JOINT AND SEQUENTIAL DSO-TSO FLEXIBILITY MARKETS: EFFICIENCY DRIVERS AND KEY CHALLENGES

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ABSTRACT

This paper compares the efficiency of two increasingly adopted transmission-distribution coordinated flexibility market models, namely: the (joint) common market and the (sequential) multilevel market. Novel mathematical market clearing formulations are first introduced for each market model and then applied through a case study to identify several practical factors impacting their efficiencies. Those factors include (i) the transmission-distribution interface pricing method, (ii) the ability of flexibility service providers to diversify their bids in sequential markets, (iii) differing entry barriers in the different market models, and (iv) the underlying varying impacts of bid formats and clearing requirements.

INTRODUCTION

In recent years, the end-consumers' energy landscape has been undergoing unprecedented changes, driven by a growing electrification of the consumers' energy space (e.g., mobility and heating), and integration of variable distributed generation and storage, with an associated pronounced impact on the consumption levels and load patterns. This, as a result, has raised key concerns regarding the availability of adequate grid capacity to support those changing load volumes and profiles, yielding a mounting necessity for congestion management; a need that could be met by a growing availability of flexibility within the distribution grids [1, 2]. As this flexibility can concurrently deliver services, not only to Distribution System Operators (DSOs), but also to Transmission System Operators (TSOs), the coordination between DSOs and TSOs in the procurement of flexibility becomes ever more essential. Indeed, DSO-TSO coordination in flexibility markets can capitalize on the value stacking potential of the offered flexibility – simultaneously meeting different systems' needs at the minimum possible cost – leading to reduced procurement costs for all operators involved [3, 4, 5, 6]. Several DSO-TSO coordination concepts have been proposed in recent large-scale European projects, where two market schemes have gained foremost popularity, namely, the *common* and *multilevel* markets [4]. The *common* market captures a joint TSO-DSO co-optimized procurement from a common pool of flexibility resources, while the *multilevel* market is a sequential scheme in which the DSOs procure flexibility first (in Layer 1), followed by the TSO procurement stage (in Layer 2). This sequential mechanism aims at increasing the potential of meeting local grid needs using local flexibility resources, which has increased the *multilevel* market's implementation potential as observed in recent pilots [7]. However, this sequential market structure can have a direct impact on the system-wide economic efficiency of the procurement process.

A number of recent works in the literature, have focused on analyzing the efficiency of these two market models [3, 4, 5]. In particular, the work in [4] has shown that the *common* market can theoretically yield the lowest system-level procurement cost (i.e., highest efficiency) as it jointly procures the flexibility needs of all participating system operators (SOs) in a co-optimized manner, from a joint pool of flexibility bids, while concurrently abiding by the operational constraints of all the grids involved. However, several practical factors can have a direct impact on this resulting efficiency, challenging its optimality. In fact, as the *multilevel* market is a sequential market, Layer 1 (i.e., the DSO layer) has the potential to be designed to account for the local characteristics and needs of the grid, lowering entry barriers and facilitating the participation of local flexibility service providers (FSPs), while Layer 2 can then accommodate the centralized large-scale characteristics of the grid. This differentiating feature can introduce cumulative efficiency benefits due to the increased level of small-scale flexibility participation. In addition, owing to the two market layers structure of the *multilevel* market, several factors including (i) pricing of power exchange at the TSO-DSO interface, (ii) FSPs bid recalculation and modification between layers, as well as (iii) bid technical requirements across markets (such as minimum bid acceptance requirements), can have a direct effect (both positive and negative) on the *multilevel* market efficiency.

In this respect, this paper aims at capturing those aspects and their resulting effects on the efficiency of both market models. To this end, we first introduce novel mathematical models for the *multilevel* and *common* markets, taking into account the locational impact of flexibility delivered from different areas of the grid, grid operational constraints, and bids' formats and limits. These market models are then employed as part of a comparative case study considering an interconnected transmission-distribution system, which enables tracking the conditions leading to a possible increase or drop in efficiencies of the *multilevel* and *common* markets and their sensitivity to those identified factors, thereby providing key recommendations for efficient DSO-TSO coordinated flexibility market designs. The case study captures the (likely negative) impact of minimum bid acceptance requirements on the *multilevel* market's efficiency, and the positive impact brought in by lower entry barriers, which the *multilevel* market can potentially deliver.

MARKET MODELS

Consider a transmission system with a set of N^T nodes and L^T lines, which is connected to multiple distribution systems, each at an interface node, where $N^I \subseteq N^T$ denotes the subset of the transmission nodes that are interface nodes, and $n^I \in N^I$ a generic interface node. To differentiate between distribution systems, we denote a distribution system connected at an interface node n^I by DSO-n^I, and we let N^{n^I} and L^{n^I} be, respectively, the sets of nodes and lines of DSO-n^I, and $n_0^{n^I} \in N^{n^I}$ be the root node of DSO-n^I, i.e., the node connecting DSO-n^I to the overlaying grid (via n^I). We denote the interface power flow between the transmission network and DSO-n^I by I_{n^I}. Using superscript T to denote elements corresponding to the transmission network and n^I for the elements related to DSO-n^I, $\forall\, n^I \in N^I$, we define the following notation. We let: $p_n^T/\, p_n^{n^I}$ be the net power injection at node n; $p_n^{o,T}/p_n^{o,n^I}$ and $d_n^{o,T}/\, d_n^{o,n^I}$ be, respectively, the base anticipated injection and load at node n (i.e., prior to the run of any flexibility market); $F_{ij}^T/\, F_{ij}^{n^I}$ the power flow over line $\{i,j\} \in L^T/L^{n^I}$ with upper limits denoted by $\bar{F}_{ij}^T/\bar{F}_{ij}^{n^I}$; and $X_{(i,j),n}^T/X_{(i,j),n}^{n^I}$ the power transfer distribution factor (PTDF) matrix translating the net injection at node n to a flow over line $\{i,j\}$. We opt for a linearized power flow computation using PTDFs, which has been widely applied in emerging flexibility markets as, e.g., in the OneNet project [8]. However, the model and analysis can be readily extended to other power flow models as, e.g., those considered in [4]. We let $U^T(n)/U^{n^I}(n)$ and $D^T(n)/D^{n^I}(n)$ be the set of FSPs providing, respectively, upward or downward flexibility at node n, where $\mu_{k,n}^T/\mu_{k,n}^{n^I}$ and $\delta_{k,n}^T/\delta_{k,n}^{n^I}$ is, respectively, the offered upward or downward flexibility by FSP k connected at node n. We let $c_{k,n}^{\mu,T}/c_{k,n}^{\mu,n^I}$ and $c_{k,n}^{\delta,T}/c_{k,n}^{\delta,n^I}$ be the submitted prices of bids $\mu_{k,n}^T/\mu_{k,n}^{n^I}$ and $\delta_{k,n}^T/\delta_{k,n}^{n^I}$, and we denote the maximum and minimum clearing quantities of those bids, respectively by $\underline{\mu}_{k,n}^T, \bar{\mu}_{k,n}^T/\underline{\mu}_{k,n}^{n^I}, \bar{\mu}_{k,n}^{n^I}$ and $\underline{\delta}_{k,n}^T, \bar{\delta}_{k,n}^T/\underline{\delta}_{k,n}^{n^I}, \bar{\delta}_{k,n}^{n^I}$. A bid that imposes a minimum clearing requirement (which can capture technical requirements of its flexibility assets) is known as a partially divisible bid. If a bid $\mu_{k,n}^T/\mu_{k,n}^{n^I}$ or $\delta_{k,n}^T/\delta_{k,n}^{n^I}$ does not impose any minimum clearing requirement, then the corresponding elements $\underline{\mu}_{k,n}^T, \underline{\mu}_{k,n}^{n^I}, \underline{\delta}_{k,n}^T$ or $\underline{\delta}_{k,n}^{n^I}$ would be equal to 0. We introduce binary $\{0,1\}$ variables $\alpha_{k,n}^{\mu,T}, \alpha_{k,n}^{\mu,n^I}$, $\alpha_{k,n}^{\delta,T}$, and $\alpha_{k,n}^{\delta,n^I}$ which denote, respectively, whether bid $\mu_{k,n}^T, \mu_{k,n}^{n^I}, \delta_{k,n}^T$, or $\delta_{k,n}^{n^I}$ is accepted (0 for not accepted, 1 for accepted) at which point the minimum clearing requirement captured by $\underline{\mu}_{k,n}^T, \underline{\mu}_{k,n}^{n^I}, \underline{\delta}_{k,n}^T$ or $\underline{\delta}_{k,n}^{n^I}$ would be imposed.

We first introduce the DSO-level and TSO-level markets, which are the building blocks for introducing the market clearing problems for the *common* and *multilevel* markets.

DSO-Level and TSO-Level Markets

Each DSO-n^I aims at purchasing flexibility offered from its own system at minimum cost to meet its grid congestion management needs. For each DSO $n^I \in N^I$, we let

$$g^{n^I}(\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}) = \sum_{k\in U^{n^I}(n)} c_{k,n}^{\mu,n^I} \mu_{k,n}^{n^I} - \sum_{k\in D^{n^I}(n)} c_{k,n}^{\delta,n^I} \delta_{k,n}^{n^I}, \quad (1)$$

be the cost function of DSO-n^I. Then, the market clearing problem for each DSO-n^I can be formulated as follows:

$$\min_{\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}, \boldsymbol{\alpha}^{n^I}} g^{n^I}(\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}), \quad (2)$$

Subject to:

$$p_n^{n^I} = p_n^{o,n^I} - d_n^{o,n^I} + \sum_{k\in U^{n^I}(n)} \mu_{k,n}^{n^I} - \sum_{k\in D^{n^I}(n)} \delta_{k,n}^{n^I}, \forall n \in N^{n^I} \setminus n_0^{n^T}, \quad (3)$$

$$p_n^{n^I} = p_n^{o,n^I} - d_n^{o,n^I} + \sum_{k\in U^{n^I}(n)} \mu_{k,n}^{n^I} - \sum_{k\in D^{n^I}(n)} \delta_{k,n}^{n^I} + I_{n^I}, \text{for } n = n_0^{n^I}, \quad (4)$$

$$F_{ij}^{n^I} = \sum_{n\in N^{n^I}} p_n^{n^I} X_{(i,j),n}^{n^I}, \forall\{i,j\} \in L^{n^I}, \quad (5)$$

$$\sum_{n\in N^{n^I}} p_n^{n^I} = 0, \quad (6)$$

$$-\bar{F}_{ij}^{n^I} \le F_{ij}^{n^I} \le \bar{F}_{ij}^{n^I}, \forall\{i,j\} \in L^{n^I}, \quad (7)$$

$$\alpha_{k,n}^{\mu,n^I} \underline{\mu}_{k,n}^{n^I} \le \mu_{k,n}^{n^I} \le \alpha_{k,n}^{\mu,n^I} \bar{\mu}_{k,n}^{n^I}, \forall k \in U^{n^I}(n), n \in N^{n^I}, \quad (8)$$

$$\alpha_{k,n}^{\delta,n^I} \underline{\delta}_{k,n}^{n^I} \le \delta_{k,n}^{n^I} \le \alpha_{k,n}^{\delta,n^I} \bar{\delta}_{k,n}^{n^I}, \forall k \in D^{n^I}(n), n \in N^{n^I}. \quad (9)$$

The DSO-level problem minimizes the total flexibility procurement cost for DSO-n^I as can be seen in (2). Constraints (3) and (4) capture the net power injection at node n differentiating, respectively, whether or not n is a root node. The interface flow I_{n^I} is considered a constant input at this point (will become a variable in the *common* and *multilevel* market formulations). Constraint (5) computes the power flow over each line $\{i,j\}$. Constraints (6) and (7) capture the system's power balance constraint and line flow limits, which are used for congestion prevention and alleviation (congestion management). Constraints (8) and (9) capture the bid limits for upward and downward flexibility bids, respectively.

The TSO's market objective is to meet its flexibility needs for congestion management and the balancing of the grid at minimum cost. The TSO' cost function is captured by

$$g^T(\boldsymbol{\mu}^T, \boldsymbol{\delta}^T) = \sum_{k\in U^T(n)} c_{k,n}^{\mu,T} \mu_{k,n}^T - \sum_{k\in D^T(n)} c_{k,n}^{\delta,T} \delta_{k,n}^T. \quad (10)$$

As such, the market clearing problem for the TSO can be formulated as follows:

$$\min_{\boldsymbol{\mu}^T, \boldsymbol{\delta}^T, \boldsymbol{\alpha}^T} g^T(\boldsymbol{\mu}^T, \boldsymbol{\delta}^T), \quad (11)$$

Subject to:

$$p_n^T = p_n^{o,T} - d_n^{o,T} + \sum_{k\in U^T(n)} \mu_{k,n}^T - \sum_{k\in D^T(n)} \delta_{k,n}^T, \forall n \in N^T \setminus N^I, \quad (12)$$

$$p_n^T = p_n^{o,T} - d_n^{o,T} + \sum_{k\in U^T(n)} \mu_{k,n}^T - \sum_{k\in D^T(n)} \delta_{k,n}^T - I_n, \forall n \in N^I, \quad (13)$$

$$F_{ij}^T = \sum_{n\in N^T} p_n^T X_{(i,j),n}^T, \forall\{i,j\} \in L^T, \quad (14)$$

$$\sum_{n\in N^T} p_n^T = 0, \quad (15)$$

$$-\bar{F}_{ij}^T \le F_{ij}^T \le \bar{F}_{ij}^T, \forall\{i,j\} \in L^T, \quad (16)$$

$$\alpha_{k,n}^{\mu,T} \underline{\mu}_{k,n}^T \le \mu_{k,n}^T \le \alpha_{k,n}^{\mu,T} \bar{\mu}_{k,n}^T, \forall k \in U^T(n), n \in N^T, \quad (17)$$

$$\alpha_{k,n}^{\delta,T}\underline{\delta}_{k,n}^{T} \leq \delta_{k,n}^{T} \leq \alpha_{k,n}^{\delta,T}\bar{\delta}_{k,n}^{T}, \forall k \in D^{T}(n), n \in N^{T}. \quad (18)$$

The TSO's market clearing problem follows the same structure as that for the DSO. The main element of differentiation is (13), which applies to all interface nodes.

Common Market

The *common* market corresponds to a co-optimized, flexibility provision in which the needs of all SOs are jointly procured while abiding by the constraints of all grids involved. As such, the market clearing problem of the *common* market can be formulated as follows:

$$\min_{\boldsymbol{\mu},\boldsymbol{\delta},\boldsymbol{\alpha}} g^{T}(\boldsymbol{\mu}^{T}, \boldsymbol{\delta}^{T}) + \sum_{n^I \in N^I} g^{n^I}(\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}), \quad (19)$$

Subject to:

$$(3)-(9)\ \forall n^I \in N^I, (12)-(18), \quad (20)$$

$$\underline{I}_{n^I} \leq I_{n^I} \leq \bar{I}_{n^I}, \forall n^I \in N^I, \quad (21)$$

where (21) capture the upper and lower limits on I_{n^I}.

Multilevel Market

The *multilevel* market is a sequential market composed of two layers. In the first layer, each of the DSOs run their own DSO-level market as the one in $(2)-(9)$, but while being able to modify the interface flow. Subsequently, the second layer is run (which is the TSO layer) which enables the TSO to use TSO-level flexibility as well as any DSO-level flexibility that was unused in Layer 1 to resolve its own congestion and balancing needs while taking into account the changes in those needs caused by the results of Layer 1. Hence, this provides priority of access for DSOs to distribution-level flexibility, as local DSO grid needs can only be resolved using such locally available flexibility. As such, the *multilevel* market (including its two layers) can be formulated as follows.

Layer 1 (cleared for each DSO-n^I, $\forall\, n^I \in N^I$*):*

$$\min_{\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}, \boldsymbol{\alpha}^{n^I}} g^{n^I}(\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}), \quad (22)$$

Subject to:

$$(3)-(9) \text{ and } (21). \quad (23)$$

Layer 2 should take into account the updated state of the distribution networks in its market clearing formulation. In addition, distribution-level partially divisible bids should also be included in Layer 2 according to whether or not they were partially cleared in Layer 1.

Layer 2:

$$\min_{\boldsymbol{\mu},\boldsymbol{\delta},\boldsymbol{\alpha}} g^{T}(\boldsymbol{\mu}^{T}, \boldsymbol{\delta}^{T}) + \sum_{n^I \in N^I} g^{n^I}(\boldsymbol{\mu}^{n^I}, \boldsymbol{\delta}^{n^I}), \quad (24)$$

Subject to:

$$(3)-(7)\ \forall n^I \in N^I, (21) \forall n^I \in N^I, (12)-(18), \quad (25)$$

$$\left(1-\alpha_{k,n}^{\mu,n^I,*}\right)\alpha_{k,n}^{\mu,n^I}\underline{\mu}_{k,n}^{n^I} \leq \mu_{k,n}^{n^I} \leq \alpha_{k,n}^{\mu,n^I}\left(\bar{\mu}_{k,n}^{n^I} - \mu_{k,n}^{n^I,*}\right), \forall k \in U^{n^I}(n), n \in N^{n^I}, \quad (26)$$

$$\left(1-\alpha_{k,n}^{\delta,n^I,*}\right)\alpha_{k,n}^{\delta,n^I}\underline{\delta}_{k,n}^{n^I} \leq \delta_{k,n}^{n^I} \leq \alpha_{k,n}^{\delta,n^I}\left(\bar{\delta}_{k,n}^{n^I} - \delta_{k,n}^{n^I,*}\right), \forall k \in D^{n^I}(n), n \in N^{n^I}, \quad (27)$$

where in (3) and (4) of (25), the base load and generation profiles at the distribution nodes account for the flexibility procured in Layer 1. In other words, in (3) and (4), p_n^{o,n^I} and d_n^{o,n^I} are, respectively replaced by $p_n^{o,n^I,*}$ and $d_n^{o,n^I,*}$ defined as follows:

$$p_n^{o,n^I,*} = p_n^{o,n^I} + \sum_{k \in U^{n^I}(n)} \mu_{k,n}^{n^I,*}, \quad (28)$$

$$d_n^{o,n^I,*} = d_n^{o,n^I} + \sum_{k \in D^{n^I}(n)} \delta_{k,n}^{n^I,*}, \quad (29)$$

where $\mu_{k,n}^{n^I,*}$ and $\delta_{k,n}^{n^I,*}$ are, respectively, the cleared upward and downward flexibility from FSP k connected at node n in Layer 1 of the *multilevel* market. Constraints (26) and (27) capture the bid limits taking into account whether partially divisible bids have been cleared in Layer 1 (where $\alpha_{k,n}^{\mu,n^I,*}$ and $\alpha_{k,n}^{\delta,n^I,*}$ denote the output values of the binary variables from Layer 1), in which case the minimum clearing requirement would no longer be needed (set to 0) as this requirement is met through the result of Layer 1.

We next introduce several key factors affecting the efficiency of the *common* and *multilevel* markets, and showcase the two markets' sensitivity to those factors using a developed case study allowing their comparison.

EFFICIENCY COMPARISON: A CASE STUDY

We introduce a case study focusing on an interconnected transmission-distribution system. The transmission network is represented by the IEEE 14-bus system, which is connected to two distribution networks, represented by the Matpower 69-bus (DN_69) and 141-bus (DN_141) systems [9]. Two cases are created from this network, depending on the system balancing need. In case 01, base injections and loads of the nodes are adapted to create an anticipated negative imbalance (total load surpassing total generation) in the interconnected system, which is resolved by upward flexibility. In addition, the lines' upper limits are adjusted to create anticipated congestion in the networks. Upward and downward flexibility bids are randomly generated and allocated to the nodes. Their quantities are aligned with the nodes' base injection/load and their prices are in the range [10, 25] €/MW (for downward) and [30, 55] €/MW (for upward). One artificial large and expensive upward bid is allocated to each distribution network, to represent the cost of an out-of-market solution, i.e., if the bids in the market are not sufficient to resolve the congestion, the DSO would resort to another technical and probably more expensive solution to solve it. Case 02 is similar to case 01 with respect to network parameters and bids, except that the base injections and loads in the transmission nodes are swapped, creating a positive total imbalance and, hence, a downward cumulative flexibility need in the system.

We first analyze the impact of pricing the interface flow on the results of the *multilevel* market. As can be seen in the *multilevel* formulation, DSOs have an opportunity to clear additional downward flexibility in Layer 1 (up to reaching the interface capacity limit) to reduce procurement cost, even if no congestions in the system remain. This impacts the imbalance position in Layer 2 (in an un-priced manner for Layer 1), which has to be corrected using Layer 2's bids. To prevent or price the unnecessary purchasing of downward flexibility, three interface pricing methods were proposed in [4], to which we respectively refer as the "No change", "Midpoint", and

"Optimal" solutions: (a) The interface flow in Layer 1 is not allowed to be modified, requiring a balanced solution in Layer 1 – mathematically, constraint (21) captured in (23) is replaced by a constant; (b) the interface flow changes are priced according to the midpoint between the most expensive downward flexibility bid and the least expensive upward flexibility bid of each distribution system, where this pricing is added to the DSOs' objective function (22); (c) The interface flow changes are priced according to the optimal interface prices obtained by running the *common* market, and this pricing is added to the DSOs' objective function (22).

The *multilevel* market is run for each of the interface pricing methods and the results are shown in Table 1. It can be seen that the *common* market (as captured in the literature [4]) is more efficient than the *multilevel* market. However, adequate pricing of the interface flow can enhance the efficiency (i.e. reduce the cost) of the *multilevel* market, up to yielding a similar efficiency than that of the *common* market.

Table 1: Impact of pricing the interface flow in the efficiency of the multilevel market (values in €).

	Common Market	*Multilevel* Market			
		Original	No change	Midpoint	Optimal
Case 01	540.95	564.49	553.10	540.95	540.95
Case 02	- 9.22	12.69	- 0.43	- 9.22	- 9.22

Secondly, we next analyze the impact of the ability of FPSs to diversify their bids in the *multilevel* market. In this market, distribution-level FSPs participate in the two layers, and, in the original formulation, these participants submit one bid, such that any remaining quantity is forwarded from Layer 1 to Layer 2 at the same original bid price, as captured in (24) - (27). We consider two variations of distribution-level FSPs bidding rules in this sequential market: (a) Distribution-level FSPs make parallel, thus separate bids to the two layers (*multilevel_p*); and (b) distribution-level FSPs can change their bid price after observing the result of Layer 1, but their remaining quantity is automatically forwarded (*multilevel_s*). These variations have a direct impact on the *multilevel* market's efficiency, which we analyze next. To analyze the *multilevel_p*, we split the distribution-level bids' maximum quantities in two lists, keeping the same price in both. Then, we vary the price in Layer 1's list by a control percentage. The goal is to represent situations where the distribution-level FSPs

1) have lower marginal costs (due to, for instance, ease of market access in Layer 1), allowing them to reduce their bid prices in Layer 1 (range: -20% to -5%);
2) expect low competition in Layer 1 and/or that prices in Layer 2 will be lower, thus they can bid higher prices in Layer 1 (range: +5 to + 20%).

For the *multilevel_s*, the same variation of the distribution-level bid prices is performed, but while the remaining uncleared quantities in Layer 1 is bid in Layer 2 instead of having two separate lists. The total resulting cost for each of the *multilevel* market variations as compared to the *common* market is shown in Figure 1.

As expected, the *multilevel_s* intersects with the original *multilevel* if prices are kept the same (0% variation), while

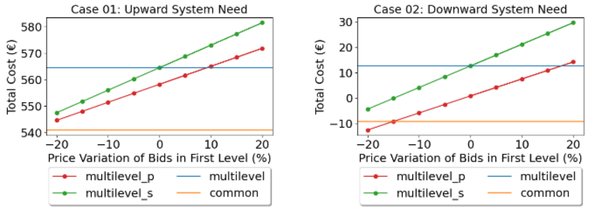

Figure 1: Impact of the bidding rule of the multilevel market in its efficiency. Left: case 01. Right: case 02.

the cost would be lower or higher (as compared to the original *multilevel*) depending on whether the distribution-level FSPs have an incentive to reduce their bid prices in Layer 1. Moreover, the *multilevel_p* returned a lower total cost than the other *multilevel* models in both cases, as splitting the bids' maximum quantity between two layers reduce the amount of downward flexibility available in Layer 1 to be purchased even after congestions have been resolved (see discussion on the interface pricing), hence reducing the total system cost. The *multilevel_p* can even become cheaper than the *common* if distribution-level FSPs have incentives to reduce their prices in Layer 1.

Thirdly, we analyze the impact of the markets differing entry requirements' on their efficiency focusing on the minimum bid quantity entry requirement. This requirement is applied to the markets with a transmission level (i.e., the *common* and Layer 2 of the *multilevel* markets) capturing the possibility of centralized markets requiring a higher minimum bid quantity requirement for participation. More specifically, we vary this requirement threshold from 0 to 2.5 MW, where bids with a maximum quantity lower than this threshold cannot participate in the *common* nor in Layer 2 of the *multilevel* (these bids are filtered out of those markets). Notice that the bids lower than the threshold can still participate in the distribution-level market (i.e., Layer 1 of the *multilevel*) representing a setting in which local markets exhibit lower bid entry requirements. The results of this entry barrier analysis are shown in Figure 2.

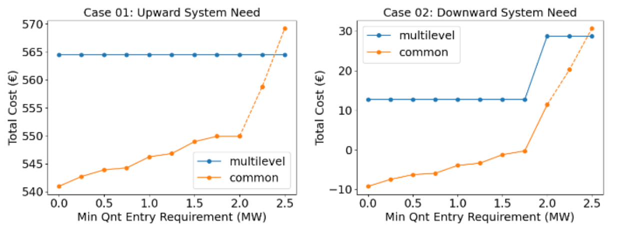

Figure 2: Impact of markets' minimum bid quantity entry requirement on their total cost. Left: case 01. Right: case 02.

As shown in Figure 2, the bid minimum quantity requirement has a bigger impact on the *common* than on the *multilevel* market, as the *common* market excludes small distribution-level bids from participating, which are, in this case study, better suited to solve the local congestions while helping in balancing the system. This entry barrier reaches an extreme case starting at a threshold of 2.0 MW (orange dashed line in plots), when no bid larger than the minimum requirement is available in the distribution systems, and their congestion is then solved using the artificial big bid (out-of-market solution). At this point, the *multilevel* can become more efficient than the *common*, given that its first layer (local congestion management) allows small bids to participate.

Finally, we analyze the impact of bids' own minimum clearing requirement (captured through partially divisible bids) on the efficiency of the two markets. For this analysis, we apply a percentage of the bids maximum quantity (ranging from 0 to 50%) to represent their minimum clearing requirement. In the case study, we consider that only bids with maximum quantity greater than 1.5 MW can be partially divisible. These modified sets of bids are then submitted to the *common* and *multilevel* markets, and the results are shown in Figure 3.

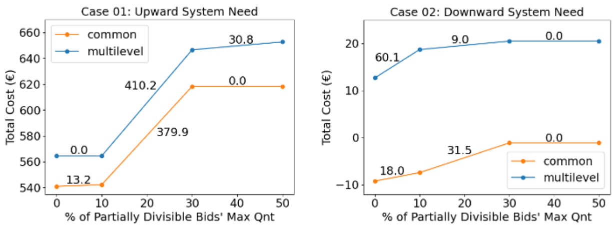

Figure 3: Impact of partially divisible bids minimum clearing requirement on the efficiency of the market models. The numbers on the lines represent the slopes. Left: case 01. Right: case 02.

As can be seen, partial bid divisibility impacts both markets, as a bid that was used for congestion management or balancing can become too expensive due to its minimum clearing requirement. For example, in the *common* market of case 01, two bids in the transmission system are selected when they have 0 minimum clearing requirement, as they are positioned in the network in a way to solve both congestion and balancing needs in the most efficient way. When the minimum clearing requirement of those bids is increased to 10% of their offered quantity, the solution still selects both of them, but with a higher volume (to respect their clearing requirement), thus increasing the market cost. When this requirement is increased to 30%, another more expensive bid (but with a lower clearing requirement) is chosen instead, which explains the high increase from 10% to 30% for case 01. For the *multilevel* market, the impact is mostly higher (see slopes of blue curves in Figure 3), as the congestion need of the distribution system is solved separately (in Layer 1), and a cheap partially divisible bid, which would have been able to solve congestion and balancing together, has now a minimum clearing requirement that is preventing it from being selected in the separate layers of the *multilevel* market. In other words, the effects of partitioning the flexibility needs of the two systems due to the split in two layers, can be exacerbated by the introduction of partially divisible bids.

CONCLUSIONS

This paper has introduced mathematical models for two commonly implemented DSO-TSO coordinated flexibility market models, namely: the *common* and the *multilevel* markets, which have then been used through a structured case-study to analyze and compare their efficiencies. The results have showcased how (i) the TSO-DSO interface pricing, (ii) the ability of FSPs to bid differently in sequential markets, (iii) the different entry barriers that each of the market models can induce, and (iv) the bid formats and inclusion of partially divisible bids can have a direct impact on the efficiencies of the two markets, driving either their convergence or divergence. The results highlight the main drivers and efficiency challenges for each of the market models, hence, providing key insights on the practical effects of their implementation.

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