to the WBPS response that only considers flexibility reduction.

Figure 5 shows the two-level structure of the BSP. The TER and WBPS sets are represented by linear transfer functions. These functions allow the simulation to be computationally lightweight. Besides, the MPC and EV charger dynamics are run in MATLAB.

4.2.1. Case 1.a

The case study evaluates a frequency restoration process where all the aggregators participate in providing balancing services in an idealistic scenario, i.e., the information exchange between the Coordinator and the SEAs is instantaneous as well as the SEAs responses are assumed to be immediate. The FCR, aFRR, and mFRR services are provided by a single SEA considering the time response of each one. Figure 7 depicts the BSP operation. In fact, Figure 7a presents how the BSP performs the services when the SO requests a power reduction of r_C=40 kW from minute 30 to 90. The Baseline power is 305.82 kW, the ideal RT power is 265.82 kW, while the BSP RT average power is 265.88 kW, achieving an average error of 22.6 W and standard deviation of 0.78 kW. Figure 7b presents the flexibility reported at every power request. The utilised flexibility is shown in the grey area. Notice that, differently from the power deviation, the flexibility is not constant. This flexibility evolution depends on the number of systems that modifies the consumption patterns, e.g., at minute 45 there is no TER-SEA flexibility because all the TERs have changed their temperature set-point; likewise, the WBPS-SEA has no flexibility at minute 75. In addition, after the ramp-down period, the flexibility returns to its steady-state capacity.

Figure 8 shows the power consumption of each SEA. Likewise, the Coordinator operation requests are observed, in which the planning phase operation is noticed every Δt_P at the minutes 30, 45, 60, and 75. Indeed, the TER-SEA is called to modify its capacity at minute 30 from 62 kW to 22 kW for



(a) Power reduction.

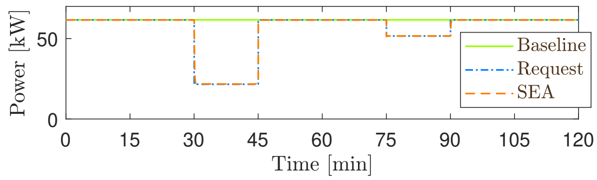
(b) Utilised flexibility.

Figure 7: BSP response in Frequency Restoration Operation for *Case 1.a*.

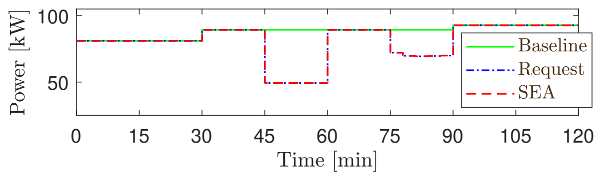
the following 15 min service provision (see Figure 8a). The initial consumption of the EVCS-SEA is 81 kW; however, the scheduled baseline during the restoration event is 89 kW. Then, the consumption is lowered to 49 kW when providing the service, from minute 45 to minute 60 (see Figure 8b). Regarding the WBPS-SEA, the initial consumption is 155 kW, and the maximum activated flexibility reaches 112 kW between minutes 60 and 75. (see Figure 8c).

Notice that the tuning phase operation is not commanding any variation to the SEAs between minutes 30 and 75, this is because of the *Case 1.a* nature, in which only one SEA is operated by the Coordinator every 15 min. However, during the last 15 min service (from minutes 75 to 90) all the SEAs are called to modify their power demand. Then, the tuning phase operation takes action in the EVCS-SEA to reduce the WBPS-SEA variations. Concerning the performance of the EVCS-SEA (see Figure 8b), in the time period between minute 75 and minute 90 the power is not constant. In fact, in this period the Coordinator modifies the EVCS-SEA commanded power, depending on the other SEAs consumption. In particular, the WBPS-SEA has small variations when following its request; then, the power request of the EVCS-SEA is modified every Tuning phase of the Coordinator operation to maintain the balance.

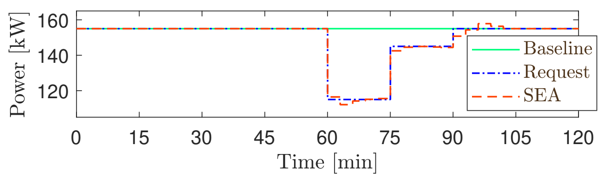
Figure 9 shows the percentage of TER and WBPS systems whose flexibility is activated by the control strategy of the corresponding SEA, to follow the power request of the coordinator. Finally, a ramp-down phase is considered at the end of the service to avoid a rebound effect of the BSP.



(a) TER SEA.



(b) EVCS SEA.



(c) WBPS SEA.

Figure 8: Single SEA response in Frequency restoration operation for *Case 1.a*.

4.2.2. Case 1.b

In this case, the Coordinator manages the SEAs with a strategy similar to the one presented by [69], considering ramp rates and times per service (see Figure 1). This case follows an idealistic scenario as in *Case 1.a*. Figure 10 illustrates the BSP operation. Figure 10a depicts the power response of the BSP when aggregating the SEAs power. The SO requests a power reduction of r=57 kW, 17 kW higher than in *Case 1.a*. The baseline power is 305.82 kW (the same as *Case 1.a*), the ideal RT power is 248.82 kW, while the resulting BSP RT average power is 249.00 kW, achieving an average error of 71.5 W with standard deviation of 0.10 kW (lower than in *Case 1.a*). Figure 10b shows the activated flexibility as the grey area. Notice that between minutes 51 and 57 there is no WBPS-SEA flexibility.

Figure 11 shows the power consumption of each SEA. The planing phase operation is carried out every Δt_P as in *Case 1.a*. Nevertheless, the Coordinator manages all the SEAs every 15 min instead of one SEA per cycle. The SEAs initial capacities are the same as in *Case 1.a*; however, the max-

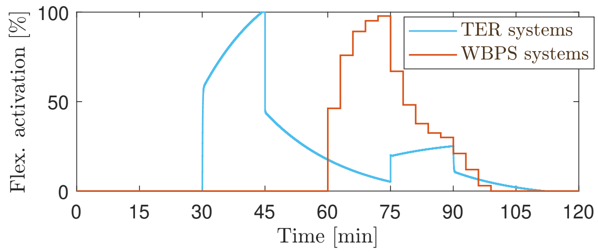
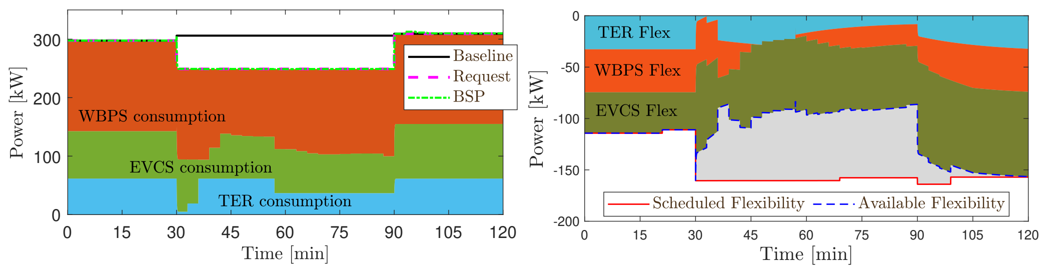


Figure 9: Flexibility activation of TER and WBPS systems (*Case 1.a*).



(a) Power reduction.

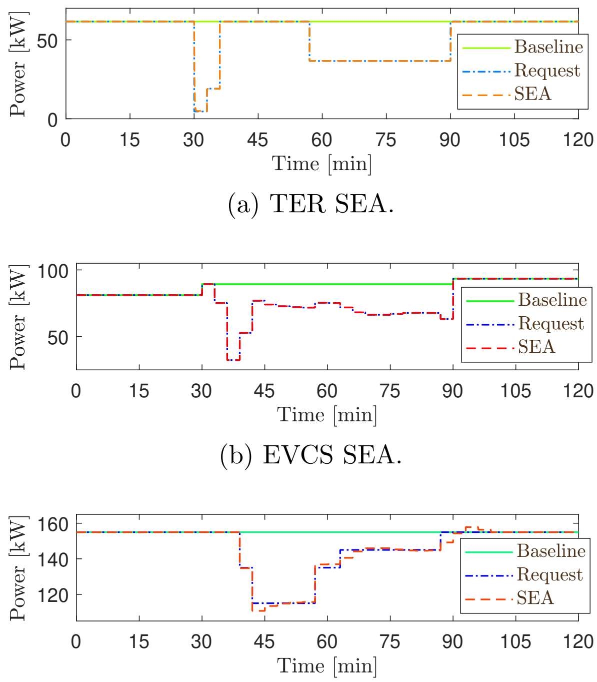
(b) Utilised flexibility.

Figure 10: BSP response in Frequency Restoration Operation for *Case 1.b*.

imum power deviations are higher (but for less time). The TER-SEA and the EVCS-SEA reduce the power as requested by the coordinator, but only for 3 min, while the maximum reduction of the WBPS-SEA is 44 kW.

The TER-SEA is the first aggregator commanded to modify consumption (see Figure 11a), as it is the only one that can provide the FCR energy service. Therefore, the maximum power is defined by the maximum capacity of this SEA in the specific time window (Δt_T =3 min in this case). Moreover, the Coordinator, during the tuning phase is constantly changing the requested EVCS-SEA power (see Figure 11b) due to the variations of the WBPS-SEA (see Figure 11c).

The percentage of systems changing temperature set-point (for TERs) as well as the percentage of systems changing pressure set-point (for WBPSs) are depicted in Figure 12. Also in this case, a ramp-down phase is considered to avoid a rebound effect at the end of the BSP energy provision.



(a) TER SEA.

(b) EVCS SEA.

(c) WBPS SEA.

Figure 11: Single aggregator response in Frequency restoration operation for *Case 1.b*.

4.2.3. Case 2

This case study assesses the provision of the energy services mFRR and RR. In particular, the mFRR service looks to stabilise the frequency of the electricity grid by considering a 12.5 min interval of full activation, i.e., much longer than in *Case 1* (30 s). This allows the BSP to provide a higher capacity due to the participation of all the SEAs and not only the faster ones. In addition, this case follows a realistic scenario that considers the commands propagation delays.

Figure 13 depicts the BSP operation. Figure 13a reports the BSP power consumption. It can be seen that the consumption stabilises after 6 min when all the SEAs are following the Coordinator requests. In this case, the SO power reduction request is r = 122.78 kW, that is, 82.78 kW higher than in *Case 1.a*, and 65.78 kW higher than in *Case 1.b*. The baseline is the same than in *Case 1*, i.e., 305.82 kW. The expected RT power is 183.04 kW, whereas the actual average BSP power is 182.93 kW. Figure 13b shows the utilised flexibility as the grey area. Notice that in this case, all

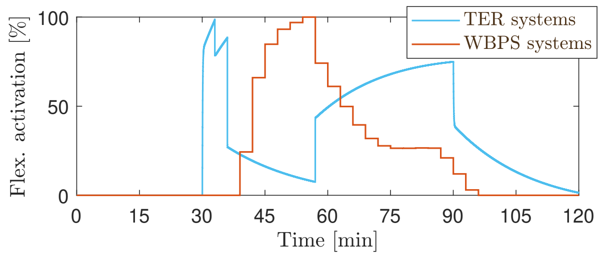
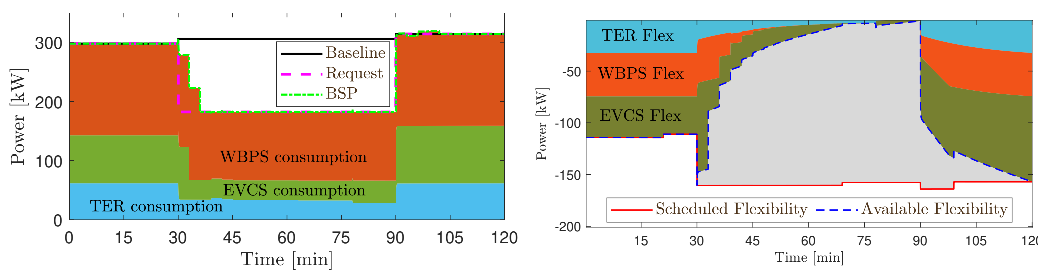


Figure 12: Flexibility activation of TER and WBPS systems (*Case 1.b*).

the BSP flexibility is consumed at the end of the service, i.e., at the minute 87. Therefore, this power request $r = 122.78$ kW is the maximum power deviation the BPS can perform in a mFRR service.

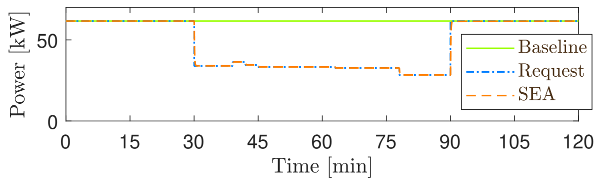


(a) Power reduction.

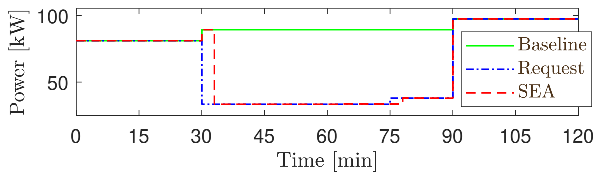
(b) Utilised flexibility.

Figure 13: BSP response in Frequency Restoration Operation for *Case 2*.

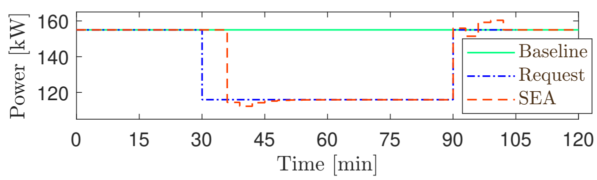
Figure 14 shows the power consumption of each SEA, taking into account the commands propagation delays. The initial power requested at minute 30 by the Coordinator to the SEAs in planning phase are: $r_{TER} = 27.72$ kW, $r_{EVCS} = 56.00$ kW, and $r_{WBPS} = 39.06$ kW. The WBPS-SEA request is not modified up to the end of the service (see Figure 14c), whereas the requests for the EVCS-SEA and the TER-SEA are modified at minute 75 due to a lack of flexibility reported by the EVCS-SEA. Notice that the TER-SEA is used to handle the other SEAs set-point change, e.g., until the EVCS-SEA achieves the new set-point at minute 78 (see Figure 14b). In the same way, the deviations of the WBPS-SEA are managed in the tuning phase by modifying the TER-SEA power (see Figure 14a).



(a) TER SEA.



(b) EVCS SEA.



(c) WBPS SEA.

Figure 14: Single aggregator response in Frequency restoration operation for *Case 2*.

The percentage of systems changing the temperature set-point (TERs) as well as the percentage of systems changing pressure set-point (WBPS) are depicted in Figure 15.

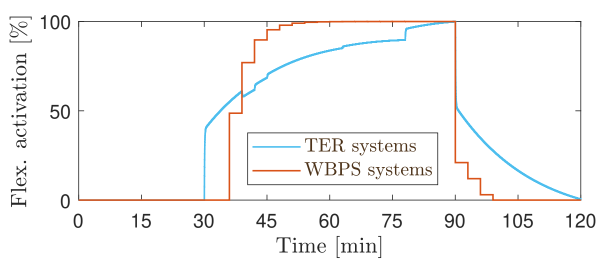


Figure 15: Flexibility activation of TER and WBPS systems (*Case 2*).

Finally, Table 4 summarises the main differences between *Case 1.a*, *Case 1.b*, and *Case 2*. It can be seen that *Case 1.b* considers a higher power reduction when considering fast services (Case 1) due to the duration of the first interval when the TER-SEA is activated (3 min). However, *Case 2* presents a much higher capacity provision due to the longer activation time. In *Case 1.b* and *Case 2* the standard deviations are lower because the tuning phase operation is constantly correcting the power deviations through SEAs set-points. In addition, the tracking average error is higher in *Case 1.b*. Nevertheless, in all cases, the error is lower than 0.03%.

Table 4: Comparison between *Case 1.a*, *Case 1.b*, and *Case 2*.

Parameter	***Case 1.a***	***Case 1.b***	***Case 2***
Max power reduction	40 kW	57 kW	122.78 kW
Activation time	20”	24”	6’2”
Tracking average error	26.6 W	71.5 W	60.1 W
Standard deviation	0.78 kW	0.10 kW	0.24 kW

5. Conclusions and Future Work

This paper has presented a unified framework of aggregation for distributed energy sources, through a two-level coordination model for a Balancing Service Provider (BSP). In particular, the low level aggregation is asset-based, i.e., there is a set of Specialised Energy Aggregators (SEAs), whereas the high-level aggregation is provided by a single Coordinator.

The Coordinator interacts with the System Operator (SO) for providing balancing services to the electrical grid within the European context of electricity balancing. Each SEA aggregates different balancing responsible parties characterised by the same asset (e.g., electric vehicle chargers) and interacts with the Coordinator. All the SEAs and the Coordinator interact in a two-level hierarchical structure that forms a BSP. The proposed interaction framework guarantees to the users a high level of information privacy protection, because the user-related information is only used by the single SEA, while each SEA sends only aggregated information to the upper level, without the possibility to recognise the single user behaviour.

The Coordinator operation is formulated as a two-phase operation. The first phase, called Planning phase, generates the scheduled energy consumption of every SEA for the next dispatch time interval. The second phase, called Tuning phase, allows to correct the unexpected SEA energy consumption variations, which are caused by the uncertainties of the flexible loads. Within this framework, the main information exchange parameters between the Coordinator and its main stakeholders, the SO and every SEA are defined. The information used is restricted to the power capacities and the balancing services to be provided. A control algorithm for the Coordinator has been derived, considering an optimal feedback control sequence. The aim of the algorithm is to minimise the power baseline-following error by taking into account the balancing service requests from the system operator.

A case study with three different SEAs has been presented to assess the validity of the solution. In the model, the type of loads managed by each SEA greatly differ in terms of technical characteristics, i.e., thermoelectric refrigeration units, electric vehicle charging stations, and water booster pressure systems.

The BSP performance has been assessed in diverse simulation campaigns for frequency restoration operations. The simulations illustrate the provision of fast services, like frequency containment reserves, as well as longer term services as replacement reserves. It was found that a higher capacity for the replacement reserve service can be provided due to the participation of multiple SEAs in this service, while only the fastest SEAs can provide rapid restoration services.

Future works will consider new services linked to the fast-frequency reserve and the inertial support, which are much more power-intensive and more compatible with assets which may be used as grid flexibility assets, yet presenting a different primary use.

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