TradeRES
New Markets Design & Models for
100% Renewable Power Systems

D4.3 - Spatial flexibility options in electricity market simulation tools

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Executive Summary

Deliverable D4.3 addresses the spatial flexibility options that are being considered by TradeRES models. D4.3 presents a report describing the spatial flexibility-related modelling components that are already implemented and those that are being designed for integration in TradeRES agent-based models. This report includes the main definitions, concepts and terminology related to spatial flexibility, as means to support the presentation of the specific models that are being developed by the project, namely about flow based market coupling, market spliting, nodal pricing, dynamic line rating, cross border intraday market, cross border reserve market, cross border capacity market, consumer flexibility aggregation, renewable energy aggregation, storage aggregation, electric vehicle aggregation and grid capacity.

Regarding the modelling components related to spatial flexibility, the existing ones are mostly addressed by the project optimization models, namely Backbone and Competes, as presented in section 3.1. The model enhancements that are being developed in the context of RESTrade and MASCEM are considering the lessons learnt from these optimization models and are addressing the integration of cross border reserve markets, the development of models to select the most suitable resources to provide flexibility; and the required models to effectively activate the flexibility.

Despite the different levels of development of each modelling component, the complete set of components covers the needs from Task 4.1 and from TradeRES project overall, regarding the modelling and study of spatial flexibility options.Thus, complementarily to the work that is being developed on temporal and sectoral flexibility, the models presented in this report enable fulfiilling the objectives of TradeRES Task 4.1.

In summary, although the existing implementations of spatial flexibility options are limited to the TradeRES optimization models, the model enhancements that are being implemented by RESTrade and MASCEM are taking advantage from the lessons learnt from the available models to create the most relevant set of spatial flexibility models required to meet the project objectives and to provide the necessary means for the simulation studies to take place in WP5.

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List of Abbreviations

aFRR	Automatic Frequency Restoration Reserve
CCER	Consumer Current Event Rat
CCR	Consumer Contextual Rate
CHR	Consumer Historical Rate
CRP	Context Rate Period
CRW	Context Rate Weather
CSR	Consumer Spatial Rate
CTR	Consumer Trustworthy Rate
DR	Demand Response
DSO	Distributed System Operator
DyLR	Dynamic Line Rating
EM	Electricity Market
ESS	Energy Storage Systems
EU	European Union
Ev	Electric vehicle
FCR	Frequency-Controlled Reserve
LER	Last Event Rate
mFRR	Manual Frequency Restoration Reserve
OTC	Over the Counter
PES	Power and Energy Systems
PF	Power Flow
PR	Preliminary Contextual Consumer Rate
RE	Renewable Energy
RES	Renewable Energy Sources
SLR	“Steady-State” Line Rating
TSO	Transmission System Operators
UR	Updated Contextual Consumer Rate

1. Introduction

Consumers will play a central role in future Power and Energy Systems (PES), and particularly in Electricity Markets (EM), according to the European Commission's regulation on European Union (EU) internal EM [1]. Consumers' flexibility and active participation in the energy transition and in EM transactions is seen as critical to balance the increasing variability from the generation side. The penetration of Renewable Energy Sources (RES) is being boosted by the ambitious goals and initiatives to increase RES generation and use that are being set all around the globe, including a strong commitment by the EU [2]

However, expecting consumers to be always rational and economic players in electricity markets may lead to inaccuracies. For instance, are all the participants willing to participate in the same way and give up part of their comfort to secure their position in the market? Most active consumers, being new players in the market, have no or insufficient knowledge regarding the actual transactions. It will take time, and suitable incentives, for these new active players to have an interest and search for the right knowledge to understand the information provided by the managing entities regarding the energy market. Also, the introduction of proper tools will be a major assistant, such as smart equipment, smart appliances, and smart meters. The uncertainty found in the active consumers' response to Demand Response (DR) events is mainly due to their behavior in a certain context – day of the week, holidays, etc.

Besides, the observed changes in the energy system are placing new constraints on eletric grids. Any ongoing grid congestion could end up with high costs and additional risks to grid stability [3]. As a reaction to the presented conserns, those issues can lead to the adjustment of market design, which was addressed in worck package 4, during D4.5 [4].

It is, therefore, essential, that suitable models are developed and tested to enable boosting the full potential of flexibility, not only from the consumers' side, but also from other relevant energy resources. This report describes the advances that are being accomplished by TradeRES regarding the design and implementation of spatial flexibility options, complementarily to the temporal and sectoral flexibility options that are described in TradeRES deliverables D4.1 [5] and D4.2 [6], respectively, and which, altogether, comprise the work that is being developed by Task 4.1 of the project.

After this introductory chapter, Chapter 2 provides an overview of the main definitions, concepts and terminology related to spatial flexibility options, in a way to facilitate the presentation, in Chapter 3, of the models that are already implemented by TradeRES and those that are being designed and implemented as enhancements aiming to meet the project goals. Finally, Chapter 4 presents the main conclusions from this report.

2. Overview of spatial flexibility options

In this chapter we define different terminologies related to spatial flexibility, by addressing and defining mechanisms that are fundamental in the context of this report.

2.1 Definitions

This report is part of the TradeRES Work Package 4 report series. The definitions that have been adopted in WP4 for the “flexibility option” and the three variations tackled, have been reported first in D4.1 [3] and are s as specified in Table 1.

Table 1: Terminology within TradeRES

Term	Explanation
Flexibility option	The ability of the power system to balance electricity demand and supply
Temporal flexibility option	Flexibility aimed at balancing out fluctuations in electricity demand and supply (stemming from, e.g., VRES system surpluses or shortages)
Sectoral flexibility option	Flexibility from technologies that couple the power sector to other sectors, the power grid to other grids, or electricity to other energy carriers
Spatial flexibility option	Flexibility that connects electricity surplus areas to electricity deficit areas

This report focuses on spatial flexibility options, while temporal and sectoral flexibility options are described in TradeRES deliverables D4.1 [5] and D4.2 [6], respectively.

2.2 Relevant concepts and terminology

2.2.1. Grid capacity

Grid capacity, in broad terms, refers to the supply and delivery capacity required to meet consumer demand, which must be prepared to satisfy the predicted maximum demand over a long-time horizon [7].

2.2.2. Flow-based market coupling

As the name indicates flow-based market coupling in a approach to couple different electricity markets, which can increase economic efficiency [8].

In the European Union, flow-based market coupling is “the target model to compute correct trading capacities between markets, while approximating physical grid constraints”[9]. EU’s intended design for providing cross-border capabilities to the electricity market is flow-based market coupling. Its capacity to account for transmission grid constraints improves trade, but it also adds to the complexity. It demands the creation of a number of parameters, many of which lack a clear consensus on how to design and compute. Flow-based market coupling is a key component in achieving a single European power market, fostering renewable energy integration, and ensuring supply security at reasonable levels [8]-[11].

2.2.3. Market splitting

Market splitting can be seen as a congestion management tool that leads to temporary or permanent geographical changes of market configuration. This tool need to be carefully implemented as it, with endogenous investment decisions can be welfare decreasing when applied in long-run liberalized markets [12].

2.2.4. Nodal pricing

There are two fundamentally distinct market structures in energy markets when it comes to space granularity: nodal pricing and zonal pricing, the second one refering to the price paid for power used or generated at a specific transmission node, taking into account grid losses and transmission congestion [13].

While nodal pricing is more difficult to implement than zonal pricing, it is considered to be more efficient as the spatial granularity is smaller and reflects better transmission system constraints [13].

2.2.5. Dynamic line rating

In reaction to environmental and meteorological circumstances, Dynamic line rating (DyLR) refers to the active variation of assumed thermal capacity for overhead power lines. Aiming to reduce grid congestion, this is done continuously in real time, based on weather conditions [14]. In that way, DyLR is considered to:

- reduce congestion on power lines;
- optmise asset utlisation;
- improve efficiency;
- reduces costs;
- increase solar and wind integration;
- reduce curtailment; and
- make power generation dispatch more cost-effective.

2.2.6. Cross border markets

Markets have never been more interconnected than the way they are presented nowadays. In the case of European Union, benefits from open markets can be seen since the Treaties of the EU embodied the principle of an open market economy. In that way, a cross border market creates a community of interest from which each member can benefit from with proper governance.

2.2.6.1. Intra-day

Intraday power trading is the continuous buying and selling of energy at a power exchange on the same day as the power is supplied. The EPEX Spot (European Power Exchange Spot Market) in Paris and the Nord Pool are Europe's major intraday power exchanges. This buying and seling process can also occur in an OTC deal (over the counter), which refers to off-market contracts executed by power buyers and sellers.

2.2.6.2. Reserve

The reserve market functions as a capacity market with extremely little notice for balancing network frequency. Transmission System Operators (TSO) may switch capacity reserves on or off in seconds when needed, providing a quick and dependable solution to stabilize the network for up to an hour .

2.2.6.3. Capacity

Trading in a capacity market is done with certificates for capacity guarantee that works as an assurance that the producer will be able to generate power throughout the specified time period whithout assuring guarantee that the producer will produce power at that specific time.

2.2.7. Aggregation

2.2.7.1. Consumers/flexibility

The fundamental idea behind consumer flexibility is to leverage residential and small commercial consumption flexibility to minimize generation reserves, which are a substantial cost for the system's safe operation, as well as to accommodate variations resulting from distributed renewable energy sources [15].

2.2.7.2. Renewable Energy

The topic of renewable energy (RE) aggregation has dominated industry conferences in recent years as many seek to lower new customers entry barriers.

REs aggregations are formed when a collection of corporations or local institutions join together to provide renewable energy as a group. With each one generating small amounts, the economic benefits of a large sale is retained. This occurs for several reasons, besides the economic benefits, e.g. the reduction of risks related to the variability of individual renewable based generators.

2.2.7.3. Storage

Energy storage offers the flexibility needed to integrate renewable generation into electricity systems and it can have consumer-led (decentralized) and aggregator-led (centralized) coordination [16].

2.2.7.4. Electric Vehicles

Electric vehicles (EVs) play an important role in energy-efficient/energy-flexible areas development and growth. The amount of energy necessary to support the daily use of EVs is increasing. Based on its penetration, the electric system must be able to handle the increase in energy and power demand caused by EV charging while avoiding negative effects on system performance, internal power balances, and power quality [17].

The previously mentioned negative effects are accentuated by the mismatch between the EV's load profile and non-programmable internal power sources as EVs may be charged during the evening, PV generation takes place during the day [17]. Due to the typical small size of EVs' load, their increasing number, and the distributed nature, the aggregation of these resources becomes essential, making their management possible and fostering the creation of new business models that can harness these resources' flexibility potential.

3. Modelling capabilities and enhancements

This chapter describes the spatial flexibility options that are already implemented by the models and systems that are part of TradeRES, and presents the model enhancements that are being designed and implemented by the project agent-based models as means to enable the incorporation of spatial flexibility in the market models developed by TradeRES.

From TradeRES ABMs, only REStrade and MASCEM are addressed in this secton. This occurs because the other systems are not prepared to deal with spatial flexibility. None of the project's ABMs had, at the beginning, any implementation of spatial flexibility, nor did they address several other points related to the other types of flexibility. Thus, and to avoid replication of components in different systems, it was decided to implement these flexibility components in these two ABMs, while others will focus on implementing other types of flexibility within the scope of the T4.1 sub-tasks, in order to cover the necessary points related to the various types of flexibility.

3.1 Existing implementations of spatial flexibility options

Spatial flexibility is a topic that has not been previously explored in depth by the agent-based models that are part of TradeRES. There are some existing features in e.g. in RESTrade and MASCEM that provide a basis to enable supporting spatial flexibility options, but there are no concrete spatial flexibility modelling components already implemented. Some examples are the work in RESTrade that includes improvements that spatial aggregations bring to the production functions of VREs. Basic aggregation modelling component are also implemented in MASCEM, however, without considering a specific spatial dimension. DyLR is also implemented in RESTrade, but DyLR by itself does not bring anything in terms of spatial flexibility, rather it should be used with specific application e.g. in relation to commercial exchanges between different zones, as described in section 3.2.1.

The design and implementation of spatial flexibility options in TradeRES agent-based systems is, therefore, a project priority, in order to supress the current limitations of these models. Despite the lack of existing implementations, agent-based models are learning lessons from the features already implemented in some of optimization models that are part of the project, namely Backbone and COMPETES. Table 2 presents the existing implementations of spatial flexibility options provided by Backbone and COMPETES according to three different market design topics [4,18].

Table 2: Backbone and COMPETES existing implementation
of spatial flexibility options or related features

Market design topics		**Backbone**	**COMPETES**
Transmission networks	Flow-based market coupling	implemented	implemented
	Market splitting	implemented	-
	Nodal pricing	implemented	implemented
	Dynamic line rating	implemented	-
Cross-border trade	Cross border reserve markets	implemented	-
	Cross border capacity markets	implemented	-
	Cross border Intra-day markets	implemented	
Aggregation	RES aggregation	implemented	implemented
	Storage aggregation	implemented	implemented
	EVs aggregation	implemented	implemented
	Consumers/flexibility Aggregation	implemented	implemented

From Table 2 it can be seen that Backbone already has implemented a significant number of features that enable spatial flexibility. In specific, Backbone supports flow-based market coupling, market splitting, nodal pricing and DyLR in the scope of transmission networks. It also supports cross border trading through the modeling of cross border reserve, capacity and intra-day markets, besides providing models for the aggregation of different energy resources, such as RES, storage, EVs and consumers.

COMPETES, in turn, supports flow-based market coupling and nodal pricing as basis for spatial flexibility provision. Aggregation models for the different energy resources are also available.

The models already provided by Backbone and COMPETES are important lessons for the adequate implementation of the spatial flexibility options within the project agent-based models, as described in Section 3.2.

3.2 Model enhancements within TradeRES

This section describes the model enhancements that are bring developed by RESTrade and MASCEM regarding the modeling of spatial flexibility options, namely regarding the integration of cross border reserve markets, the development of models to select the most suitable resources to provide flexibility; and the required models to effectively activate the flexibility (see [19] for a complete overview about ancillary services).

3.2.1. RESTrade

The main RESTrade model enhancements related to spatial flexibility concern the development and integration of cross border reserve markets.

Control reserves are essential to guarantee the security of supply, being used to balance the power system frequency, guaranteeing that it does not deviate more than 1% [19-22]. Typically, three control reserves that are available, and they activated sequentially: frequency-controlled reserve (FCR), automatic frequency restoration reserve (aFRR), and manual FRR. Normally, only synchronized generators, fast-starting stand-by generators and fast-responsive players with high ramp rates have the technical requirements to supply the control reserves [19-22].

The FCR or primary control reserve is mandatory in Europe, being its reserved capacity of 3,000 MW in the south and central Europe region. It is activated decentralized via frequency measurements, being activated after a frequency oscillation in 15s and until being replaced by the secondary reserve [19,21].

The aFRR or secondary control reserve has its capacity size determined by national TSOs according to the ENTSO-E rules. Its control is centralized, being automatically activated by the TSO via an automatic gain control signal. It is activated in 30 seconds being active until being replaced by tertiary control. One of the main issues of aFRR capacity on markets consists in the lack of competition in some countries. Another situation is that some electricity markets/control zones do not have an aFRR energy market, being the aFRR energy paid by the mFRR (manual FRR) energy price. This is not an efficient procedure since aFRR's participants may have different marginal costs when comparing with mFRR's participants. Coupled markets can benefit from a common cross border aFRR market, increasing the market competition as it happens in Nordpool [23].

The mFRR or tertiary control reserve is activated centralized by the national TSO, being its activation time around 15 minutes. They can stay active until the frequency oscillation is mitigated to values lower or equal than 1%. The mFRR energy market has a higher number of participants when comparing with the aFRR markets, and it also can benefit from the increased competition that cross-border reserve markets can bring.

Table 3 presents the characteristics of the cross-border reserves markets that are implemented in the RESTrade system.

Table 3: Cross-border reserves markets implemented in RESTrade system.

Mechanism	aFRR capacity	aFRR energy	mFRR energy
Procurement	Separated upward and downward capacity based on expected maximum consumption, and vRES production	Separated upward and downward energy based on 5–15 minutes dispatch to cover frequency deviations	Separated upward and downward energy based on 15–30 minutes dispatch to cover frequency deviations
Bidding	Implicit and asymmetrical	Implicit and asymmetrical	Implicit and asymmetrical
Payment scheme	Pay-as-bid/marginal pricing	Marginal pricing/ Pay-as-bid	Marginal pricing / Pay-as-bid
Trading Procedure	Automatic match/Auction	Auction/ Automatic match	Auction/Automatic match
Cross-border capacity	Implicit allocation (SLR or DyLR)	Implicit allocation (SLR or DyLR)	Implicit allocation (SLR or DyLR)
Market Splitting	In case of cross-border congestions	In case of cross-border congestions	In case of cross-border congestions
Explicit trading	Yes, in case of market splitting	Yes, in case of market splitting	Yes, in case of market splitting
Gate-closure	2 hours-ahead	25 minutes-ahead	25 minutes-ahead
Time unit	5–15 minutes	5–15 minutes	15–30 minutes
Minimum bid size	0.1 MW	0.1 MWh	0.1 MWh

Cross border trades are limited by the capacity of the interconnection transmission lines (tie-lines). Normally, the tie-lines capacity is reserved for commercial trades of the coupled markets, avoiding market-splitting. However, TSOs traditionally design and explore the tie-lines capacity using a seasonal “steady-state” line rating (SLR), which uses conservative extreme weather conditions. These conditions slightly vary according to each country. For instance, in Portugal, an incident wind speed around 0.6 m/s, an irradiance higher than 1000 W/m^2 and average ambient temperatures that vary seasonally according to different geographical locations are considered [24,25]. The designed capacity of the tie-lines considered these conservative weather conditions to cables designed to achieve a maximum temperature.

Normally, the maximum ampacity of the cable is computed for the maximum designed temperature, considering a thermodynamic model of the cable of the IEEE 738-2018 numerical model with fixed weather conditions, obtaining the designed capacity of the cable [26]. However, during real-time operation the conductor’s temperature is continuously changing according to electrical, meteorological and physical conditions. Dynamic line rating (DyLR) numerical models consider the continuous change of the conductor's temperature, computing it, which can be then used to detect congestions or an extra capacity that can be used in the cable. The Kuipers & Brown [27] and the CIGRÉ [28] are the most used DyLR models used.

The RESTrade system (presented in [29]) already has DyLR models, using the CIGRÉ model as reference, which enables to compute the extra capacity of the overhead transmission power lines. The literature indicates that on average DyLR allows increasing the line's capacity between 10% to 30% over the SLR during 80% of the time, identifying that the capacity is overestimated during 20% of the time [30-32]. When the capacity of an electric power line is overestimated considering the real-time meteorological conditions, it can increase the cable's temperature above its maximum temperature, conducting to its degradation. This situation can be avoided if TSOs directly measure the cable's temperature, otherwise, only using DyLR numerical models can avoid it.

Against this background, TSOs can consider coupled cross border markets and adopt DyLR analysis, benefiting from reliable real-time temperatures of the tie-lines and close to real-time weather forecasts, to mitigate possible congestions and identify extra capacities according to the programmed cross border commercial trade. The use of cross-border reserves market considering DyLR is the main sectoral model enhancement of the RESTrade system. Considering the used tie-lines capacity for commercial trade, if close to real-time TSOs verify a congestion in a specific tie-line that conducts to market splitting of the cross-border reserve markets, TSOs should apply the DyLR to that line and verify if an extra capacity is obtained. Therefore, the use of DyLR can support the efficient use of interconnection capacity, avoiding market splitting.

Figure 1 identifies how a congestion can be detected in a specific tie-line.

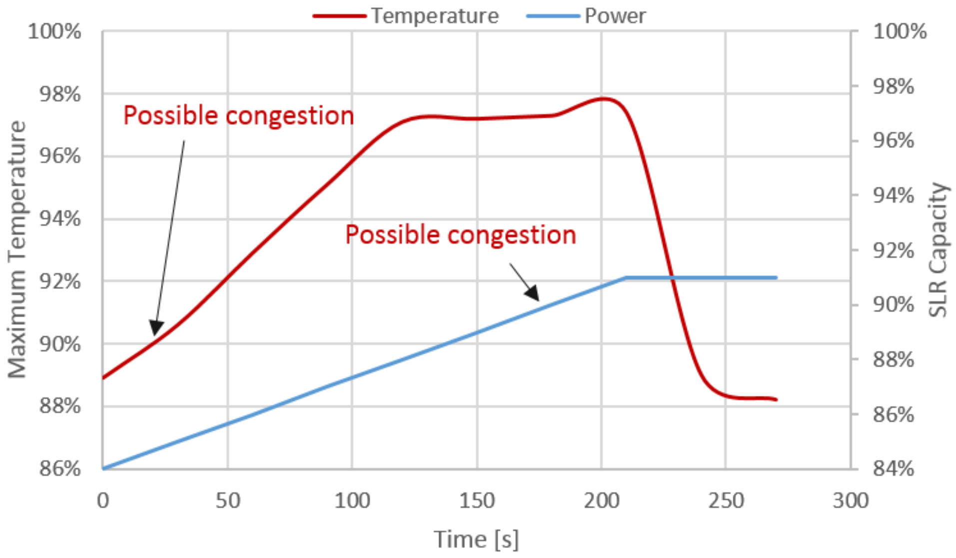

Figure 1: Detecting congestion through temperature measured or programmed capacity used of the tie-lines.

When it is possible to measure the tie-line's temperature, if it gets close to the maximum designed temperature TSOs should detect it as a congestion and try to reduce its energy flow to avoid the line's degradation. If it is not possible to measure the tie line's temperature, the TSO should verify if the programmed power will be close to the maximum SLR capacity of the line. In case of being close to the maximum SLR capacity instead of detecting it as a congestion the TSO should use a DyLR numerical model to compute an approximate value of the tie-line's temperature, verifying if it is congested or not. From Figure 1 it can be verified that a possible congestion is detected due to an increase in the cable's temperature after 20s, but the power that is passing through the line is a bit far from its maximum SLR capacity, that has been programmed to increase. Under this situation, the TSO should send a signal for downward control of the power plant(s) that affected the power flow of this line, reducing its/their programmed power, which happens after a bit more than 200s. However, after 200s the injected power in the line is higher conducting to a possible congestion, but the temperature of the cable is falling, so, the TSO should verify that the tie-line is not congested by measuring its temperature or using a DyLR numerical model that can also be used to compute its extra capacity.

Figure 2 presents the benefits of using DyLR to enable the cross-border trade of reserve markets.

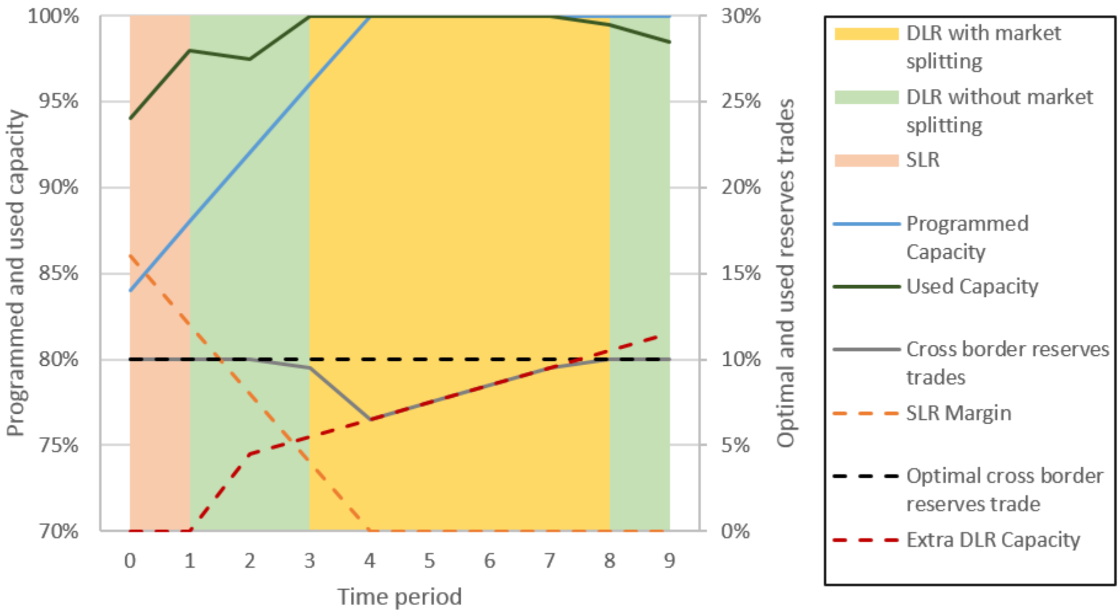

Figure 2: Programmed and used cross border capacities, such as the optimal and used cross border reserves trades

Analysing Figure 2 is possible to verify that the programmed capacity (blue line) before the cross-border reserves market will achieve the commercial capacity after time period 4 (dashed orange line), disabling the possibility of cross border trades of reserves. The optimal cross-border trade of reserves is 10% during the entire period (dashed black line). Using the SLR will allow to trade cross-border reserves without the need of using DyLR, but conducts to market splitting after period 1. After period 1, the computation of the DyLR allows obtaining an extra capacity (dashed red line). Considering the programmed capacity, the extra DyLR capacity and the optimal trade of cross border reserves is possible to verify that during time period 1, 2 and 8 is possible to trade cross border reserves without market splitting, while from period 3 to 8 is possible to trade reserves with market splitting.

When the SLR margin (dashed orange line) is higher than the optimal trading value of cross border reserves (dashed black line), there is no need to use DyLR. If the sum of the SLR margin with the extra DyLR (dashed red line) is equal or higher than the optimal trading value of cross border reserves, there is no market splitting. Otherwise, if the SLR margin is zero without using DyLR, it is not possible to trade cross border reserves.

3.2.2. MASCEM

When power network problems are foreseen and flexibility is required to solve them it is important to reach suitable decisions on which resources should be activated and how such activation should be done. The model that is begin designed and implemented by MASCEM aims at providing responses to these challenges by developing the means to select the most suitable resources to provide flexibility according to the characteristics of these resources and to the needs of the system; and the required models to effectively activate the flexibility. This model involves several MASCEM agents, namely the TSO, the DSO, the Aggregator, the Market Operator, and multiple Player agents, which represent the different energy resources, e.g. consumers, prosumers, EVs, energy storage systems. Figure 3 provides an overview of the model under development.

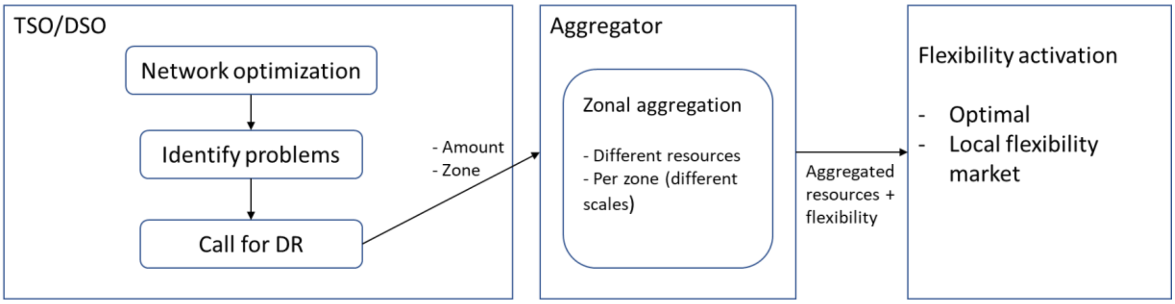

Figure 3: Spatial flexibility model overview.

From Figure 3 one can see that the model starts with a preliminary power network validation (either at the distribution or transmission level), with the aim of identifying potential problems in the power flow (see Power Flow service described in D4.5 [4]). If potential problems are expected, a call for Demand Response (DR) is lauched by the DSO or TSO agent to one or several Aggregator agents, which aggregate different energy resources within specific network areas. The Aggregator will select the most suitable players to be called upon the DR event, according to these players' charactetristics, past behaviour and localization (section 3.2.2.1). Once the players are identified, the flexibility activation takes place through two alternative models. The first refers to an optimal scheduling of the local area resources, considering the available flexibility from behalf of the selected players (section 3.2.2.2), while the second refers to a specific market model for flexibility trading (section 3.2.2.3).

3.2.2.1. Flexibility provision participants aggregation and selection

Two different approaches are proposed for the participants selection: aggregation according to selected characteristics or definition of a consumer trustworthy rate.

Firstly, aggregation was already widely employed and proved to be a useful approach to understand the consumer's load consumption profile [10] Clustering methods can be used in numerous circumstances and the input characteristics have a huge influence on the results [11]. In this case, the selected method is most common unsupervised machine learning algorithm for partitioning, k-means [12] The search for the centroid value, that represents each group, intends to allocate the data into non-overlapping subsets, a *k* cluster. The centroid is found when the distance between an element and the remaining is minimal. However, the k must pre-defined since can affect the output since one of the main problems refers to the initialization. This method needs the number of clusters from a dataset a priori, which, normally, is unknown. However, validity indices are used to find the optimal number of clusters for a dataset (Kopt), and the one used in this study was the Silhouette method – the maximum value of silhouette score represents the Kopt [13]. Having this value, k-means is applied to the the known consumer characteristics, and groups are found. One example for the application of this method can be seen in the Figure 4, where the Kopt equals 2 and the k-means method distributed the consumers between these groups, according to similar attributes. The group that gathers the ones with higher level of performance, for a certain context, are chosen to participate.

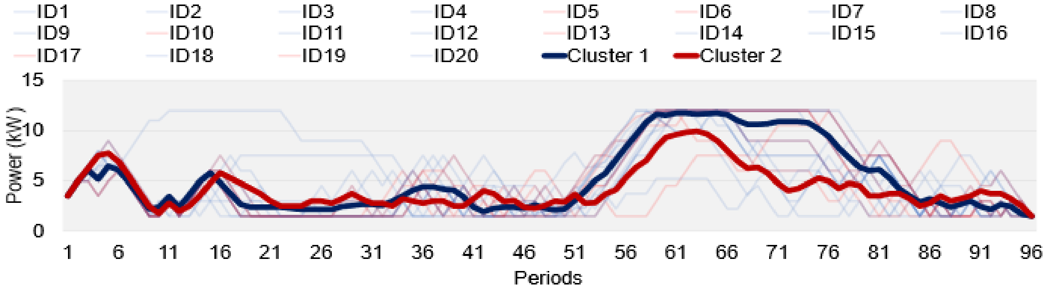

Figure 4: Application of Silhouette method to find the optimal number of clusters, applied to the k-means method.

Second, a trustworthy rate can be designed to classify the expected performance from a small consumer for the context in which the DR event will be triggered – defined as Consumer Trustworthy Rate (CTR). Being defined according to several consumer characteristics factors – the so-called independent rates. As can be seen in Figure 5 is divided into two phases: Preliminary Contextual Consumer Rate (PR) and, after the event, Updated Contextual Consumer Rate (UR). If a consumer does not have any previous information, for instance, when it is the first time participating in DR events, the lowest rate is assigned, and from there, the consumer can improve the CTR. This assumption is applied to all independent rates in the same situation.

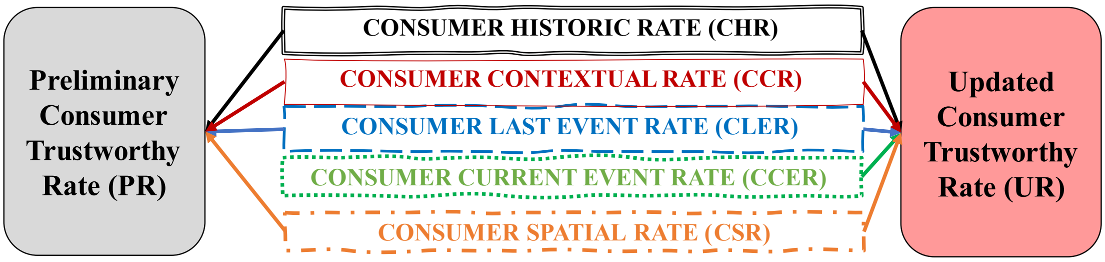

Figure 5: Contextual Consumer Rate definition for both stages: Preliminary and Updated.

Consumer Historical Rate (CHR) is represented with a double black borderline in Figure 5. This independent rate represents the historical information for the performance of each consumer in previous events at similar contexts – such as the day of the current week and the temperature recorded at the time of the event. With this, a dataset search is performed to find consumer samples that can meet the requirements. For the weather conditions, a comparison between the current temperature within a defined temperature range is performed. CHR is defined by the average of the performances in the same context. Consumer Contextual Rate (CCR), the continuous red line in Figure 5, considers two perspectives: Context Rate Period (CRP) and Context Rate Weather (CRW). CRP changes according to the daily availability of the consumer – which can be different for a certain day of the week and period of the day. CRW changes according to the willingness to participate in certain weather conditions – in this case, the temperature recorded in the period of the event. Each one has a ω weight assigned for the CCR formulation. Consumer Last Event Rate (LER), in Figure 5 with a discontinuous blue borderline, displays the performance of the active consumer in the last event of the same context (weekday, period, and temperature). The addition of this performance rate is important to understand and update the consumer's behavior. Alone, it could misrepresent the active consumer performance since it can be very volatile. With CHR, a complete understanding of the performance tendency could be represented. The proposed method represents this concept with the Consumer Spatial Rate (CSR) regarding Spatial Flexibility. In this approach, the Aggregator can have access to the grid bus where the violation was detected. For instance, Figure 6 shows two examples where the Aggregator applies the proposed approach.

First, in Figure 6a, the managing entity has no information regarding the location of the active consumers who provide the flexibility, having only 62 participants for the DR event in this example. The reduction was enough to solve the voltage limit violation in this situation. After Figure 6b, having this information regarding the spatial flexibility, only 26 active consumers were requested for the event reduction. This number was also sufficient to resolve the voltage limit violation for this period. However, from the economic perspective, the Aggregator has more benefits in considering the spatial flexibility concept since the small consumers near this location can be crucial to solving the problem; therefore, it must have participation priority.

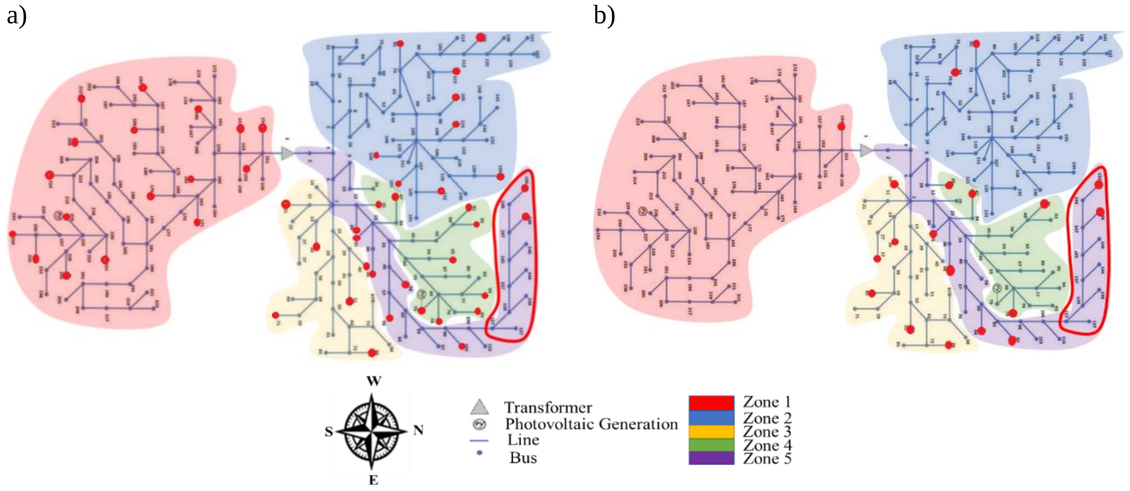

Figure 6: Scenario comparison a) without spatial knowledge, b) with spatial knowledge.

In this way, CSR is added to the formulation of the initial CTR. Equation (1) adds LR along with CHR and CLER for this initial trustworthy rate.

$$PR = \omega_{P\_CHR}\, CHR + \omega_{\ P\_CLER}\, CLER + \omega_{\ P\_CSR}\, CSR + \omega_{\ P\_CCR}\, CCR \tag{1}$$

where ω_{P_CHR}, $\omega_{\ P\_CLER}$, $\omega_{\ P\_CSR}$ and $\omega_{\ P\_CCR}$ represent the weight that represents the importance assigned to CHR, CLER, CSR and CCR, respectively, in the Preliminary Consumer Trustworthy Rate.

After classifying all the active consumers, an analysis is performed, and the ones selected to participate in the DR event are identified, e.g. those that are classified above a denominated minimum.

3.2.2.2. Optimal flexibility scheduling

The proposed model for optimal flexibility scheduling comprises several steps, involving the DSO, Aggregator, and Active consumers agents. Figure 7 shows a diagram that depicts the proposed methodology in full.

The model starts with the Distributed System Operator (DSO) performing the load forecast for the community – in a higher or lower time range, meaning, weekly or real-time approach. After, DSO performs a Power Flow (PF) and the respective analysis, using the PF service described in D4.5 [4], looking for any issues that may occur in the considered network. If none is detected, the scheduling is performed normally. On the other hand, if any violation is detected, the DSO must request a load reduction to each community manager, the Aggregator. This entity will then trigger a DR event. The active consumers, with a contract, must provide information of the available demand flexibility, their availability, and the willingness to participate in this context. After the participants for flexibility provision are selected, according to the models described in 3.2.2.1, the Aggregator can move forward to the optimal resource scheduling phase. A linear approach is employed to manage the community optimally – the objective function (OC_t) aims to minimize operational costs from the Aggregator perspective, as seen in Equation (2). To ease the comprhension from the following formulation, Table 4 describes and defines the variables and parameters.

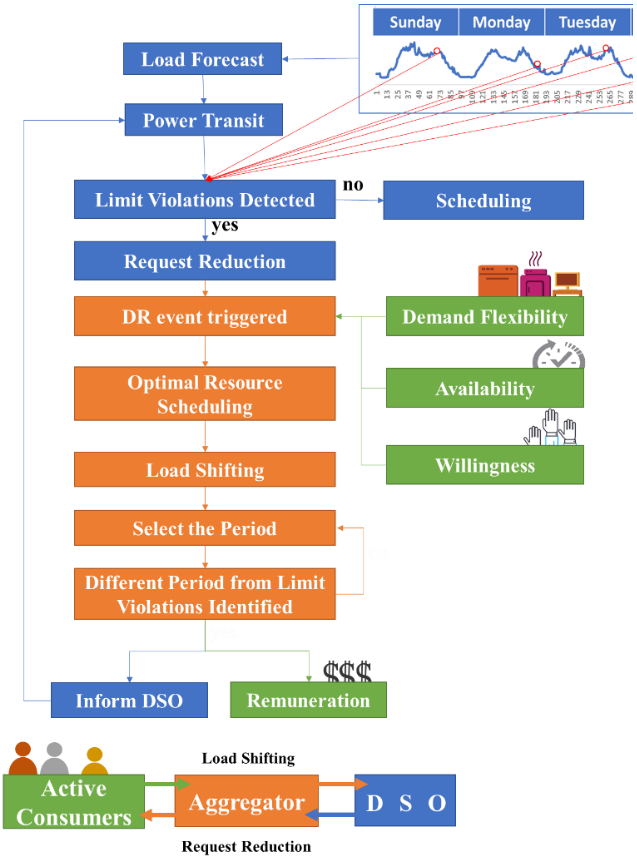

Figure 7: Proposed methodology: interaction between DSO, Aggregator, and Active consumers to solve voltage limit violations.

It should be highlighted that time resolution is not hourly but in a 15-minute basis. This assumption is needed to adjust consumption to the tariff at play, since consumption is in a 15-minute basis, while the tariff is in an hourly basis. All the costs were considered in m.u. to ease this assumption.

$$\begin{aligned} min\ \ OC_t = & \sum_{p=1}^{P}\left[P_{RES_{g,t}} C_{RES_{g,t}}\right] + \sum_{c=1}^{C}\left[P_{DR_{c,t}} C_{DR_{c,t}}\right] + \sum_{s=1}^{S}\left[P_{Suppliers_{s,t}} C_{Suppliers_{s,t}}\right] + P_{NSP_t} C_{NSP_t} \\ & + \sum_{v=1}^{V}\left[P_{EVd_{v,t}} C_{EVd_{v,t}}\right] + \sum_{b=1}^{B}\left[P_{ESSd_{b,t}} C_{ESSd_{b,t}}\right] \end{aligned} \tag{2}$$

$$c,t,g,s,b,v \in \mathbb{Z} : c,t,g,s,b,v > 0$$

The objective function represented in Equation (2) is subjected to several constraints – Equation (3) to Equation (19). Firstly, to achieve the network power balance, in other words, the equilibrium between consumption and generation, Equation (3) is defined. The notation includes indices in parentheses, e.g. $P_{c,t}^{initial}$ is the initial load consumption for consumer c and period t. The sum of the difference between the initial load the EV charge, the ESS charge, and the requested reduction should equalize the value from to the total generation within RES units, external suppliers, EV discharge, and ESS discharge.

$$\sum_{c=1}^{C}[P_{c,t}^{initial} + P_{EVc_{v,t}} + P_{ESSc_{b,t}} - P_{DR_{c,t}}] = \sum_{g=1}^{G}\left[P_{RES_{g,t}}\right] + \sum_{s=1}^{S}\left[P_{Suppliers_{s,t}}\right] + \sum_{v=1}^{V}\left[P_{EVd_{v,t}}\right] + \sum_{b=1}^{B}\left[P_{ESSd_{b,t}}\right] + P_{NSP_t} \qquad c,t,g,s \in \mathbb{Z}:\ c,t,g,s > 0 \tag{3}$$

Table 4. Nomenclature from Optimal Resource Scheduling phase.

$C_{DR_{c,t}}$	Cost from Demand Response active consumer *c* on period *t* (m.u.)
$C_{ESSd_{b,t}}$	Cost from Energy Storage System b on period *t* (m.u.)
$C_{EVd_{v,t}}$	Cost from Supplier *s* on period *t* (m.u.)
C_{NSP_t}	Non-Supplied Power Cost on period *t* (m.u.)
$C_{RES_{g,t}}$	Cost from Renewable-based Sources unit *g* on period *t* (m.u.)
$C_{Suppliers_{s,t}}$	Cost from Supplier *s* on period *t* (m.u.)
$E_{b,t}^{stor}$	Operation capacity of Energy Storage System b on period *t* (kW)
$E_{b,t}^{stormax}$	Maximum value from operation capacity of Energy Storage System b on period *t* (kW)
$E_{b,t}^{stormin}$	Minimum value from operation capacity of Energy Storage System b on period *t* (kW)
$E_{v,t}^{ev}$	Operation capacity of Electric Vehicle v on period *t* (kW)
$E_{v,t}^{evmax}$	Maximum value from operation capacity of Electric Vehicle v on period *t* (kW)
$E_{v,t}^{evmin}$	Minimum value from operation capacity of Electric Vehicle v on period *t* (kW)
$P_{DR_{c,t}}^{Max}$	Maximum Contribution from Demand Response active consumer *c* on period *t* (kW)
$P_{DR_{c,t}}$	Power from Demand Response active consumer *c* on period *t* (kW)
$P_{ESSd_{b,t}}$	Power from discharging Energy Storage System b on period *t* (kW)
$P_{EVc_{v,t}}^{max}$	Maximum charging value of Electric Vehicle v on period *t* (kW)
$P_{EVc_{v,t}}$	Charging value of Electric Vehicle v on period *t* (kW)
$P_{EVd_{v,t}}^{max}$	Maximum discharging value of Electric Vehicle v on period *t* (kW)
$P_{EVd_{v,t}}$	Power from discharging Electric Vehicle v on period *t* (kW)
$P_{RES_{g,t}}^{Max}$	Maximum Power from Renewable-based Sources unit *g* on period *t* (kW)
$P_{RES_{g,t}}^{Min}$	Minimum Power from Renewable-based Sources unit *g* on period *t* (kW)
$P_{RES_{g,t}}^{total}$	Total Contribution Limit from Renewable-based Sources unit *g* on period *t* (kW)
$P_{RES_{g,t}}$	Power from Renewable-based Sources unit *g* on period *t* (kW)
$P_{b,t}^{chmax}$	Maximum charging value of Energy Storage System b on period *t* (kW)
$P_{b,t}^{dchmax}$	Maximum discharging value of Electric Vehicle v on period *t* (kW)
$P_{c,t}^{initial}$	Initial Power from active consumer *c* on period *t* (kW)
$P_{NSP(t)}$	Non-Supplied Power on period *t* (kW)
$P_{Supplier\ (s,t)}^{Max}$	Maximum Power from Supplier *s* on period *t* (kW)
$P_{Supplier\ (s,t)}^{Total}$	Total Contribution Limit from Supplier *s* on period *t* (kW)
$P_{Supplier(s,t)}$	Power from Supplier *s* on period *t* (kW)
$X_{b,t}^{essch}$	Charging status from Energy Storage System b on period *t* (kW)
$X_{b,t}^{essdch}$	Disharging status from Energy Storage System b on period *t* (kW)
$X_{v,t}^{evch}$	Charging status from Electric Vehicle v on period *t* (kW)
$X_{v,t}^{evdch}$	Disharging status from Electric Vehicle v on period *t* (kW)

According to each context, Equation (4) represents the maximum contribution requested from each active consumer to a DR event. Since they have a contract with the Aggregator, it is expected that each participant contributes with the amount requested. The CTR was defined to reduce uncertainty but does not guarantee that the requested reduction equals the actual reduction.

$$P_{DR_{c,t}} \leq P_{DR_{c,t}}^{Max} \qquad c,t,\in \mathbb{Z}: c,t > 0 \tag{4}$$

To define limits for the RES units' contribution, Equation (5) to Equation (7) allows the Aggregator to control the upper and lower bounds and the total value of generation provided from each different technology.

$$P_{RES_{g,t}} \leq P_{RES_{g,t}}^{Max} \qquad g,t,\in \mathbb{Z}: g,t > 0 \tag{5}$$

$$P_{RES_{g,t}} > P_{RES_{g,t}}^{Min} \qquad g,t,\in \mathbb{Z}: g,t > 0 \tag{6}$$

$$\sum_{g=1}^{G} \left[P_{RES_{g,t}}\right] \leq P_{RES_{g,t}}^{total} \qquad g,t,\in \mathbb{Z}: g,t > 0 \tag{7}$$

Equation (8) and Equation (9) represent the external suppliers' constraints, constraining the maximum capacity and the total amount of generation provided from this source to suppress the demand side needs.

$$P_{Suppliers_{s,t}} \leq P_{Suppliers_{s,t}}^{Max} \qquad s,t,\in \mathbb{Z}: s,t > 0 \tag{8}$$

$$\sum_{s=1}^{S} \left[P_{Suppliers_{s,t}}\right] \leq P_{Suppliers_{s,t}}^{total} \qquad s,t,\in \mathbb{Z}: s,t > 0 \tag{9}$$

Regarding the ESS constraints, the optimal scheduling is constrained with Equation (10) to Equation (14). Firstly, the limits for the operation capacity. After, Equation (11) and Equation (12) bound the ESS charge and ESS discharge, respectively. These equations include one binary variable, that along with Equation (13), guarantee the impossibility of charging ($X_{(s,t)}^{essch}$) and discharging ($X_{(s,t)}^{essdch}$) during the same period *t*. Finally, Equation (14) is introduced to maintain the power balance within the ESS – the previous state of what was charged and discharged.

$$E_{b,t}^{stormin} \leq E_{b,t}^{stor} \leq E_{b,t}^{stormax}, \forall t \in \{1, \ldots, T\}, b \in \{1, \ldots, B\} \tag{10}$$

$$0 \leq P_{ESSc_{b,t}} \leq P_{b,t}^{chmax}.X_{b,t}^{essch}, X_{b,t}^{essch} \in \{0,1\}, \forall t \in \{1, \ldots, T\}, b \in \{1, \ldots, B\} \tag{11}$$

$$0 \leq P_{ESSd_{b,t}} \leq P_{b,t}^{dchmax}.X_{b,t}^{essdch}, X_{b,t}^{essdch} \in \{0,1\}, \forall t \in \{1, \ldots, T\}, b \in \{1, \ldots, B\} \tag{12}$$

$$X_{b,t}^{essdch} + X_{b,t}^{essch} \leq 1, \forall t \in \{1, \ldots, T\}, b \in \{1, \ldots, B\} \tag{13}$$

$$E_{b,t}^{stor} = E_{b,t-1}^{stor} + P_{ESSc_{b,t}} + P_{ESSd_{b,t}}, \forall t \in \{1, \ldots, T\}, b \in \{1, \ldots, B\} \tag{14}$$

The final five equations presented refer to the EVs. Like the ESS, Equation (15) represents the operation capacity limits, Equation (16) the charge, and Equation (17) the discharge limits per period. With Equation (18), one can guarantee the impossibility of charging ($X_{(v,t)}^{evch}$) and discharging ($X_{(v,t)}^{evdch}$) during the same period *t* .

$$E_{v,t}^{evmin} \leq E_{v,t}^{ev} \leq E_{v,t}^{evmax}, \forall t \in \{1, \ldots, T\}, v \in \{1, \ldots, V\} \tag{15}$$

$$0 \le P_{EVc_{v,t}} \le P_{EVc_{v,t}}^{max}.X_{v,t}^{evch}, X_{v,t}^{evch} \in \{0,1\}, \forall t \in \{1, \dots, T\}, v \in \{1, \dots, V\} \tag{16}$$

$$0 \le P_{EVd_{v,t}} \le P_{EVd_{v,t}}^{max}.X_{v,t}^{evdch}, X_{v,t}^{evdch} \in \{0,1\}, \forall t \in \{1, \dots, T\}, v \in \{1, \dots, V\} \tag{17}$$

$$X_{v,t}^{evdch} + X_{v,t}^{evch} \le 1, \forall t \in \{1, \dots, T\}, v \in \{1, \dots, V\} \tag{18}$$

$$E_{v,t}^{ev} = E_{v,t-1}^{ev} + P_{EVd_{v,t}} + P_{EVc_{v,t}}, \forall t \in \{1, \dots, T\}, v \in \{1, \dots, V\} \tag{19}$$

With the results from the optimal resource scheduling phase, the Aggregator should notify the participants. In this approach, the DR program designated load shifting is applied. So, the periods where the load should be moved should be convenient to both active consumers and the market operators, avoiding discomfort or other voltage limit violations – phase "Different Period from the Limit Violations Identified." In a real-time perspective, where the Aggregator only has information regarding the current violation, this phase may not be applied due to the lack of knowledge from this entity, having the possibility of shifting a load to a period where a limit violation can be identified in the future.

All these outputs should be informed to the DSO. Then, the results are used as an input to a second OPF, which guarantees the elimination of the voltage limit violation. Once this information is confirmed, the Aggregator should update the CTR to all the active consumers, which the participant was required according to Equation (20).

$$\begin{aligned} UR \; = \; \omega_{\,U\_CHR}\, CHR \; + \; \omega_{\,U\_CLER}\, CLER \; + \; \omega_{\,U\_CSR}\, CSR + \; \omega_{\,U\_CCR}\, CCR \\ + \; \omega_{\,U\_CCER}\, CCER \end{aligned} \tag{20}$$

where $\omega_{\,U\_CHR}$, $\omega_{\,U\_CLER}$, $\omega_{\,U\_CSR}$, $\omega_{\,U\_CCR}$ and $\omega_{\,U_CCER}$represent the weight that represents the importance assigned to CHR, CLER, CSR, CCR, and Consumer Current Event Rate (CCER), respectively, in the Updated Consumer Trustworthy Rate. CCER, represented with a green dotted line in Figure 5, defines the rate according to the actual response of the consumer to the event: if responded as requested, the resulting rate is high. The opposite applies, and the active consumer is penalized with a lowered value of RR. The UR is highly important for the Remuneration Phase because the compensation value is defined according to the performance. Again, as Figure 6 shows, the proposed methodology is crucial to avoid unnecessary costs from the Aggregator perspective. Considering the spatial flexibility concept, the expenses with remuneration for the participation in DR events can be reduced to a value closer to an optimum. Otherwise, the loop starts again with more active consumers – changing the denominated minimum of CTR acceptable for this event, giving the opportunity to the ones with lower performance values or adding the other clustering groups to the loop.

3.2.2.3. Local flexibility market

The local flexibility market that is being developed for integration in MASCEM allows the pre-selected consumers to set their individual flexibility price and flexibility volume to trade, considering an asymmetric pool-based local market. This negotiation mechanism is designed according to the recent European Union regulatory framework, which promotes consumers active participation [30].

The used mathematical formulation in this work is also proposed in this section. Equation (21) represents the operation costs for DSO.

$$OC^{DSO} = \sum_{t=1}^{T} (LC_t + LMC_t) \tag{21}$$

where OC^{DSO} represents the total cost (EUR) of operation for the DSO, LC_t represents the cost of losses in period t and LMC_t represents the local market costs (acquisition of non-frequency AS) in period t. Equation (22) represents the calculation of losses cost:

$$LC_t = \sum_{l=1}^{L} \left(WL_{l,t} \times Cp_l\right), \forall\, t \in T \tag{22}$$

where $WL_{l,t}$ are the energy losses (kWh), Cp_l is the per kilowatt-hour cost of power losses (EUR/kWh). Equation (23) represents the local market costs for period t:

$$LMC_t = FlexC_t + AggC_t, \forall\, t \in T \tag{23}$$

where $FlexC_t$ represents the costs with the demand flexibility, $AggC_t$ represents the cost with the payment to the aggregator (or local market operator), corresponding to period t. Equation (24) represents the cost of the pool market.

$$FlexC_t = \sum_{c=1}^{C} \left(Offer_{c,t}^{W} \times Clearing_t^{price} \times Offer_{c,t}^{bin}\right), \forall\, t \in T \tag{24}$$

where $Offer_{c,t}^{W}$ is the energy reduction (kWh) of offer c at period t, $Clearing_t^{price}$ is the clearing price of cut (EUR/kWh) at period t, $Offer_{c,t}^{bin}$ is a binary variable of offer c at period t and C is the total number of customers.

The term $Offer_{c,t}^{W}$ and $Offer_{c,t}^{P}$ are considered inputs for the problem while $Offer_{c,t}^{bin}$ are decision variables. The decision variables are presented in equation (25), and are composed by a binary operator indicating the acceptance of an offer:

$$Offer_{c,t}^{bin} = \begin{cases} 1, & If\ the\ offer\ is\ selected \\ 0, & otherwise \end{cases}, \forall\, c \in C, \forall\, t \in T \tag{25}$$

where $Offer_{c,t}^{bin} = 1$ means that offer c in period t is selected for DSO and $Offer_{c,t}^{bin} = 0$ if the offer is not selected.

Variables $Offer_{c,t}^{bin}$ and $Clearing_t^{price}$ are obtained using the function presented in equation (26). The Asymmetric pool model is one of the pool models applied in market trading, in which only sale offers (i.e., players' flexibility) are received and there is only one flexibility buyer with a defined amount of target flexibility, without a pre-defined price.

$$\left(Clearing_t^{price}, Offer_{c,t}^{bin}\right) = \mathbf{Auction}\left(Offer_{c,t}^{W}, Offer_{c,t}^{P}\right) \tag{26}$$

where $\mathbf{Auction}$ is a function that returns the $Clearing_t^{price}$ and $Offer_{c,t}^{bin}$ represents the price and the offers accepted and rejected considering the asymmetric pool model (see Figure 8 for an illustrative example). The results obtained from the function described in equation (26) have a direct impact in the corresponding values of operational costs (calculated with equation (21)).

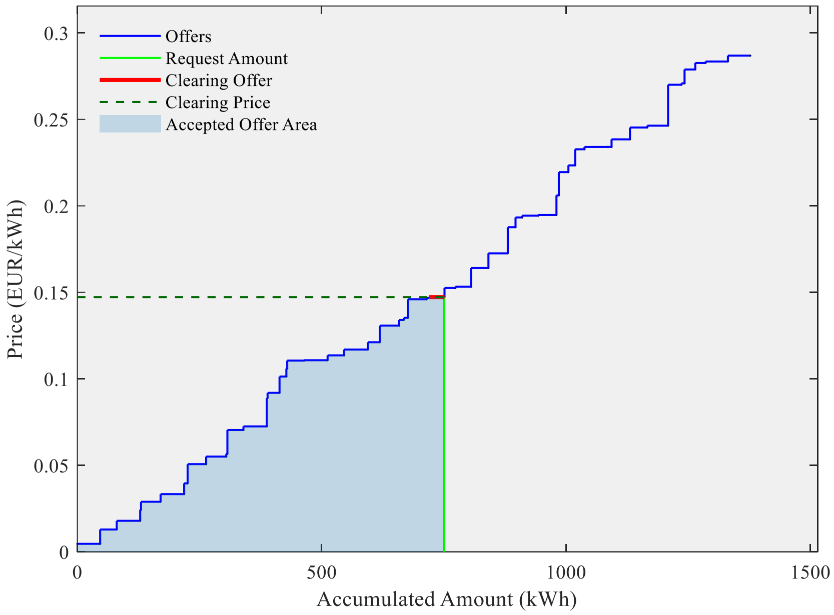

Figure 8: Asymmetric pool.

The inputs for the auction are offers with energy and price information. This function ($\mathbf{Auction}(.)$) receives the inputs and returns as outputs the clearing price and the corresponding accepted offers. In a first step, the offers are sorted in ascending considering the offer prices, and the accumulated quantity of electricity is added. When the accumulated quantity of the lowest priced offers equals the requested quantity, the clearing price is determined by the price of the offer that matched the requested quantity, and all orders with prices below this quantity are accepted.

Besides the incorporation of this basis version of the asymmetric local flexibility market in MASCEM, a new model evolution is also being designed in order to incorporate spatial information in the auction process itself. Hence, besides activating the required flexibility among the set of pre-selected players, according to the needs of the system and to players' characteristics, priorities are going to be assigned to each individual player, according to the distance of the player to the nearest point of the power network in which a potential problem has been identified. We envisage adding these player priorities into the auction function so that the sorting of the first offers to be accepted is done, not only according to the offer price, but also considering the player priority. In this way, we expect to maintain a level of competitiveness in the market, by incentivizing the acceptance of the lowest prices, while simultaneously prioritizing the acceptance of flexibility offers from players that are geographically closer to the critical points of the network.

4. Conclusion

TradeRES is developing new market models and designs to accommodate a power system with near 100% VRE. It is, therefore, essential, that flexibility from the multiple involved resources is captured in its full extent. TradeRES Task 4.1 is devoted to the exploration and implementation of flexibility options that can be incorporated in the project studies and simulations. This deliverable, in particular, exposes the advances and developments that are being accomplished with regard to spatial flexibility options.

Thus, D4.3 includes an overview of the main definitions, concepts and terminology related to spatial flexibility options, and the presentation of the components that are already implemented and those that are being designed and implemented as enhancements aiming to meet the project goals.

Although the related available existing models are limited to optimization models provided by COMPETES and Backbone, such experiences are providing important lessons for the development of spatial flexibility options in the scope of TradeRES agent-based models. These enhancements are being developed by RESTrade and MASCEM and regard the integration of cross border reserve markets, making use of DyLR; the development of components to select the most suitable resources to provide flexibility; and the required processes to effectively activate this flexibility. The selection of the most suitable resources to provide flexibility is designed according to the needs of the system and to the characteristics of these resources, their past behaviour and localization. The flexibility activation takes place through two alternative models. The first refers to an optimal scheduling of the local area resources, considering the available flexibility from behalf of the selected players, while the second refers to a specific market model for flexibility trading, enabling the competitive participation of different players, while prioritizing the provision of flexibility from the players that are located nearest to the points of the network in which problems are foreseen.

Overall, although some of the presented tools are more mature and already being integrated by the agent-based models and others are still being designed and implemented, they, as a whole, cover the needs from Task 4.1 and from the project overall, regarding the modelling and study of spatial flexibility options. In this way, these models will also enable fulfilling the requirements from WP5 regarding the studies and simulations to be performed at different levels, e.g. individual resources' flexibility study in the scope of local electricity markets, cross-border markets for regional and pan-European market studies, and aggregation models for all the addressed markets.

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