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Cross-border DSM as a complement to storage and RES in congestion management markets

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ABSTRACT

This paper proposes a regional congestion management (CM) market framework based on the cross-border use of demand-side flexibility resources, focusing on flexible load connected or aggregated at the transmission level, but also considering flexibility of storage and renewable energy sources (RES). It compares the CM potential of national and cross-border resources in an interconnected transmission system in South-East Europe (SEE). The studies observe the role of location, flexible capacity, availability and type of resource, as well as the cost of congestion elimination, on the effectiveness of CM. The cost-effectiveness of CM is critically assessed based on a bid selection algorithm that considers different bidding scenarios, predefined line flow reduction on a critical line, as well as the operating constraints of the transmission network.

1. Introduction

Power system ancillary services are required for balancing generation and load and managing power flows and voltages within given constraints. The integration of variable renewable energies in power systems and the introduction of strict requirements for their secure operation have put forward the need for additional ancillary services providers, besides conventional generators. In this context, demand side management (DSM) can provide a significant contribution, along with other flexible resources, such as storage (STO) systems and generation flexibility, including renewable energy sources (RES). The use of DSM for provision of ancillary services has been enhanced by the development of control and communication technologies. Nowadays, DSM is among the most looked upon solutions for ensuring system stability and reliability under conditions of high penetration of non-synchronous generators, which are essential for achieving the goal of decarbonisation. The European Commission estimated a (theoretical) DSM potential of 100 GW in 2016, and about 160 GW by 2030 [1]. About half of this potential is expected to come from commercial and domestic end-users, in addition to currently participating industrial users.

1.1. Literature review

One of the main DSM classifications recognises incentive-based (explicit) and price-based (implicit) DSM programmes. Explicit programmes promote changes in electricity use by customers in response to a requirement from an aggregator/retailer or system operator. As a reward for their response to the request, the customers receive an incentive (payment or credit), separate from their electricity rate [2]. Explicit DSM enables demand to participate in the wholesale, balancing and ancillary services markets, as described in the survey in [3]. Price-based (implicit) DSM programmes also envisage adjustments in electricity use by customers, but these are motivated by the electricity price change [2]. The main impediments for fully harnessing DSM potential have been identified in slow market integration and regulatory barriers [4,5]. Having in mind that generators have traditionally been providers of flexibility in power systems, the market requirements and products have been developed according to their capabilities. In order to attract demand-side resources to the markets, some market participation requirements, such as oversized minimum bids (>1MW), extended duration or availability requirements, high frequency of activations and short recovery periods, as well as symmetric bids [3,6], should be reconsidered. Overcoming these barriers should enable explicit DSM to compete in all market timeframes: day-ahead (DAM), intraday (IDM) and balancing (BM) markets, as well as in capacity mechanisms, either as single or aggregated load. The aggregators, as intermediaries between the consumers (or prosumers) and electricity markets, have become enablers for market integration of DSM [7]. The value of flexibility

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becomes higher for timeframes closer to real time [8], which makes DSM especially attractive for balancing and ancillary services. Furthermore, DSM can be used to provide voltage and frequency support and alleviate congestion [9–11], an increasingly important phenomenon for power system operators. Congestion is the result of limited transfer capability, which further depends on power flow limits, voltage magnitudes, generator reactive power capabilities and transient stability [12].

1.2. Research gaps

In the past, congestions in transmission networks occurred mostly at the interconnections. Therefore, transmission system operators (TSOs) have established procedures for cross-border CM [13]. These procedures aim to prevent congestions by performing calculation and allocation of cross-border transmission capacities and congestion forecast. However, congestions can still occur and should be eliminated in real time by corrective actions such as network topology changes or by using FACTS devices [14]. In most cases, adjustments in power injections (generation/load) at certain nodes in the network are required to eliminate congestions [15,16]. Furthermore, due to the increased uncertainties related to the transition towards clean energy, congestions may occur more frequently and even in the distribution networks [17]. System operators do not own the required resources for congestion elimination, and they should contract providers of ancillary services for CM using a market-based procurement method. For example, market-based CM at transmission level, proposed in [18], uses aggregation of dispersed small-scale consumers, producers and prosumers in distribution network. At the distribution level, the concept of flexibility markets is introduced to allow distribution system operators to procure flexibility services, including services for CM [19–21]. The regional integration of electricity markets has shown that the increased competition and pooling of resources leads to reduced costs of power system operation and increased efficiency in the use of resources [22]. The existing EU regulatory frameworks support the development of regional markets, but there are still some barriers for participation of flexibility resources related to the requirements of the organized markets [3,23], and the security of the power system [12].

1.3. Main contributions

This paper aims to illustrate how the integration of DSM, in addition to other flexibility resources, into the electricity markets, especially those operating in close to real time, acts as an efficient tool for CM. An attempt to show this has been made in the EU H2020 project CROSSBOW [24], by developing an innovative DSM integration platform (DSM-IP) [25]. The platform comprises of communication interfaces for monitoring and control of dispatchable (flexible) loads, advanced algorithms for optimal, coordinated control of DSM assets for improved power flows and network operability in the presence of high penetration of RES, as well as interfaces with regional control centres, TSO-DSO coordination platform, and applications for business and market actors. This paper relies on the DSM-IP functionalities to investigate the cross-border use of both, aggregated local distributed DSM assets and large (industrial) DSM assets connected directly to the transmission network. It addresses a number of critical factors for the participation of DSM and other flexible resources (STO and RES) in CM markets, including their location, size, availability and type, as well as the cost of congestion elimination. It should be noted that CM in this paper considers only steady state real power flow limits of the lines, as the observed DSM assets can provide only real power capability. The main contributions of the paper can be summarised as follows:

- A regional CM market framework is proposed based on the DSM-IP principle of eliminating congestion in the network by using the available flexibility resources at regional level, with minimum costs.
- The paper analyses, in a critical manner, the cost- effectiveness of using DSM and STO flexibility for CM at national and regional level. Participation of RES has been explored as an additional source of flexibility, while the flexibility of conventional generators is not considered.
- The analyses rely on a representative model of a real interconnected power system in South-East Europe (SEE) and consider network operating limits and realistic assumptions about the available flexibility. Real data, obtained from the regional TSOs, were used to develop the representative network model in DIgSILENT/PowerFactory and determine the flexibility of industrial end-users.
- The case studies are based on future developments (10-year horizon), relying on the data collected through surveys among the TSOs in the observed region. The data have been analysed to provide realistic assumptions regarding demand growth, expected flexibility of distribution networks, as well as the penetration level of renewables and their location.
- The methodology developed in the paper can be replicated to other regions, and further extended to regional balancing markets.

1.4. Paper structure

The remaining of the paper is organised as follows. Section 2 introduces the proposed congestion management market framework, including the bid selection algorithm. Section 3 describes the operating scenarios and the test network. Results are presented in Section 4 and discussed in Section 5. Section 6 concludes the main findings of the paper.

2. The proposed congestion management market framework

2.1. Market timeframe and basic principles

The aim of the regional CM market framework is to minimise the cost of CM by using available flexibility resources. The CM market should enable adequate activation of flexibility resources throughout the network to eliminate congestion. It should also follow the principles of transparency, competitiveness, and cost effectiveness. A regional CM market contributes to increased competitiveness as it allows participation of flexibility providers at a cross-border level. The existence of a large pool of providers and their diversity will increase the cost effectiveness in the provision of services to TSOs. Providing clear rules and access to different providers under equal conditions guarantees the transparency of the congestion elimination process. Participation in the CM market may be an attractive option for various providers of flexibility such as DSM, STO and RES owners, and even for some conventional producers. The providers of flexibility should undergo a prequalification process to participate in the market. This process ensures that all candidate providers have the technical capabilities to respond to the requests of the TSOs.

The proposed timeframe of CM markets is presented in Fig. 1, based on [26] and the principles of operation of the balancing markets [21]. Two different processes can be identified: i) reservation of capacity (reserve capacity market), and ii) activation process (energy market). The reservation of capacity for CM can be done on a long-term basis

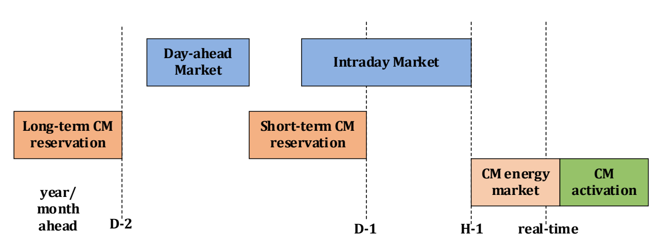

Fig. 1. Proposed CM market timeframe.

(yearly or monthly) if the TSO foresees occurrence of congestions in the network in its long-term analyses. Additional reservation of capacity for CM can be done on the short-term CM capacity market which opens after the closure of the DAM. Since the DAM positions of the market players are known, more accurate congestion forecast can be done, enabling an improved assessment of the available flexibility for CM from the providers. The procedure for reservation of capacity for CM is similar to capacity reservation for balancing. It consists of an auction where multiple flexibility providers bid for receiving a payment for availability.

This paper focuses on the CM energy market, where the selected capacity providers from the CM capacity market should provide bids in the CM energy market along with other flexibility providers. The possibility to include flexibility providers, other than the reserved ones, in the CM energy market contributes to increased competitiveness and decreased costs of congestion elimination. The market clearing procedure is performed in real time. If a congestion occurs, appropriate flexibility assets are selected to mitigate the congestion. Apart from price, the location of the candidate flexibility assets, power network parameters and topology play a significant role in the selection of the appropriate bids. In the CM market, simultaneous activation of bids for upward and downward regulation is needed at different locations in the network (nodes). The need for more input data and the increased complexity of the bid selection procedure has led to a delayed development of CM markets compared to the balancing markets. However, there is extensive ongoing research for the possibilities of combined or fully integrated CM and balancing markets [26].

2.2. The bid selection algorithm

The bid selection algorithm, illustrated in Fig. 2, requires the following input data:

- bids for flexibility – including available capacity, direction (upward and downward), price for activated energy (e.g., EUR/MWh), and location of the assets providing flexibility in the transmission network (node of connection);
- equivalent model of the regional transmission network – the model should include not only the network parameters and topology but also the injected power at the nodes (resulting from the power flow or state estimation).

For the given operating point, the algorithm selects the bids that will enable reduction of the power flow at the congested lines, while not causing congestion at other elements in the network and with the minimal total cost of activation. The selection of bids becomes a minimization of the overall cost (1) subject to inequality constraints with respect to the maximum flexibility (upward or downward) of each resource (1a) and maximum line loading (1b), and equality constraint with respect to the required reduction of the line flow Δ_L (1c).

$$min\left\{\sum_i c_i|\Delta P_i|\Delta t\right\} \tag{1}$$

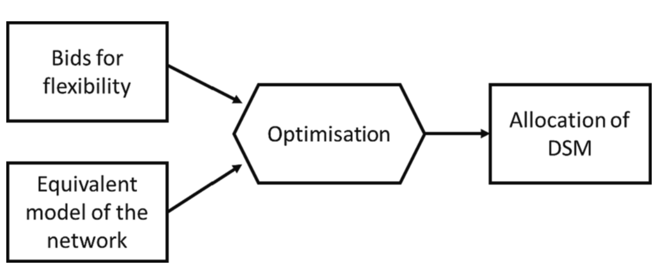

Fig. 2. Flowchart of the proposed CM market framework.

Subject to:

$$\Delta P_i^{min} \leq \Delta P_i \leq \Delta P_i^{max} \tag{1a}$$

$$\left|P_j - \sum_i DF_{ji}\Delta P_i\right| \leq P_j^{max} \tag{1b}$$

$$\sum_i DF_{Li}\Delta P_i - \Delta_L = 0 \tag{1c}$$

The algorithm, as one of the functionalities of DSM-IP, minimizes the overall cost, while ensuring that the flexibility limits are not breached, and that the simultaneous manipulation of flexible resources would result in the desired reduction of line flow Δ_L without overloading other lines in the system. c_i is the price of activated energy of bid i over the period Δt (in this paper, assuming it is one hour), ΔP_i is the increased/decreased amount of power of the asset(s) from the bid i, ΔP_i^{min} and ΔP_i^{max} are the limits of the offered flexibility, which may be time dependent, i.e., change in every time step (every hour), P_j is the flow of line j before congestion management, P_j^{max} is the maximum power capacity of line j, and DF_{ji} is the distribution factor (DF) between the asset i and the line j. DF, which is based on the DC transmission network model [27], is defined as follows:

$$DF_{ji} = \frac{\Delta f_j}{\Delta PI_i} \tag{2}$$

where Δf_j is the change in real power flow along line j following a change in power injection at bus i, ΔPI_i. DF can be positive or negative, depending on the location of the flexible asset, with reference to the observed line and the direction of the real power flowing along that line. DF does not depend on the operating point but on the topology of the network.

To achieve a reduction in line flow, Δf_j should be positive, which means that for a positive DF, injection at bus i would have to be increased and vice versa. This is especially important when deciding the direction of the change in injection at buses with flexible resources, as some resources generate power while others consume it. Following the definition of the DF (2) and the sensitivity-based methodology described in [12], each line in the system will have its ranking list of the most effective flexibility assets for CM, based on the expected line flow reduction for that line (Δf_j). If, relying on (2), we define the effectiveness ($\mathscr{E}$) of DSM-based CM as the change (reduction) in real power flow along the line (3), and the cost of CM as (4), then the ratio between effectiveness and the cost (i.e., the cost-effectiveness) can be defined as in (5). Following the execution of the bidding algorithm, this ratio expresses the power reduction (in MWs) per one monetary unit (MU). A reciprocal ratio shows the amount of MUs to achieve a certain CM effectiveness. The benefit of using these ratios, when individual flexibility resources are observed, is that they are based solely on the information about the location (*DF*) and the price of the bid (*c*) - no information about the available flexibility is needed. When multiple resources are used in a coordinated way, the cost-effectiveness becomes as shown in (6) – in this case, flexibility is included in the expression.

$$\mathscr{E} = DF \bullet \Delta PI \tag{3}$$

$$C = c \bullet \Delta PI \tag{4}$$

$$\mathscr{E}/C = DF/c \tag{5}$$

$$\mathscr{E}/C = \frac{\sum_i(DF_i \bullet \Delta PI_i)}{\sum_i(c_i \bullet \Delta PI_i)} \tag{6}$$

3. Operating scenarios and the test network

With the aim to illustrate the benefits of regional (cross-border) use of demand-side flexibility in CM, simulations are performed on a representative model of a 158-bus power system consisting of four neighbouring countries (areas) in the SEE region, shown in Fig. 3. The transmission network in the region is well developed with 16 interconnections between the neighbouring systems. At present, these systems do not face frequent congestions. However, with the anticipated transition towards clean energy, with higher RES penetration and increased demand at the distribution level, congestions are likely to become a frequent and important issue. Table 1 shows the present and future (a 10-year planning horizon) RES penetration in the four countries of SEE, based on the feedback received from the regional TSOs. The penetration is calculated as the share of RES in the total installed generation capacity in the observed system. The changes in RES penetration level (in %) result from new wind and solar power plants on one side (11 solar plants and 23 wind power plants in total), and shutting down some of the thermal power plants in the region on the other. Most wind power plants are installed in area 3, while most PV plants are in area 4. The "present" penetration level in Table 1 was observed at the beginning of the CROSSBOW project (in 2017–2018), hence this paper focuses on the future RES penetration level.

Flexible demand-side assets (loads and storage in the form of pump hydro power plants) in the observed system are listed in Table 2. There are 36 assets expected to be available as flexibility resources in the future (10-year planning horizon), while the highlighted ones in the table (12 in total) refer to the present flexibility. The IC index refers to industrial customer, DN represents aggregated demand-side flexibility of a distribution network, and STO refers to storage. In this paper, "limited flexibility" refers to the present situation (12 DSM and STO assets, with 670.5 MW flexible capacity in total), while "full flexibility" corresponds to the expected, increased flexibility in the SEE region, with 36 assets and 1659 MW flexible capacity in total. In order to capture future operating conditions, where congestions occur more frequently in the observed network, case studies will assume high RES penetration level (14 %, as presented in Table 1) and increased demand at the distribution level. Under such conditions, several lines in the system are overloaded, among which four will be observed, as listed in Table 3 and marked in Fig. 3 with thick black lines. (Note: Further details about the network parameters cannot be provided due to confidentiality reasons).

The case studies investigate the technical and market aspects of the participation of flexibility resources in CM. The technical aspects do not

Table 1
RES Penetration in SEE Region at present and in the Future.

Renewables	Penetration level	
	Present	Future
Wind	718 MW/4 %	2112 MW/12 %
Solar	0 MW/0 %	434 MW/2 %
Total	718 MW/4 %	2546 MW/14 %
Flexible assets (DSM + STO)	670.5 MW	1659 MW

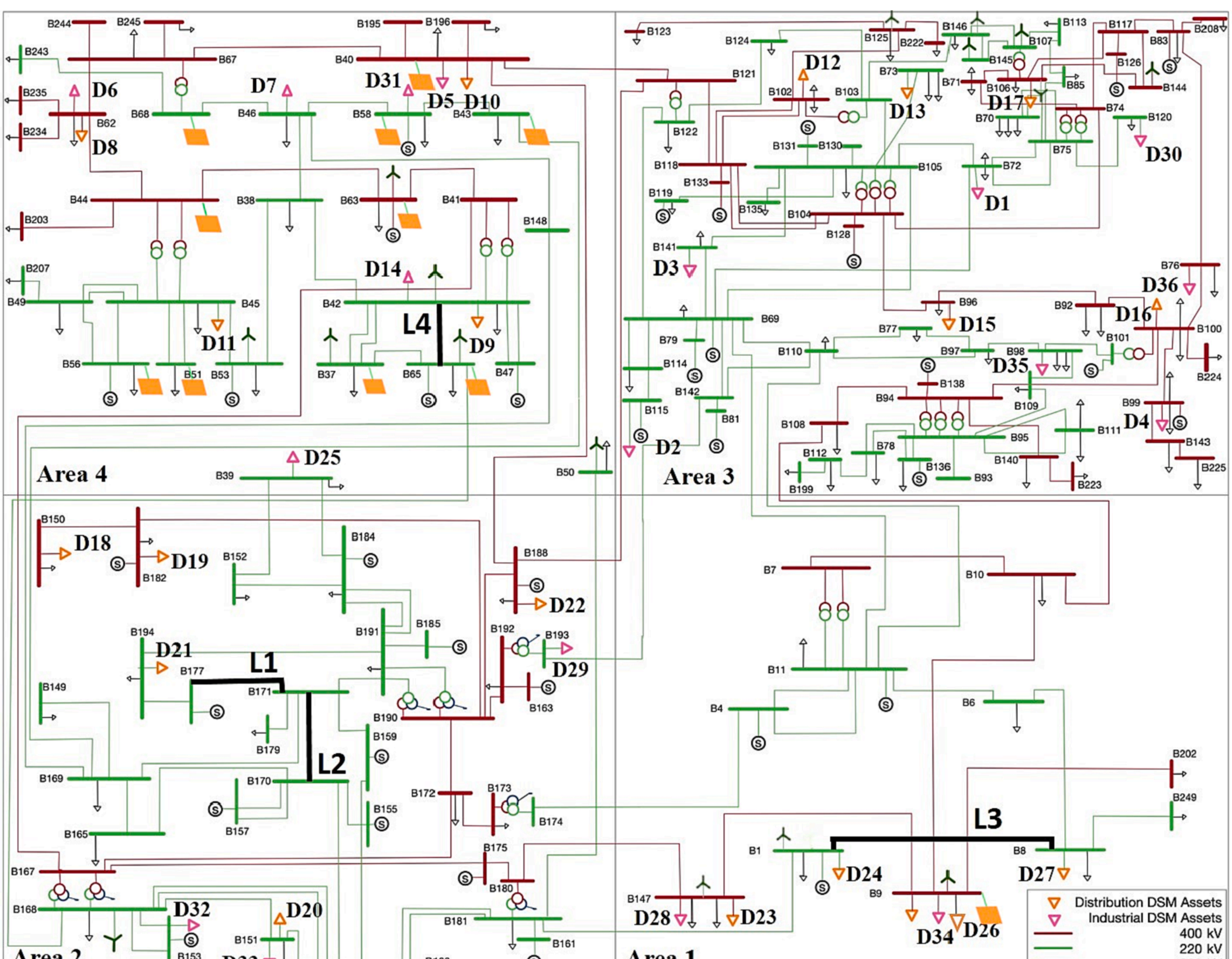

Fig. 3. Representative network single line diagram.

Table 2
DSM and Storage Assets and Their Flexibility.

Asset name	Flexibility (MW)	Asset name	Flexibility (MW)	Asset name	Flexibility (MW)
D1_IC	**30**	D13_DN	181	**D25_IC**	**9**
D2_STO	**280**	**D14_IC**	**20**	D26_DN	35
D3_IC	**4**	D15_DN	51	D27_DN	24
D4_IC	**24**	D16_DN	70	D28_IC	16
D5_IC	**8**	D17_DN	83	D29_IC	12
D6_IC	6	D18_DN	78	D30_IC	5
D7_IC	5	D19_DN	32	D31_IC	7
D8_DN	80	D20_DN	30	**D32_STO**	**220**
D9_DN	29	D21_DN	32	**D33_IC**	**20**
D10_DN	68	D22_DN	29	**D34_IC**	**50**
D11_DN	20	D23_DN	15	**D35_IC**	**5**
D12_DN	78	D24_DN	2	**D36_IC**	**0.5**

Table 3
Congested Lines.

Line name	Area	Line flow	Loading before CM
LN187 (L1)	2	412 MW	137 %
LN182 (L2)	2	304 MW	101 %
LN1 (L3)	1	290 MW	96 %
LN25 (L4)	4	268 MW	90 %

consider the bid selection algorithm and include:

1) CM potential of national vs regional resources, to assess the benefits of regional integration of the CM market.
2) CM potential of different flexibility technologies (DSM, STO and RES) is compared for the SEE system to identify potential gaps in their development.
3) Contributions of small (<50 MW flexible capacity) and large DSM flexibility providers are compared to assess the need for participation of small users.

Market aspects rely on the bid selection algorithm and comprise the following:

1) The cost-effectiveness of different flexibility technologies for CM is compared under probabilistic prices to evaluate the benefits of each technology when two constraints of the bid selection algorithm, namely (1b) and (1c) are not considered.
2) The cost of CM is compared under different pricing schemes for RES, DSM and STO, taking into account the bid selection algorithm.

The market aspects consider real-life conditions, where most flexible units can provide flexibility in one direction only, depending on their operating mode (e.g., a flexible load operating at full capacity can only be curtailed, not increased, while a discharged storage unit can only be charged). In addition, it is assumed that RES units are either generating at full capacity or not generating at all, depending on the local weather or maintenance. This leads to limited availability of the flexibility providers for CM. The availability is determined based on the operating mode of the unit and the sign of the DF between the unit and the congested line. In order to simulate these realistic conditions, the operating mode of each flexible asset is chosen randomly: flexible loads can be either consuming power or not (hence their load can be either reduced or increased, respectively), while STO units are either charged or discharged (hence, they can either discharge or charge, respectively). Generation of the RES units can only be curtailed if they are generating, otherwise, if they are not generating, they cannot bid. It should be noted that the randomly chosen combination of availabilities of all flexible resources is the same in all the three bidding cases to facilitate comparison between the results.

4. Results

4.1. Participation of flexibility resources in congestion management: Technical aspects

4.1.1. National vs cross-border use of flexibility resources for efficient CM

The effectiveness of CM for L1 in area 2 (see Fig. 3), with national only and cross-border flexibility resources, is shown in Fig. 4.

The figure illustrates the expected line flow reduction of L1 following a coordinated (concurrent) control of the 10 most influential flexible assets (DSM, STO and RES) for this line (based on the ranking list generated using the sensitivity analysis [12], as mentioned in Section 2.2). It is clear that in the case of cross-border use of resources, a smaller amount of procured flexibility (about 700 MW) yields a significantly larger line flow reduction (almost 250 MW) compared to the national resources only (up to 1100 MW of flexibility required for about 5 MW line flow reduction). This emphasises the effectiveness of cross-border procurement of flexible resources for CM.

A summary of procured flexibility and the corresponding line flow reduction for the four observed lines is given in Fig. 5, where for L2, same as for L1, smaller flexibility (and hence the cost) yields much larger line flow reduction when cross-border resources are used. L3 can have a significant line flow reduction with cross-border assets compared to national resources, however more cross-border flexibility needs to be procured for this. In the case of L4, both national and cross-border resources result in similar congestion alleviation, but only when a significant portion of national-level flexibility is procured (around 2000 MW, instead of around 500 MW of cross-border flexibility). Therefore, the cost of flexibility procurement for CM services is expected to be lower when transnational resources are used instead of national only.

In a more realistic scenario, where only DSM and STO are used (curtailment of RES for the provision of CM is not a desirable option as it impedes the low carbon operation of the power network), the CM potential of the flexibility resources drops visibly (up to about three times), as shown in Fig. 6. The possible line flow reduction is still higher when using cross-border resources, however, the required flexible capacity is

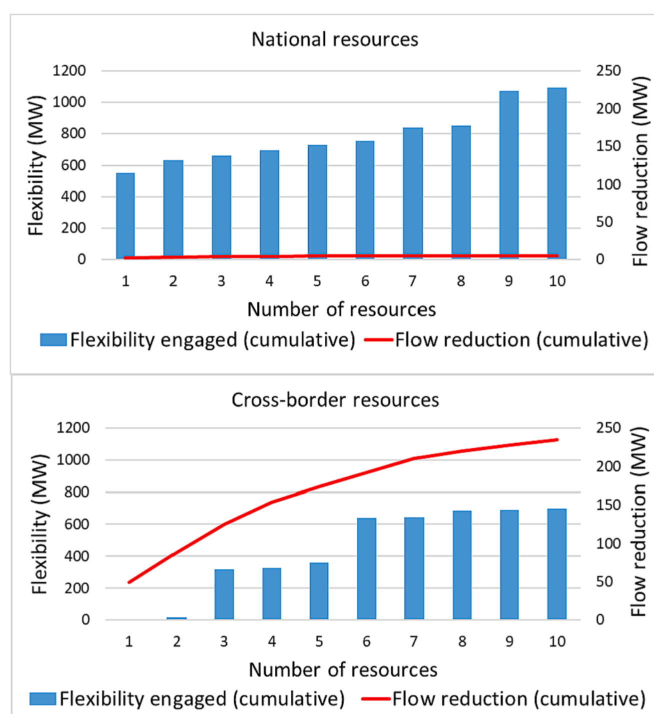

Fig. 4. The change in cumulative line flow reduction of L1 with national (top) and cross-border resources (bottom) when DSM + STO + RES are used.

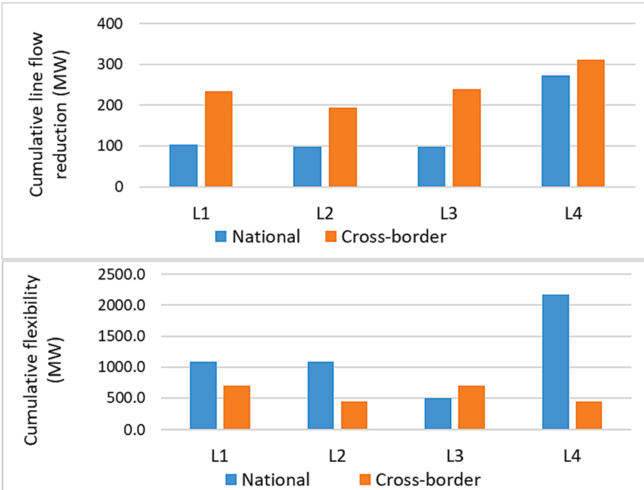

Fig. 5. The change in cumulative line flow reduction with national (top) and cross-border resources (bottom) when DSM + STO + RES are used.

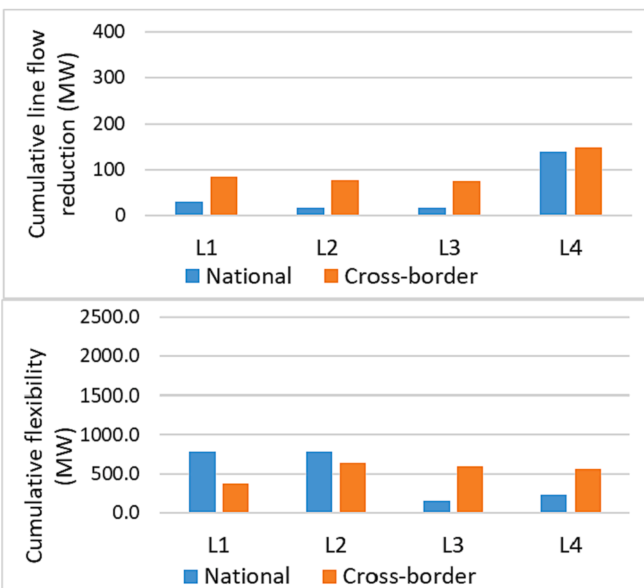

Fig. 6. The change in cumulative line flow reduction with national (top) and cross-border resources (bottom) when DSM + STO are used.

often higher as well (L3 and L4). Even though the observed lines are surrounded by distributed DSM and STO assets (Fig. 3), their flexible capacity may not be sufficient for CM. The SEE system should therefore have higher penetration of DSM and STO assets to enhance the effectiveness of CM if RES do not participate.

4.1.2. CM potential of different flexibility technologies in the SEE region

A similar analysis, with respect to the expected line flow reduction when using the first 10 most influential flexibility resources, for all the lines in the observed system is shown in Fig. 7. The range of cumulative line flow reduction with limited and increased flexibility (i.e., with present and future number of flexible DSM and STO assets, as well as including RES) shows that the CM effectiveness with the expected future DSM flexibility improves visibly only for some lines (as the distribution of the values is very similar in the left and middle figure). The maximum line flow reduction reaches 700 MW with full flexibility, while it is <600 MW for limited flexibility. If, however, RES units are added as flexible resources (the figure on the right), possible line flow reduction is

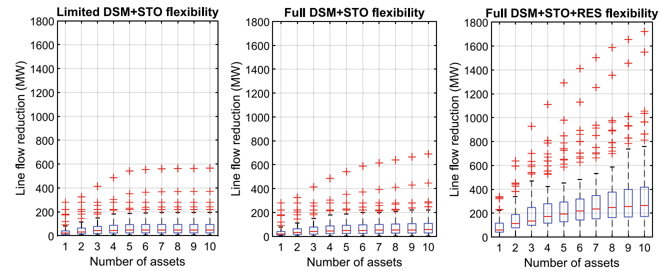

Fig. 7. Range of line flow reduction for all lines in the system, with full and limited DSM + STO flexibility, and full DSM + STO + RES flexibility.

up to three times higher (almost 1800 MW, though this value should be adopted as theoretical since the power flows in the system do not reach such a high level and no power flow reduction of that extent would be required). The figure illustrates that, even with the expected increase in flexibility, DSM and STO will still have much lower CM potential than the RES, whose total estimated flexible capacity is around 50 % higher. This emphasises the need for higher penetration of DSM (i.e., more flexible loads connected directly to the transmission network or aggregated within the distribution network) and STO if these resources are to be used for CM.

4.1.3. Potential for CM of large and small flexible units

When assessing the DSM potential for CM, both large and small units should be considered. Different countries have different minimum bid size requirements (e.g., between 2 MW and 55 MW for the interruptibility schemes in some EU countries [28]). Fig. 8 illustrates the contribution of small and large DSM and STO assets in the overall line flow reduction, taking the top 10 ranked assets for each of the four congested lines. As seen in the figure, the small assets contribute visibly to CM (between 31 % and 50 %). This clearly shows the importance of smaller flexible units in CM (individual or aggregated), and a great potential for their participation in CM markets.

4.2. Participation of flexible resources in congestion management: Market aspects

4.2.1. Cost-effectiveness of different flexibility technologies in CM markets

The cost-effectiveness of DSM, STO and RES, as defined in (5) for individual assets, for the four lines is compared in Fig. 9, across a range of bids. Considering the high volatility of bid prices in the market [28,29], one hundred Monte Carlo simulations were run to simulate a range of possible combinations of bids, between 1 and 10 MU with uniform distribution (where 1 MU may refer to, for example, €30). As seen in the figure, for most assets with different bidding scenarios, the cost-effectiveness for CM does not change much, however for each observed line (L1–L4) there are some RES and/or DSM assets whose cost-effectiveness varies significantly. It should be noted that the two STO units have the largest flexible capacity among all the individual assets, however their cost-effectiveness may not be favourable for CM,

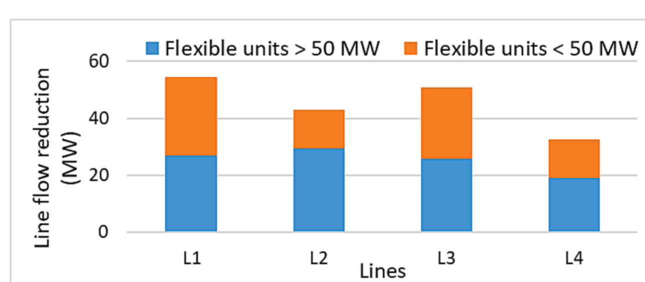

Fig. 8. Contributions of small (<50 MW) and large (>50 MW) DSM and STO units in congestion management.

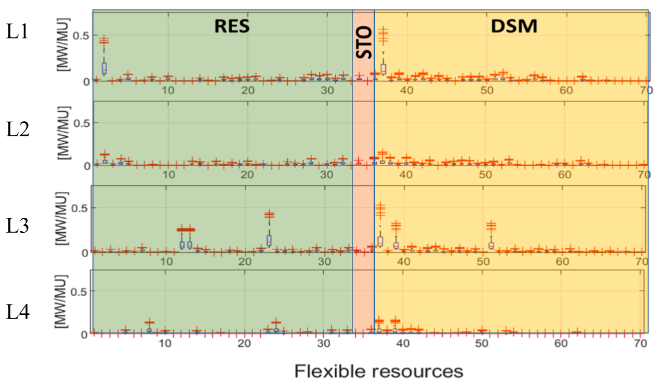

Fig. 9. Distribution of $\mathscr{E}/C$ values for RES, STO and DSM units, taking into account different bids.

especially in some bidding cases.

4.2.2. The cost of CM in a market environment

The rest of the analyses consider the bid selection algorithm (Section 2.2), where different flexible providers have different bid prices. In order to simplify the approach by disregarding real bid prices as they are highly volatile, three cases are observed, as shown in Table 4, illustrating different ratios (rather than absolute values) of bid prices where one of the three types of flexibility resources has a higher cost. All the assets of the same type of technology are assumed to have the same bid price. Fig. 10 illustrates the share of different technologies in the line flow reduction for the bidding case 1 from Table 5 for two scenarios: 1) with full (theoretical) availability, assuming that each flexible resource can provide both, downward or upward flexibility and 2) with limited (realistic) availability of the flexible units, as described at the end of Section 3. The bid selection algorithm assumes that the desired reduction of line flow Δ_L, defined in (1c), is 50 MW. Fig. 10 also shows the percentage of used flexibility (based on the total theoretical flexibility) and the cost (in MU) to achieve the desired flow reduction for each line. The figure illustrates that the shares of different flexibility providers change for some lines, as well as the resulting cost of the service.

In the theoretical case, assuming all flexible assets are available, CM for all lines is fully provided by RES (though only about 10 % or less of total RES flexibility is deployed). In the more realistic case, STO units are used for L1–L3 (about 45 % of the total STO flexibility) due to their lower bid price compared to DSM. The cost of the service increases for all lines when realistic availability is considered (bottom of Fig. 10), as more STO flexibility needs to be engaged. Although the cost-effectiveness of individual STO assets was lower than RES and DSM (see Fig. 9), the results in Fig. 10 reflect a more realistic situation with limited availability of flexible assets and network constraints described by (1a)–(1c).

In the second bidding case from Table 4, where RES have the highest bid price, more flexible capacity has to be procured, with participation from all the three types of flexibility (see Fig. 11). A significant portion (up to 40 %) of DSM flexibility is used for L1-L3 in the theoretical case, however in the realistic conditions, STO is predominantly used. When realistic availability is considered, and less DSM assets are available, more RES units have to be engaged, hence increasing the overall cost of CM. This again implies the need for higher flexibility of DSM and STO,

Table 4
Bids for CM.

	DSM price (MU/MW)	Storage price (MU/MW)	RES price (MU/MW)
Case 1	10	1	1
Case 2	1	1	10
Case 3	1	10	1

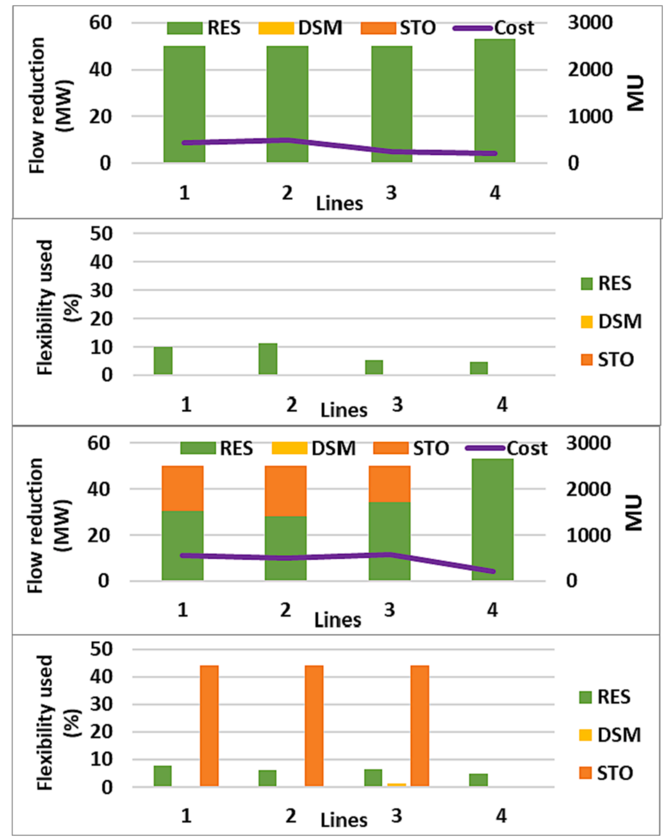

Fig. 10. Contributions of DSM, STO and RES in line flow reduction, bidding case 1; Top: full availability of flexible assets, Bottom: random availability of flexible assets.

which are already distributed around the observed lines, to reduce the requirement for RES curtailment for efficient CM.

In the third bidding case, presented in Fig. 12, the RES remain the main providers of CM, with slightly increased cost in real-life conditions. In this scenario, STO assets do not participate due to their high price, while the engagement of DSM is very limited as the flexible capacity of DSM is smaller than RES capacity in the electrical vicinity of the observed lines.

Finally, a comparison of the total cost and cost-effectiveness of CM is made in Table 5, based on the three bidding cases from Table 4 ("T" refers to the theoretical value, while "R" represents a realistic value, corresponding to limited availability of resources). The case with the highest cost is the one where RES curtailment has the highest bids price due to a significant increase in procured flexibility. The cost is three to five times higher in this case than in the other two, where the cost is often very similar. This shows the necessity for harnessing more flexibility from other resources (DSM and STO) that would enable higher penetration of RES in the future and reduce the cost of CM.

Although using national resources only should enable 50 MW line flow reduction for each line independently, as shown in Fig. 6, no feasible solution in this case could satisfy the constraints of the bid selection algorithm described in (1). Therefore, if national resources were used, they could achieve the predefined 50 MW line flow reduction, however at least one line in the system would be overloaded as a result of this. For this reason, the cost of CM with national and cross-border resources could not be compared, thus making evident the advantage and the need for cross-border CM market.

5. Discussion

The analyses of participation of different flexibility resources in CM

Table 5
CM cost and cost-effectiveness for the three bidding cases.

L	Case 1		Case 2		Case 3	
	Cost (MU)/Cost-effectiveness (MW/MU)					
	T	R	T	R	T	R
1	445/0.11	560/0.09	1454/0.03	2915/0.02	444/0.11	560/0.09
2	502/0.10	502/0.10	1569/0.03	2433/0.02	501/0.10	501/0.10
3	243/0.20	588/0.08	966/0.05	2583/0.02	168/0.30	529/0.09
4	212/0.24	212/0.25	892/0.06	896/0.06	117/0.43	212/0.25

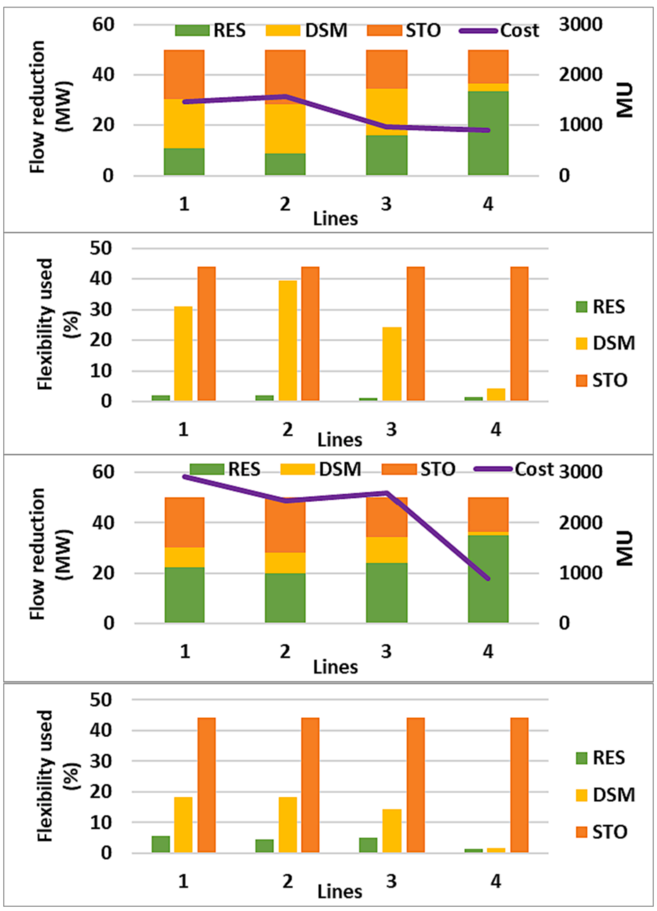

Fig. 11. Contributions of DSM, STO and RES in line flow reduction with prices included, bidding case 2; Top: full availability of flexible assets, Bottom: random availability of flexible assets.

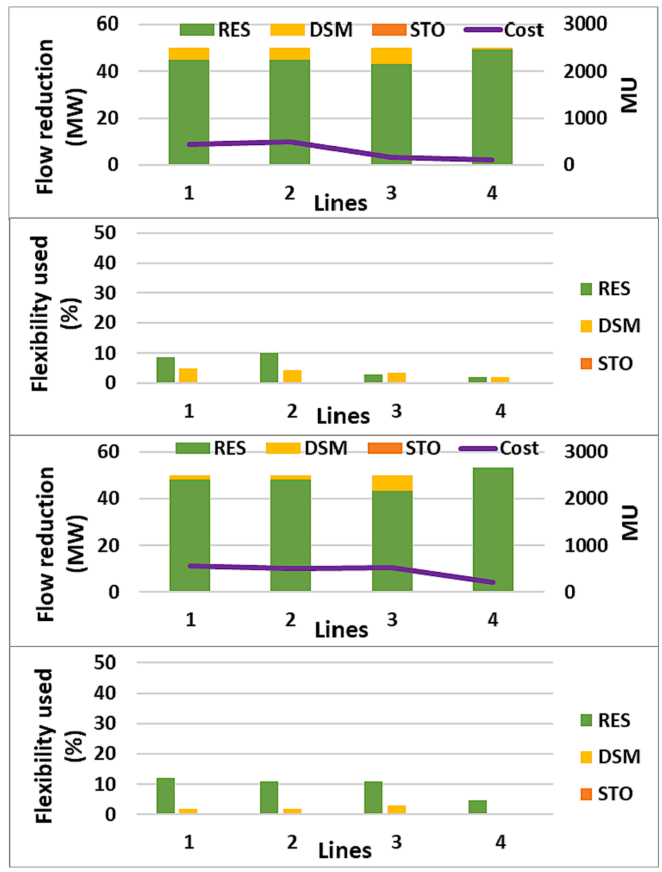

Fig. 12. Contributions of DSM, STO and RES in line flow reduction with prices included, bidding case 3; Top: full availability of flexible assets, Bottom: random availability of flexible assets.

markets have confirmed the following:

- Cross-border participation of flexibility in CM is more effective compared to national in terms of the required capacity of flexibility sources for the same level of congestion alleviation. As shown in Fig. 4, the same amount of flexible capacity could yield 250 MW line flow reduction if cross-border assets were used, against 5 MW line flow reduction if only national assets were used. This is due to the larger number of available resources in cross-border procurement, where some resources may have high DF or large flexible capacity, and hence allow more efficient CM at a lower cost.
- The effectiveness of cross-border CM increases with the use of small flexible units (<50 MW) and hence their participation in CM markets is highly justifiable and should be encouraged, as illustrated in Fig. 8, where participation of small units in the line flow reduction was between 31 % and 50 %. The effectiveness of CM depends on the DF and hence, for any critical line in the system, coordinated control of a number of small units can be highly beneficial for CM.
- The difference in pricing and limited availability of resources will affect the level of contribution of each type of flexible asset (DSM, STO, RES) and the total cost of CM, as shown in Figs. 10–12. Nevertheless, in all three bidding cases, only part (<50 %) of the total theoretical flexibility is used for the flow reduction at the observed lines for each of the three technologies considered. This shows a high potential for the remaining flexibility to provide other types of services, especially if they are related to frequency support, i. e., not dependent on the location of the resource.
- Among all the three flexibility technologies in the observed transmission system in SEE, RES have shown to be the most effective in alleviating congestion (as shown in Fig. 7). In order to facilitate cost-effective CM and at the same time allow low carbon operation of the network (by avoiding RES curtailment), higher flexibility at the existing points of connection of DSM and STO assets should be encouraged. Considering that the effectiveness of CM depends on the

asset location (i.e., the DF) and flexible capacity, both investing into a small number of large DSM assets or a large number of dispersed small DSM assets would yield significant improvements in CM potential. Furthermore, an important benefit of DSM and STO assets is that they can provide both upward and downward flexibility (subject to their operating mode), making them suitable for CM of different lines in the system, as they may require positive or negative change in power injection at the influential buses (following the definition of DF in (2)). RES are assumed to be able to provide only downward flexibility, by being curtailed if needed.

- Although some flexibility resources showed high cost-effectiveness for CM on individual basis, when realistic constraints are introduced (described by the bid selection algorithm and limited availability of flexible assets due to their operating mode), their effectiveness is no longer justifiable.

The running of the CM energy market, which is centralized at the regional level, can be assigned to one of the TSOs from the region. This is similar to assigning the role of a Market Coupling Operator according to CACM regulation [30]. Alternatively, the Regional Coordination Centre runs the market. In both cases, it is important to establish communication channels for acquiring information about the network state, availability and control of flexibility providers in the whole region. This is essential, as the activation of flexibility providers is done in real time and the state of the network and the activated flexibility providers should be monitored to ensure that congestion is efficiently eliminated. Another issue is the financial settlement and clearing of market participants and the TSOs. For this purpose, the entity that will operate the market should acquire these services from a clearinghouse. It should be noted that the studies reported in this paper consider that RES units may provide the required flexibility services under the same conditions and in a similar manner as other providers. The aim is to show the theoretical flexibility of the observed system if all flexibility resources were considered, as well as to provide a useful comparison between the CM potential of DSM and STO against the one provided by RES in the SEE region. The use of RES for flexibility provision was discussed in detail in [31] and [32], while its use for frequency support was described in [33].

6. Conclusion

This paper has compared flexibility potential of national and cross-border flexibility resources for CM markets in the interconnected transmission system in SEE. It addressed a number of critical factors for the participation of DSM and other flexible resources (STO and RES) in CM markets, including their location, size, availability and type, as well as the cost of congestion elimination. The bid selection algorithm has shown that flexibility resources with high individual cost-effectiveness may not be cost-effective for CM when realistic constraints are taken into account. The paper has illustrated that, with the expected level of integration, DSM, as well as STO, can act as an efficient tool for CM in the transmission system. Although DSM assets are more dispersed in the observed SEE region, CM potential of RES is still higher due to its higher flexible capacity (mostly installed in the northern part of the region). Therefore, with higher flexibility of DSM resources, and not necessarily higher dispersion, CM markets could benefit from DSM and STO with higher overall cost-effectiveness, allowing for more sustainable regional transmission network operation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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