COMILLAS
UNIVERSIDAD PONTIFICIA

ICAI

Máster en Ingeniería Industrial

TRABAJO FIN DE Máster

Assessment of market schemes for TSO-DSO Coordination

Autor: Pourya Saadati

Director: Prof. Dr. José Pablo Chaves Ávila

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Madrid

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título

Assessment of market schemes for TSO-DSO Coordination en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el

curso académico 2022/07 es de mi autoría, original e inédito y

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El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido

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Fdo.: Pourya Saadati Fecha: 20/ 07//2022

Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO

Fdo.: Prof. José Pablo Chaves Ávila Fecha: 20/ 07//2022

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RESUMEN DEL PROYECTO

Increasing the number of DERs in recent year and their possibility of supplying the needs and consumption, makes them as a very critical source for fulfilling the security and the reliability of the power system. In recent years, the DER procurement by the TSO and the DSO is growing, as well. Having this in mind, utilizing from this network should not cause any problem for the network, and entities in the network. Having a counter-activation or high procurement of the certain DER by one entity can endanger the security, reliability as well as the other entity's benefit. In this regard, there is a need for setting the coordination between the TSO and DSO to effectively control, manage and utilize these resources and the system, and to cost-effectively provide security and reliability in the power system. To achieve this, a high investigation and study is needed for defining the coordination schemes for the TSO and DSO. This thesis work aims at providing three main efficient coordination schemes and entailing some variants for each scheme. For arriving to this target, a deep study over the coordination schemes from research papers and projects (2015-2021) is performed. Having this coordination schemes, the features, pons, cons and the missing links of the market schemes are extracted. Moreover, all the reviewed market schemes are classified based on their common features. Finally, all the possible coordination schemes are defined based on the key features. Regarding this literature review, and reviewing the mathematical modelling of different market schemes, the paper suggest different mathematical modeling for the proposed coordination schemes, and the scenario will be defined to authenticate the mathematical modeling.

Palabras clave: Distribution System Operator (DSO), Transmission System Operator (TSO), Distributed Energy Resources (DER), TSO-DSO Coordination

1. Introducción

In recent years, the concerns on climate change enforce to propose alternative actions and plan to facilitate utilizing clean energy instead of fossil fuels aiming at having a sustainable future in the energy sector. The high penetration of Distributed Energy Resources (DERs) will play a key role in the successful decarbonization of the energy sector. By increasing the DERs, the ability to effectively control, manage and utilize these resources will become critical, and the system operators seeks a way to cost-effectively provide the security and reliability in the power system[1]. Non programmability nature and consequently higher uncertainty of DERs (e.g., PV and wind) may endanger the reliability of the grid and may violate the network constraints in certain areas and time periods. Connection of different types of DERs to the distribution system implies a need for distinct management process for them. The increment of DERs leads to a shift from unidirectional to a bidirectional power flow, since the central bulk power plant will not be the only responsible for power

generation and delivery, and the DERs will be involved to produce a significant energy for the customers. These facts implies that the planning will have to be done in a coordinated way[2]. The emergence of these resources introduces new roles for the DSO to more actively operate the network and illustrates a higher need for communication between DSO and the TSO. As addressed in [2] The active management of the distribution grid will not only allow the integration of a larger number of DER into the system but may also potentially reduce total costs of distribution companies.
Reference [2] indicates that the new era for the power system requires an improvement in five main aspects, namely: (a) a whole system approach, especially in network planning and investment, (b) greater coordination between TSO-DSO, (c) data exchange between SOs, (d) use of flexibility from DER, (e) fairer cost-sharing. The TSO-DSO coordination is defined as the roles and responsibilities of each system operator while procuring and using system services provided by the distribution grid [3]. The procurement of flexibility services from DER requires optimal coordination between the transmission system operator (TSO) and the distribution system operator (DSO)[4].
The consideration of distribution network constraints to facilitate and ensure the effective provision of DER services to the TSO is the core of every TSO-DSO coordination [5]. In this regard, the activation of the specific flexibility resources should not violate the constraints of the network and should not endanger the integrity of the distribution network. According to [6], even though the active network management by DSO can be beneficial to the customers, it can bring a countereffect for the TSO. Conversely, procuring the flexibility from DERs by the TSO to balance the network, may endanger the security of the DSO grid. Reference [7] [8], [9] present three points for increasing the TSO-DSO coordination namely: 1) Assignment of responsibilities and the interaction between TSO and DSO, 2)Focus on specific market phases (e.g., pre-qualification, procurement), 3)how these market phases are organized through a proper market design.

2. Definición del proyecto

In this thesis work the first aim is to obtain a perfect understanding of different available TSO-DSO coordination schemes, draw a comparison between them, categorize the coordination schemes based on their common features, and to address the essential needs and the missing links of each coordination schemes. The Second target is to model new coordination schemes to fulfil the requirements, solve the missing links, and add more credit to the previous coordination schemes. In this essence, it is relevant to determine whether a specific market scheme for TSO-DSO coordination brings acceptable economic performances. Hence, given the possible alternatives, the aim is to economically assess how the different coordination schemes perform considering the different contexts and scenarios. The results obtained from the economic assessment of different market schemes are then compared. Moreover, the modelled Coordination schemes will be analysed and compared in terms of their total cleared quantity, as well as their technical feasibility, while defining different scenarios.

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Capítulo 1. INTRODUCCIÓN

In recent years, the concerns on climate change enforce to propose alternative actions and plan to facilitate utilizing clean energy instead of fossil fuels aiming at having a sustainable future in the energy sector. The high penetration of Distributed Energy Resources (DERs) will play a key role in the successful decarbonization of the energy sector. By increasing the DERs, the ability to effectively control, manage and utilize these resources will become critical, and the system operators seeks a way to cost-effectively provide the security and reliability in the power system[1]. Non programmability nature and consequently higher uncertainty of DERs (e.g., PV and wind) may endanger the reliability of the grid and may violate the network constraints in certain areas and time periods. Connection of different types of DERs to the distribution system implies a need for distinct management process for them. The increment of DERs leads to a shift from unidirectional to a bidirectional power flow, since the central bulk power plant will not be the only responsible for power generation and delivery, and the DERs will be involved to produce a significant energy for the customers. These facts implies that the planning will have to be done in a coordinated way[2]. The emergence of these resources introduces new roles for the DSO to more actively operate the network and illustrates a higher need for communication between DSO and the TSO. As addressed in [2] The active management of the distribution grid will not only allow the integration of a larger number of DER into the system but may also potentially reduce total costs of distribution companies.

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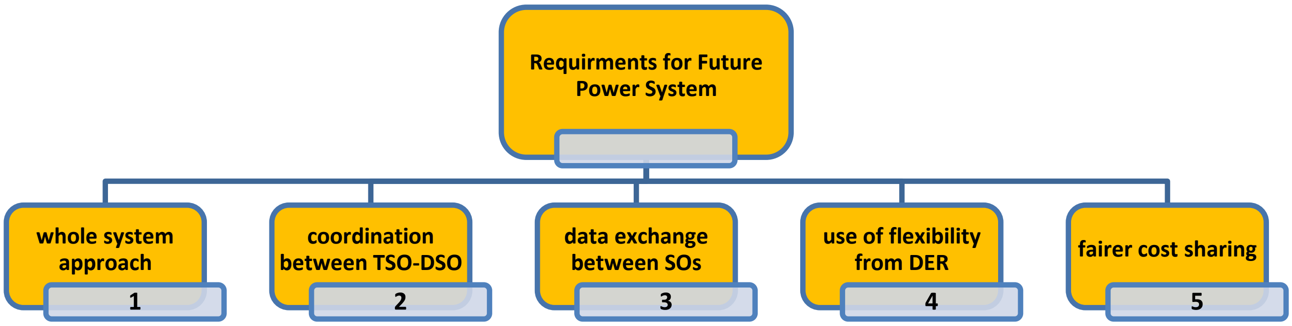

Although all 5 actions are required in order to cope with the new era of the power system, the goal of this paper is to comprehensively cover the ways to effectively set the coordination between TSO and DSO in performing different actions highly focusing on procuring flexibility from DERs and ensuring the fair cost allocation to the DERs.

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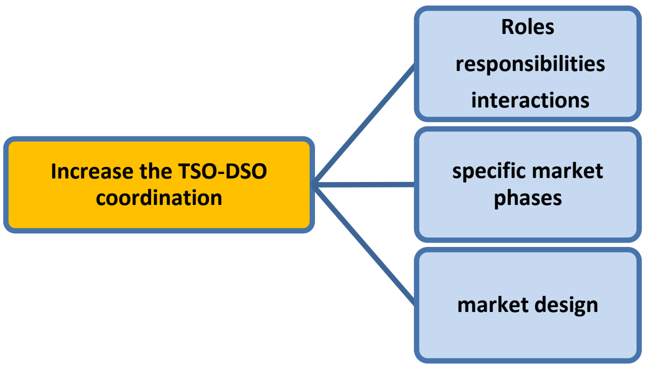

1.1 MOTIVACIÓN DEL PROYECTO

This thesis work is performed in IIT under the supervision of Prof. Dr. José Pablo Chaves Ávila, and the kind indications of Dr. Matteo Troncia and DR. Leandro Lind on the subject of the "Assessment of market schemes for TSO-DSO Coordination". The subject of the thesis has been selected after the consultation with Prof.Chaves and based on the road map and need of the IIT, as well as the high interest of the author on the topics related to the electricity market. It is desirable that the results are authentic and fruitful.

Capítulo 2. ESTADO DE LA CUESTIÓN

The TSO-DSO coordination is defined as the roles and responsibilities of each system operator while procuring and using system services provided by the distribution grid [3]. The procurement of flexibility services from DER requires optimal coordination between the transmission system operator (TSO) and the distribution system operator (DSO)[4].

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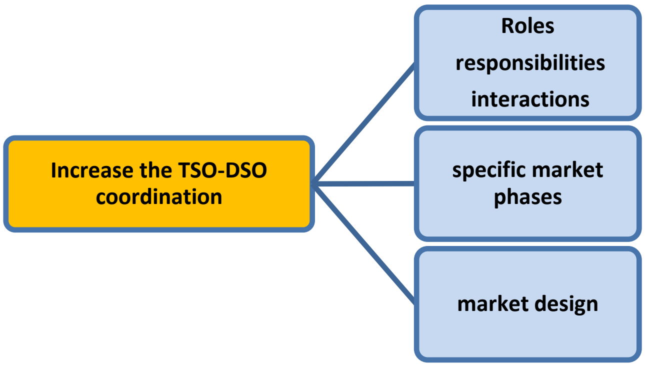


In the following a brief description of these three will be described:

1.Assignment of responsibilities and the interaction between TSO and DSO

The roles of each stakeholder within the market should be well-defined to pave the road to determine the most efficient coordination schemes. Effective coordination is achieved only if each market party knows its responsibilities in detail to avoid any overlapping activities. More importantly, due to the evolution of the power system from a fully centralized generation scheme to a more decentralized one, the roles and responsibilities of each market party must be updated and well-considered due to the upcoming needs. Having decentralized

generations and the need for the transmission system to apply the resources connected to the distribution system for its stable, and secure operation enforces the TSO to have better coordination with DSO while adopting new roles[4], [9]. For fulfilling the TSO-DSO coordination, the system operator(s), market operator(s), buyers, sellers, etc. should be defined properly. In a European power system, TSO and DSO are the system operators (SOs) in the transmission and distribution network, respectively. TSO as the system operator currently is in charge of managing the power flows in the network, fulfilling the activities related to balancing the energy, taking into account the grid constraints. These activities are become more complex and enfandorces the TSO to elaborate his procedure for procuring the flexibilities in an appropriate market framework enabling the participation of all resources. DSO, on the other hand, is responsible for ensuring a secure operation in the distribution performing a more active role in the distribution system management an,drce having an enhanced relationship with other grid users. In contrast to the conventional DSO, this entity must be able to have a better observability over the distribution system, have a smart measurement via deploying smart equipment, and be involved with data management and aggregation, and data exchange. More importantly, he should be neutral in deploying the resources for the flexibility market, and solve the local system issues (e.g., local congestion management, local balancing, etc.) via well management and procurement of flexibility resources. Furthermore, there are other commercial parties responsible for different actions in the market. The commercial parties may be an aggregator of the flexibility resources, a market operator, a flexibility provider, and an entity as the buyer of the flexibilities. Having these parties in the market may enhance the market performance (e.g., increase liquidity by facilitating the small resources participation via aggregating). However, a non-coordination of these parties with other market entities may endanger the security of the market.
considering [3], other than TSO-DSO coordination and interaction, a direct relationship between all the buyers and sellers must be established and any intermediary should be agreed upon by all parties. Moreover, all market parties should be able to interact with one another within market. Furthermore, system operators should exchange all the relevant information from their grid and the relevant connected assets, from structural data to more dynamic data which allows flexibility procurement without creating issues on the grid. In [2] indicates that the data exchange will play an important role in TSO-DSO interactions. In this context, data exchange involves platforms, protocols, timesteps, and data exchanged between TSO and DSO for operational purposes.

2. Focus on specific market phases

The required coordination for the TSO and DSO should be considered in different phases of the procurement of system services, operational planning, development, and the investment. The coordination needed for providing the services to solve the system issues are well defined in [1], [10]. These phases are namely, 1. preparatory Phase, 2. forecasting phase, 3. market phase, 4. monitoring and act

ivation phase, 5. Measurements and settlement phase.

These 5 phases will be explained in the following table to have a better perspective on the subject:

No	Phase name	Short description, key words	Basic required coordination
1	**preparatory phase**	1)requires the **product definition** and the **pre-qualification** 2)In **product definition**, flexibility product requirement is established, and the products are defined 3)**pre-qualification** examines whether the resource is compliant for providing the flexibility services considering its feasibility and without causing any technical issues for the network 4) **product pre-qualification** determines if the resource in charge of providing flexibility products is feasible or not and if it can meet the minimum requirement set by the SOs. 5) in **grid pre-qualification** each SO verifies that the participation of the resources connected to his grid will not risk the grid constraints	**For product definition**: 1) if they jointly define the product, coordination needed 2)the product specification must be agreed upon and defined in coordinated manner for TSO and DSO if the products are shared in one single marketplace, or if the products of one market are used in another market operated by another system operator. **For grid-prequalification**: if the flexibility resource is not located at the same grid where the flexibility is being pre-qualified, the assessment of the impact on each system operators must be carried out to avoid any problem for each SO **For product-prequalification:** if product prequalification for several MOs is carried out by a single interface, it requires coordination between SOs and the shared interface.

2	**forecasting phase**	1) predicting the state of the network in the future, using the historical and/or real-time data as well as calculation tools to determine if the capacity of the network ensures safe operation. 2) Forecast can be performed in the short-term, medium-term, and long-term. 3) If forecasting shows the need for action, a reinforcement, or procuring the flexibility is required for the future secure operation	Since the forecasting for the network and the next required actions influence the whole system and not a specific area, coordination and confirmation by both system operators are required
3	market phase		This phase requires the most coordination between TSO and DSO and IMO for every single actions. In this phase, the system operator(s), market operator(s), the buyer(s), seller(s), etc should be defined in the market, and the coordination between all of the responsible entities must be established. coordinated in order to avoid any overlapping function, double bid selection, etc. [1]

[1] TSO-DSO coordination in market phase will be comprehensively discussed in this paper.

Considering the aforementioned information provided in the explanatory part and the summary table, in order to efficiently perform and solve the network issues, there is a pivotal need for the TSO-DSO coordination for each phase. However, evaluating the coordination between system operators for all the phases is out of the scope of this paper, and the aim is to comprehensively dedicate the effort to investigating the required coordination in the third phase, called the market phase. Regarding this, in the next section, the papers related to the market-based TSO-DSO coordination mostly concentrating on Market phase coordination will be addressed. However, due to the inter-relation between market phases, some references define the coordination for another phase as well as the market phase.

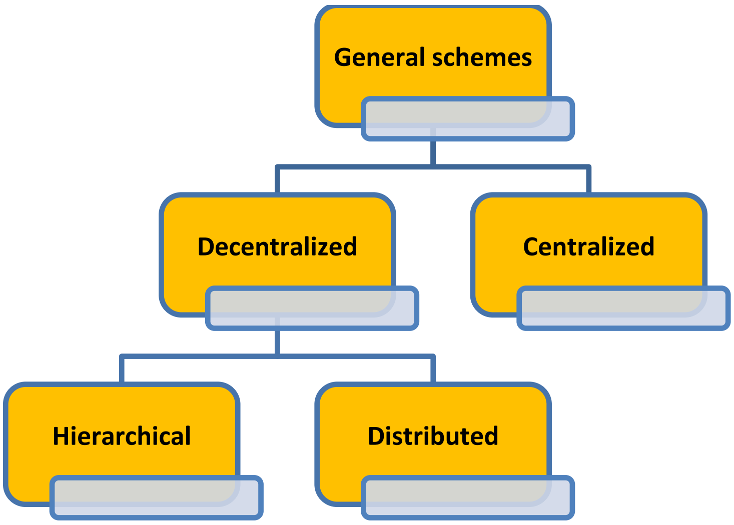
3. Market design for procurement of the flexibility resources

The design of the market must provide the situation in which the market parties have the most efficient interaction with one another. The level and the complexity of the interaction are dependent on the specific task within the market. As already mentioned in the previous section, different market phases are taking place while providing the flexibility services, and the roles associated with these phases (e.g., the role of each system operator in the procurement phase) may differ depending on the scheme under analysis. Among all the phases, the procurement and the activation of flexibility resources require the most attention for coordination and will be explained in this paper. Hence, the market design has to facilitate this coordination by enabling ways for more effective interaction between system operators. As addressed in [3], for better coordination some principles should be agreed upon by both TSO and DSO stimulating market parties in providing flexibility to ensure the power system operates cost-effectively and reliably. Both TSO and DSO should facilitate the participation of all market parties and service providers while considering a non-discriminated, transparent market with high liquidity [2], [3], [12]. This implies the high need for clear rules for collecting and validating bids. The bids should be validated according to the economic and technical merit order and the grid prequalification to be financially, technically feasible for the whole system without endangering the system security [3]. Moreover, both system operators must be agreed to provide a market-based approach for trading the flexibility affordably, from a local level to European cross-border scales [3]. As mentioned in [8] implementing the market undergoes an investment for achieving higher observability, controllability, as well as higher cost for active operation and the quicker deterioration of the network assets (due to efficient utilization of assets). It is worth saying that the high number of separated or hierarchical marketplaces would introduce some entry barriers and may reduce the liquidity of the market missing some potential suppliers. As [8] indicates, the validation and as a result higher number of DER services will allow a much higher certainty and higher liquidity in the market, which allows the SO to increase its reliance on DER reducing costs for the market, as well as the whole system. Higher dependency on the DERs for providing the flexibility services and increment in controllable assets introduce different technical and economic challenges from a complex system operation and essential adequate coordination to the need for new regulations and policies to be defined [8]. As in [3], In the case of many marketplaces, the economic efficiency and system security must be guaranteed avoiding the countereffect of several activation bids, double activation, gaming, etc. Furthermore, the flexibility services can be traded in different marketplaces with different time frames and scales, from a wholesale to ancillary market, or specific markets for each flexibility service, like balancing or congestion market, which requires high coordination between the SOs.

REVIEW OF THE TSO-DSO COORDINATION SCHEMES

As presented in [7] not a one-size-fits-all coordination scheme, meaning that a multitude of coordination schemes that propose different solutions can be addressed for different needs in different situations. However, considering the combination of the needs in a specific circumstance, one coordination scheme can be defined by manipulating some features to be suitable to that circumstance.

There are several TSO-DSO coordination schemes introduced so far in several projects and papers works and the aim of them is to propose methods to increase the level of coordination between the SOs[12]. As mentioned in [12], in general, two main coordination schemes are available from a centralized format to a very decentralized one. In the former scheme, the TSO is the only entity responsible for procuring the flexibility services in both transmission and distribution using resources in the whole network. On the other hand, the decentralized scheme is one in which more than one market is available, and each SO is responsible for minimizing its own operation cost. Moreover, this decentralized TSO-DSO coordination are categorized as hierarchical or distributed. In the former scheme, the interaction between distributed resources in the distribution system and the transmission power system is like a leader-follower type, where the leader has fixed decision variables and leads the followers in making a decision. On the other way around, in distributed scheme, local RESs connected to the market communication graph can potentially be selected to meet the load.



Starting from this general categorization, taking into account the distinction between central and local needs, number of markets, the type of buyers of the flexibility services, and accessibility of the TSO to DERs[7], in addition to the roles and responsibilities of each market party, type of market design, and concentration on each procurement phases[8], [9], several coordination schemes are addressed.

Considering the previous papers on market-based TSO-DSO coordination, reference [13] proposes three coordination models, namely "Total TSO model", "minimal DSO", and "market DSO (Models c1,c2)". The author in [14] describes two different visions, first, based on centralized-whole-system optimization and second, based on decentralized optimization structure. Literature [15] proposes three different coordination schemes namely, "DSO leader", "DSO follower", and "TSO-DSO iterations". In [4], the author provides and well formulates the two first market schemes of [15], as well as the "Centralized AS market" and "shared balancing responsibility AS market" . In [2], the author summarizes the TSO-DSO coordination into three different coordination: first, "Network service markets centralized on the TSO", second "TSO runs a central market while DSO runs a Local market", and third a "single platform for the local and central market". [9], [16], [17] address the five coordination schemes for the SmartNet projects namely "Centralized AS market model", "Local AS market model", "Shared balancing responsibility model", "Common TSO-DSO AS market model", and "Integrated flexibility market model". In [3], the author reviews and investigates the feasibility of the market model considered in the SmartNet, and in [6], the paper provides an overview of the Smartnet project considering the Italian scenario . In [18], the paper proposes the models considering the activation of reserves for balancing a real-time deviation in the net load of the transmission or distribution node for five different market schemes, namely, "Centralized Common TSO-DSO market", "decentralized Common TSO DSO market", "Centralized Ancillary Services market", "Local Ancillary Services market", and "Shared Balancing Responsibility". In [19], a TSO-DSO balancing coordination model is mathematically formulated on a case study in southwest of England. [20] presents a hierarchical coordination scheme depending on the coordination scheme where the DSO is responsible for DERs. Reference [21] propose a DSO–TSO Coordination for Day-Ahead Operation Planning. In [22], the author discusses the solutions for inter-TSO cooperation solutions as well as solutions that are being adopted by DSOs, the need and the solution for cooperation between TSO and DSO and depending on where structural congestion will occur and which borders will be managed. Reference [23] firstly defines three agents procuring DER services and then develops three coordination schemes in detail. Three coordination options are presented in [10] namely, "separated TSO and DSO congestion management", "combined TSO and DSO congestion management, with separated balancing" and "combined balancing and congestion management for all system operators together". There is three main coordination scheme defined in [5], "the TSO-Managed Model", "TSO-DSO Hybrid managed Model", and" DSO-Managed Model". In [24], for EU-Sys flex two main coordinated optimization models have been identified. The first optimization model is the Centralized and the second is the decentralized optimization model. In the Euniversal project [25], six coordination schemes are addressed and [26] proposes a systematic characterization of ancillary services for TSOs, and DSO local system services and reviewing, three main TSO-DSO coordination mechanisms in line with the Euniversal project. In [27], The crossbow project introduces some other coordination schemes within the project.[28]proposes different coordination schemes for the INTERRFACE project. In Reference [8], the CoordiNet project as one of the latest project for the TSO-DSO coordination schemes introduces 7 coordination models which will be elucidated in this paper comprehensively. Regarding [29], [30], the OneNet project utilizes some of the coordination schemes identified in the CoordiNet project.

From the references indicated in this reference review, the goal is to select more-related and recent projects and paper works on to the market-based TSO-DSO coordination scheme and try to expand their content so as to provide a better vision over the aforementioned topic.

As proposed in[13], a **Total TSO model, Minimal DSO**, **market DSO** are the three possible market models. The summary of these market models are as follows

Total TSO model

- There is only one single market for the whole system.
- TSO performs a whole-system optimization with full observability of all grid.
- TSO aims to aggregate the DERs for the wholesale market participation
- DSO's functions are limited only to some operational aspects of the power system to ensure reliability

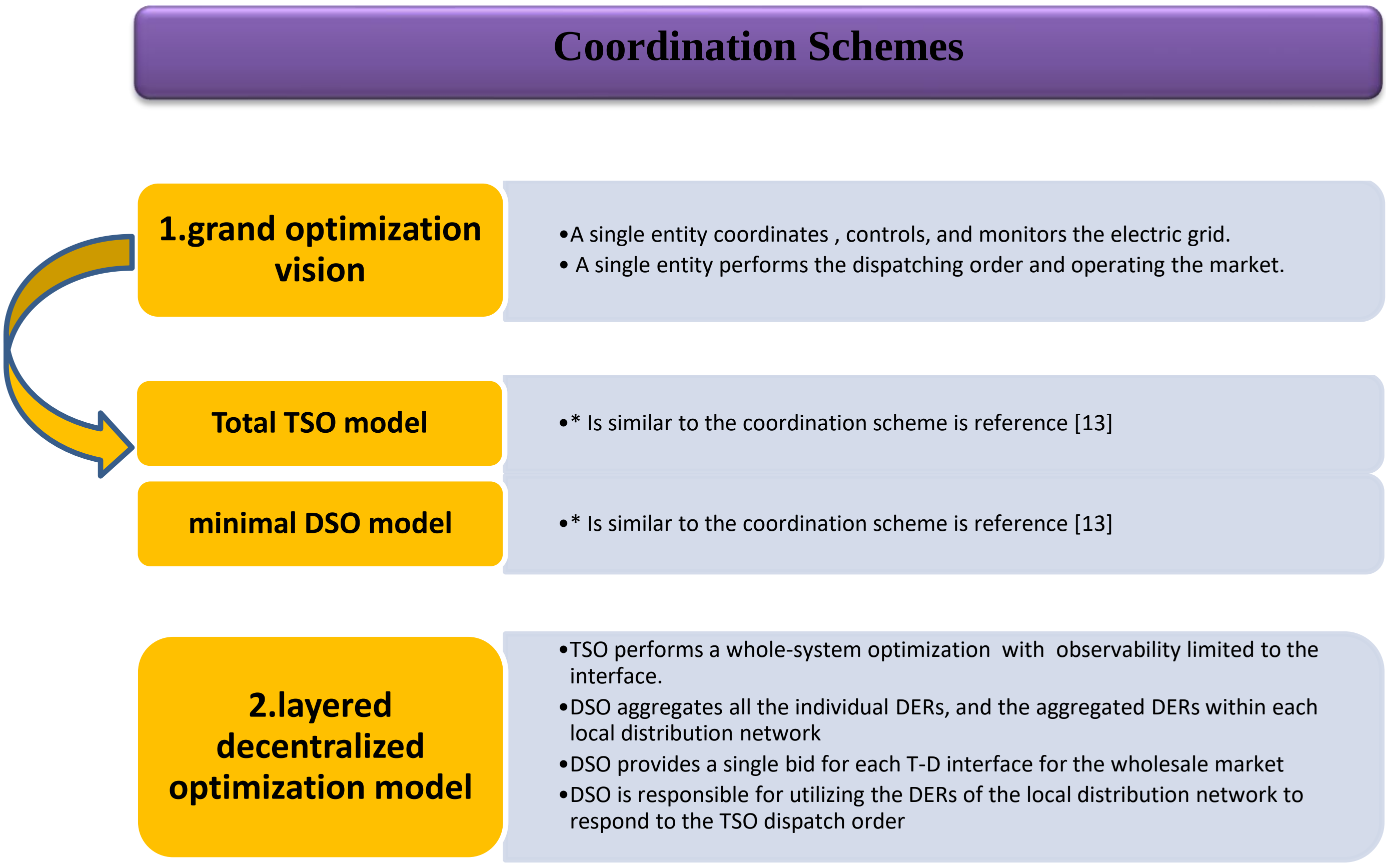
Minimal DSO

- There is only one single market for the whole system.
- TSO performs a whole-system optimization with the observability limited to TSO-DSO interface.
- DSO provides the services in terms of interconnection to the distribution system .
- . DSO coordinates the DER and provide the flexibility services to wholesale market conidering the individaul and aggregated resources

market DSO

- There is only one single market for the whole system.
- TSO performs a whole-system optimization with the observability limited to the aggregated DERs, and not the detailed modeling of each DERs
- DSO not only perform the operational aspects of distribution grid, but also coordinate the aggregators and/or aggregate the DERs himself.

A similar coordination model is addressed in [14] where the "**grand optimization vision**", **layered decentralized optimization model** has been introduced. The main concept of these market models are as follows:

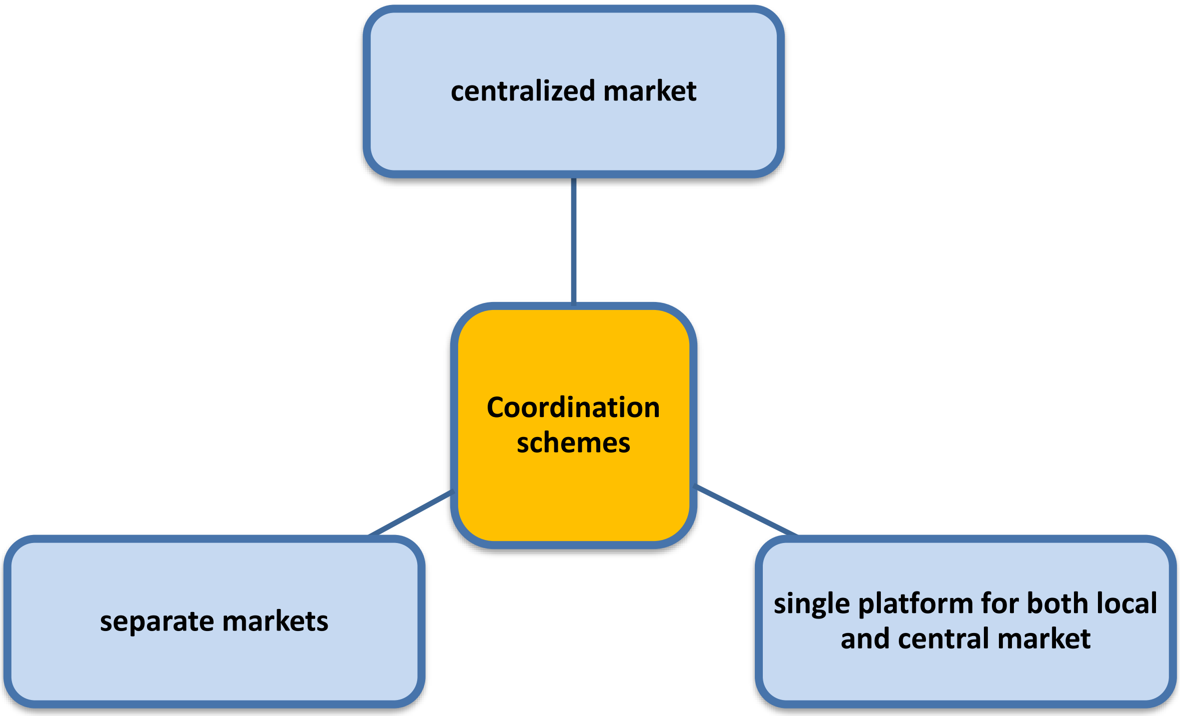


in [2], the author proposes three main coordination schemes reviewing the previous paper works. These coordination schemes mainly focus on the market-based coordination scheme between TSO and DSO.

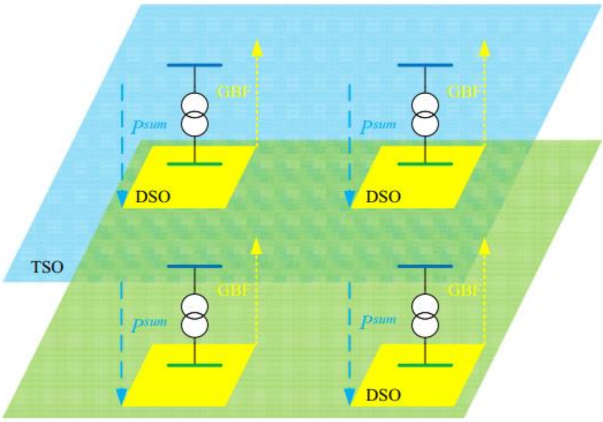
The first coordination scheme implies a **centralized market** operated by the TSO for procuring the network services. This coordination is compatible with the current power system introducing some new roles and modifications.

The second scheme in this paper is 2 **separate markets** where the TSO runs a central market and the DSO runs a local market. In this model, TSO and DSO procure the flexibility for their network utilizing their belonging resources. The low liquidity in the local market is one of the challenges for this scheme from the literature point of view.

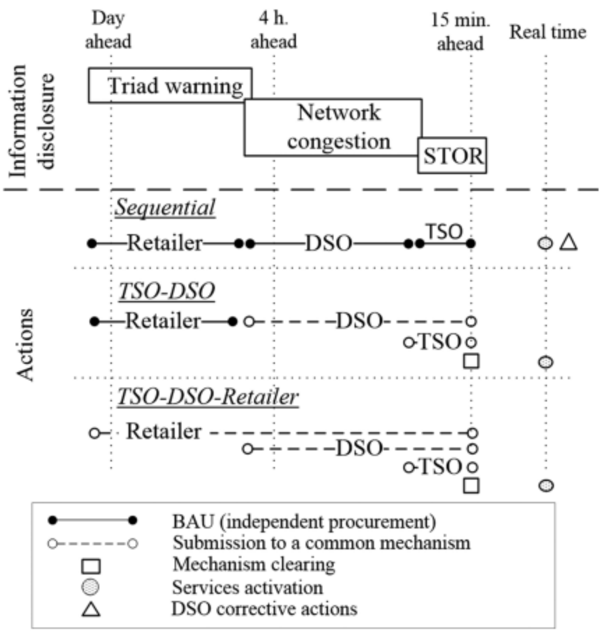
The third coordination scheme is **the single platform for both local and central markets** in which higher coordination is needed since both system operators are procuring flexibility in the same market. Moreover, running a single platform and a clearing algorithm is complex in this model.



The reference [20] proposes a **hierarchical coordination mechanism** for the coordination of the TSO and DSO in economic dispatch operations. Moreover, the problems and challenges associated with dispatching are addressed and solved via proposing a new coordination scheme and providing the formulating of the dispatching energy and reserves. Considering the scope of the literature review the coordination scheme will be elucidated only. The paper presents a concept of generalized bid function (GBF) as unified communication between TSO and DSO to avoid unnecessary extra information exchange such as detailed network information. These parameters are used by TSO to incorporate the marginal cost of DERs located in the distribution network to the dispatch of the entire power system. The hierarchical coordination, each DSO fulfills its required power from the TSO market. However, the DSO can utilize the power from DERs for its own use, but they are too small and may cause a higher cost for the system. In this market scheme, the DSO is responsible for aggregating the bids and submitting them to the central ancillary market using the GBF, based on the bender decomposition of the optimization algorithm. For better clarification of the general model, it is depicted in fig()



The paper [23], firstly identifies TSO, DSO, and the retailers as the buyers of the flexibility services. The author defines the retailers in Grand Britain as the entity responsible for contracting the energy to match the demand of his customer. Regarding these buyers in the market, three possible market designs namely, one **sequential design**, and **TSO-DSO mechanism**, **and TSO-DSO-Retailer mechanism** have been proposed. The summary of the market mechanisms are elucidated hereunder:



Coordination Schemes

sequential design

- The retailer is the buyer of the flexibility besides TSO and DSO.
- The buyers can procure the flexibility from shared resources, but in separate market.
- Each buyer procures the required flexibility in its own market operated by itself, without bid forwarding with the priority for retailer, DSO, TSO repectively.

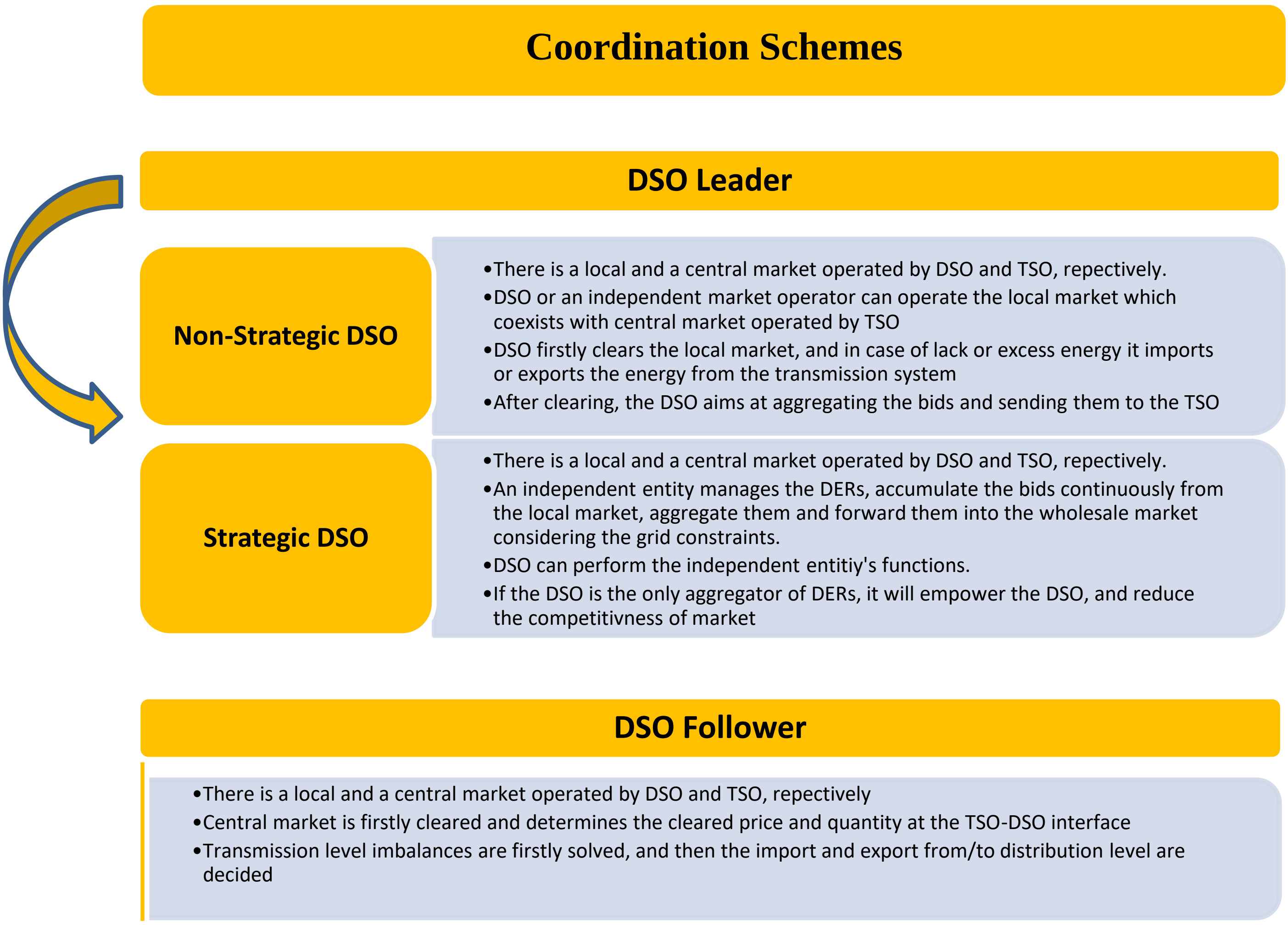
TSO-DSO mechanism

- There is a common market for TSO and DSO and a separate market for retailer to procure flexibility
- The retailer procures flexibility in a separate market, but using the shared resources.
- The priority to procure the flexibility is for Retailer, DSO, and then TSO, respectively.

TSO-DSO-Retailer mechanism

- There is a common market for TSO, DSO, and retailer to procure flexibility, using shared resources.
- The priority to procure the flexibility is for Retailer, DSO, and then TSO, respectively.

In [15], regarding the previous works and projects, the paper categorizes three different coordination schemes between local and central electricity market applicable in both academic and real-world system and identifies independent local electricity market. In each coordination scheme, the operational process and information exchange, the advantages, and disadvantages of each coordination scheme have been discussed. The coordination schemes are named **DSO leader, strategic DSO**, **DSO follower**. The summary of the coordination schemes are described below:



TSO-DSO iteration

- There is a local and a central market operated by DSO and TSO, repectively
- Hierarchical coordination applying the iteratively communicating GBF from DSO to TSO
- Bidding strategy for market users is updated iteratively until reaching the pre-defined convergence criteria.
- As an illustation in fig (), the LA buys energy from WEM and sells to DNEM or vice versa depending on the benefit he gains from price difference between the two markets

[31] proposes "**full integration market model**", " **Enhanced Bulk Balancing Authority (BA) Model**" and " **Enhanced Bulk Balancing Authority (BA) Model**". The summary of these coordination schemes are as follows:

Coordination Schemes

Full integration market model

- . There is only one single market for whole system.
- TSO or IMO can operate the market clearing in a centralized way
- TSO considers all the constraints of the whole network.

Enhanced Bulk BA Model (1)

- There is only one single market for whole system.
- BA is the entity responsible for operating the system, network balancing, etc.
- BA gathers all the submitted bids and after performing the clearing.
- DSO should exchange the information related to the status ofthe distribution network with the BA
- BA directly dispstches the DERs without any intermediate entity.

Enhanced Bulk BA Model

- There is only one single market for whole system.
- BA is the entity responsible for operating the system, network balancing, etc.
- BA gathers all the submitted bids and after performing the clearing.
- DSO should exchange the information related to the status ofthe distribution network with the BA
- BA sends dispatch orders to the DSO and DSO is the entity to execute them.

Reference [5] identifies the **TSO-managed model, TSO-DSO hybrid managed model, and DSO-managed model** as the coordination schemes. In the following the main concept of these coordination schemes are delivered:

Coordination Schemes

TSO-managed model

- A single entity (TSO or IMO) is the responsible for dispatching the flexibility resources in whole system.
- DSO's responsibilities are correspondent to the conventional DSO.
- DSO communicates the essential data with the TSO.
- The aggregation of the DERs performed by the aggregators.
- Observability of TSO is only limited to the point where the aggregated DER is presented.

TSO-DSO hybrid managed model.

- TSO is the only entity operating a single market.
- There is only one economic dispatch model for the whole system.
- DSO is the entity responsible for validation and pre-qualification respecting the DSO grid constraints.
- The aggregation of the DERs performed by the aggregators.
- DSO can also procure the flexibility from the central market to solve its grid issues.

DSO-managed model

- TSO is the only entity operating a single market.
- There is only one economic dispatch model for the whole system.
- DSO is the entity responsible for validation and pre-qualification respecting the DSO grid constraints.
- The aggregation of the DERs can be performed by the DSO or aggregator.
- The TSO will send only the aggregated dispatch order if DSO is aggregator of DERs
- If the DSO is the aggregator, the DSO sends the DER dispatch order to the individual DERs, in response to TSO aggregated dispatch order.
- DSO do not exchange the operational data with the TSO.

In [22], the paper proposes firstly three system sates for categorizing congestion management approaches while investigating the interaction between market and grid operations. It defines three colors namely, ***green, orange, and the red*** for this purpose to represent a concept like traffic light.

The **green state** is specified for the fit and forgot or for a well electricity market design. For the former, If the network is over dimensioned, the system operators perform passively without any need for the special action in the green sate and no need for redispatching, or curtaliment in the following states (orange and red). In the latter, the system operator aims to send the economic signals to the grid users for an efficient grid utilization and by doing so, it defines a concept as **congestion pricing approach** for the green state. However, defining such an approach requires a border definition within the network so as to specify the capacity to the grid users of that specific border to mitigate the congestion. The border definition can be performed in 4 ways between two transmission system, transmission system and its user, transmission system and distribution system, and the distribution system and its users. Considering these borders, system operator can allocate the capacity to each border where there is a congestion issue inside. After allocating the capacity and clearing the market, system operator updates the congestion forecast, and in case mismatch between market outcome and network statue is detected, the system operator performs the congestion relieving measures, like a corrective dispatch. This redispatch happens in the **orange state** which is the second state defined in this paper and will be addressed in following sections. In case of well market design since the borders are optimally defined and allocated, and there is less need for congestion relieving measures in the orange and red system states. The allocated capacity in green state, is performed in a wholesale market applying either explicit auction or the implicit one. The definition of these auctions are presented in [22]. As mentioned, a market-based capacity allocation applying implicit or explicit approach has been proposed in this paper, and three different TSO-DSO coordination can be identified depending on where the structural congestion may happen.

In the first case, author proposes **Only the (UD-D) border has structural congestion**, meaning that only there is congestion within the distribution grid without having any other congestion issues in the rest of the grid. In this case, an implicit or explicit auction can be applied for this border. In the explicit approach, the responsibility of the DSO is to calculate and offer the grid capacity to the market users, and the market can be operated by the DSO or by an independent market operator. On the other hand, using the implicit approach in the market, the clearing algorithm of the wholesale market should be solved considering the constrained border. Moreover, having implicit auctions implies different zones within the main zone (in this case in UD-D border) owing different price for each zone. Note that in this model, as well as following models, the border between 2 transmission system always applies the implicit capacity allocation.

In the second case, **Only the (D-T) border has structural congestion** has been adopted. In this model there is a congestion at the interface between two network levels. Similar to previous model, one of the explicit or implicit approach could be applied. For the former approach, TSO must perform some calculation respecting the interface with neighboring TSO while he is calculating the allocated capacity for each market participants to mitigate D-T congestion. In this explicit auction, the market participants can be either DERs and aggregators of the wholesale market, or the resources connected to the transmission system. On the other way around, in case of implicit auction, same scheme is depicted as the first case.

In the third case, the author presents, **Both the (D – T) and (UD – D) borders have structural congestion,** implying a structural congestion in both distribution network, as well as transmission and distribution interface. In this model, different implicit and explicit approaches can be assigned for each one of borders. This model will be complex due to different zones within zone, different pricing for each zone, and probably the need for inter-related capacity allocation for TSO and DSO. In this model, the possible approach is to give the priority for TSO-DSO congestion management before solving the congestion issues within distribution network.

As indicated after allocating the capacity and clearing the market in green state, if there is a mismatch between market outcome and network statue, the system operator performs the congestion relieving measures, like a corrective dispatch. This action is specified for the **orange state**, where the system operator should procure the reserve for the redispatching. For a better clarification, after the wholesale and intraday market, if still some congestion issue presented in the network, the reveling measures are performed. The specification and the procedure for relieving measures and consequently, need for redispacthcing has been well addressed in [22] in detail, where the TSO and DSO could perfom redispatching in their grid . at the distribution level, the concept grasped from the literature is that the DSO is reposnible for the procuring the flexibility connected to its netwrok to solve the congestion issues unsolved from previous state. Regarding this redispacthing , three different coordinated approaches has been identified by the literature.

The first option is **the TSO-FSP model**. In this coordination scheme, an explicit auction is implemented for allocating the capacity for the structural congestion at the TSO-DSO interface and/or within distribution network. in this coordination both TSO and DSO can calculate the border capacity, but the flexibility services are procured by the TSO only.

The second coordination scheme is the **TSO-DSO model**, where both system operators jointly procure the flexibility, and the capacity can be implicitly allocated similar to the one presented in the cross-border TSO-TSO coordination.

Another coordination scheme is proposed considering the **centralized market model of SmartNet**, where the TSO is the only entity procuring the flexibility once the congestion issues are presented in the borders, and DSO has no responsibility other than pre-qualification.

Finally, if flexibility allocation for solving the congestion cannot solve the congestion, the **red state** is defined at which the system operator performs the curtailment of the generations or the load to overcome the congestion. In this state there is the cooperation between TSO and DSO, only if they have already had the coordination in previous state for relieving the congestion. There is also another case where the coordination needed which is addressed in[22] , but it is out of scope of this literature review.

GREEN STATE

(UD-D) border has structural congestion

- There is congestion within the distribution grid
- implicit or explicit auction can be applied for this border
- in explicit auction, market can operated by the DSO or by an IMO
- In explicit auction, the resources can be individual DERS and aggregated DERs.
- Having implicit auctions implies different zones within the main zone with different price for each zone.
- In implicit auction, the clearing algorithm of the wholesale market should be solved considering the constrained border.

(D-T) border has structural congestion

- There is a congestion at the interface between two network levels.
- one of the explicit or implicit approach could be applied.
- in explicit auction , TSO allocates the capacity for each market participants to mitigate D-T congestion.
- In explicit auction, the resources can be individual DERS, aggregated DERs and transmission system resources.
- Implicit auction is similar to previouse model.

(D – T) and (UD – D) borders have structural congestion

- There is a structural congestion in both distribution network, and TSO-DSO interface.
- Different implicit and explicit approaches can be assigned for each one of borders.
- The approach is to give the priority for solving the TSO-DSO border congestion management

ORANGE STATE

TSO-FSP model

- only TSO is the responsible for operating the market.
- -DSO is not involved in the procurement and activation process
- -An explicit auction is performed for solving the structural congestion in the TSO-DSO interface, and distribution network.
- Both TSO-DSO are responsible for calculating the border capacity.

TSO-DSO model

- There is only one common market for the whole system.
- Both system operators jointly procure the flexibility.
- Also, capacity can be implicitly allocated similar to the one presented in the cross-border TSO-TSO coordination

centralized market model

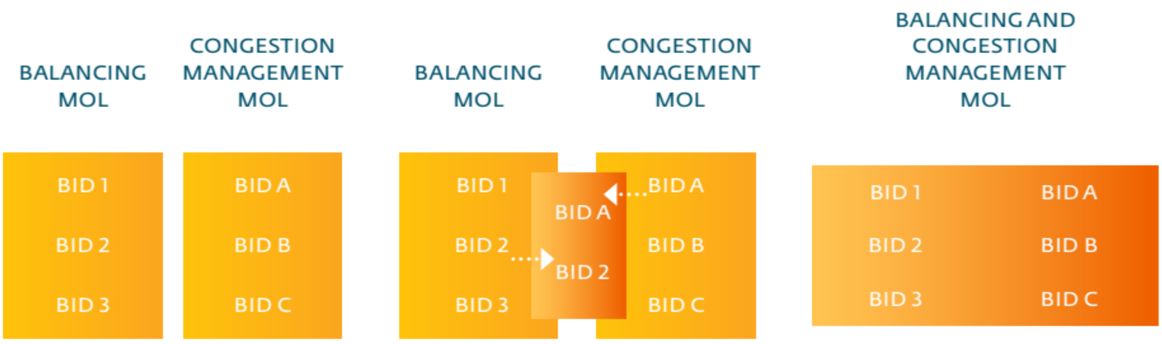
- Only TSO is the responsible for operating the market.
- DSO is not involved in the procurement and activation process, but performs the pre-qualification
- DSO performs the conventional roles without accessing the market
- The TSO does not consider the distribution system constraints when performing economic dispatch.

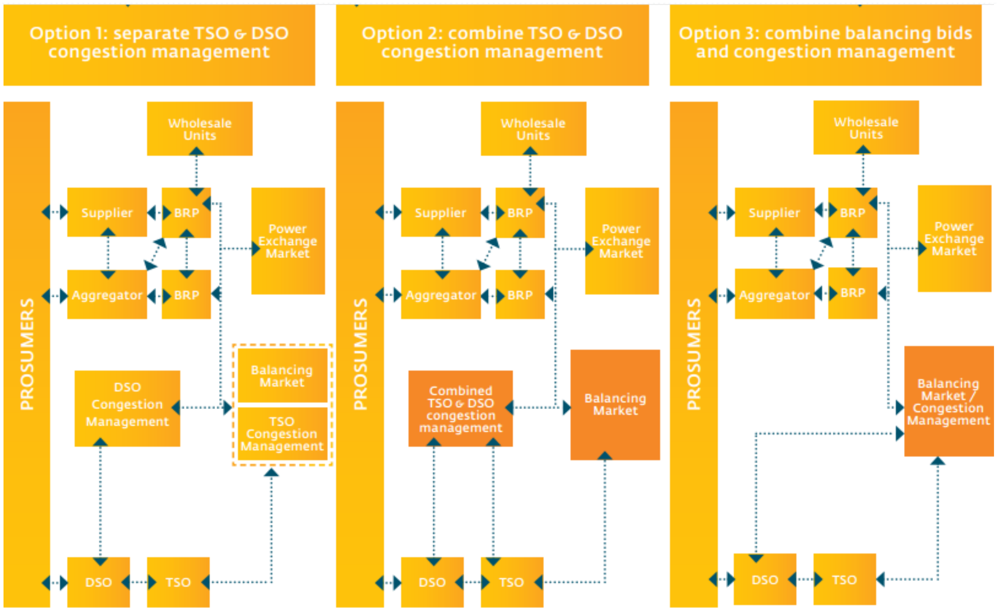
RED STATE

- system operator performs the curtailment of the generations or the load to overcome the congestion
- cooperation between TSO and DSO, only if they have already had the coordination in previous state (green, orange)

The paper [10] introduce a unique definition for the market as a Merit (MOL) Order list. If this MOL is separated, it implies of having a separated market, while having a combined MOL even composing of subset MOL is supposed as the combined market. Regarding the MOLs, this paper firstly identifies three different coordination schemes for procuring both balancing and congestion management services, and then classifies them as fully separated to a fully combined market, and then aims to understand the advantage and disadvantage of each market model.

The paper introduces the 1) **separated TSO and DSO congestion management , 2) combined TSO and DSO congestion management, with separated balancing, and 3) the combined balancing and congestion management for all system operators together.**





Coordination Schemes

separated TSO and DSO congestion management	•There are different seperate markets. •Each system operator procures the required flexibility in its own market using its own resources, without bid forwarding to other market, •The higher-level market is operated by the TSO, and lower level by DSO •DSO is the entity for dispatching the DERs with a priority in procuring the flexibility. •In case of combined balancing and congestion management for TSO, a shared MOL is used.
combined TSO and DSO congestion management, with separated balancing	•There are 2 separate markets coexist and operated by different market operator. • The bid of each market can be forwarded to another market if necessary. •Although it is composed of 2 markets, one of these markets is a central market, and the other one is a common market. But, in general, its main structure is multi-level market. •TSO not only is the operator of balancing market, but also jointly operate the congestion management market. • In TSO-DSO congestion management a shared MOL is used • TSO has direct access to DERs in each of fragmented market.
combined balancing and congestion management for all system operators together	•TSO and DSO jointly operate market and jointly procure the flexibility for the network need in common market. •TSO and DSO are both the DER dispatcher based on the needs •Since some bids are also used for procuring flexibility to solve the balancing issues, there is a priority for balancing to access the bids. •The bids must include the locational information, otherwise not usable for congestion management.

SmartNet project as one of the most authentic project for the TSO-DSO coordination schemes defines different market models namely: **Centralized AS market model for smartNet, Local AS market model , Shared balancing responsibility model, Common TSO-DSO AS Market model, Integrated flexibility market model.** In the following the summary of the SmartNet coordination schemes are elucidated

Coordination Schemes

Centralized AS market mode for smartNet

- Only TSO is the responsible for operating the market and dispatching the flexibility resources
- TSO is the only buyer of the flexibility
- DSO is not involved in the procurement and activation process
- DSO performs the conventional roles without accessing the market
- A very limited data exchange needed between the system operators
- The TSO does not consider the distribution system constraints when performing economic dispatch.

Local AS market model

- Both TSO and DSO are the buyer and the operator in their own market.
- The priority to procure the DERs is for lower-level market.
- The local market firstly performs clearing the bids.
- TSO can only access the uncleared bids coming from DSO market.
- local and central needs are addressed through different markets which coexist.
- Only aggregation of the DERs can participate in the local market

Shared balancing responsibility model

- Each buyer procures the required flexibility in its own market using its own resources, without bid forwarding to other market.
- The higher-level market is operated by the TSO, and lower level by DSO
- Both TSO and DSO manage the balancing in their own grid independently
- DSO balancing activity should be coordinated with the TSO according to a pre-defined schedule, where the energy flow in the interconnection points is determined
- The pre-defined schedule can be defined either for each TSO-DSO interconnection point or only for some of them

Common TSO-DSO AS Market model

- TSO and DSO jointly operate market and jointly procure the flexibility for the network need in common market.
- TSO and DSO are both the DER dispatcher based on the needs
- similar scheme in case of centralized variant, where only one single market exist.
- in case of decentralized variant, smaller local DSO market coexist within common market.
- DSO only has access to the DERs in the distribution network for solving issues.
- In decentralized format, some bids associated to the local area are firstly cleared in local DSO market, however there is no priority for any SOs to procure the flexibility.

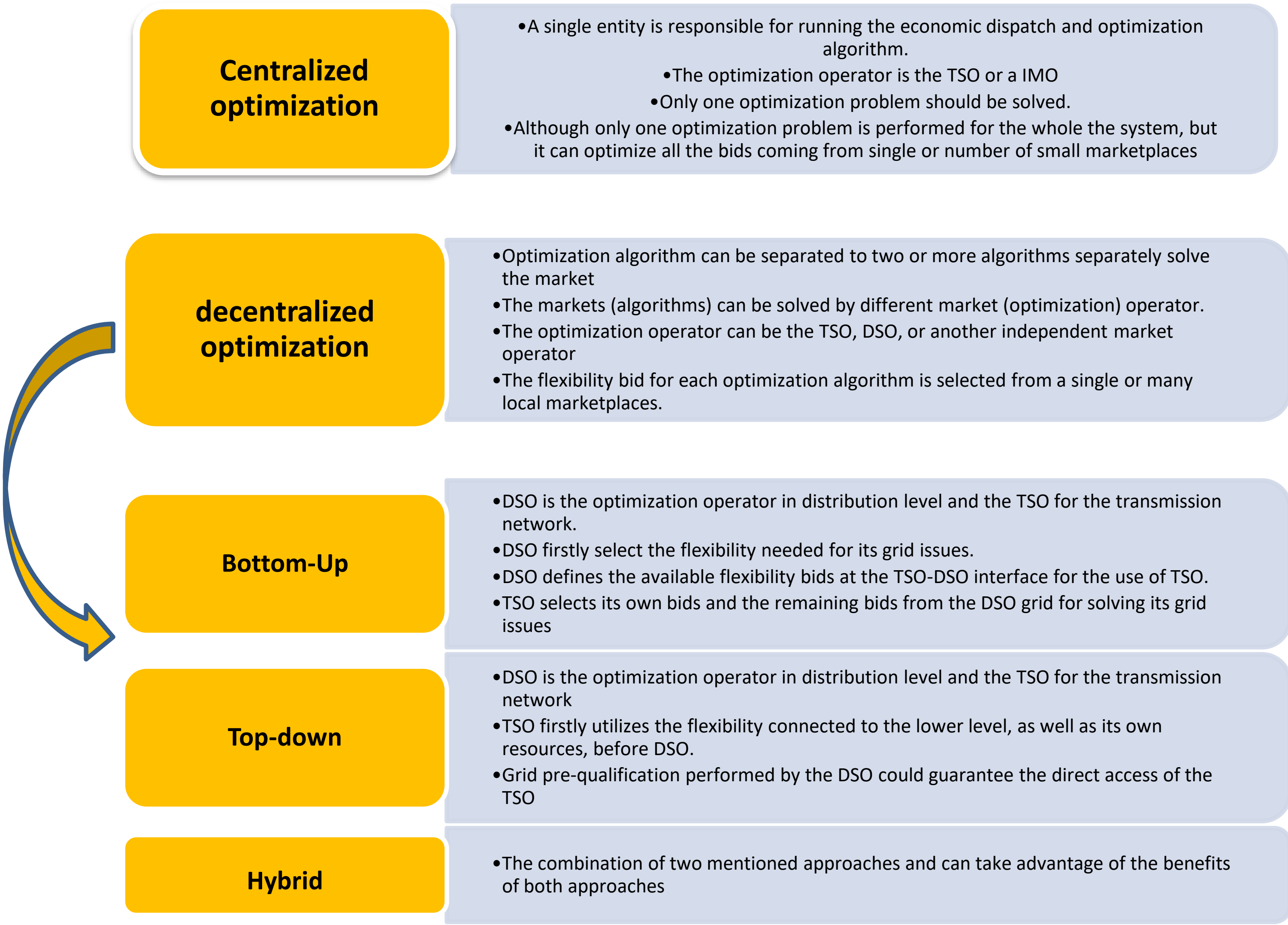
Integrated flexibility market model

- TSO, DSO, FSPs are the buyers of the flexibility
- One single market is operated by an IMO
- The resources are shared, and no entity has priority for procuring the flexibility.

EU-SYSFLEX

As presented in [24], the EU-SysFlex aims at identifying the long-term requirements of the future European power system considering the high penetration of the RES. The subject related to the concept of this paper is that the EU-SysFlex develops the role models to describe the responsibilities and interactions between system operators (regulated players) and deregulated players (in particular flexibility service providers), for system service provision by both centralized and decentralized energy resources. In this literature review for the EU-SysFlex different market models are described and they will be compared. Considering the TSO-DSO coordination, this project proposes two optimization model.

The optimization models presented in this project are **centralized optimization**, **decentralized optimization.** For the latter, there are 3 different variants namely, **bottom-up approach, top-down approach, and hybrid approach**. In the following a brief description has been depicted:



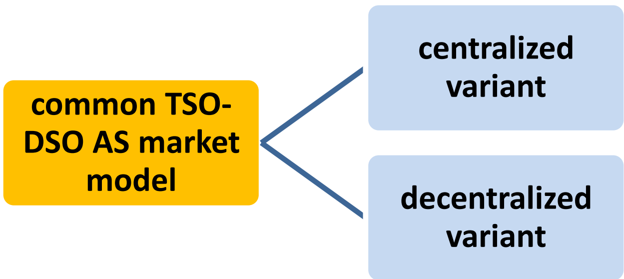
As mentioned in [28], [29], the CROSSBOW project firstly aims at identifying the shared use of resources for the cross-border RES and storage units management with a low operational cost and high economic benefit for the RES and storage units. The related subject extracted from CROSSBOW project is that it tries to improve the control of exchange power at interconnection points. In this regard, it proposes a set of use cases for TSO-DSO cooperation and the goal of literature is to review the ones with a focus on the market TSO-DSO coordination.

The **first use case** is **the enhanced grid visibility**. it admits the need for improvement the observability, granularity and transparency of the data, which requires a sufficient information exchange between the system operators. The detailed information about this use case is addressed in [28].

The **second use case** is the **congestion management** where the paper introduces 3 different congestion management cases, firstly congestion management in distribution network utilizing voltage control, secondly, the congestion management in distribution network utilizing power flow control, and thirdly the congestion management in distribution network utilizing network reconfiguration. In this use case the CROSSBOW project proposes a **common TSO-DSO AS market model** as the main scheme for the project. The main objective of the coordination scheme is to lower the procurement cost. This coordination scheme provides a common market where both TSO and DSO can procure the flexibility from all the resources connected to the network and are jointly responsible for the market operation. For this model, two different alternatives have been proposed:

firstly, **the centralized variant** where all network constraints are integrated only in one optimization model and TSO and TSO are jointly responsible for market operation of common TSO-DSO market. However, the independent market operator can also operate the market in this case. in centralized variant, this coordination scheme integrates all the constraints of the network on both levels, as well as the local flexibility needs.

secondly, **the decentralized variant** where the local DSO market for local constraints runs firstly and the result are sent to a AS market operated by the TSO. Afterward, the result of the second market sends back to the first market to find the most optimal solution. In this model, the TSO and DSO are jointly responsible for the outcome of separate markets. In decentralized variant, in contrast to the local flexibility market model in previous literature, there is no priority for the DSO to procure the local flexibility to solve local issues, but it depends on the combined optimization of both needs at both grid level.



The **third use case** is the **whole sale access**, in which the TSO and DSO should facilitate the participation of the all the resources, as well as all the consumers. In this model, an integrated market for all the flexibility services is favorable for hosting all active customers which can maximize the value of their assets in the system within this integrated market. Creating a fragmented market for each TSO or DSO endangers the ability of the resources to maximize their economic potential. Moreover, the resources should be able to be aggregated in any connection point and any marketplace. The market framework should define the roles and cooperation in procuring the resources by the TSO and DSO. The

CROSSBOW adopts some use cases namely "Market participation, system market platform for balancing market, etc. which determines and assesses the feasibility of the balancing and ancillary service market using the distribution resources. CROSSBOW aims at analyzing these use cases and enables the seamless utilization of these distribution resources in the market.

Finally, the last use case is the **better use of flexibility resources in distribution side**, considers the TSO-DSO collaboration in the distribution network to allow higher penetration of RES. CROSSBOW proposes a framework for promoting and adoption of virtual storage plant for different stakeholders by defining some use cases such as Frequency support by VSP coordination, voltage support by VSP coordination, etc. The detailed information about this use case is presented in [28]

The CoordiNet project[8] is one of the latest projects of the Horizon 2020 and a twin for the INTERRFACE project, which aims at establishing a coordination for the TSOs, DSOs, and FSPs. The project proposes various scheme considering different roles and responsibilities associated to the stakeholders and the type of market design. This project introduces a categorization structure that helps to group similar coordination needs together, even though they might differ regarding certain market design characteristics. The flexibility services identified for the coordiNet are mainly for congestion management, frequency control, voltage control, controlled islanding. Moreover, the coordiNet entails three different demonstrators namely, Spain, Greece, and Sweden composing 12 various Business Use cases (BUCs).

For both system operators, interaction and data exchange is needed to fulfil their responsibilities and they are required to get an insight in the neighboring grids in function of the transmission and distribution grid planning, connection and access procedures, observability area definition and supervision and control. This project start proposing the coordination schemes by identifying different classification layers. These classification layers illustrate a distinction between the central and local needs, the buyers of the flexibility in the market, number of markets in each coordination scheme, and the possibility of the TSO to access to the DERs. The central and local needs are placed in the first decision layer, where central needs refer to the collection of services, and entailing products, which can be provided on a central level, while local needs are those needs that are characterized by a certain geographical location which entails that only flexibility providers connected to the distinct location in the electricity grid can provide the required flexibility service. In these market schemes, TSO, DSO and other commercial parties are the probable buyers of the flexibilities and the second decision layer is based on them. Moreover, the third layer considers the number of markets, which is one if only local, or only central, or an integrated market exist; and more than one when there are combination of local and central or distributed market composing one or more markets. Finally, the last classification layer defines whether the TSO can have the access to the DERs to procure the flexibility services for its need out of its operating area. Having these classification layer in mind, coordiNet proposes 7 different coordination schemes which will be described in detail in the following sections of this paper.

The first market scheme is **Local market model** which introduces only a single market procuring the flexibility services for the local needs without any inter-relation or interaction with a probable central market, and consequently no need for the coordination. This model can be applied to the controlled islanding cases or the area without transmission network. However, for technical reasons the coordination is needed in the TSO-DSO interface point. In this market obviously the DSO is only buyer and operator of the market, and since the market is work completely in an isolated manner, TSO access is not applicable in this model. Consecutively, in this model, there is no need for a massive data exchange with TSO (if available) and low degree (or no) coordination needed. Moreover, it will facilitate the participation of Small DERs in the local market. However, due to the low number of DERs in a local area it may cause a low liquidity and higher cost for procuring the flexibility.

Central market model as the second scheme also proposes a single market which procure flexibility services for the central needs. The only buyer of the flexibility is the TSO and depending on the structure of the market, the TSO may have access to the DERs or not. In this model, DSO performs the conventional roles without active participation in the market. In this coordination scheme similarly to smartNet project, if the TSO does have direct access to flexible sources connected to the distribution grid, the DSO can perform different rule-based mechanisms or other regulated signals (not market-based) to respect the grid constraint. However, if these non-market mechanisms include a high standard on grid constraints it may influence the efficient operation and act as a barrier for the integration and participation of DER in market. As the result of this coordination scheme, no further coordination needed with respect to the current market, since the TSO is the only operator and procures the flexibility for the central need without any higher communication need with DSO, except informing the TSO about the DSO constraints. Moreover, since the operational cost, and essential communication is low, this model is applicable with a high efficiency, when the distribution grid constraints are low.

In the common market coordination scheme both central and local needs should be addressed and both system operators procure the flexibility services from a single market to solve the problems in their grid. This single market combines both central and local market as a common market. Moreover, even if there is only one single platform or multiple smaller platforms within this scheme, only one single market optimization happens, and all the flexibility requirements are jointly optimized for both DSO and TSO at the same time. As the result of this scenario, the computational process is demanding, all the bids submitted in the market must include a locational information, and all the process and products must be applicable for both TSO and DSO, which implies a more complex model. Having this model, the resources cannot perform gaming in the market since they do not have the opportunity to submit bids in different markets, and due to simple trading strategy, they tend to participate in this market. Finally, the cost for procuring flexibility services for solving locational problems may be high.

Similarly, to the previous model, **Integrated market model** presents a single market for procuring the flexibilities. In this market, both regulated and non-regulated (commercial market party) entities are identified as the buyers of the flexibility for resolving the grid constraints. Since TSO and DSO are not exclusively the buyer of the flexibility, for ensuring the neutrality and transparency of the market an independent market operator is required. As the result of a high number of buyers and the flexibility service providers, the liquidity of the market is high, and the cost of the flexibility services are more reasonable. Furthermore, the probability of gaming is low, and the bid submission can take place in one single market. Products in the market must be defined in a way to be acceptable for all parties, which implies a higher complexity and higher cost. Likewise, the bids formulation not only should be aligned with all parties, but also must contain the locational information. Similar to previous model, procuring flexibility for local problem solving may be costly. However, due to the introduction of commercial party like BRP, a lower need for reserve activation needed, as it involves in resolving the imbalances. As the consequence of defining commercial party following problems may occur: firstly, since the commercial party also is the buyer of flexibility, it may buy the flexibility with a higher price which cause the higher buying price also for the system operators in the market; secondly, TSO hardly can anticipate the flexibility needed for balancing purposes since the BRP can buy flexibility in real-time and solve some of their balancing issues, and finally, it endangers the development and liquidity of the intraday markets.

In **Multi-level market model**, the procurement of the flexibility services can be performed separately for each system level, and the local and central needs are addressed through different markets which coexist. The main feature of this market is that, even though it is composed of different markets, the TSO has access to DERs. However, TSO access is limited to the uncleared flexibility bids of the local market. On the other hand, if the TSO access to DERs is prohibited, the market model converts to a fragmented market. in consequence of this model, the markets (especially local market) will suffer a low liquidity and a higher flexibility procurement cost. However, the entry barrier is lower for the local market. Moreover, a high ICT cost for handling the data exchange between the markets, and an effort for avoiding double activation in different market are required in this model. On the other hand, since products are mainly adapted for each specific market, participating to another market for them imply a complex trading strategy, forecasting exercise and some new specifications. This market model can be correspondent to the Local AS market model in smartNet, or the non-strategic DSO leader presented in this literature review before.

The **fragmented market model** as the sixth coordination scheme in CoordiNet, is similar to the multi-level market presented before, with a slight difference in which the TSO does not have access to the DERs. In this essence, the TSO and DSO can procure flexibility only using their belonging resources. In this model, the liquidity might be low especially in local market, while introduces a lower entry barrier for DERs. Furthermore, the product specification definition and updating the product features are easier in this model since they are not bided in other markets. Regarding this market scheme specification, the model is comparable to the shared responsibility model of the SmartNet.

Finally, a **distributed market model** is defined in this project where peers are the sole buyers and the providers in the market within one or more distributed market. In this model, a peer-to-peer market setup can be implemented using a fully distributed network. this market model, is not compatible with current regulations, and may cause a low system wide overview. In this market model, each peer considers its own objective in the market, there is no guarantee of the optimal social welfare, there is a high uncertainty on how TSO and DSO needs should be considered, and as a result of not implementing well, energy imbalance or constraint violation may happen.

In the following table, all the coordination schemes in CoordiNet project are presented and the characteristics of each of them are addressed. The table firstly shows if the market aims at procuring the flexibility to fulfill the local need or the central need, then illustrates the buyers of the flexibility as well as market operators in the market and afterward, indicates the number of sub-markets within the market. Moreover, in addition to DSO's actions as the system and market operator, it illustrates if the DSO has an active rule in distribution network for procuring the local flexibilities for its own needs and determines his level of action within the network for each coordination scheme. On the other hand, the interaction between TSO and DSO and TSO and DERs is dictated for each coordination scheme, and the main features, advantages, disadvantages and the application of each scheme are discussed.

Coordination scheme	Which SO needs?	buyer	market operator	N. markets	TSO direct access?	DSO passive active?	DSO solve local need via market-based approach?	Interaction between DSO, TSO	Feature Advantage disadvantage Application
Local market model	Local	DSO	DSO	1	NA	Active DSO	Yes	NO interaction	**Main Feature** -Only procuring the flexibility services for the local needs -The bids are only used in the local market -No coordination with TSO is needed, -only a TSO-DSO coordination for technical reasons (if TSO exist) **Advantage** -No need for complex data exchange to TSO (if available) -A very low degree of coordination needed -Low entry barrier for the DERs **Disadvantage** -Probability of low liquidity due to low number of flexibilities in local area - Higher flexibility procurement cost due to low liquidity **Application**

									-Area with controlled islanding -Area without transmission network
Central market model	Central	TSO	TSO	1	YES NO	Passive DSO	NO	Low interaction	**Main Feature** -only a single market procuring flexibility services for the central needs. -DSO performs the conventional roles without accessing the market. -DSO performs non-market-based mechanisms to fulfill the grid constraints. **Advantage** -no further coordination needed with respect to current market -operational cost, and essential communication is low if distribution constraint is low. - low complexity in product definition **Disadvantage** -if DSO non-market mechanisms has strict standards, it may influence the efficient operation DER's integration -Not efficient if the distribution constraint and DER resources are high. **Application** -Applying to the current electricity market. -Area with low distribution network constraints.
Common market model	Local central	TSO DSO	TSO DSO	1	Yes	Active DSO	Yes	High interaction	**Main Feature** -Both central and local needs should be addressed in a single market. - it can consist of many small markets within single market.

									-without regard to the number of smaller market, one single optimization is performed. -Flexibility requirements are jointly optimized for both DSO and TSO **Advantage** - less complex trading strategy as they bid in a single market -no need for market selection to bid as they bid in a single market - the resources cannot perform gaming - high level of liquidity in market **Disadvantage** - Demanding optimization simultaneously for DSO and TSO needs -Higher computational requirements - Complexity for product definition - need for geographical information within products - risk for higher market price for congestion management. -need for high data exchange and high coordination. **Application** -Area where there is a good ICT platform, high observability, and a good coordination for TSO-DSO

Integrated Market Model	Local central	TSO DSO Commercial party	IMO	1	Yes	Active DSO	Yes	High interaction	**Main Feature** - A single market for procuring the flexibilities -Both central and local needs should be addressed in a single market. - In addition to SOs, other parties are able to buy flexibility - the market operator is IMO **Advantage** - less complex trading strategy as they bid in a single market -no need for market selection to bid as they bid in a single market - high level of liquidity in market - more efficient market operation and optimal market equilibrium - Efficient market operation from grid constraint point of view - higher level of imbalances resolved by the market (BRP) and potentially lower need for reserves activation as a last resort. - A risk for system operator no being able to buy flexibility with the optimal cost as it will be given to the highest willingness to pay -The neutrality of the market is ensured. - The probability of gaming is low as they bid in one single market **Disadvantage** **- high complexity for product definition** - need for geographical information within products - risk for higher market price for congestion management.

									- More complex to determine the amount of required balancing energy by TSO due to the presence of BRPs or other parties -A risk for liquidity of intraday due to the third-party existence in the market **Application** -in market where non-regulated buyers exist. -in area where there is a good ICT platform, high observability, and a good coordination for TSO-DSO
Multi-level market model	Local Central	TSO DSO	TSO DSO	>1	Yes	Active DSO	Yes	High interaction	**Main Feature** - procurement of the flexibility services can be performed separately for each system level using their own resources. - local and central needs are addressed through different markets which coexist. - TSO access is limited to the uncleared flexibility bids of the local market. - different system operator is in charge of different markets. **Advantage** - low complexity for product definition - lower entry barrier for DERs - low computational requirement for each market. **Disadvantage** -Low liquidity I the market especially in local market

									-Higher cost for procuring flexibility due to lack of economy of scale -High communication required between system operators -possibility of the gaming and double bid activation in different market - a complex trading strategy for resources **Application** -in area where there are high number of DERs -in area with good ICT system for high data exchange requirement.
Fragmented market model	Local Central	TSO DSO	TSO DSO	>1	NO	Active DSO	YES	Medium interaction	**Main Feature** - procurement of the flexibility services can be performed separately for each system level using their own resources. - local and central needs are addressed through different markets which coexist. -TSO does not have access to the DERs even to the uncleared bids from lower markets - different system operator oversees different markets. **Advantage** - low complexity for product definition - lower entry barrier for DERs -low computational requirement for each market. **Disadvantage** - low liquidity in the market especially in local market - risk of higher cost for procuring flexibility due to lack of economy of scale.

									low communication required between system operators **Application** -In area where there are high number of DERs -In area where the TSO does not require the DER to solve the grid issues
Distributed **Market model**	Local	Peers		>1	NA	NA	NA	NA	**Main Feature** -peers are the sole buyers and the providers in the market - one or more distributed market exist -Peer-to Peer transactions take place **Advantage** -Peers can easily trade with another peer in a market where there is not a central entity for operating market. -empowers prosumers and consumers - cause a higher flexibility procurement using small resources **Disadvantage** -Higher uncertainty on how address the TSO and DSO needs -No guarantee for reaching optimal social welfare -Energy imbalance and constraint violation -Lack of systemwide overview -Market participants may have higher autonomy

									-Not compatible with current regulation **Application** -In area where there are number of prosumer and individual producers aiming at buying and selling energy. -in area where a blockchain platform is implemented and peers can trade without the supervision of the third party.

As indicated in [25], Under the European H2020 program, the EUniversal Project has the main objective to foster the universal access of system operators to the available flexibility, mainly provided by Distributed Energy Resources (DER), through the interaction with new Flexibility Markets and innovative services. the project aims to tailor the concept of the Universal Market Enabling Interface (UMEI) which look to overcome the limitations that the system operators, especially the Distribution System Operator (DSO), experience in the use of flexibilities, addressing the interlinking of electricity markets with active network management. Euniversal identifies market organizations for the TSO and DSO to procure the flexibilities under coordinated mechanisms. This project has depicted six coordination schemes with a high concentration on the market schemes identified in the SmartNet (SmartNet [9]). The project reviews on the different aspects of the SmartNet coordination schemes and propose a new model as the combination of the second and the third scheme of the SmartNet project. In this project, the focus is mainly on the functional aspects and less involved with the organizational aspects. In this regard, the essential functions in each market schemes will be investigated and the entity responsible for performing that function is not considered in the project. Since the project literature depicts a detailed perspective of the coordination schemes (whether already defined in SmartNet or not), the aim is to review all the schemes presented in this literature.

The first scheme is the **centralized flexibility market**, where the flexibility service is procured only by the TSO in a single centralized market, similar to the current electricity market. However, describing this scheme emerges new required functionalities within the existing market. Moreover, the pre-qualification of the services must be performed to guarantee that the constrains will not be violated in the distribution network. In general, the DSO is not able to procure the flexibility, but it is able to perform the flexibility pre-qualification and validation, which in case of advanced coordination, this DSO validation can be performed close to real time before the activation of bids selected by the TSO.

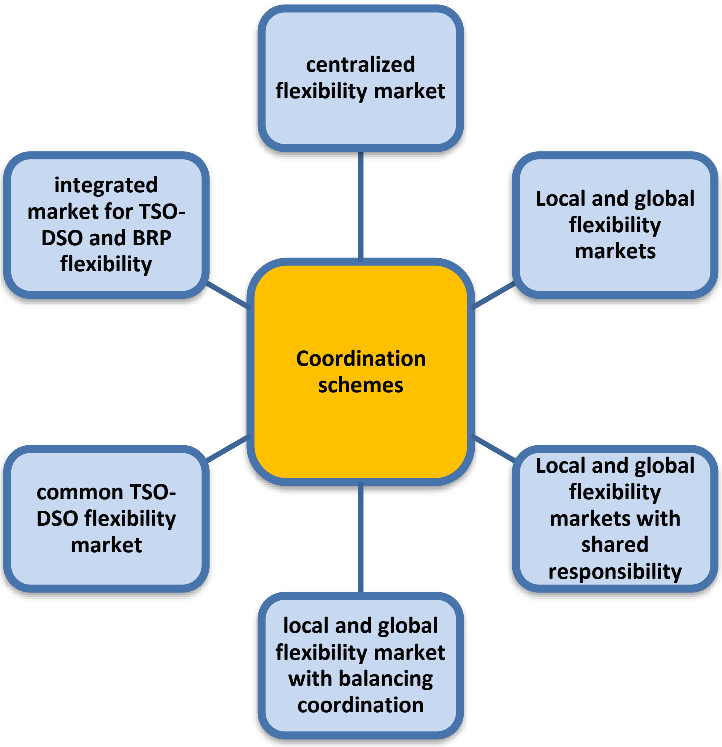
The second coordination scheme is **local and global flexibility markets.** In this case two different coordination schemes are addressed. In the first scheme, the DSO is the operator of its own market and the buyer of the flexibility aiming at solving the local network issues by procuring the flexibility from local DERs. After clearing the market by DSO, the remaining bids can be forwarded to the TSO for its potential needs, taking into account the distribution network constraints violation. The second scheme, on the other hand, does not consider any coordination between TSO and DSO for the provision of regulated flexibility (system services). However, a well coordination takes place between market operator and the DSO (or between Iberian MIBEL and DSO) to give the opportunity to DERs to participate in the energy market (Day-ahead and intraday market) to provide the commercial flexibility for the BRP. In this second model, the DSO is involved with same functions as it has in the first model.

The third coordination scheme presented in this project is **local and global flexibility markets with shared responsibility**. Considering this scheme, in contrast to the previous case at which TSO could have access to the remaining bids of local market, the TSO is not allowed to have a direct access to the DER bids. However, the DSO is responsible for providing the pre-defined profile for the TSO at the TSO-DSO interface while using its own resources. Regarding the mentioned mechanism, TSO is not required to know much about the DER's location, and its knowledge is limited to know to which DSO grid the DER belongs.

The fourth coordination scheme which is uniquely introduced in this project **is local and global flexibility markets with balancing coordination**. This scheme is the combination of previous 2 schemes. In this market scheme, the TSO is responsible for solving the imbalance as the result of DSO resource activation. Similarly, to second and the third scheme, DSO procures the flexibility offered in the local market for the local need, then informs the TSO in case of potential imbalance, and finally TSO will act for balancing the system. In this market, the remaining bids of the local market may be used or not in the TSO market depending on the market procedure.

Another coordination scheme is Common TSO-DSO flexibility market where both system operators are unified in a common market procuring flexibility for their needs. The bid selection and clearing should be performed in a coordinated way considering all the constraints of the network. Moreover, the location of each resource should be known if it is used for solving constraints issues.

The last market scheme for **the TSO-DSO coordination purpose**, is integrated market for TSO-DSO and BRP flexibility. In this market model, all the parties including TSO, DSO and BRP compete for the flexibility resources. However, the system operator must guarantee the secure operation of their grid by selecting the most suitable bids among all the submitted bids. Similar to the previous scheme, if the flexibility is used for fulfilling the grid constraints the location must be available within the bid.



As indicated in references [29], [30], OneNet project is funded by the European Union for the Horizon 2020 project, targets on proving a seamless integration of all the actors from grid operators and customers in the electrical network across the Europe by providing common market design for Europe and defining the products and parameters for the grid services. There are other goals defined within OneNet perspective such as common IT architecture which are out of scope of this literature review. OneNet project also aims at facilitating the participation of new generation of grid services such as demand response, storage and distributed generation and creating the customer centric approach to grid operation while proposing a new market, services and the products within the market. The OneNet focuses mainly on mechanisms which provide the system services and flexibility market rather than energy market design. As in [30], five general pillars have been depicted within the theoretical market frameworks , namely 1) Entire market architecture, 2) sub-market coordination, 3)market optimization 4) market operation, 5) grid constraints. Among all mentioned, only the second pillar will be discussed, as it is related to the goal of this paper. As indicated, the theoretical market framework is defined in this project and applied to different clusters, namely, Northern, Southern, Western, and the Eastern cluster. In each of these cluster different demonstrators have been defined with their specific market design regarding their aims and characteristics. There are three clusters within each cluster (re-clustring) namely, TSO-DSO market-based coordination, DSO market-based coordination, and technical TSO-DSO coordination and the goal is to generally explore these re-clusters within this initial literature review. The focus for the market-based TSO-DSO coordination, and market-based DSO coordination is to identify the ways to procure the flexibility services within whole system, and local level, respectively, in an efficient and cost-effective way from the resources connected to both transmission and distribution levels. Moreover, the technical TSO-DSO coordaintion aims at establishing the direct link between TSO-DSO for information exchange purposes.

For the OneNet project, the coordniNet market frameworks are taken into account as the initial point and a reliable reference. However, due to some differences between the purpose of coordiNet and OneNet project, an extra modification is required to fill the gaps, as in coordiNet the main goal was to proposing TSO-DSO interactions and not flexibility procurement process, pricing methods, etc.

As indicated above, the second pillar discussed for the theoretical market framework is the sub-market coordination. In this pillar allocation principal of the flexibility has been mentioned which requires a coordination between system operators. The allocation principle determines how the amount of flexibility at the transmission or distribution level is divided between different 1) services, 2) system operators, and 3) sub-markets. For the second topic on the system operator's allocation principle of flexibility, the project refers to the EU-SysFlex project where the bottom-up coordination, Top-down coordination, and hybrid coordination are addressed which has been already elucidated in section () in this paper. The bottom-up coordination is the priority for the DSO in flexibility selection with the decentralized optimization. The Top-down coordination is the priority of the TSO and decentralized optimization, and the hybrid one is the no priority and the decentralized optimization. Regarding the EY-SysFlex, the [30] indicates the different optimization options, such as centralized, decentralized and the distributed organization.

Regarding the re-clustering in OneNet, the demonstrators that belong to the market-based TSO-DSO coordination apply a coordination scheme for the TSO and DSO and considers the ways and rules on how the flexibility is allocated between system operators and how they procure the flexibility for system needs. On the other hand, for the demonstrators belong to the DSO market0based coordination, the mechanisms are to procure the flexibility services to solve local needs. The former coordination is adopted only the DSO has exclusive access to the DERs. Finally, the demonstrators belong to the technical-based TSO-DSO coordination aims at establishing a direct link between two system operators for directly exchanging data and request for operation actions.

For the market-based TSO-DSO approach, OneNet project points to test two coordination schemes for each demonstrator to provide a coordinated way to procure and allocated the flexibility in the market to each system operator. These two coordination schemes which already addressed in CoordiNet are 1) multilevel market 2) common market.

In the Multilevel TSO-DSO market, two layers of submarkets exist. The TSO and DSO are the only buyer of the first and the second layer, respectively. Moreover, the TSO can have access to the DER's bids via bid forwarding mechanism from DSO to TSO. These bids shared with the TSO can be individual bids or the aggregation of the bids, while respecting the grid constraints. in tis market, DSO has the priority for procuring the flexibility. this market scheme is applied for the medium and short timeframe for procuring the flexibility from week-ahead to the near-real-time. This market scheme provides the opportunity for procuring the availability and the activation of active and reactive power products for the local and central needs. This coordination scheme is implemented for the Cypriot demonstrator (in southern cluster) and polish demonstrator. The specification of the market design for above demonstrator is addressed in [30].

In the common TSO-DSO market, there is a unique layer composed of many sub-market where both DSO and TSO are the buyers involved in procuring the flexibility services provide by the same FSPs. Despite the Multilevel TSO-DSO level, this market covers all the timeframes from long-term to near-real-time. In this market scheme also both active and reactive products are traded so as to solve the grid issues. The Northern cluster market adopts this market scheme in this project.

For **market-based DSO coordination** aims at solving the local issues procuring the belonging DERs without a negative effect on other areas. Depending on the market design, an interaction may exist with other system operator. This market scheme has been implemented for Spain, Czech Republic, Slovenia and Hungry demonstrator, and the specification about the market design of each demonstrator is addressed in [30]. This market scheme covers all the timeframes and similarly to the previous market-based TSO-DSO coordination, it allows the availability and activation of active and reactive power products.

The long-term and short-term sub-markets within this scheme differs in term of timing and product acquisition.

For **Technical-based TSO-DSO coordination**, it mainly concentrated on technical aspects of the TSO-DSO coordination. This coordination is performed for French, Portuguese, and Greek demonstrators.

This table illustrates all the coordination schemes discussed in this literature review to present a better clarification and perspective over the projects and papers and their proposed coordination schemes. In the table the market operators, system operators, buyers and sellers of flexibility are presented as the basic information for each coordination scheme. Moreover, the table illustrates the entities in charge for dispatching DERs as well as the DER's aggregator and determines the priority for flexibility procurement for each entity, and level of TSO access to DERs. Finally, based on the characteristic of each model, an equivalent coordination scheme is proposed from the schemes presented in CoordiNet project.

<table>
<tr><th>Ref</th><th colspan="2">Name of coordination scheme</th><th>Equivalent in coordiNet</th><th>MO</th><th>DER dispatcher</th><th>Buyer</th><th>DER aggregator
Bid aggregator</th><th>Priority</th><th>TSO access to the DERs?</th></tr>
<tr><td rowspan="3">11</td><td colspan="2">Total TSO model</td><td>Central market model</td><td>TSO</td><td>TSO</td><td>TSO</td><td>TSO</td><td>Exclusivity for TSO</td><td>Yes (directly) [2]</td></tr>
<tr><td colspan="2">Minimal DSO</td><td>Central market model</td><td>TSO</td><td>DSO</td><td>TSO</td><td>Aggregator</td><td>Exclusivity for TSO</td><td>YES (indirect)</td></tr>
<tr><td colspan="2">market DSO</td><td>Central market model</td><td>TSO</td><td>DSO</td><td>TSO</td><td>Aggregator(C1)
DSO (C2)</td><td>Exclusivity for TSO</td><td>Yes (indirect)</td></tr>
<tr><td rowspan="2">12</td><td rowspan="2">grand optimization vision</td><td>Total TSO model</td><td>Central maket model</td><td>TSO</td><td>TSO</td><td>TSO</td><td>TSO</td><td>Exclusivity for TSO</td><td>Yes (directly)</td></tr>
<tr><td>Minimal DSO</td><td>Central maket model</td><td>TSO</td><td>DSO</td><td>TSO</td><td>Aggregator</td><td>Exclusivity for TSO</td><td>Yes (indirect)</td></tr>
</table>

[2]. TSO access to the DERs can be classified into two different ways. A **direct access** is for the cases that the TSO can directly procure the flexibility services without any intermediate party. Note that if the TSO can access the aggregation of the DERs directly, it is also considered as the direct access. If the individual DER bid, or aggregated bids are forwarded from a lower-level market to the TSO market, and TSO utilizes them, TSO has **indirect access** to the DERs.

	layered decentralized optimization model	Central maket model	TSO	DSO	TSO	DSO	Exclusivity for TSO	Yes (indirect)
2	a centralized market	Central maket model	TSO	TSO	TSO	Not defined	Exclusivity for TSO	Yes (direct)
	separate markets	Fragmented market model	TSO DSO	TSO DSO	TSO DSO	Not defined	No priority	No
	the single platform for both local and central market	Common market model	TSO DSO	TSO DSO	TSO DSO	Not defined	No priority nor exclusivity for TSO and/or DSO	Yes (direct)
20	a hierarchical coordination mechanism	Central market model	TSO	DSO	TSO DSO	DSO	Priority for TSO	Not defined
23[3]	sequential design	fragmented market model	TSO DSO Retail er	TSO DSO Retailer	TSO DSO Retailer	Not defined	Priority for retailer, then DSO and then TSO	Yes (direct)

[3] In this scheme, all the market parties have access to a shared resources but procure the flexibility taking into account the priority. It composed of three market schemes, in some cases it is a mixture of 2 coordination schemes of coordiNet.

	TSO-DSO mechanism		fragmented market model + Common market model	TSO DSO Retailer	TSO DSO retaile	TSO DSO retailer	Not defined	Priority for retailer, then DSO and then TSO	Yes (direct)
	TSO-DSO-Retailer mechanism		Common market model	Not defined	TSO DSO retailer	TSO DSO retailer	Not defined	Priority for retailer, then DSO and then TSO	Yes (direct)
13	DSO leader	Non-strategic DSO	Multi-level market model	TSO DSO or IMO	DSO	TSO DSO	DSO	Priority for DSO	Yes (indirect)
		strategic DSO	Multi-level market model	TSO	DSO	TSO DSO	DSO IMO	Priority for DSO	Yes (indirect)

				DSO or IMO					
	DSO follower		Multi-level market model	TSO DSO	TSO/DSO (case1) DSO (case 2)	TSO DSO	Not defined	priority for TSO	Yes (case1) (direct) No (case2)
	TSO-DSO Iteration		Multi-level market model	TSO DSO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for TSO and/or DSO	Yes (indirect)
32	full integration market model		Central market model	TSO IMO	TSO	TSO	Not defined	Exclusive for TSO	Yes(diret)

	Enhanced Bulk Balancing Authority (BA) Model (A)	Central market model	BA	BA	BA	Not defined	Exclusivity for TSO	Yes(direct)
	Enhanced Bulk BA Model (B)	Central market model	BA	DSO	BA	Not defined	Exclusivity for TSO	Yes(indirect)
7	TSO-managed model	Central market model	TSO IMO	TSO	TSO	Aggregator	Exclusivity for TSO	Yes(direct)
	TSO-DSO hybrid managed model	Central market model	TSO	TSO	TSO DSO	Aggregator	Depending on the type of service	Yes(diret)
	DSO-Managed Model[4]	Central market model	TSO	TSO DSO	TSO	Aggregator DSO	Depending on the type of service	Yes(diret)
22	TSO-FSP model	Central market model	TSO	TSO	TSO	Not defined	Exclusivity for TSO	Yes(direct)

[4] In general description of this market scheme, only one single market is considered which assign this market to the central market model. However, two alternative models are described, which already elucidated in this literature review. In case of considering them, this model cannot be categorized as the central market model, since in those models, the local market is defined, which in those cases, it can be assigned to multi-level market model (first alternative) and fragmented market (second alternative), and consequently, the roles and specifications are different.

	TSO-DSO model	Common market model		TSO DSO	TSO DSO	TSO DSO	Not defined	No priority nor exclusivity for TSO and/or DSO	Yes(direct)
	centralized market model	Central market model		TSO	TSO	TSO	Not defined	Exclusivity for TSO	Yes(direct)
3	separated TSO and DSO congestion management (with balancing market separated or combined with TSO congestion management)	fragmented market model		TSO DSO	DSO	TSO DSO	Not defined	exclusivity for DSO	NO
	combined TSO and DSO congestion management, with separated balancing	Multi-level market	Common market model	TSO DSO	TSO DSO	TSO DSO	Not defined	No priority nor exclusivity for TSO and/or DSO	Yes (direct)
			Central Market model	TSO	TSO	TSO	Not defined	Exclusive for TSO	Yes (direct)

	combined balancing and congestion management for all system operators together		Common market model	TSO DSO	TSO DSO	TSO DSO	Not defined	No priority nor exclusivity for TSO and/or DSO	Yes (direct)
8	Centralized AS market mode for smartNet		Central market model	TSO	TSO	TSO	Aggregator	Exclusive for TSO	Yes (direct)
	Local AS market model		Multi-level market model	TSO DSO	DSO	TSO DSO	Aggregator	priority for DSO	Yes (indirect)
	Shared balancing responsibility model		fragmented market model	TSO DSO	DSO	TSO DSO	Aggregator	Exclusive for DSO	NO
	Common TSO-DSO AS Market model	Centralized variant Decentralized variant	Common market model	TSO DSO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for TSO and DSO	Yes (direct)

	Integrated flexibility market model		Integrated market model	IMO	TSO DSO	TSO DSO FSP	Aggregator	No priority nor exclusivity for FSP, DSO, TSO	Yes (direct)
24	centralized optimization		Central market model	TSO DSO IMO	TSO	TSO	Not defined	Exclusive for TSO	Yes
	decentralized optimization	bottom-up approach	Multi-level market model	TSO DSO	DSO	TSO DSO	Not defined	Priority for the DSO	Yes (indirect)
		top-down approach	Multi-level market model	TSO DSO	TSO DSO	TSO DSO	Not defined	Priority for the TSO	Yes (direct)
		hybrid approach	Multi-level market model	TSO DSO	TSO DSO	TSO DSO	Not defined	No priority nor exclusivity for DSO, TSO	Yes (direct)

28	common TSO-DSO AS market model	centralized variant	Common market model	TSO DSO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for DSO, TSO	Yes (direct)
			Integrated market model	IMO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for DSO, TSO	Yes (direct)
		decentralized variant	Common market model				Aggregator	No priority nor exclusivity for DSO, TSO	Yes (indirect)
24 (interface)									
25	centralized flexibility market		Central market model	TSO	TSO	TSO	Aggregator	Exclusive for TSO	Yes (direct)
	local and global flexibility markets (first scheme)		Multi-level market model	TSO	DSO	TSO	Aggregator	priority for DSO	Yes (indirect)

			DSO		DSO			
	local and global flexibility markets with shared responsibility	fragmented market model	TSO DSO	DSO	TSO DSO	Aggregator	Exclusive for DSO	NO
	local and global flexibility markets with balancing coordination[5]	Multi-level market model	TSO DSO	DSO	TSO DSO	Aggregator	priority for DSO	Yes (indirect)
	Common TSO-DSO flexibility market	Common market model	TSO DSO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for TSO, DSO	Yes (direct)
	integrated market for TSO-DSO and BRP flexibility	Integrated market model	IMO	TSO DSO	TSO DSO FSP	Aggregator	No priority nor exclusivity for CMP, DSO, TSO	Yes (direct)

[5] This coordination scheme is composed of a separate local congestion market run by DSO, and a central balancing market run by TSO. After clearing the local market, if a imbalance is detected, the DSO inform TSO to balance the network. Moreover, a bid forwarding from local to central market may happen. So the best classification is to assign this scheme to the multi-level scheme of coordiNet.

[29], [30]	the common TSO-DSO market	Common market model	TSO DSO	TSO DSO	TSO DSO	Aggregator	No priority nor exclusivity for TSO, DSO	Yes (direct)
	Multilevel TSO-DSO market	Multi-level market model	TSO DSO	DSO	TSO DSO	Aggregator	priority for DSO	Yes (indirect)

Equivalent to central market model of CoordiNet

In this table all the coordination schemes similar to central coordination scheme of CoordiNet are gathered and the main features, advantages, and disadvantages of each scheme are discussed. Moreover, the source of difference of each coordination scheme compared to CoordiNet is addressed.

Ref	NAME	Main difference with respect to CoordiNet
11	Total TSO model	**Main Similarity with CoordiNet:** -TSO performs the economic dispatch and whole-system optimization with observability of all grids. -TSO is the only buyer and the only market operator. **Main difference with CoordiNet:** -TSO also is responsible for facilitating the transaction among DERs, clearing and settlement for the inert-DER transaction, etc. -TSO is responsible for DER aggregation to let the resources to participate in wholesale market. -The scheme is defined for providing the flexibility services for the wholesale market.

11	Minimal DSO	**Main Similarity with CoordiNet:** -TSO is the entity performs the economic dispatch. -The aggregator is responsible for DERs aggregation -TSO is the only buyer and the only market operator. **Main difference with Coordinet:** -TSO economic dispatch limited until the T-D interface -The DSO coordinates the DERs and provide the services in the interconnection point of TSO and DSO. -TSO does not have observability on the distribution grid. -DSO sends dispatch order to DERs in response to TSO dispatch order.
11	market DSO (C1, C2)	**Main Similarity with CoordiNet:** -TSO is the entity performs the economic dispatch. - In C1, the aggregator is responsible for DERs aggregation -TSO is the only buyer and the only market operator. **Main difference with Coordinet:** **-**Only the aggregation of the DERs must participate in the network.

			-In C2, the DSO is responsible for aggregating the individual DERs. -In C2 only one single aggregated bid can be submitted by DSO per TSO-DSO interface. - TSO economic dispatch limited until the T-D interface using aggregated bid only.
12	grand optimization vision	Total TSO model	*As same as the model of reference 11 for TOTAL TSO model.[6]
		minimal DSO	* As same as the model of reference 11 for minimal DSO.
12	layered decentralized optimization model		**Main Similarity with CoordiNet:** - TSO is the entity performs the economic dispatch -TSO is the only buyer and the only market operator. **Main difference with Coordinet:** - TSO economic dispatch limited until the T-D interface using aggregated bid only. - DSO aggregates the individual DERs and aggregated DERs within each local distribution network. - TSO optimizes the transmission system without having the observability over the distribution network. - Each local DSO has the responsibility to perform balancing in local distribution network - DSO performs the economic algorithm to select a way to be most-effective for the system and the DERs

[6] . in some cases, some reviewed papers or projects are applied the coordination schemes of other previous papers/projects without modification. Hence, further information about the features associated to this row is addressed to the reference at which these coordination schemes are generally available.

2	a centralized market	**Main Similarity with CoordiNet:** -TSO is the only buyer and the only market operator. -TSO dispatches the DERs - TSO had direct access to the DERs.
20	hierarchical coordination mechanism	**Main Similarity with CoordiNet:** -TSO is responsible for performing the economic dispatch of whole system. -TSO is the only market operator **Main difference with CoordiNet**: -DSO can buy the flexibility services for solving its grid issues. -DSO can also use its own DERs (out of market platform) to solve its own issues. -DSO is responsible for aggregating the bids and submitting them to the central ancillary market - Applies GBF as a unified communication between SOs to avoid unnecessary information exchange.
32	full integration market model	**Main Similarity with CoordiNet:** -A single entity is responsible for operating a central market for whole network. - The TSO is the only buyer and DER dispatcher.

		- A single optimization problem is solved for whole network. **Main difference with Coordinet:** -Central market could also be operated by an IMO.
32	Enhanced Bulk Balancing Authority (BA) Model (A)	**Main Similarity with CoordiNet:** -A single entity is responsible for operating a central market for whole network. - A single entity (BA) is responsible for sending dispatching order to DERs. -DSO considers the distribution grid constraints and communicate with the TSO. **Main difference with Coordinet:** -Balancing Authority (BA) is responsible for operating the network, as well as operating the market. -BA is responsible for ensuring the balancing the whole system and takes into account all the constraints.
32	Enhanced Bulk BA Model (B)	**Main Similarity with CoordiNet:** -A single entity is responsible for operating a central market for whole network. -DSO considers the distribution grid constraints and communicate with the TSO.

		Main difference with CoordiNet: -DSO is responsible for sending dispatching order to DERs in response to TSO order. -Balancing Authority (BA) is responsible for operating the network, as well as operating the market. -BA is responsible for ensuring the balancing the whole system and takes into account all the constraints.
7	TSO-managed model	**Main Similarity with CoordiNet:** - A single entity (TSO) is the responsible for dispatching the flexibility resources in whole system. - DSO's responsibilities are correspondent to the conventional DSO. - DSO communicates the essential data with the TSO. -The aggregation of the DERs performed by the aggregators. **Main difference with CoordiNet:** - IMO can be also an independent market operator instead of TSO - - the observability of TSO is only limited to the point where the aggregated DER is presented.
7	TSO-DSO hybrid managed model	**Main Similarity with CoordiNet:** **-**TSO is the only entity operating a single market. - there is only one economic dispatch model for the whole system. - DSO communicates the essential data with the TSO. -DSO is the entity responsible for validation and pre-qualification respecting the DSO grid constraints. -The aggregation of the DERs performed by the aggregators**.** **Main difference with CoordiNet:** -DSO can also procure the flexibility from the central market to solve its grid issues.
7	DSO-Managed Model	**Main Similarity with CoordiNet:** **-**TSO is the only entity operating a single market. - there is only one economic dispatch model for the whole system.

		- DSO communicates the essential data with the TSO. -DSO is the entity responsible for validation and pre-qualification respecting the DSO grid constraints. **Main difference with CoordiNet:** -The aggregation of the DERs can be performed by the DSO or aggregator**.** - The TSO will send only the aggregated dispatch order if DSO is aggregator of DERs **-** if the DSO is the aggregator, the DSO sends the DER dispatch order to the individual DERs, in response to TSO aggregated dispatch order. **-** DSO do not exchange the operational data with the TSO.
22	TSO-FSP model	**Main Similarity with CoordiNet:** -only TSO is the responsible for operating the market. **-** DSO is not involved in the procurement and activation process **Main difference with Coordinet:** - An explicit auction is performed for solving the structural congestion in the TSO-DSO interface, and distribution network. -Both TSO-DSO are responsible for calculating the border capacity.
22	centralized market model	**Main Similarity with CoordiNet:** **-O**nly TSO is the responsible for operating the market. -DSO is not involved in the procurement and activation process, but performs the pre-qualification **-**DSO performs the conventional roles without accessing the market **Main difference with Coordinet:** -The TSO does not consider the distribution system constraints when performing economic dispatch.
8	Centralized AS market mode for smartNet	**Main Similarity with CoordiNet:** **-**only TSO is the responsible for operating the market and dispatching the flexibility resources **-**TSO is the only buyer of the flexibility -DSO is not involved in the procurement and activation process **-**DSO performs the conventional roles without accessing the market **-** a very limited data exchange needed between the system operators **Main difference with Coordinet:**

		-The TSO does not consider the distribution system constraints when performing economic dispatch.
24	centralized optimization	**Main Similarity with CoordiNet:** -A single entity is responsible for running the economic dispatch and optimization algorithm. - only one optimization problem should be solved. **Main difference with CoordiNet:** **-**Although only one optimization problem is performed for the whole the system, but it can optimize all the bids coming from single or number of small marketplaces.
25	centralized flexibility market	**Main Similarity with CoordiNet:** -only TSO is the responsible for dispatching the flexibility resources and operating the market. -only one single market is available for the whole system, considering all the constraints. -DSO is responsible for flexibility pre-qualification -DSO is not involved in the procurement and activation process

equivalent to common market model of CoordiNet

In this table all the coordination schemes similar to common market model of CoordiNet are gathered and the main features, advantages, and disadvantages of each scheme are discussed. Moreover, the source of difference of each coordination scheme compared to CoordiNet is addressed.

Ref	NAME	Main feature Main adv/ disadv
2	the single platform for both local and central market	• **Main Similarity with CoordiNet:** • -TSO and DSO are both jointly operate the market • -TSO and DSO are both the buyer of the flexibility • -TSO and DSO are both the DER dispatcher based on the needs
23	TSO-DSO mechanism	• **Main Similarity with CoordiNet:** -TSO and DSO procure the required flexibility in a common market. **Main difference with Coordinet:** -There is a common market for TSO and DSO and a separate market for retailer to procure flexibility -The retailer procure flexibility in a separate market, but using the shared resources. -The priority to procure the flexibility is for Retailer, DSO, and then TSO, respectively. •
23	TSO-DSO-Retailer mechanism	• **Main Similarity with CoordiNet:** -TSO and DSO procure the required flexibility in a common market. **Main difference with Coordinet:** -There is a common market for TSO, DSO, and retailer to procure flexibility, using shared resources. -The priority to procure the flexibility is for Retailer, DSO, and then TSO, respectively.
3	combined balancing and congestion management for all system operators together	• **Main Similarity with CoordiNet:** • -TSO and DSO jointly operate market and jointly procure the flexibility for the network need in common market. • -TSO and DSO are both the DER dispatcher based on the needs **Main difference with Coordinet:**

			• -Since some bids are also used for procuring flexibility to solve the balancing issues, there is a priority for balancing to access the bids. • - The bids must include the locational information, otherwise not usable for congestion management. •
8	Common TSO-DSO AS Market model	Centralized variant	• **Main Similarity with CoordiNet:** • **-** TSO and DSO jointly operate market and jointly procure the flexibility for the network need in common market**.** • -TSO and DSO are both the DER dispatcher based on the needs • **-** similar scheme in case of centralized variant, where only one single market exist. • - in case of decentralized variant, smaller local DSO market coexist within common market. **Main difference with CoordiNet:** **-** DSO only has access to the DERs in the distribution network for solving issues. - In decentralized format, some bids associated to the local area are firstly cleared in local DSO market, however there is no priority for any SOs to procure the flexibility. •
		Decentralized variant	
28	common TSO-DSO AS market model	centralized variant	• **Main Similarity with CoordiNet:** • **-** TSO and DSO jointly operate market and jointly procure the flexibility for the network need in common market**.** • -only one single market exists in this scheme • -TSO and DSO are both the DER dispatcher based on the needs •
		decentralized variant	• **Main Similarity with CoordiNet:** • -There are some small DSO local markets within the common market. • - The local markets are firstly run and the results are sent to the TSO market.

			• -This common market is jointly operated by TSO and DSO, and both are responsible for the outcome of separate market. • - There is a combined optimization for the needs in both system level.
25	Common TSO-DSO flexibility market		• **Main Similarity with CoordiNet:** • **-** TSO and DSO jointly operate market and jointly procure the flexibility for the network needs in common market**.** • -TSO and DSO are both the DER dispatcher based on the needs.
29,30	the common TSO-DSO market		• * As same as the model of reference () (smartnet) for minimal DSO.

Equivalent to integrated market model of CoordiNet

In this table all the coordination schemes similar to integrated market model of CoordiNet are gathered and the main features, advantages, and disadvantages of each scheme are discussed. Moreover, the source of difference of each coordination scheme compared to CoordiNet is addressed

Ref	NAME	Main feature Main adv/ disadv	Main difference with CoordiNet
8	Integrated flexibility market model	**Main Similarity with CoordiNet:** -TSO, DSO, FSPs are the buyers of the flexibility - One single market is operated by an IMO -The resources are shared, and no entity has priority for procuring the flexibility.	
25	integrated market for TSO-DSO and BRP flexibility	the system operator must guarantee the secure operation of their grid by selecting the most suitable bids among all the submitted bids location must be available within the bid	
28	common TSO-DSO AS centralized variant	**Main Similarity with CoordiNet:** - TSO and DSO jointly procure the flexibility for the network need in common market. -only one single market exists in this scheme -TSO and DSO are both the DER dispatcher based on the needs.	

	market model		- scheme integrates all the constraints of the network on both levels, as well as the local flexibility needs. - IMO is the responsible for operating the single market for whole system.

Table 5. equivalent to multi-level market model of CoordiNet

Ref	NAME		Main feature Main adv/ disadv
13	DSO leader	Non-strategic DSO	**Main Similarity with CoordiNet:** -Both TSO and DSO are the buyer and the operator in their own market. -The priority to procure the DERs is for lower-level market. -TSO can only access the uncleared bids coming from DSO market. -DSO is the entity responsible for DER dispatching **Main difference with CoordiNet:** -An IMO also can be in charge of operating local market, if DSO is not in charge.

			-DSO not only export the energy for TSO use, but also import the energy if needed. - DSO is responsible for aggregating the bids and forward them to the TSO market.
		strategic DSO	**Main Similarity with CoordiNet:** -The priority to procure the DERs is for lower-level market -DSO is the entity responsible for DER dispatching **Main difference with CoordiNet:** -An IMO is in charge of operating local market and not the DSO. -A third party (e.g., IMO) is responsible for aggregating local market bids and provide them for wholesale market. -DSO can be the aggregator of the DERs in addition to other third parties.
	DSO follower		**Main Similarity with CoordiNet:**

		- Both TSO and DSO are the buyer and the operator in their own market -There are 2 markets for TSO and DSO communicating with one another. - in case 2, the DSO is responsible for DER dispatching, and TSO does not have direct access to DERs **Main difference with CoordiNet:** -In case 1, both DSO and TSO can dispatch the DERs, and TSO has direct access to DERs. -The higher-level market firstly is cleared prior to local market clearing. -After solving the transmission system issues, the energy exchange will happen between two levels. -The energy exchange is bidirectional and not unidirectional.
	TSO-DSO Iteration	**Main Similarity with CoordiNet:** - Both TSO and DSO are the buyer and the operator in their own market - There are 2 hierarchical market namely for TSO and DSO, communicating with one another. **Main difference with CoordiNet:**

		-A load aggregator participates in both wholesale and local market. -Depending on Load aggregator benefit, it can but energy from one market and sell to another one. -The energy exchange is bidirectional in this scheme. -Neither DSO nor TSO has priority in procuring the flexibility. -Bidding strategy for market users is updated iteratively until reaching the pre-defined convergence criteria.
3	combined TSO and DSO congestion management, with separated balancing	**Main Similarity with CoordiNet:** - There are 2 separate markets coexist and operated by different market operator. - The bid of each market can be forwarded to another market if necessary. **Main difference with CoordiNet** -Although it is composed of 2 markets, one of these markets is a central market, and the other one is a common market. But, in general, its main structure is multi-level market. -TSO not only is the operator of balancing market, but also jointly operate the congestion management market. - In TSO-DSO congestion management a shared MOL is used - TSO has direct access to DERs in each of fragmented market.

8	Local AS market model		**Main Similarity with CoordiNet:** -Both TSO and DSO are the buyer and the operator in their own market. -The priority to procure the DERs is for lower-level market. -The local market firstly performs clearing the bids. -TSO can only access the uncleared bids coming from DSO market. -local and central needs are addressed through different markets which coexist. **Main difference with CoordiNet:** -Only aggregation of the DERs can participate in the local market
	decentralized optimization	bottom-up approach top-down approach hybrid approach	**Main Similarity with CoordiNet:** -Both TSO and DSO are the optimisation operator in their market. - separated markets can apply separate optimization algorithm. - In bottom-up approach the bids can be forwarded from the DSO to TSO. - in bottom-Up approach, the priority is for the DSO - in hybrid approach, the priority can be for the DSO depending on the adopted market. **Main difference with CoordiNet** - Market operator can be an IMO -Depending on the type of decentralized optimization, the energy can be transferred to the DSO market. - in top-down approach, the TSO can access to the DERs. - in top-down approach, DSO performs the grid pre-qualification to ensure that the direct access of TSO o DERs does not violate the DSO grid constraints.

25	local and global flexibility markets	**Main Similarity with CoordiNet:** Both TSO and DSO are the buyer and the operator in their own market. -The priority to procure the DERs is for lower-level market. -The local market firstly performs clearing the bids. -TSO can only access the uncleared bids coming from DSO market. -local and central needs are addressed through different markets which coexist.
25	local and global flexibility markets with balancing coordination	**Main Similarity with CoordiNet:** **-**There are 2 markets with the possibility of bid forwarding and communicating with one another. -The DSO is the market operator for the local market, and TSO is responsible for balancing market. **Main difference with CoordiNet** **-** The local market aims at procuring the DERs for solving local issues, and in case of causing imbalance in the network, the TSO is responsible for solving the grid imbalance. **-**DSO communicate with TSO to inform about the possible imbalance.
30], [3	Multilevel TSO-DSO market	* As same as the model of reference (), (smartnet) for minimal DSO.

Equivalent to fragmented market model of CoordiNet

In this table all the coordination schemes similar to fragmented market model of CoordiNet are gathered and the main features, advantages, and disadvantages of each scheme are discussed. Moreover, the source of difference of each coordination scheme compared to CoordiNet is addressed.

Ref	NAME	Main feature Main adv/ disadv
2	separate markets	**Main Similarity with CoordiNet:** - TSO runs a central market, and the DSO runs a local market - TSO and DSO procure the flexibility for its own network utilizing their belonging resources - No bid forwarding from distribution level to transmission
23	sequential design	**Main Similarity with CoordiNet:** -Each buyer procures the required flexibility in its own market without bid forwarding **Main difference with CoordiNet:** - The retailer also is the buyer of the flexibility besides TSO and DSO. -The buyers can procure the flexibility from shared resources, but in separate market. -The priority to procure the flexibility is for Retailer, DSO, and then TSO, respectively.
3	separated TSO and DSO congestion management (with	**Main Similarity with CoordiNet:** -Each buyer procures the required flexibility in its own market using its own resources, without bid forwarding to other market, -The higher-level market is operated by the TSO, and lower level by DSO

	balancing market separated or combined with TSO congestion management)	-DSO is the entity for dispatching the DERs with a priority in procuring the flexibility. **Main difference with CoordiNet** -In case of combined balancing and congestion management for TSO, a shared MOL is used.
8	Shared balancing responsibility model	**Main Similarity with CoordiNet:** -Each buyer procures the required flexibility in its own market using its own resources, without bid forwarding to other market. -The higher-level market is operated by the TSO, and lower level by DSO **Main difference with CoordiNet** -Both TSO and DSO manage the balancing in their own grid independently -DSO balancing activity should be coordinated with the TSO according to a pre-defined schedule, where the energy flow in the interconnection points is determined - The pre-defined schedule can be defined either for each TSO-DSO interconnection point or only for some of them
25	local and global flexibility markets with shared responsibility	**Main Similarity with CoordiNet:** -Each buyer procures the required flexibility in its own market using its own resources, without bid forwarding to other market. -The higher-level market is operated by the TSO, and lower level by DSO - TSO is not allowed to have access to the DER bids. **Main difference with CoordiNet** - The DSO must provide a pre-defined profile for each TSO-DSO interconnection, while using his own resources.

- Constructing the coordination schemes based on the key features

	Market operator			D con	BUYER			acce DER?	Int flow F0, F1,F2
	TSO	DSO	IMO		TSO	DSO	CMB		
Local market _v1				NA				NA	F0
Local market_v2				NA				NA	F0
Local market_v3				NA				NA	F0
Central market_v1									F2
Central market_v2									F0
Central market_v3									F2
Central market_v4									F0
Central market_v5									F2
Central market_v6									F2
Central market_v7									F2
Central market_v8									F0
Central market_v9									F2
Central market_v10									F0
Central market_v11									F2
Central market_v12									F0
Common market_v1									F2
Common market_v2									F2
Common market_v3									F2
Common market_v4									F2
Common market_v5									F2
Common market_v6									F2
Separate_market_v1				NA					F0
Separate_market_v2									F1
Separate_market_v3									F2
Separate_market_v4									F1
Separate_market_v5									F2

The table (0) illustrates all the possible coordination schemes divided into 4 main categories namely local, central, common, and separate market models. These coordination schemes are categorized based on 5 pillars.

The first pillar determines the parties in charge of operating the market. In this regard, the TSO, DSO and independent market operator (IMO) can be considered as the market operators. It is worth saying that the IMO can always be the alternative market operator on behalf of TSO and DSO.

- In local market, an IMO can operate the market instead of DSO
- In central market, an IMO can operate the market instead of TSO
- In common market, an IMO can operate the market instead of TSO and DSO
- In separate market, two separate IMO can operate the market instead of both TSO and DSO

However, having the IMO is a must in some cases for ensuring the neutrality of the market. In the table, the block associated to the IMO is colored in dark blue. In these cases, due to the presence of the CMB, it is indispensable to select the IMO for operating market.

Another key point regarding the table is that for both common and separate coordination scheme, the presence of the TSO and DSO are essential. However, in the common market, the TSO and DSO jointly operate the single market, while in the separate market, TSO and DSO separately operate their own market. In order to distinguish the difference, the pillar for the separate market is colored with this blue.

The second pillar illustrates whether the TSO (or even an IMO on behalf of TSO) respects the distribution network constraints within its market-clearing algorithm or not. This block is not applicable for the cases related to the local market classification, as there is no TSO as the market operator. It is worth saying that for the common market, considering the constraints of the distribution grid is indispensable part and cannot be neglected, and this is the reason why in all cases, the associated block is colored in blue.

The third pillar determines the buyer of the flexibility. In this regard, TSO, DSO, and (Commercial Market Buyer) CMB are considered as the buyers. As shown, depending on different market design, the combination of three buyers can be presented in the market. For the first three categories the existence of the (CMB) is taken into account. However, for the last category (separate market model), only TSO and DSO are considered as the buyers of the flexibility services, otherwise the number of alternatives for the separate market are large. Moreover, in some cases, having the CMB in each separate market is inexplicable. Moreover, in the central market category, the DSO is never considered as the buyer, since in that case, it can be similar to the common market, except there is only one entity are in charge of operating market, however, somehow DSO can participate the market as the seller of the aggregated resources.

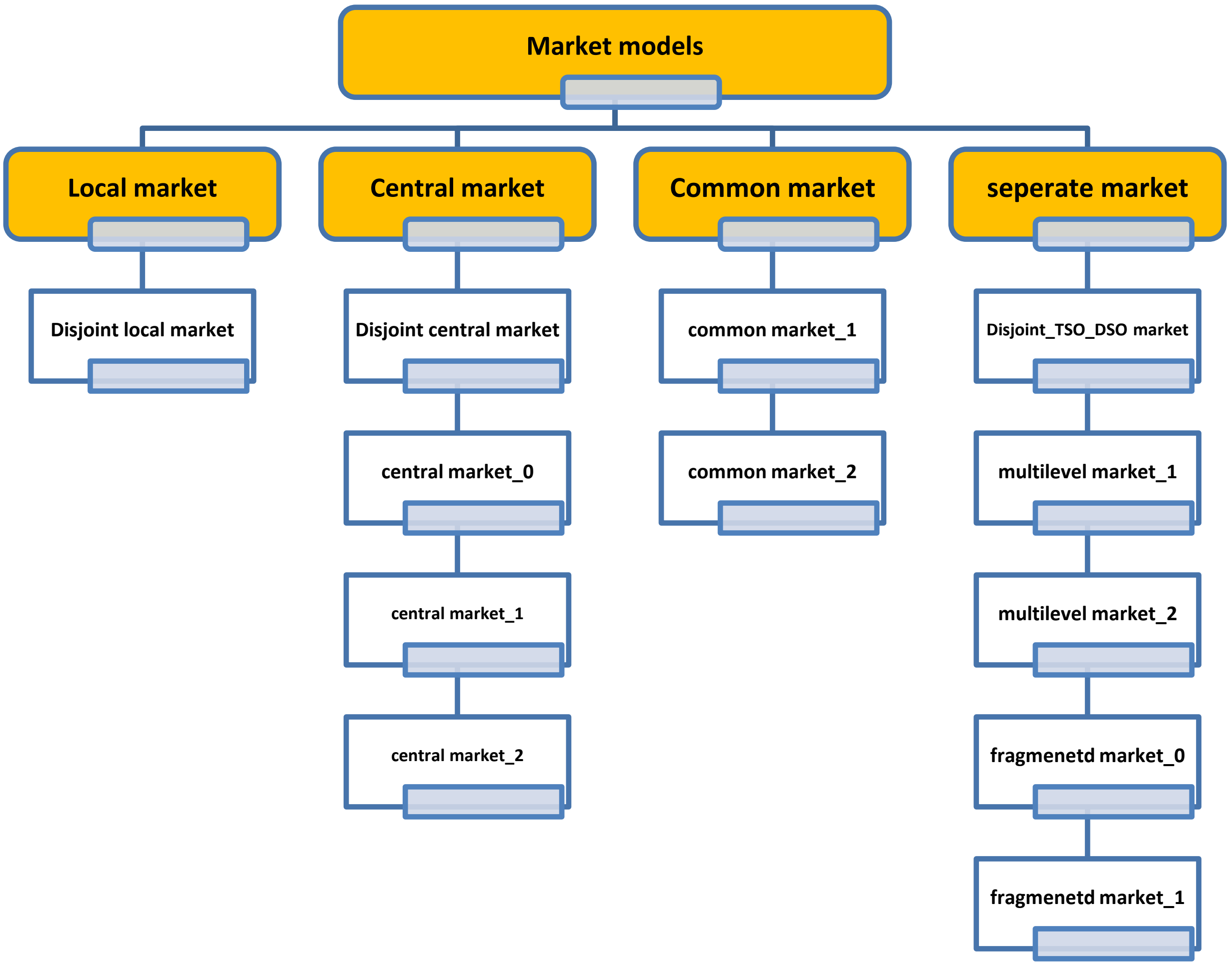
The **fourth pillar** shows the accessibility of the TSO as the buyer to the flexibility resources in the distribution network. In some cases, the TSO is able to procure the DERs to solve the grid issues. Having access to these resources does not essentially mean that the market-clearing algorithm also respect the constraints and depending on the market design it may differ.

Finally, the **fifth pillar** determines the interface flow between the networks, which can affect the market design and the mathematical formulation of the coordination schemes. There are three cases anticipated for the interface flow.

- The first case considers the interface flow to be constant, in this case any procuring of the flexibility in any market level should not violate the interface flow(F0).

- The second case mostly applicable for the separate markets considers a constant interface flow for the second layer market (TSO market) and a variable interface flow from the first layer point of view. This case happens when the congestion mitigation by the DSO in the distribution network cause and imbalance and the TSO be in charge of the imbalance solving. Hence, the distribution network will indirectly take advantage of the TSO flexibility procuring while the interface flow is variable in a pre-defined limit.
- The third case is the situation where the TSO can directly access the DERs in the distribution network, and also distribution network benefits from the indirect flexibility sharing. In this case, the interface flow from both layer perspective is considered to be variable in the pre-defined limit.

Among all the alternatives for the coordination schemes some are considered as the most common and applicable one regarding their characteristic and the previous paper works and projects. In this regard, applicable coordination schemes, only considering the TSO and/or DSO as the buyer of the flexibility are selected for the rest of work in this thesis work.


Market models
Local market
Central market
Common market
seperate market
Disjoint local market
Disjoint central market
central market_0
central market_1
central market_2
common market_1
common market_2
Disjoint_TSO_DSO market
multilevel market_1
multilevel market_2
fragmenetd market_0
fragmenetd market_1

Economic aspects of the TSO-DSO coordination, Quantitative assessment:

Evaluation of combinations of coordination schemes and products for grid services based on market simulations

Reference [35] which is one of the deliverable report of the **CoordiNet** project targets on evaluating the relevant combinations of the services and the coordination schemes using market simulations and quantitative analyses as well as qualitative analyses. This report is firstly focusing on the structure of the different coordination schemes evaluating the efficiency of the market-based flexibility procurement in each of them using the game theory and some optimization approaches. Moreover, it aims at identifying and analyzing the gap by creating market models which enable an assessment and analyze of the optimality in flexibility procurement.

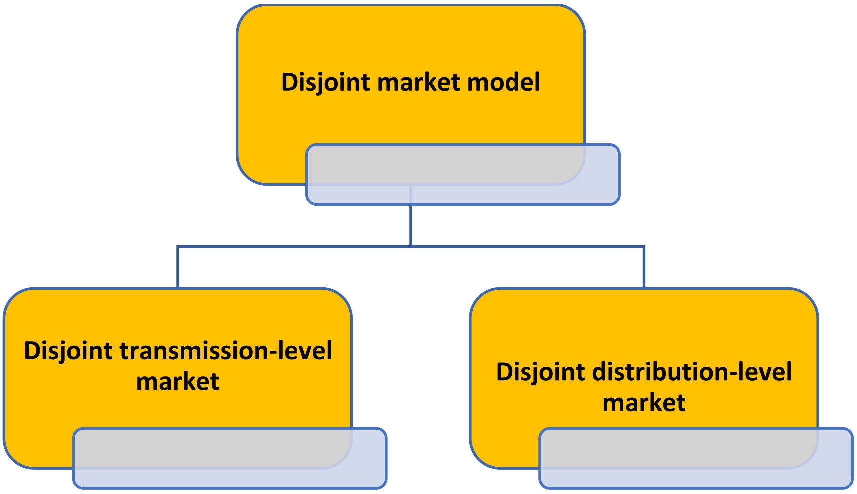
For comparing the coordination schemes from the perspective of performance, economic efficiency and their properties, the paper identifies different mathematical model for different coordination schemes aiming at introducing an optimization-based market clearing model for each coordination. Having this mathematical model, the author is able to perform the optimization/efficiency analysis over the coordination schemes and provides other variants for some of the coordination schemes by slightly modifying the original coordination scheme.

Based on the coordination scheme review over the CoordiNet project in section () of this paper, 7 different coordination schemes have been introduced. The summary of these fundamental coordination schemes as well as their general features and classification indicators are available in table (). Considering [35], among all the proposed coordination schemes, the local, central, common, multilevel and fragmented coordination schemes are selected. Moreover, having modification in each one of these coordination schemes, the author could propose some new alternatives to be able to comprehensively analyze and compare different options fulfilling the possible gaps in each fundamental coordination schemes. Obviously, the fundamental features in table () are not sufficient to cover all the possible features that could differ within each coordination schemes, and further classification criteria is needed. Based on primary and new classification criteria, in next section all the coordination schemes under analyze including the alternatives are discussed.

Features, mathematical model and definition of the coordination schemes under assessment

Disjoint market model

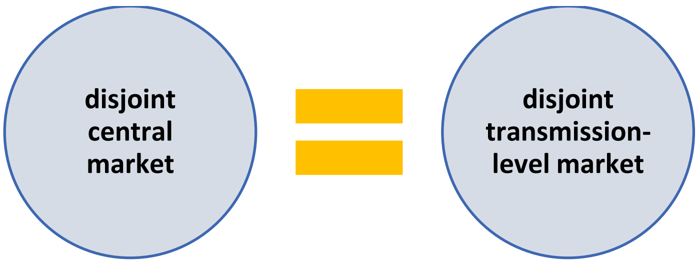
As shown in fig (), the paper firstly introduces two main building blocks namely, disjoint transmission-level market and distribution -level market. The disjoint market definition, in general, implies the fact that there is not sharing of the flexibility between SOs, and consequently, SOs must procure the flexibility only from their own networks. In this regard, not only there is no direct sharing, but also the indirect sharing of the resources is prohibited. Moreover, the network information exchange between SOs is not required for these schemes, and no overlap between the markets occurs.



Each one of these 2 market schemes can be mathematically modelled, and by modifying some parameters and variables of these mathematical model and/or using the combination of these models, as well as defining some new dimensions and features, other coordination schemes can be mathematically modeled and analyzed. In the following these 2 market schemes and their mathematical models are described more in detail.

Disjoint transmission-level market

In this market model, the TSO is the only entity procuring the flexibility from the resources connected to the transmission system. This market scheme is similar to the central market defined in CoordiNet while not having a direct access to DERs by the TSO. fig () illustrates this similarity



mathematical model for this scheme enables the cost-effective flexibility procurement while respecting the limitation of the transmission network, and the technical limits of the submitted bids. The limitations of the transmission network are captured by the power flow equations and the flow limits inequality constraint, through linearization of the power flow equations. The linearization of the power flow equation can be guaranteed using the DC power flow or using the sensitivity factors. In the latter case, a Generation Shift Factor (GSF) or the Power Transfer Distribution Factors (PTDF) can be applied within the market clearing problem. In the proposed model the GSF is applied for the linearization of the power flow equations. Moreover, as this market model is a disjoint market, the interface flow between transmission and distribution should be kept constant and considered this way in the mathematical model. The detailed mathematical model of paper for the disjoint transmission-level market is presented in [37] and following figure represents an abbreviated version:

$$\min_{\Delta \boldsymbol{P}, \Delta \boldsymbol{D}} C(\Delta \boldsymbol{P}, \Delta \boldsymbol{D})$$

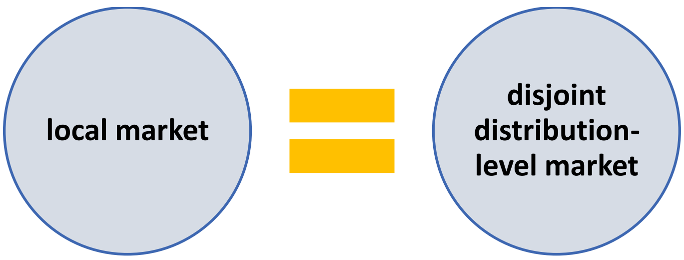
s.t

$$\begin{aligned}
F(\Delta \boldsymbol{P}, \Delta \boldsymbol{D}, \boldsymbol{P^o}, \boldsymbol{D^o}, \boldsymbol{T^P}, \boldsymbol{U}) &= \boldsymbol{0} && \longleftarrow \text{Power flow eqs}\\
G\big(\Delta \boldsymbol{P}, \Delta \boldsymbol{D}, \boldsymbol{P^o}, \boldsymbol{D^o}, \boldsymbol{T^P}, \boldsymbol{U}\big) &\leq \boldsymbol{0} && \longleftarrow \text{Flow limits}\\
\boldsymbol{0} \leq \Delta \boldsymbol{P}, \Delta \boldsymbol{D} &\leq \Delta \boldsymbol{P^{max}}, \Delta \boldsymbol{D^{max}} && \longleftarrow \text{Bid limits}\\
T_i^P &= constant\ \forall i && \longleftarrow \text{TSO-DSO Interface flow}
\end{aligned}$$

The goal of this mathematical problem is the minimization of the cost for procuring the flexibility while respecting the constraints within networks and the bids and keeping the interface flow constants. In order to have perspective over the model and avoid any repetitive information in the future the **parameters and variables** of the model are defined once. In this regard, $\Delta \boldsymbol{P}$ and $\boldsymbol{\Delta D}$ are the purchasing level of upward and downward flexibility, $C(\Delta \boldsymbol{P},\ \Delta \boldsymbol{D})$ is a cost function for purchasing those bids based on their submitted bid prices, $\boldsymbol{Po}$, $\boldsymbol{Do}$ represent the scheduled base generation and load profiles before activation of flexibility, $\boldsymbol{U}$ represents an abstract collection of different constants including network parameters (and GSFs), and finally, TiP represents the interface flow between the transmission and distribution system at connection point i.

Disjoint distribution-level market

In this market model, the DSO is the only entity procuring the flexibility from the resources connected to the distribution system. This market scheme is similar to the local market defined in CoordiNet while not having any indirect sharing of the resources. fig () illustrates this similarity



The mathematical model for this scheme enables the cost-effective flexibility procurement while respecting the limitation of the distribution network, and the technical limits of the submitted bids. In addition to the flow limits (similar to transmission level market), the voltage limits and reactive power limits should be included in the market clearing problem. This market model should ensure a secure operation of the network, a competitive and fair remuneration for all parties, and a reliable, transparent and timely market clearing. In this market model, the interface flow must be remained constant while DSO procures the flexibility for the distribution network while not imposing any further imbalance or other network issues at the distribution level. The mathematical model of the disjoint distribution-level model is as follow:

$$\min_{\Delta \boldsymbol{p}_i, \Delta \boldsymbol{d}_i} c(\Delta \boldsymbol{p}_i, \boldsymbol{\Delta d}_i)$$

s.t

$$\begin{aligned}
&f_i(\Delta \boldsymbol{p}_i, \boldsymbol{\Delta d}_i, \boldsymbol{p}_i^o, \boldsymbol{d}_i^o, T_i^p, \boldsymbol{u}_i) = \boldsymbol{0} && \text{Power flow eqs}\\
&g_i(\Delta \boldsymbol{p}_i, \boldsymbol{\Delta d}_i, \boldsymbol{p}_i^o, \boldsymbol{d}_i^o, T_i^p, \boldsymbol{u}_i) \le \boldsymbol{0} && \text{Flow limits, voltage limits, reactive power limits}\\
&\boldsymbol{0} \le \Delta \boldsymbol{p}_i, \boldsymbol{\Delta d}_i \le \Delta \boldsymbol{p}_i^{max}, \boldsymbol{\Delta d}_i^{max} &&\\
&T_i^P = constant && \text{TSO-DSO Interface flow}
\end{aligned}$$

The mathematical problem is modeled similar to the disjoint transmission-level market except using the lower-case letters for the quantities and the variables. This mathematical problem is linearized applying the linear distribution network representation and the linearization of the flow constraints leading to a linear programming (LP) formulation. This LP formulation enables incorporating a network model and limits, as well as voltage magnitude and reactive power calculations in the market clearing. The LP formulation applies the LinDistFlow representation which in general neglects the branch loss terms and can lead to a authentic result if the branch loss is low.

Central market

This market model is similar to what already discussed as one of the basic coordination schemes of the CoordiNet where the TSO is the only buyer of the flexibility, and can directly procure the DERs, and at the same time respect all the limitation and constraints of the transmission and distribution system. The main difference of this scheme with the disjoint central market is the variable interface flow, which allows the interface flow to be modified within pre-defined limit. Moreover, since TSO utilizes the distribution system resources and respects all the constraints, sharing of the flexibility as well as sharing network information are taken into account. The mathematical model of this scheme is represented as follows:

$$\min_{\Delta P,\Delta D,\Delta p,\Delta d} C(\Delta P,\Delta D) + \sum c(\Delta p_i,\Delta d_i) \quad \longleftarrow \text{Paid by TSO}$$

s.t

$$\begin{aligned}
&F(\Delta P,\Delta D,P^o,D^o,T^P,U) = 0\\
&G(\Delta P,\Delta D,P^o,D^o,T^P,U) \leq 0\\
&0 \leq \Delta P,\Delta D \leq \Delta P^{max},\Delta D^{max}\\
&\text{-------------}\\
&\left.\begin{aligned}
&f_i(\Delta p_i,\Delta d_i,p_i^o,d_i^o,T_i^P,u_i) = 0\\
&g_i(\Delta p_i,\Delta d_i,p_i^o,d_i^o,T_i^P,u_i) \leq 0\\
&0 \leq \Delta p_i,\Delta d_i \leq \Delta p_i^{max},\Delta d_i^{max}
\end{aligned}\right\} \forall i\\
&\text{-------------}\\
&\left.\begin{aligned}
&T_i^P = h(\Delta p_i,\Delta d_i,p_i^o,d_i^o)\\
&T_i^{P,min} \leq T_i^P \leq T_i^{P,max}
\end{aligned}\right\} \forall i
\end{aligned}$$

As seen from the above mathematical formulation, the mathematical model associated to the disjoint transmission and distribution level are presented together under the umbrella of a central mathematical model while respecting all the constraints of both levels. The objective function aims at minimizing the cost of flexibility procurement from the transmission and distribution resources, which will be paid by the TSO as the only entity responsible for buying the flexibility.

If the central market despite of utilizing distribution system resources does not consider the distribution constraints, it is categorized as one of the variants of the central market called *central_no_network* coordination scheme. The mathematical formulation of this scheme is equivalent to the previous one except not considering the distribution network constraint. Obviously, the result of the market clearing will not guarantee a secure operation of the system.

Variant(s) of Central market	
central_no_network coordination scheme	•only TSO procures the flexibility services for the central needs. •TSO procure the flexibility from both network level. •**The distribution network constraints are not taken into account.**

Common market

This market model is similar to what already discussed as one of the basic coordination schemes of the CoordiNet where the TSO and DSO are the buyers of the flexibility, and TSO can directly procure the DERs. In this scheme, the TSO and DSO can jointly procure the flexibility to fulfill the needs associated to the networks using a single order book where all the resources are pooled together. This market is jointly operated and cleared while respecting all the limitation and constraints of the transmission and distribution system. A common market merges both disjoint market as a unified market and allows the interface flow to be modified within pre-defined limit. Moreover, since TSO utilizes the distribution system resources and respects all the constraints, sharing of the flexibility as well as sharing network information between SOs are taken into account. The mathematical model of this scheme is represented as follows which shows a similar mathematical model as central market, expect DSO also is the buyer of the flexibility:

$$\min_{\Delta P, \Delta D, \Delta p, \Delta d} C(\boldsymbol{\Delta P}, \boldsymbol{\Delta D}) + \sum c(\boldsymbol{\Delta p_i}, \boldsymbol{\Delta d_i})$$

s.t

$$\begin{aligned} & F(\boldsymbol{\Delta P}, \boldsymbol{\Delta D}, \boldsymbol{P^o}, \boldsymbol{D^o}, \boldsymbol{T^P}, \boldsymbol{U}) = \boldsymbol{0} \\ & G(\boldsymbol{\Delta P}, \boldsymbol{\Delta D}, \boldsymbol{P^o}, \boldsymbol{D^o}, \boldsymbol{T^P}, \boldsymbol{U}) \leq \boldsymbol{0} \\ & \boldsymbol{0} \leq \boldsymbol{\Delta P}, \boldsymbol{\Delta D} \leq \boldsymbol{\Delta P^{max}}, \boldsymbol{\Delta D^{max}} \end{aligned}$$

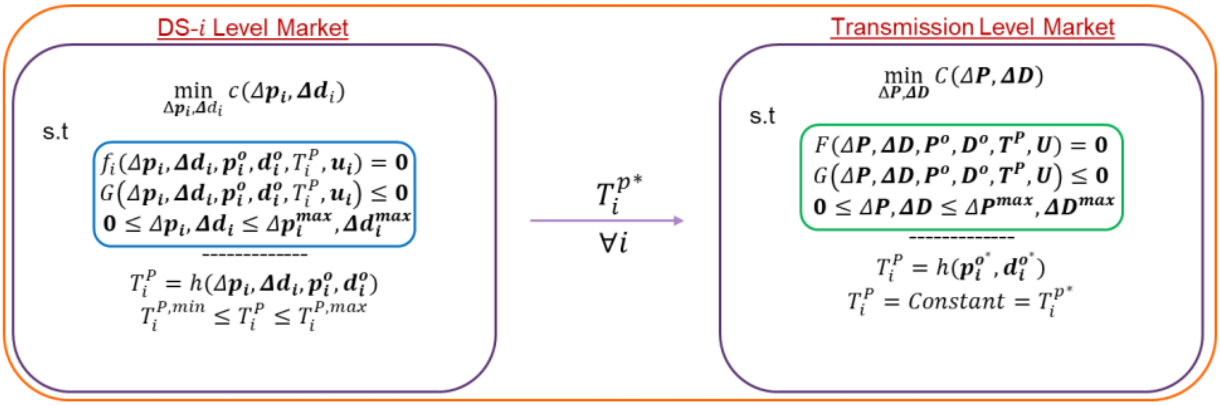
$$\left.\begin{aligned} & f_i(\boldsymbol{\Delta p_i}, \boldsymbol{\Delta d_i}, \boldsymbol{p_i^o}, \boldsymbol{d_i^o}, T_i^P, \boldsymbol{u_i}) = \boldsymbol{0} \\ & G(\boldsymbol{\Delta p_i}, \boldsymbol{\Delta d_i}, \boldsymbol{p_i^o}, \boldsymbol{d_i^o}, T_i^P, \boldsymbol{u_i}) \leq \boldsymbol{0} \\ & \boldsymbol{0} \leq \boldsymbol{\Delta p_i}, \boldsymbol{\Delta d_i} \leq \boldsymbol{\Delta p_i^{max}}, \boldsymbol{\Delta d_i^{max}} \end{aligned}\right\} \quad \forall i$$

$$\left.\begin{aligned} & T_i^P = h(\boldsymbol{\Delta p_i}, \boldsymbol{\Delta d_i}, \boldsymbol{p_i^o}, \boldsymbol{d_i^o}) \\ & T_i^{P,min} \leq T_i^P \leq T_i^{P,max} \end{aligned}\right\} \quad \forall i$$

As seen from the above mathematical formulation, the mathematical model associated to the disjoint transmission and distribution level are presented together under the umbrella of a central mathematical model while respecting all the constraints of both levels. The objective function aims at minimizing the cost of flexibility procurement from the transmission and distribution resources, which will be paid by the TSO and DSO (in contrast to the central market model) as the buyers of the flexibility.

Fragmented market

A fragmented market can be modeled as a composition of 2 disjoint transmission and distribution-level market coexisting while their cooperation is limited only to an indirect flexibility sharing. In another word, firstly, layer 1 composing of 1 or more disjoint distribution-level market(s) is cleared in order to solve the issues associated to the distribution network. Solving these issues, may cause some imbalances in the transmission network by modification to the interface of DSO-TSO flow. Consequently, the TSO runs a disjoint central market to solve the congestion and the balancing in his network, as well as the imbalance caused in the layer 1 clearing. Two SOs, while running their own market, are only required to share the common constraints such as TSO-DSO interface and no further network information sharing is needed, as the second layer market does not respect the distribution constraints in its clearing algorithm. Furthermore, the interface flow can vary in layer 1 within a pre-defined limit, while it should be constant in the layer 2. However, the interface flow in layer 2 can be updated based on the result of the distribution-level market at the first stage. In this scheme the TSO does not have direct access to the DERs at distribution network and consequently no direct flexibility sharing is allowed, while the indirect flexibility sharing takes place for the layer 1 in case of imbalance imposed by the DSO. In following the mathematical representation of the scheme is depicted:



As presented, both disjoint transmission and distribution- level market concurrently coexist, with the possibility of interface flow variation in the layer 1. The rest of the formulation proves the aforementioned discussion about this coordination scheme.

Different variants for the fragmented market model can be defined and will be discussed in the following:

The first variant of this scheme is **Fragmented_0,** This coordination schemes is similar to its associated market scheme, except, in this scheme, the interface flow of the layer 1 is obliged to be constant, meaning that the indirect flexibility sharing is not allowed any more.

The second variant of this scheme is **Fragmented_penalty.** This coordination scheme is similar to its associated market scheme, however, the price for the interface flow is set as an externality which is dependent on the submitted bids and offers to the market. This conveys that the interface flow variance is allowed for the layer 1 and priced according to the price of market. This price is set at the midpoint between the most expensive downward flexibility bid and the least expensive upward flexibility bids, generally aiming at prohibiting unnecessary downward flexibility procurement in layer 1. As it is a fragmented market, only indirect flexibility sharing cause a interface flow when the TSO tries to mitigate the imbalance by procuring from its own resources and this influences the layer 1 network.

The last variant for this coordination scheme is **Fragmented_penalty_optimal.** Similarly, as in the previous scheme, the interface flow is priced, However, the method for the pricing differs and is based on the clearing price of the virtual common market. This procedure implies that an optimal price is set based on all the bids and offers in the whole system via applying a virtual common market. However, running such a market requires an information sharing, which in this case the fragmented market must be able to provide this information for the virtual common market, otherwise having this procedure is not applicable for this market scheme.

Variant(s) of Fragmented market	
Fragmented_0	**The interface flow of the layer 1 is obliged to be constant, and hence no any flexibility sharing between 2 network**
Fragmented_penalty	**The interface flow is variable, and the price for the interface flow is set as an externality, and set based on layer 1 downward and upward cost.**
Fragmented_penalty_optimal	**The interface flow is variable, and the price for the interface is set based on the clearing price of the virtual common market**

Multilevel Market model

A multilevel market also can be modeled as a composition of 2 disjoint transmission and distribution- level market. Unlike the fragmented market model, the direct flexibility sharing can be performed when the TSO can directly access to the DERs in distribution system. Similarly, to fragmented market, firstly, layer 1 composing of 1 or more disjoint distribution-level market(s) is cleared in order to solve the issues associated to the distribution network. Solving these issues, may cause some imbalances in the transmission network by modification to the interface of DSO-TSO flow. Consequently, the TSO runs a disjoint central market to solve the congestion and the balancing in his network, as well as the imbalance caused in the layer 1 clearing, using resources connected to both layers. This implies that the distribution network still is influenced by the indirect flexibility sharing of the transmission network. Regarding this and the direct access of the TSO over DERs, the flow at the interface can be variable in both layers within a pre-defined limit. Moreover, since the TSO also procures the flexibilities from distribution network, he should respect the constraints of this network level, and this should be indicated in the mathematical model. In this essence, high network information sharing should be taken place between the SOs. In general, having the sequential markets with the ability to modify the bids before submitting in upper layer market, allows the FSPs to adapt their bidding strategy and consequently increase their chance to have more cleared bids in the market.

Different variants for the multilevel market model can be defined and depending on that, some bids from layer 1 can be submitted at the layer 2 market in different ways. However, there is always a priority for the DSO to procure the flexibility from the submitted bids from his belonging resources.

The first variant of the multi-level market is defined for the case when the TSO does not respect the distribution network constraints even when procuring flexibility from the DERs. This variant is called **multilevel_no_network scheme** at which the market clearing will not guarantee safe network operation without imposing the violation in the network.

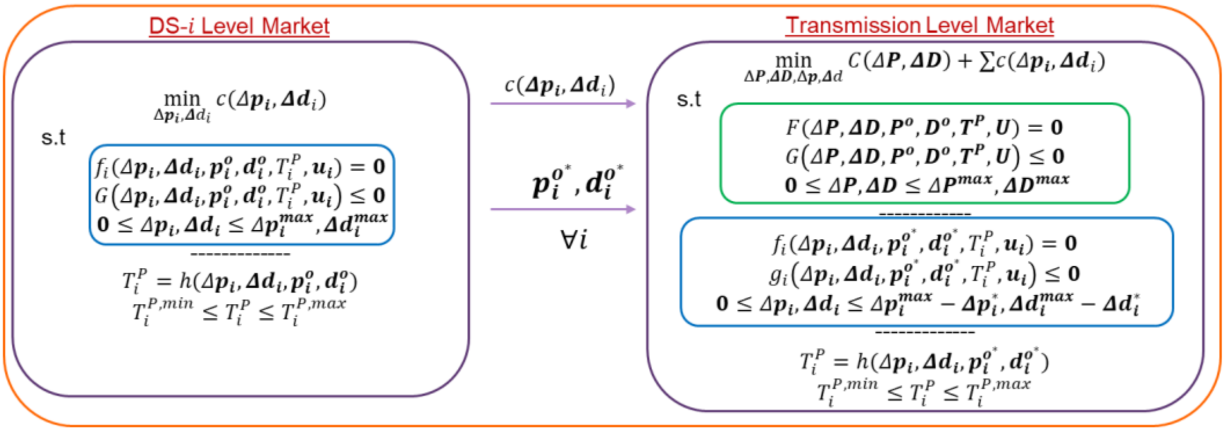
The second variant is **Multilevel_v1.** In this model, after layer 1 clearing, uncleared bids from layer 1 market can be directly forwarded to the layer 2 market without being modified.

The third variant is called **Multilevel_v2,** where the FSP connected to the distribution level, can submit bids in layer 2 while not knowing about the result of layer 1 clearing. In this configuration the FSP should select the proportion of its capacity and the price for bidding in layer 1 and layer 2 in a parallel way. Since the FSP does not have information about layer 1 clearing before the clearing of layer 2, it must bid the market parallelly, however in essential the market structured in a sequential manner.

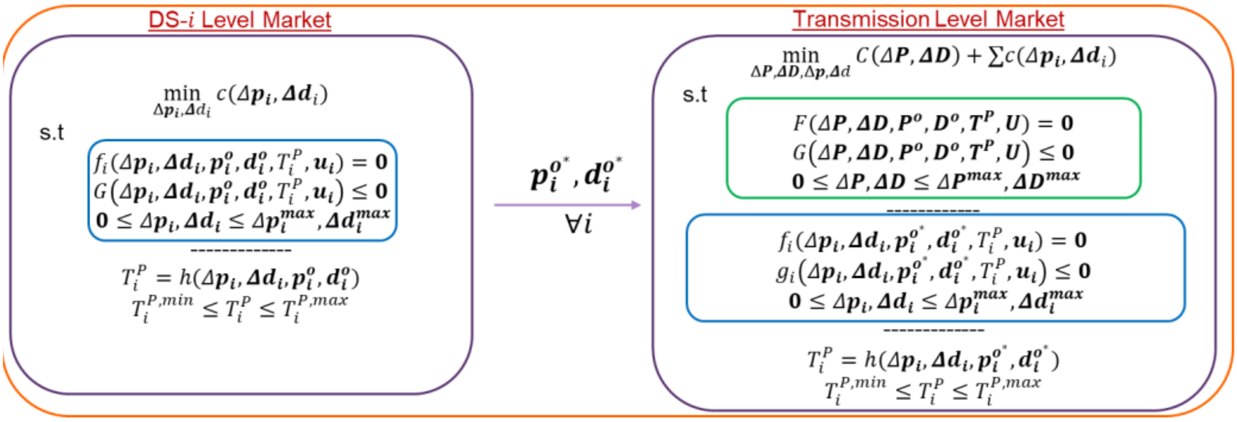
The fourth variant of this market scheme is **Multilevel_v3** at which FSP can also bid in 2 market levels, but in this case, it already knows the result of layer 1 market clearing prior to submitting bids in layer 2. In this situation, the FSP can modify its associated uncleared layer 1 bids and re-submit them in the consecutive market.

The mathematical models related to **Multilevel_v1, Multilevel_v2,** and **Multilevel_v3** can be depicted as follows:

These mathematical formulations associated to **Multilevel_v1.** Obviously, the transmission market level aims at minimizing the cost while procuring flexibility cost from both transmission and distribution without violating any limitation. For this reason, the cost and the constraints of the distribution system are included in transmission level market formulation. As seen the uncleared bids of layer 1 market will be forwarded to layer 2 market without changing in their quantity and the price. Moreover, in this mathematical model, the interface flow can be modified for the layer 1 and layer 2 for their indirect and direct flexibility sharing, respectively.



Following figure provides the representation of the mathematical model for **Multilevel_v2,** and **Multilevel_v3.** The mathematical formulation is similar to one presented for the to **Multilevel_v1,** except that the bids are modified and submitted to the second layer with an updated quantity and price.



Another variant of the multilevel associated to the unpriced interface flow is **Multilevel_v4**. In general, since clearing of the layer 2 requires a clear representation of the distribution network, an information sharing must be implemented for the multilevel scheme. However, this information sharing can be challenging and burdensome. In this regard, **Multilevel_v4** introduces a third layer (in addition to layer 1 and 2) which aims at redispatching to resolve any issues caused by the layer 2 market clearing, knowing all the constraints of the distribution network. In contrast to previous multilevel variants, layer 2 market clearing does not respect the distribution network constraints and this duty is assigned to the layer 3 to resolve any violation considering the distribution grid limitations.

Other variants of this scheme is called **Multilevel_vn_0** (includes Multilevel_v1_0, Multilevel_v2_0, and Multilevel_v3_0 and Multilevel_v4_0)**.** These coordination schemes are similar to their associated market scheme (e.g., Multilevel_v1_0 is associated to Multilevel_v1), except, in these schemes the interface flow of the layer 1 is mandated to be constant, meaning that the indirect flexibility sharing is not allowed any more.

Other configuration related to the multilevel coordination scheme, is Multilevel_vn_penalty (includes, Multilevel_v1_penalty, Multilevel_v2_penalty, and Multilevel_v3_penalty, Multilevel_v4_penalty). Again, these coordination schemes are similar to their associated market scheme, however, the price for the interface flow is set as an externality which is dependent on the submitted bids and offers to the market. This conveys that the variable interface flow is allowed and priced according to the price of market. This price is set at the midpoint between the most expensive downward flexibility bid and the least expensive upward flexibility bids, generally aiming at prohibiting unnecessary downward flexibility procurement in layer 1.

Another set of variants for this coordination scheme is **Multilevel_vn_penalty_optimal** (include Multilevel_v1_penalty_optimal, Multilevel_v2_penalty_optimal, and Multilevel_v3_penalty_optimal**)** Similarly, as in the previous set of schemes (e.g., Multilevel_v1_penalty), the interface flow is priced for these variants. However, the method for the pricing differs and is based on the clearing price of the virtual common market. This procedure implies that an optimal price is set based on all the bids and offers in the whole system via applying a virtual common market.

Following figure represents a summary of all the variants of the multilevel market.

Variant(s) of Multilevel market

multilevel_no_network scheme	**Constraints of the distribution network not included in the layer 2 clearing of market**

Multilevel_vn

Multilevel_V1	**Uncleared bids of layer 1 market will be forwarded to layer 2 market, without any change**
Multilevel_V2	**Bids are submitted in layer 2 while not knowing about the result of layer 1 clearing**
Multilevel_V3	**Bids are submitted in layer 2 while knowing about the result of layer 1 clearing**
Multilevel_V4	**A third layer aims to resolve any issues caused by the layer 2 market clearing, considering the constraints of the distribution network.**

Multilevel_vn_0

Multilevel_V1_0 . . .	**All are the same as their original coordination schemes, except the interface flow is constant for all the variants.**

Multilevel_vn_penalty

Multilevel_V1_penalty . . .	**All are the same as their original coordination schemes, where the interface flow is variable, and the price for the interface flow is set as an externality, based on layer 1 downward and upward cost.**

Multilevel_vn_penalty_optimal

Multilevel_V1_penalty_optimal . . .	**All are the same as their original coordination schemes, where interface flow is variable, and the price for the interface is set based on the clearing price of the virtual common market**

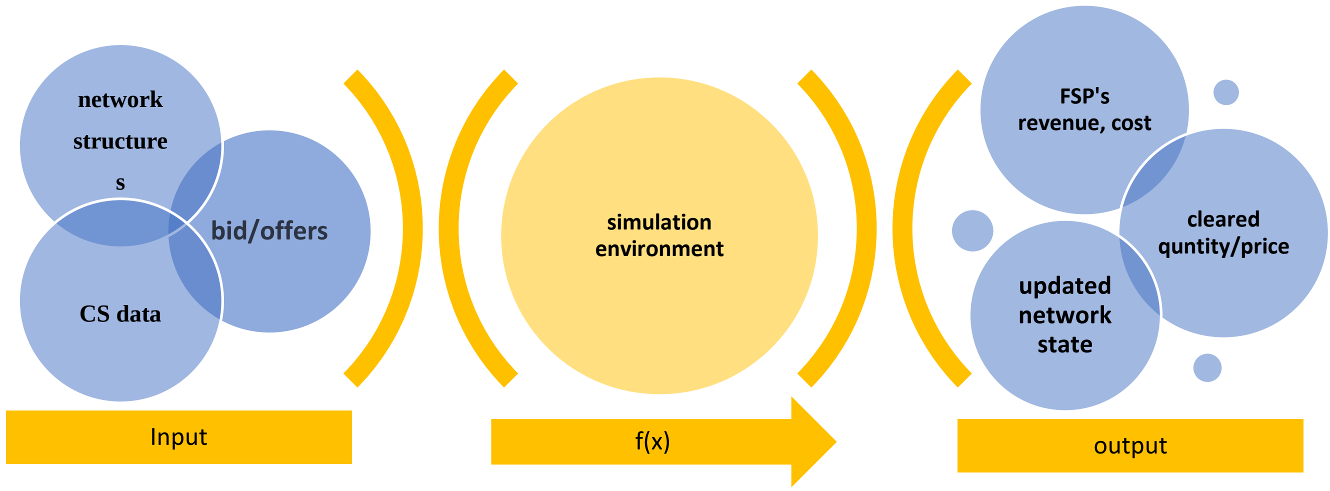
Knowing all the possible coordination schemes and variants, the goal of the paper is to set up a simulation environment for a case study aiming at performing a comparison of the different schemes regarding the procuring cost of the flexibility and the effects of different interface flow pricing.

Case Study: Comparison of the Different Coordination Schemes & Effects of pricing of interface flows

The paper proposes an interconnected system composed of the IEEE 14-bus transmission network connected to three distribution networks, namely, the Matpower 18-bus, 69-bus, and 141-bus systems. For simulating the network and performing the comparison between different coordination schemes in the case study, some assumptions are considered.

In this network, each distribution grid is connected to the transmission network only through one connection point. Moreover, the demand profile of each bus as well as capacity limits of the lines are already known. In this regard, any congestion in distribution network, and any congestion and imbalance in transmission network is already anticipated in the initial state without any flexibility activation. For creating order book, upward, downward flexibility bids are created at different nodes for which the price are selected from a uniform distribution in the range of [10,15] €/MWh for downward, and [50,55] €/MWh for the upward flexibility. Moreover, the maximum bid quantities for each node are generated considering the base demand or base supply at that node. For providing the upward flexibility, the base demand can decrease to 0, or the base supply increase by 50%. In contrast, for the downward flexibility, the base demand can increase by 50%, or the supply demand decrease to 0. Regarding this, the price and the quantities of the bids, and offers are drawn arbitrarily. Furthermore, it is assumed that 0, 2 or 4 bids can be submitted per node in the system and there is a possibility for the nodes to be cleared partially. The results focus on the single time period; however, the multi-time period result can be achieved if the intertemporal constraints are added to the optimization problem.

Regarding the input, the simulation environment captures a constant set of data for all the coordination schemes including similar order book and network structures. In contrast, the requirement of each scheme (e.g., network representation needs, the access to flexibility bids from different grid level, etc.) are considered solely for each coordination scheme. In this simulation, although the order book is similar for all coordination shames, for some schemes, it can be modified depending on their characteristic (e.g., for common market a unified order book and for disjoint market, it is split depending on the grid to which resources are connected). Considering the input and the assumptions in the simulation environment, the output provides the cleared quantity as well as clear bids, the price of the cleared bid, the updated network state with the activation of flexibility, and the revenues of FSP and their cost. Following figure shows the summary of the input, output of the simulation environment.



simulation assumption

- Each distribution grid is connected to the transmission network only through one connection point.
- The demand profile of each bus as well as capacity limits of the lines are already known.
- Any congestion in distribution network, and any congestion and imbalance in transmission network is already anticipated in the initial state without any flexibility activation.
- For creating order book, upward, downward flexibility bids are created at different nodes for which the price are selected from a uniform distribution
- The maximum bid quantities for each node are generated considering the base demand or base supply at that node
- For the upward flexibility, the base demand can decrease to 0, or the base supply increase by 50%.
- For the downward flexibility, the base demand can increase by 50%, or the supply demand decrease to 0
- The price and the quantities of the bids, and offers are drawn arbitrarily.
- 0, 2 or 4 bids can be submitted per node in the system and there is a possibility for the nodes to be cleared partially
- Simulation environment captures a constant set of data for all the coordination schemes including similar order book and network structures
- The requirement of each scheme (e.g., network representation needs, the access to flexibility bids from different grid level, etc.) are considered solely for each coordination scheme

Numerical results based on defined coordination schemes:

Criteria for the comparison of the coordination schemes:

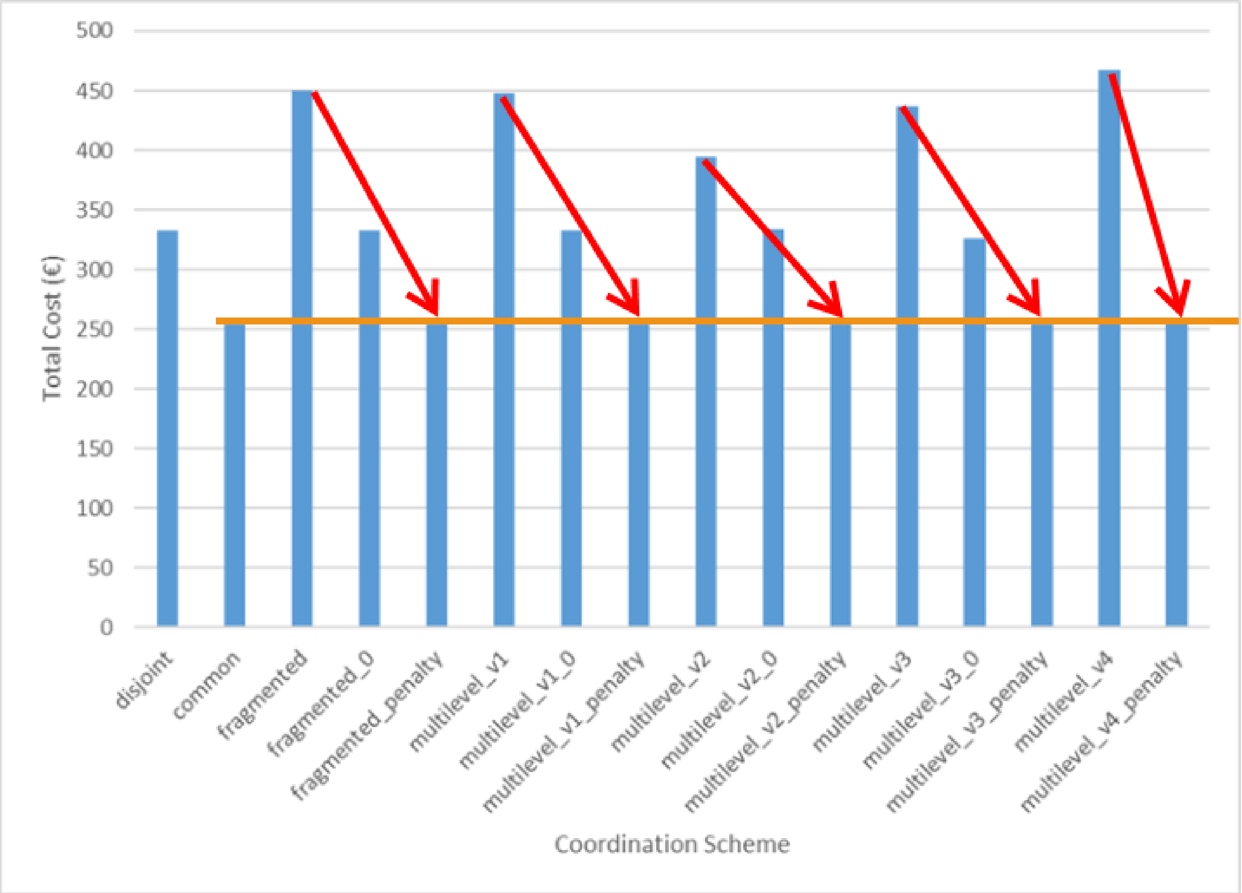
The comparison between different coordination schemes can be based on different criteria which leads to select the best coordination scheme while performing a trade-off between various criteria. In the following table some coordination scheme selection criteria are presented and :

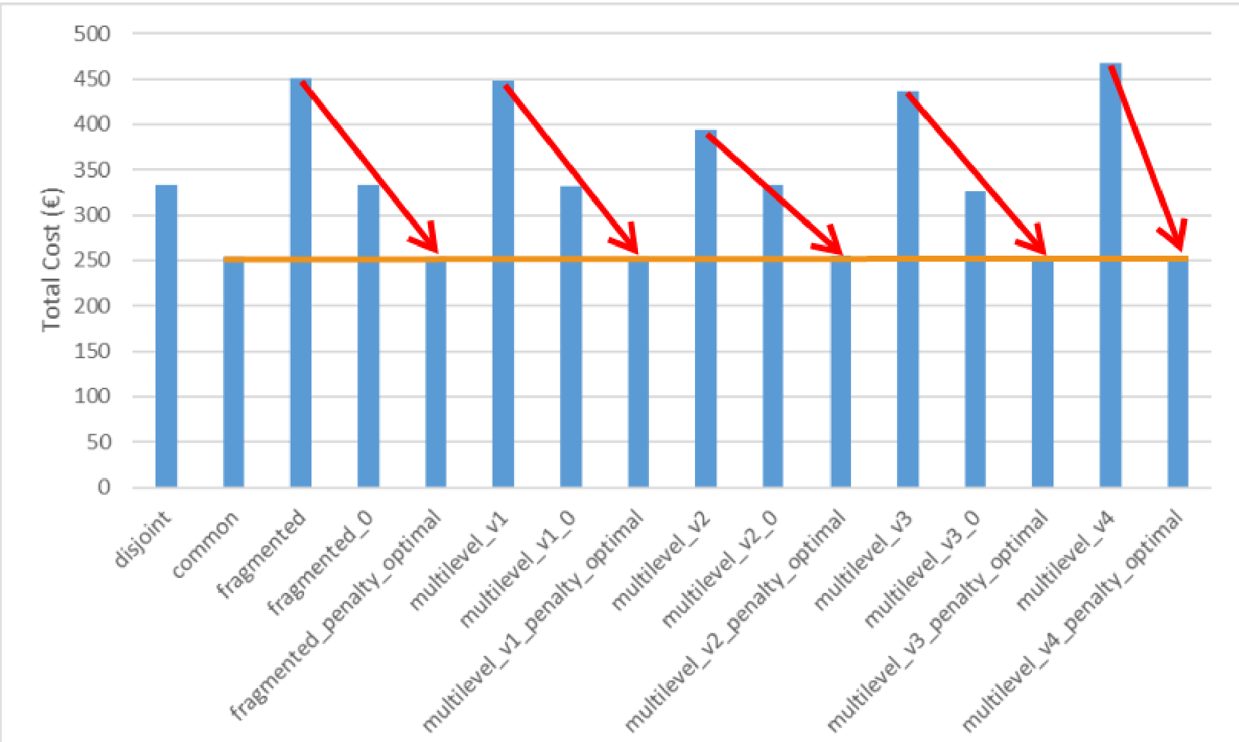
CS comparision criteria

- National grid charactristic
- Design and specification of the flexibllity products
- Entrance cost to the market
- Technical and financial entry barriers
- economic effeceincy from total procurment cost
- ...

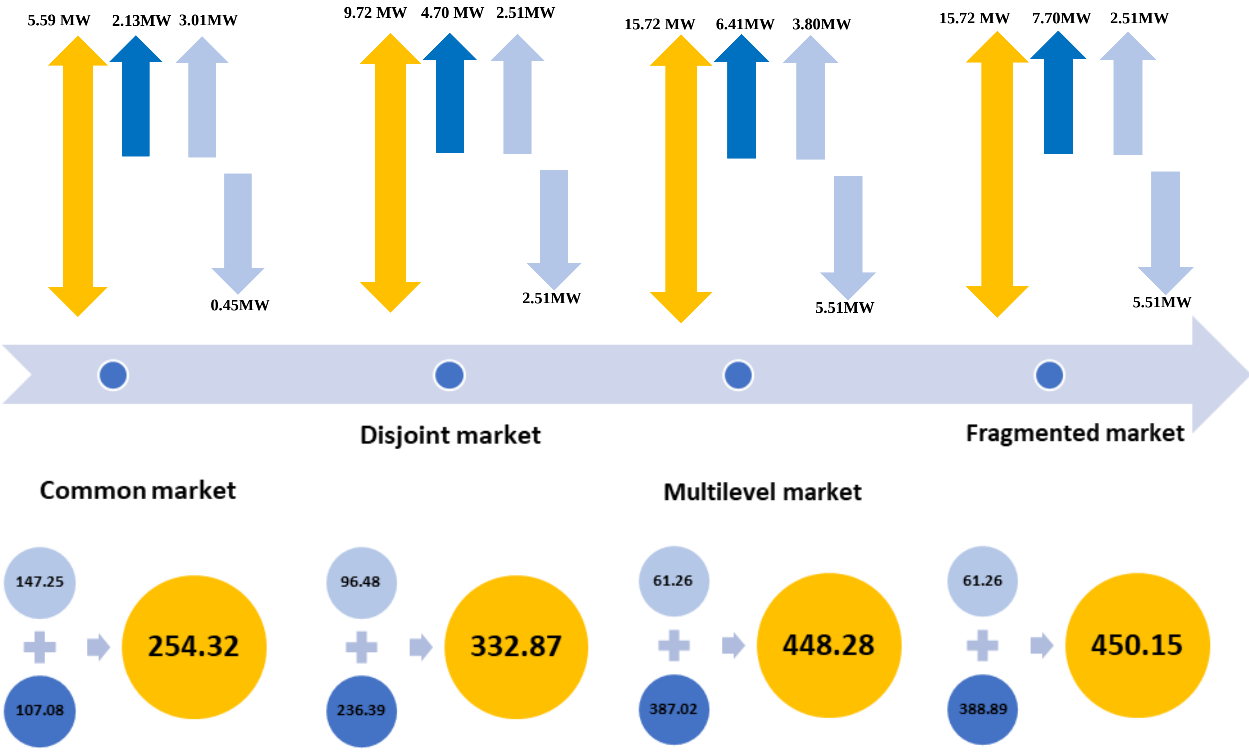
Different coordination schemes must be compared from different point of view in order to select the best scheme among all. However, the focus of the paper is to calculate the latter criteria in table () which concerns the efficiency of the procurement process while considering the same financial/technical entry requirement for all the coordination schemes. In this respect, having same requirements, reduce the entry barrier that might be presented for some of the coordination schemes allowing all the participants to participate in the market without eliminating any bid.

After running the simulation based on the input data and the global assumption for all the schemes and the assumptions specifically for each scheme, the final result is depicted in the following figure:


Total Cost (€)
500
450
400
350
300
250
200
150
100
50
0
disjoint
common
fragmented
fragmented_0
fragmented_penalty
multilevel_v1
multilevel_v1_0
multilevel_v1_penalty
multilevel_v2
multilevel_v2_0
multilevel_v2_penalty
multilevel_v3
multilevel_v3_0
multilevel_v3_penalty
multilevel_v4
multilevel_v4_penalty
Coordination Scheme


Total Cost (€)
500
450
400
350
300
250
200
150
100
50
0
disjoint
common
fragmented
fragmented_0
fragmented_penalty_optimal
multilevel_v1
multilevel_v1_0
multilevel_v1_penalty_optimal
multilevel_v2
multilevel_v2_0
multilevel_v2_penalty_optimal
multilevel_v3
multilevel_v3_0
multilevel_v3_penalty_optimal
multilevel_v4
multilevel_v4_penalty_optimal

As depicted in the above figure and figure (0), starting from the fundamental coordination schemes (**disjoint market, common market, multilevel market_v1, fragmented market**), it is obvious that the total precuring cost is the least for the common market is the highest for the fragmented market. Figure(0) shows the procurement cost of each fundamental scheme. The light blue arrows represent the upward and downward flexibilities in distribution network, dark blue is associated to the amount of upward flexibility (as there is not downward flexibility in transmission network), and orange arrow represents the total quantity of the flexibility in whole system. Moreover, the light and dark blue circles represent the cost for procuring flexibility from the distribution network, and the transmission network, respectively, and the orange circle shows the total procuring cost of flexibility in €.



As shown in the above figure, it is possible to compare the coordination schemes in terms of their procured quantity and the cost for procuring the flexibility resources. In this comparison, the common coordination scheme procures less flexibilities and as the result owns a lower cost for procuring the flexibility resources. Having look at the detailed flexibility procurement of this market scheme, it is palpable that its upward flexibility procurement from distribution network is higher than the one in transmission network. Moreover, the downward flexibility procurement is very low in the case of common coordination scheme. On the other hand, for the fundamental fragmented market discussed in section (), the quantity of the total flexibility procurement is triple with respect to the common market. It procures much higher upward flexibility resources from the transmission network than distribution network, and the downward flexibility procurement from the distribution network is a large quantity.

This simulation is performed in the case in which the interface flow is unpriced. In this respect, the coordination schemes such as fragmented and the multilevel tend to procure the low-cost flexibility resources in the first layer. This performance in buying the first layer resources may cause the imbalance in the system and the TSO will be responsible to solve this issue buy procuring other resources. This imbalance does not endanger the benefits of the first layer market operator (since interface flow is unpriced) and it causes a further procurement of the flexibility by the second layer market to solve the issues.

Having this analysis, it results that the common market is the most efficient coordination scheme from both total procured quantity and the total cost of the flexibility procurement. This conclusion is valid in case of having the same set of flexibility bids and other requirements for all the under-analyze schemes (however, depending on the scheme they should be adapted). For an illustration, all the small-scale resources are allowed to participate in such a market. In practice, some obstacles such as different technical and economical requirements for each market, products, etc., results in different market design and consequentially, different outcome will be achieved. However, theoretically, a higher pooling of the resources (e.g., as in common market), where there is no priority of access for any SO is the most efficient one.

As illustrated in fig (), the comparison between **multilevel market_v1, multilevel market_v2, multilevel market_v3,** where unpriced interface flow is defined, implies that the **multilevel market_v2** can be the most efficient one among all**.** As discussed in section (), **multilevel market_v2,** is the scheme where the FSPs can submit the bids in the layer 2 while not knowing the result of the clearing in layer 1. In this respect, the number of bids is split between two market and as a result, that they can submit less bids in the layer 1 and obviously less unneeded downward bids in this layer. Procuring less unneeded downward bids (which in principle is already guaranteed a higher DSO benefits), causes less imbalance in the system and requires less TSO effort for solving this issue in the network. In this regards, lower total procured quantity and total system cost is achieved. On the other hand, the total cost for the **multilevel market_v3** implies a slightly lower value with respect to **multilevel market_v1**, which is not related to the market design, but mostly is associated to the bid prices randomly selected from a uniform distribution in the second layer.

As discussed in section (), Introducing various methods for pricing the interface flow, leads to have **Multilevel_vn_0, Multilevel_vn_penalty**, **Multilevel_vn_penalty_optimal,** which in this case, n represents the variant number.

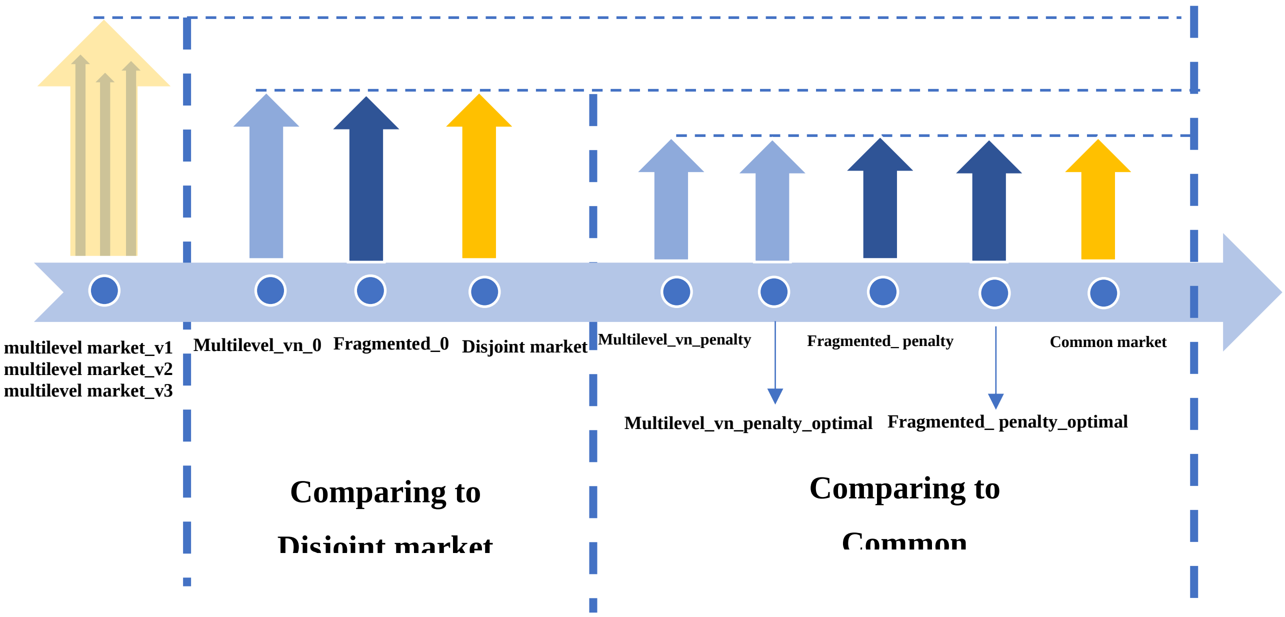
For the **Multilevel_vn_0**, the flow interface is fixed at a certain amount which implies the DSO to not only mitigate the congestion in the layer 1 network, but also solve the imposed imbalances by itself. In this instance, if the DSO cause imbalance as the result of its flexibility procurement, it must solve the imbalance within the distribution network. Hence, DSO will not anymore procure the unneeded downward flexibility to increase its profit while solving the congestion issues. For **Multilevel_vn_0,** all the for variants: Multilevel_vn_1, Multilevel_vn_2, Multilevel_vn_3, Multilevel_vn_4 will undergo a same total cost in their market.

In the case of **Multilevel_vn_penalty**, as indicated in the previous sections**,** since the interface is priced regarding the flexibility price of the layer 1, procuring unneeded downward flexibility by the DSO will threaten its profit. In this instance, if the DSO makes an imbalance in the system by procuring downward flexibility, the price associated to the interface flow will be higher than procuring the upward bids in the layer 1. In this variant the total cost of all the Multilevel_v1_penalty, Multilevel_v2_penalty, Multilevel_v3_penalty, Multilevel_v4_penalty, are the same and can be estimated as same as **Common coordination scheme.**

In **Multilevel_vn_penalty_optimal** variant, as the interface flow is set optimally based on the virtual common market clearing price, again unneeded DSO downward flexibility is avoided, and less total flexibility procurement is needed. In this case, the total cost of all the versions is similar to the **Multilevel_vn_penalty** and consequently similar to the **common coordination schemes**. In this variant, achieving an optimal clearing price by running a virtual common market needs a high network information sharing.

Comparing different variants of the fragmented coordination schemes namely **Fragmented_0, Fragmented_ penalty, Fragmented_penalty_optimal,** concludes to select the most efficient one. **Fragmented_0** owns a similar total cost as disjoint market and multilevel_vn_0 since the variable interface flow is not allowed in this scheme. Moreover, the **Fragmented_0, Fragmented_ penalty, Fragmented_penalty_optimal**, which characterized with the priced interface flow, undergoes the same total cost, and estimated to be equal to the Multilevel_vn_penalty and Multilevel_vn_penalty_optimal.

Comparing all the variants of the multilevel and fragmented market with one another as well as disjoint and the common market results to the following graphical summary in figure(0)



As presented, the total cost related to the **Multilevel_vn_0** and Fragmented_**0** are approximated to be similar to the **disjoint market**. On the other hand, the total cost for **Multilevel_vn_penalty**, **Multilevel_vn_penalty_optimal, Fragmented_ penalty**, and **Fragmented_ penalty_optimal** are equal and are estimated as the one in the **common market**. This comparison shows that latter case with the similar cost as common market is the most efficient variant, however, considering the priced interface flow, disjoint market is the less efficient one. From a practical point of view the variants such as **Multilevel_vn_penalty** and **Fragmented_ penalty** is the most practical one, however there is a risk of gaming by the market participants in setting their bid price. Moreover, for running a **Fragmented_ penalty_optimal,** the virtual common market requires the network information which implies the need of the fragmented market to provide the higher information for this purpose.

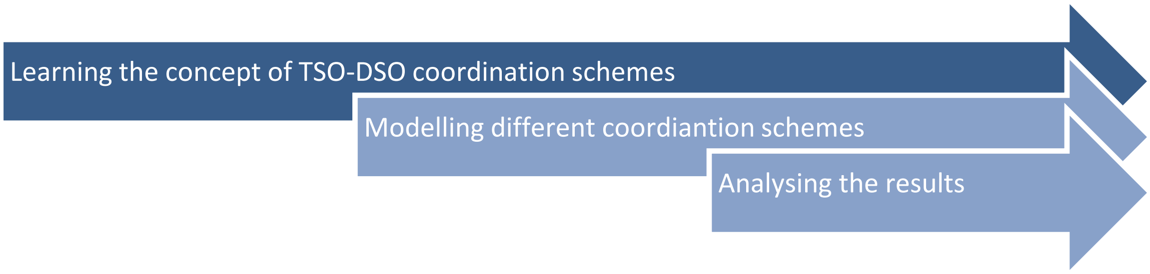
Last but not least, for the **Multilevel_v4,** it seems that adding new layer may cause a higher cost for the flexibility procuring. However, this can be true for the unpriced interface flow condition, but in case of proper pricing the interface flow, the total cost of **Multilevel_v4** (Multilevel_v4_penalty, Multilevel_v4_penalty_optimal) can estimated similar to all other Multilevel_vn_penalty and Multilevel_vn_penalty_optimal variants, as well as common market.

Capítulo 3. DEFINICIÓN DEL TRABAJO

3.1 JUSTIFICACIÓN

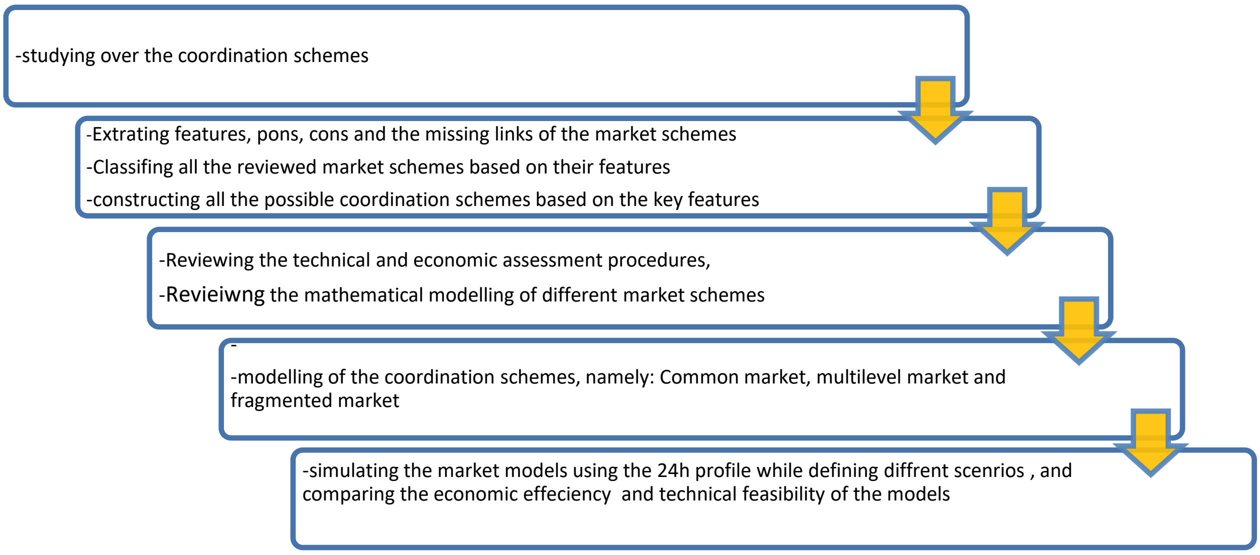
3.2 OBJETIVO

In this thesis work the first aim is to obtain a perfect understanding of different available TSO-DSO coordination schemes, draw a comparison between them, categorize the coordination schemes based on their common features, and to address the essential needs and the missing links of each coordination schemes. The Second target is to model new coordination schemes to fulfil the requirements, solve the missing links, and add more credit to the previous coordination schemes. In this essence, it is relevant to determine whether a specific market scheme for TSO-DSO coordination brings acceptable economic performances. Hence, given the possible alternatives, the aim is to economically assess how the different coordination schemes perform considering the different contexts and scenarios. The results obtained from the economic assessment of different market schemes are then compared. Moreover, the modelled Coordination schemes will be analysed and compared in terms of their total cleared quantity, as well as their technical feasibility, while defining different scenarios.



3.3 METODOLOGÍA

For achieving to the desired goal, a deep study over the coordination schemes is performed by reviewing almost 80 percent of published papers,. Following this literature review, the features, pons, cons and the missing links of the studied market schemes are noted, and the results are written down representing the initial section of the thesis. The various coordination schemes are classified considering their similarities with the seven market schemes in the CoordiNet project. In this regard, all the reviewed market schemes are classified in seven main categories, and the similarity and the differences with the associated coordiNet project's coordination scheme are addressed. Regarding all the obtained knowledge so far, all the possible coordination schemes are Constructed based on the key features, and the most relevant and applicable one is chosen. After all, by reviewing the mathematical modelling of different market schemes with high concentration on the CoordiNet project formulation strategies, the concept of the modelling is obtained. Having look at the different projects and the research papers, the concept of the modeling is formed. This modeling is proposed in a way that can fulfill and solve the gaps of the previous works or at least complete the previous work by identifying and introducing new features. The coordination schemes which are defined are technically and economically feasible for the power system, and this will be proved in the following sections.



3.4 PLANIFICACIÓN Y ESTIMACIÓN ECONÓMICA

Presentación temporal de las actividades a realizar y estimación del coste de desarrollo.

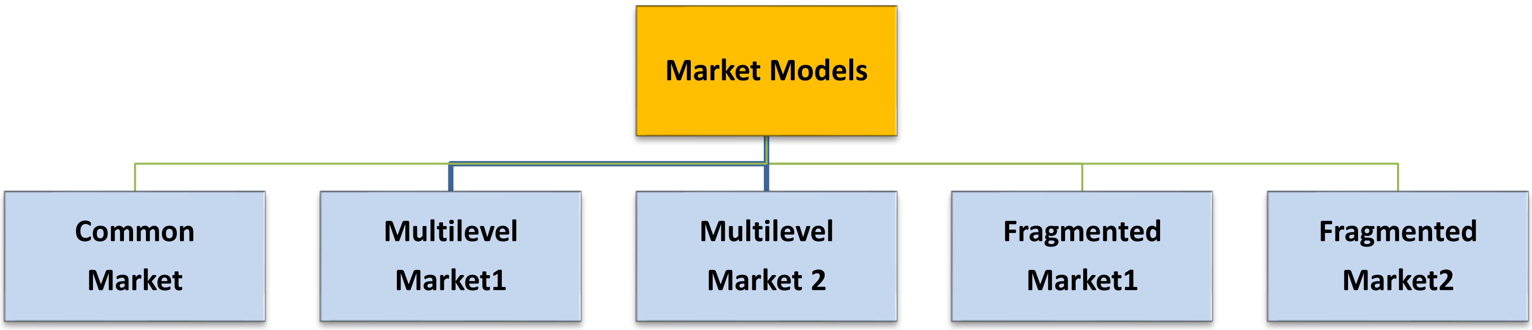
Capítulo 4. SISTEMA/MODELO DESARROLLADO

4.1 ANÁLISIS DEL SISTEMA

…

4.2 DISEÑO

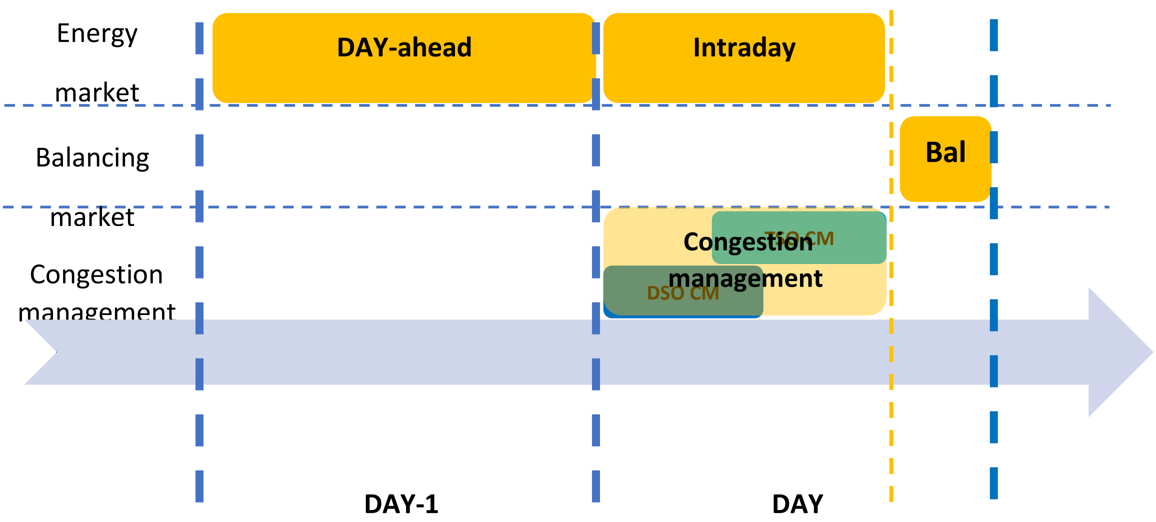
Considering all the projects reviewed and the deep analysis over the projects, three different coordination schemes are defined:



The detailed description of each these coordination schemes, as well as their difference will be presented in the following sections.

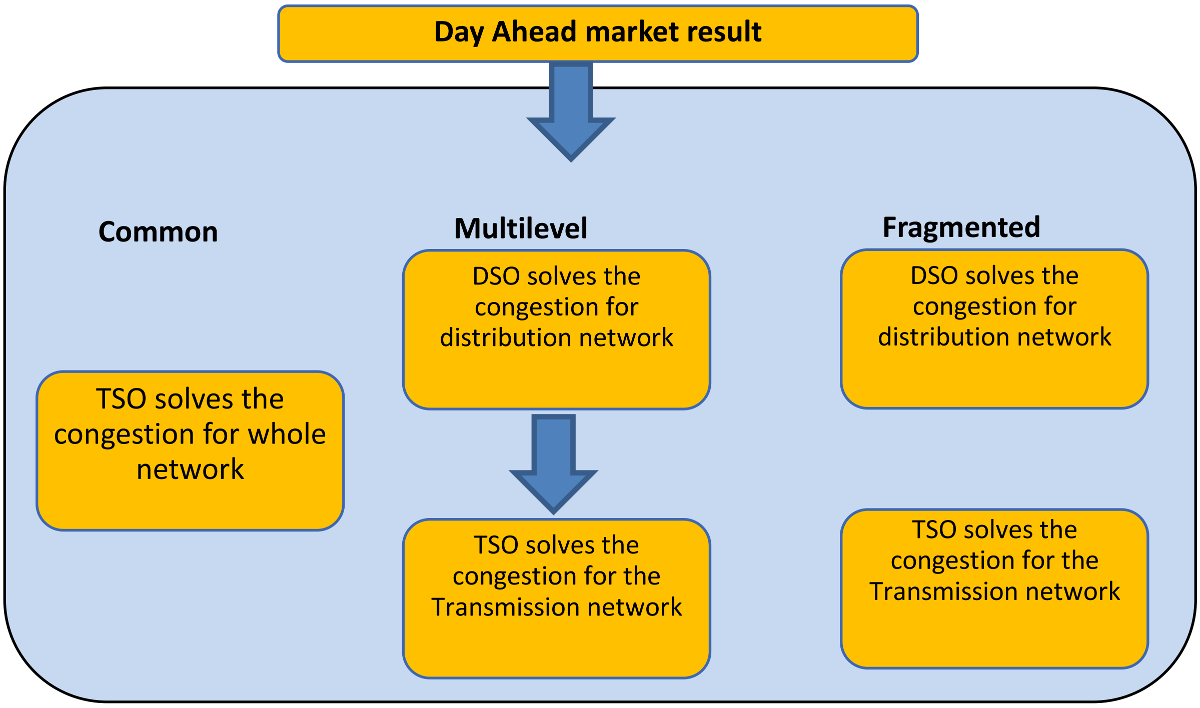
Having these coordination schemes, the goal is to implement the congestion management market applying these schemes.

It is important to have an understanding about the place of the congestion management market in the time horizon. The sequence of the markets is as follows:



As shown in the above picture, the Congestion management market is placed after the day-ahead market. The result of the day-ahead will be delivered to the congestion management as the input. After the congestion management market, the balancing market take place. In definition, the day-ahead market in a day before the delivery performs a wholesale market without considering the network . After DA market”, Checks if DA market is feasible and does re-dispatch to solve possible problems. And Near real-time”, solve the deviations between DA schedule and real-time

Having look at the following graph, it is obvious that the result of the day ahead market is fed to the congestion management market. we have three different market modeled defined as the starting point of the modelling.

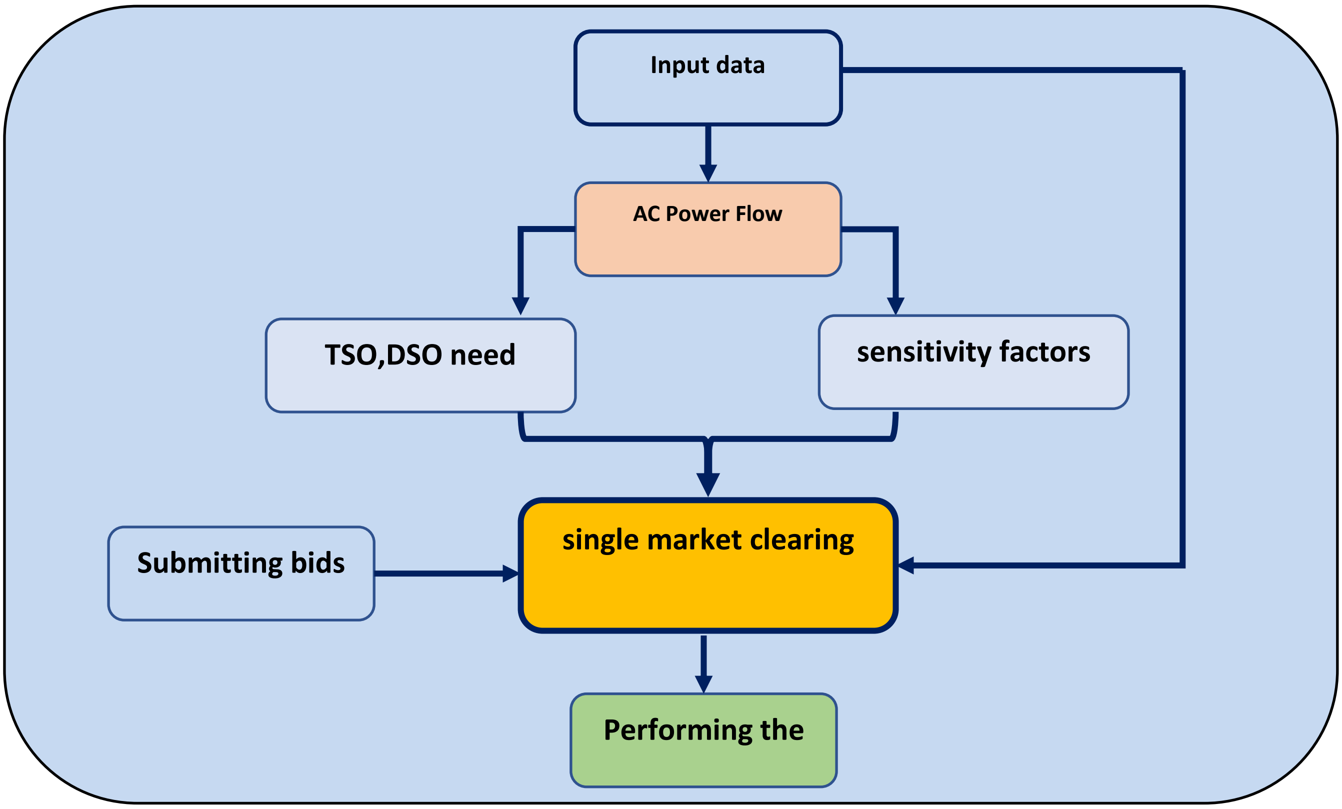


In the common market, TSO and DSO are the buyers of the flexibility for the whole network, considering all the constraints of the network. Moreover, Both central and local needs should be addressed in a single market. in this model, Flexibility requirements are jointly optimized for both DSO and TSO. In the proposed model, the network representation is not used in market clearing algorithm

In the multilevel market modelling, procurement of the flexibility services can be performed separately for each system level using their own resources. Also, local and central needs are addressed through different markets which coexist. Moreover, TSO access is limited to the uncleared flexibility bids of the local market. in this market model, different system operator is in charge of different markets. In principal, in this coordination scheme, the DSO firstly procures the flexibility from distribution network for its needs, and then the TSO procures the flexibility resources for solving the congestion management and the system balancing issues causes by DSO, using the bids connected to the transmission network, plus the uncleared bids forwarded from the distribution network. In this case, forwarded uncleared bids can be modified in size and quantity. In general the interface is priced having higher price than the downward and upward flexibility of the distribution level market. this price also can be set using the virtual common market price. In the mathematical modeling, the network representation is not used in market clearing.

For the fragmented market, procurement of the flexibility services can be performed separately for each system level using their own resources. Moreover, local and central needs are addressed through different markets which coexist. The TSO does not have access to the DERs even to the uncleared bids from lower markets In our model, the DSO firstly procures the flexibility from the distribution network for its needs, and it is allowed to impose imbalancing for higher network. After then, the TSO preforms the transmission market clearing using the resources connected to the transmission network resources, and solve any imbalance caused by DSO. Likewise, the network representation is not used in market clearing

In following it shows the flowchart for the common market model:

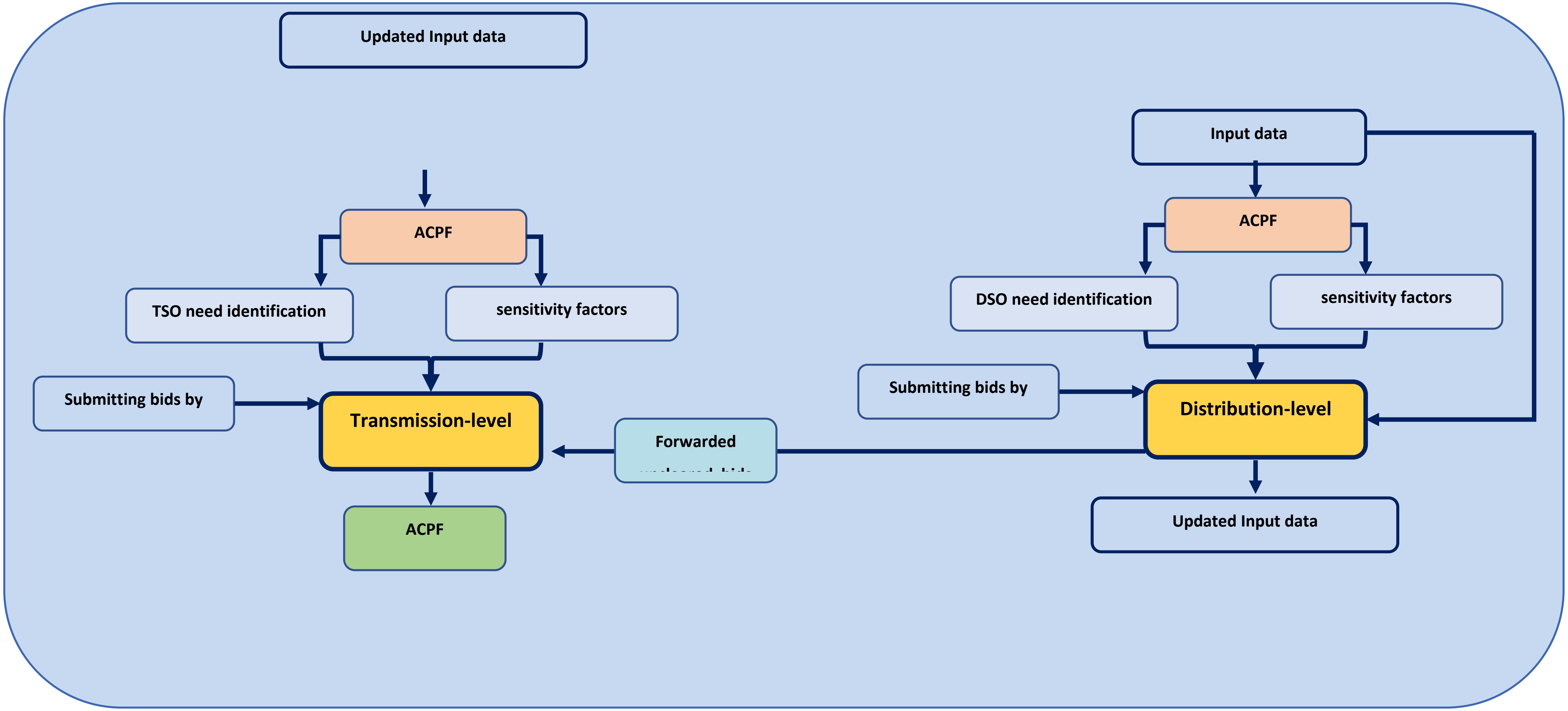


Having look at the flowchart, the load and generation profile are the output of the day-ahead market and is the input for the congestion management market. Based on the input data, the ACPF is performed and the congested areas are detected. Moreover, the sensitivity of each line with respect to each bus is calculated. Having this information along with the bids submitted by FSPs, the market is cleared. As soon as the result of the market optimization is received, the post evaluation is performed by running another ACPF.

Here is the mathematical formulation of the common market modelling. As seen form the formulation, the objective function is the minimization of the cost of procuring the flexibilities. And there are some constraints defined for these aim.

$min \sum_{h \in H} \left[\sum_{f \epsilon F^U} C^U_{f,h} p^U_{f,h} + \sum_{f \epsilon F^D} C^D_{f,h} p^D_{f,h} + VOLL(\alpha_{r,h}) \right]$ s.t.		(1)
$P^{TSO,DSO}_{r,h} + \sum_{f \epsilon F^U} PTDF_{f,r} p^U_{f,h} - \sum_{f \epsilon F^D} PTDF_{f,r} p^D_{f,h} - (\alpha_{r,h}) \leq 0$,	$\forall_r \in R^U, R^D, \forall_h \in H$	(2)
$\sum_{f \epsilon F^U} p^U_{f,h} - \sum_{f \epsilon F^D} p^D_{f,h} = 0$	$\forall_h \in H$	(3)
$\sum_{f \epsilon F^D} p^D_{f,h,i} \leq \lvert T\_capacity_{h,i} \rvert$	$F^D \in F^{DSO,i}, i \in \{0,1\}, if\ T\_capacity_{h,i} \leq 0$	(4)
$P^{Umin}_{f,h} \leq p^U_{f,h} \leq P^{Umax}_{f,h}$	$\forall_f \in F^U, \forall_h \in H$	(5)
$P^{Dmin}_{f,h} \leq p^D_{f,h} \leq P^{Dmax}_{f,h}$,	$\forall_f \in F^D, \forall_h \in H$	(6)
$\alpha_{r,h} \geq 0$	$\forall_r \in R, \forall_h \in H$	(7)

In following it shows the flowchart for the Multilevel market model


Updated Input data
Input data
ACPF
ACPF
TSO need identification
sensitivity factors
DSO need identification
sensitivity factors
Submitting bids by
Transmission-level
Forwarded
Submitting bids by
Distribution-level
ACPF
Updated Input data

Having look at the flowchart, the load and generation profile are the output of the day-ahead market and is the input for the distribution-level congestion management market. Based on the input data, the ACPF is performed, and the congested areas are detected. Moreover, the sensitivity of each line with respect to each bus is calculated. Having this information along with the bids submitted by FSPs, the market is cleared. As soon as the result of the market optimization is received, the post evaluation is performed by running another ACPF. Once the distribution-level market is cleared, the updated load and generation profile will be sent for the usage of the transmission level market. Having the same procedure as the distribution-level market, and using the bids submitted from the transmission resources, as well as the uncleared forwarded bids of the distribution-level market, the transmission-level market is cleared.

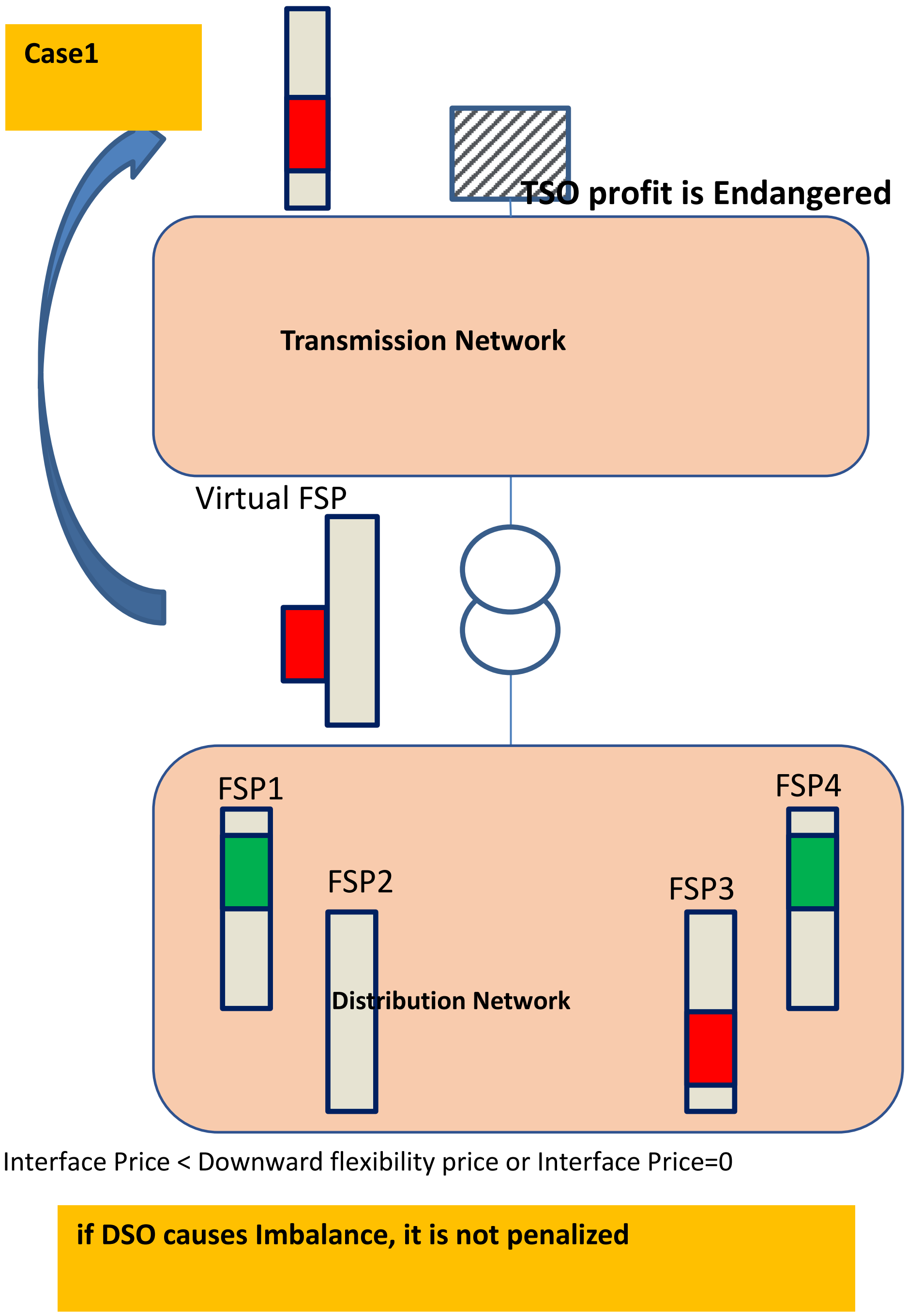
Here is the mathematical formulation of the multilevel market modelling. As seen from the formulation, the objective function is the minimization of the cost of procuring the flexibilities. And there are some constraints defined for this aim.

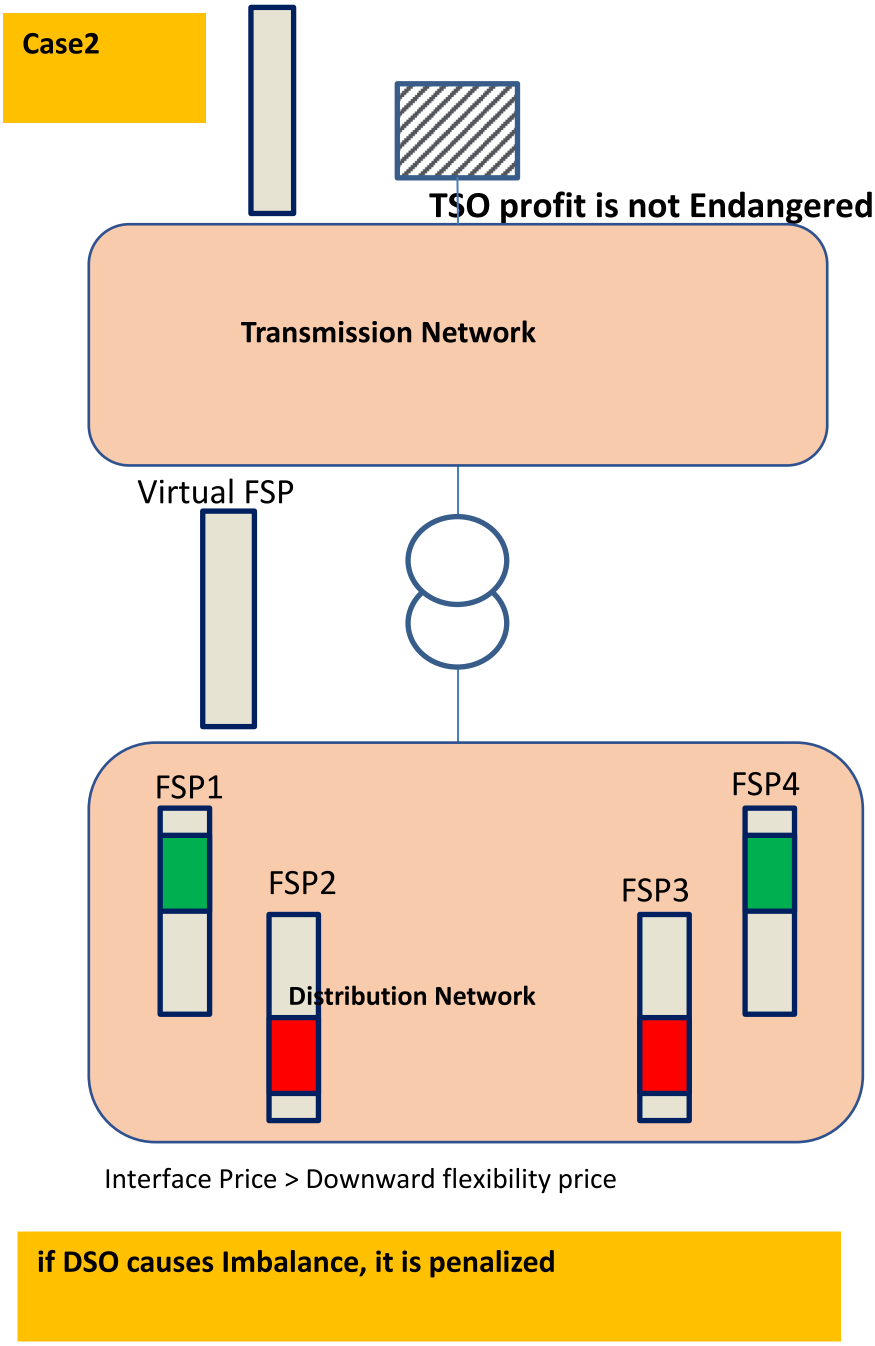
$min \sum_{h \in H} \left[\sum_{f \epsilon F^U} C^U_{f,h} p^U_{f,h} + \sum_{f \epsilon F^D} C^D_{f,h} p^D_{f,h} + VOLL(\alpha_{r,h}) \right]$ s.t.		(1)
$P^{DSO}_{r,h} + \sum_{f \epsilon F^U} PTDF_{f,r} p^U_{f,h} - \sum_{f \epsilon F^D} PTDF_{f,r} p^D_{f,h} - (\alpha_{r,h}) \leq 0$,	$\forall_r \in R^U, R^D, \forall_h \in H$	(2)
$\sum_{f \epsilon F^U} p^U_{f,h} - \sum_{f \epsilon F^D} p^D_{f,h} = 0$	$\forall_h \in H$	(3)
$P^{Umin}_{f,h} \leq p^U_{f,h} \leq P^{Umax}_{f,h}$	$\forall_f \in F^U, \forall_h \in H$	(4)
$P^{Dmin}_{f,h} \leq p^D_{f,h} \leq P^{Dmax}_{f,h}$,	$\forall_f \in F^D, \forall_h \in H$	(5)
$\alpha_{r,h} \geq 0$	$\forall_r \in R, \forall_h \in H$	(6)

Uncleared bids

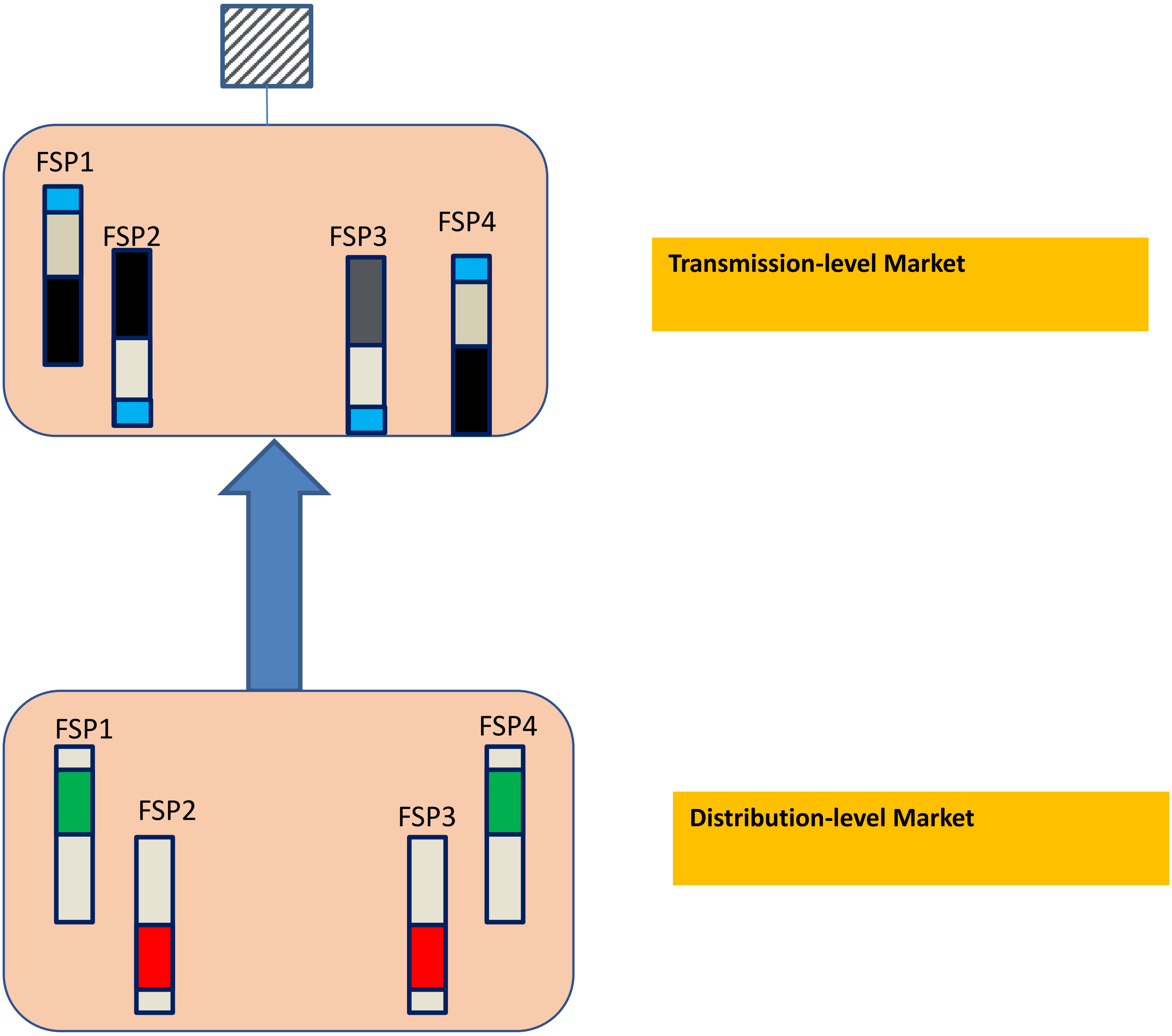
$min \sum_{h \in H} \left[\sum_{f \epsilon F^U} C^U_{f,h} p^U_{f,h} + \sum_{f \epsilon F^D} C^D_{f,h} p^D_{f,h} + VOLL(\alpha_{r,h}) \right]$ s.t.		(1)
$P^{TSO}_{r,h} + \sum_{f \epsilon F^U} PTDF_{f,r} p^U_{f,h} - \sum_{f \epsilon F^D} PTDF_{f,r} p^D_{f,h} - (\alpha_{r,h}) \leq 0$,	$\forall_r \in R^U, R^D, \forall_h \in H$	(2)
$\sum_{f \epsilon F^U} p^U_{f,h} - \sum_{f \epsilon F^D} p^D_{f,h} = 0$	$\forall_h \in H$	(3)
$\sum_{f \epsilon F^D} p^D_{f,h,i} \leq \lvert T\_capacity_{h,i} \rvert$	$F^D \in F^{DSO,i}, i \in \{0,1\}, if\ {}_{T\_capacity_{h,i}} \leq 0$	(4)
$P^{Umin}_{f,h} \leq p^U_{f,h} \leq P^{Umax}_{f,h}$	$\forall_f \in F^U, \forall_h \in H$	(5)
$P^{Dmin}_{f,h} \leq p^D_{f,h} \leq P^{Dmax}_{f,h}$,	$\forall_f \in F^D, \forall_h \in H$	(6)
$\alpha_{r,h} \geq 0$	$\forall_r \in R, \forall_h \in H$	(7)

For the multilevel market model, the fair-cost allocation can be done considering following:


Case1
TSO profit is Endangered
Transmission Network
Virtual FSP
FSP1
FSP2
FSP3
FSP4
Distribution Network
Interface Price < Downward flexibility price or Interface Price=0
if DSO causes Imbalance, it is not penalized


Case2
TSO profit is not Endangered
Transmission Network
Virtual FSP
FSP1
FSP4
FSP2
FSP3
Distribution Network
Interface Price > Downward flexibility price
if DSO causes Imbalance, it is penalized

There is another mechanism to avoid the counter activation in the multi-level market model:



Based on what is said, two different variants can be addressed for the multilevel:

Multilevel market1

Two separated market, 1) distribution-level and 2) for transmission-level market

Uncleared bids of distribution-level market can be forwarded to Transmission-level market

The price for interface flow is zero, or lower than the most expensive downward flexibility in distribution-level market

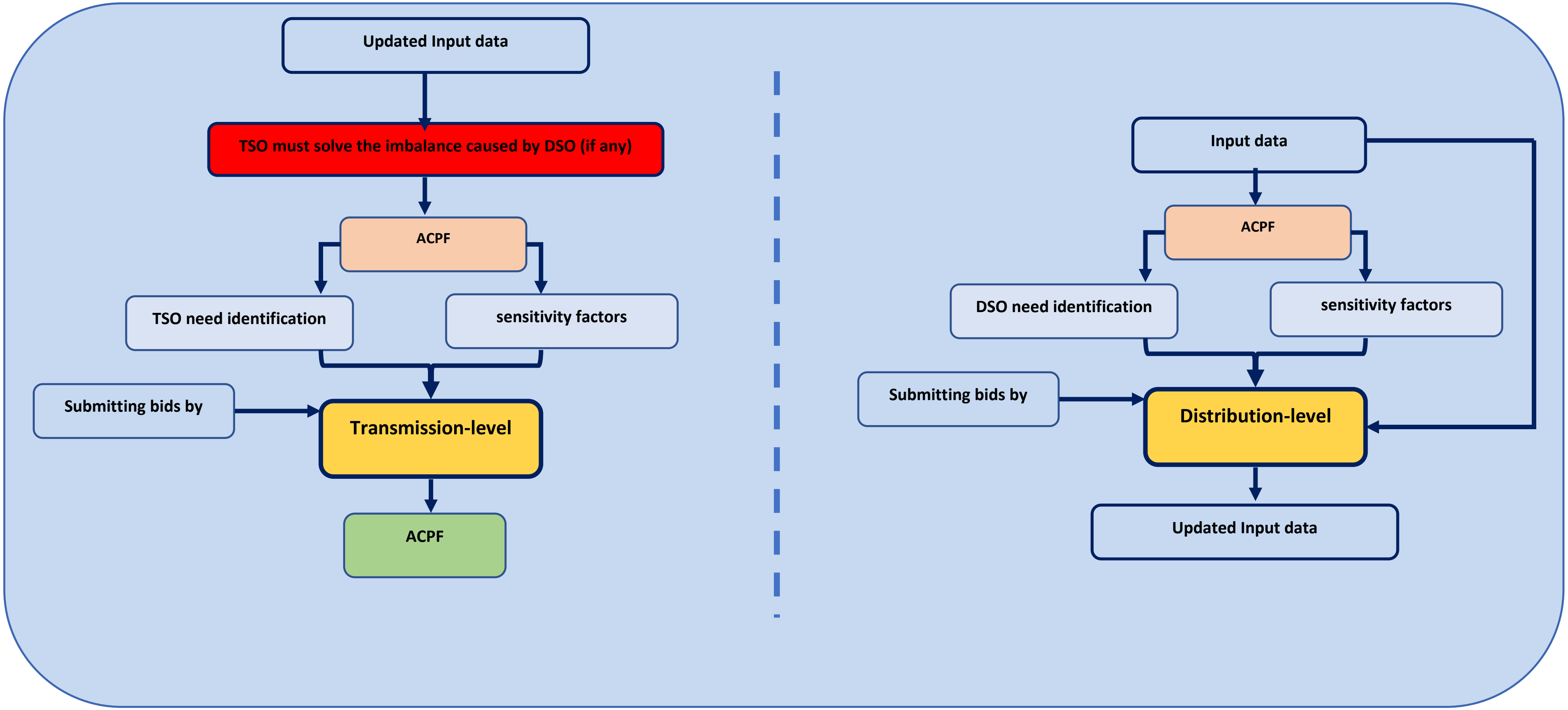
Multilevel market 2

Two separated market, 1) distribution-level and 2) for transmission-level market

Uncleared bids of distribution-level market can be forwarded to Transmission-level market

The interface flow higher is than the most expensive downward flexibility in distribution-level market

In the following there is the flowchart of the fragmented model:


Updated Input data
TSO must solve the imbalance caused by DSO (if any)
ACPF
TSO need identification
sensitivity factors
Submitting bids by
Transmission-level
ACPF
Input data
ACPF
DSO need identification
sensitivity factors
Submitting bids by
Distribution-level
Updated Input data

Having look at the flowchart, the load and generation profile are the output of the day-ahead market and is the input for the distribution-level congestion management market. Based on the input data, the ACPF is performed, and the congested areas are detected. Moreover, the sensitivity of each line with respect to each bus is calculated. Having this information along with the bids submitted by FSPs, the market is cleared. As soon as the result of the market optimization is received, the post evaluation is performed by running another ACPF. Once the distribution-level market is cleared, the updated load and generation profile will be sent for the usage of the transmission level market. Having the same procedure as the distribution-level market, and using the bids submitted from the transmission resources, the transmission-level market is cleared.

Distribution-level market

$min \sum_{h \in H} \left[\sum_{f \epsilon F^U} C^U_{f,h} p^U_{f,h} + \sum_{f \epsilon F^D} C^D_{f,h} p^D_{f,h} + VOLL(\alpha_{r,h}) \right]$ s.t.		(1)
$P^{DSO}_{r,h} + \sum_{f \epsilon F^U} PTDF_{f,r} p^U_{f,h} - \sum_{f \epsilon F^D} PTDF_{f,r} p^D_{f,h} - (\alpha_{r,h}) \leq 0$,	$\forall_r \in R^U, R^D, \forall_h \in H$	(2)
$\sum_{f \epsilon F^U} p^U_{f,h} - \sum_{f \epsilon F^D} p^D_{f,h} = 0$	$\forall_h \in H$	(3)
$P^{Umin}_{f,h} \leq p^U_{f,h} \leq P^{Umax}_{f,h}$	$\forall_f \in F^U, \forall_h \in H$	(4)
$P^{Dmin}_{f,h} \leq p^D_{f,h} \leq P^{Dmax}_{f,h}$,	$\forall_f \in F^D, \forall_h \in H$	(5)
$\alpha_{r,h} \geq 0$	$\forall_r \in R, \forall_h \in H$	(6)

Transmission-level market

$min \sum_{h \in H} \left[\sum_{f \epsilon F^U} C^U_{f,h} p^U_{f,h} + \sum_{f \epsilon F^D} C^D_{f,h} p^D_{f,h} + VOLL(\alpha_{r,h}) \right]$ s.t.		(1)
$P^{TSO}_{r,h} + \sum_{f \epsilon F^U} PTDF_{f,r} p^U_{f,h} - \sum_{f \epsilon F^D} PTDF_{f,r} p^D_{f,h} - (\alpha_{r,h}) \leq 0$,	$\forall_r \in R^U, R^D, \forall_h \in H$	(2)
$\sum_{f \epsilon F^U} p^U_{f,h} - \sum_{f \epsilon F^D} p^D_{f,h} = 0$	$\forall_h \in H$	(3)
$\sum_{f \epsilon F^D} p^D_{f,h,i} \leq \lvert T\_capacity_{h,i} \rvert$	$F^D \in F^{DSO,i}, i \in \{0,1\}, if\ T\_capacity_{h,i} \leq 0$	(4)
$P^{Umin}_{f,h} \leq p^U_{f,h} \leq P^{Umax}_{f,h}$	$\forall_f \in F^U, \forall_h \in H$	(5)
$P^{Dmin}_{f,h} \leq p^D_{f,h} \leq P^{Dmax}_{f,h}$,	$\forall_f \in F^D, \forall_h \in H$	(6)
$\alpha_{r,h} \geq 0$	$\forall_r \in R, \forall_h \in H$	(7)

Applying the same concept, as for the multilevel, here, two variant for the fragmented market can be introduced:

Fragmented market1

Two separated market, 1) distribution-level and 2) for transmission-level market

Uncleared bids of distribution-level market cannot be forwarded to Transmission-level market

The price for interface flow is zero, or lower than the most expensive downward flexibility in distribution-level market

Fragmented market2

Two separated market, 1) distribution-level and 2) for transmission-level market

Uncleared bids of distribution-level market cannot be forwarded to Transmission-level market

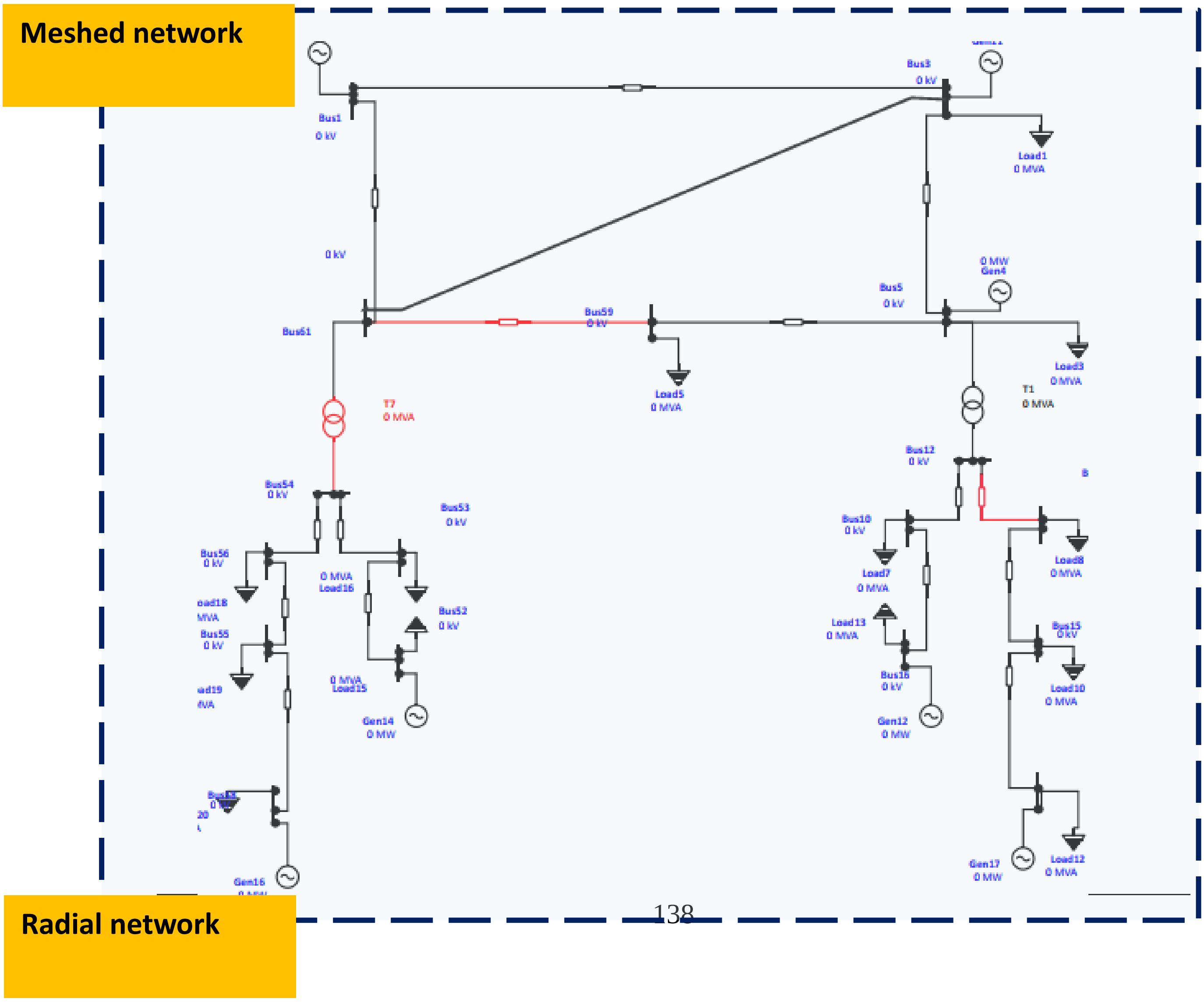
The interface flow higher is than the most expensive downward flexibility in distribution-level market

4.3 IMPLEMENTACIÓN

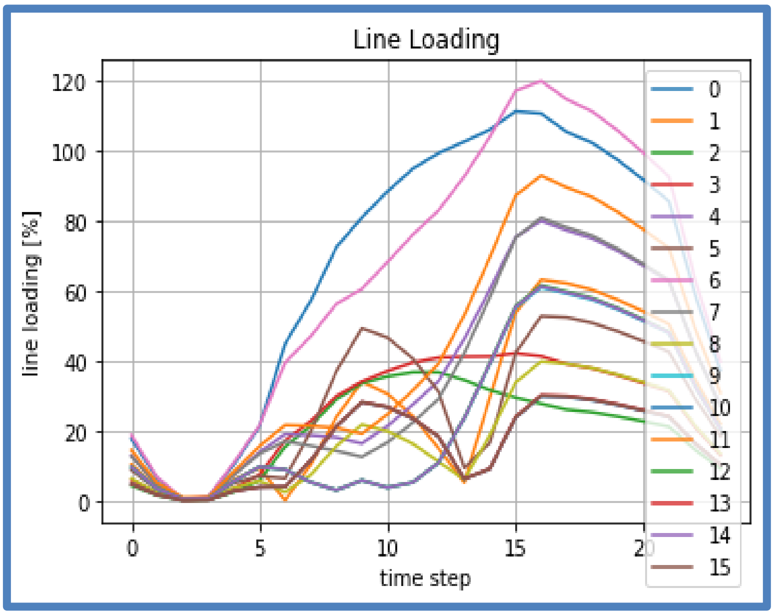
Having these modeling in mind, for analyzing the efficiency of the market models, it should be implemented in a certain case study.

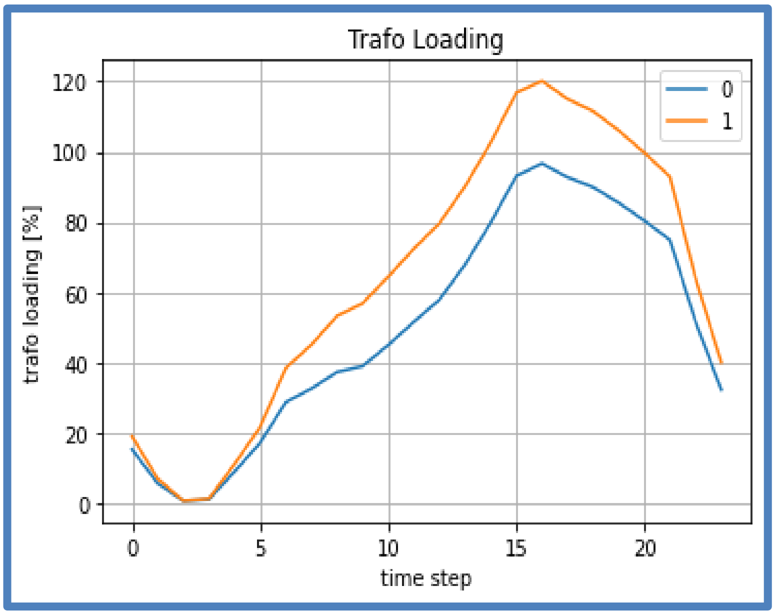
In the following the network is presented. This network contains a 5-bus meshed transmission network and two separated radial distribution lines.

There are 3 congestion highlighted in red:



Following graphs, shows the congestion of the line. Line 0 in transmission network, line 6 in distribution network, and transformer 1 is congested:





	Congested_Line	Time	Overload %	Flexibility_Need %	Flexibility_Need MVA	Flexibility_Need MW
0	0	13	102.392360	2.392360	9.530487	9.345411
1	0	14	105.766522	5.766522	22.972192	22.526088
2	0	15	111.005744	11.005744	43.843769	42.992353
3	0	16	110.403382	10.403382	41.444128	40.639311
4	0	17	105.141620	5.141620	20.482759	20.084997
5	0	18	102.042063	2.042063	8.135000	7.977024
6	6	14	103.728975	3.728975	0.645877	0.633335
7	6	15	116.835663	16.835663	2.916022	2.859395
8	6	16	119.654912	19.654912	3.404331	3.338221
9	6	17	114.456557	14.456557	2.503949	2.455324
10	6	18	110.972097	10.972097	1.900423	1.863518
11	6	19	105.466311	5.466311	0.946793	0.928407

	Congested_Trafo	Time	Overload %	Flexibility_Need %	Flexibility_Need MVA	Flexibility_Need MW
0	1	14	102.566587	2.566587	0.769976	0.755024
1	1	15	116.797065	16.797065	5.039119	4.941263
2	1	16	120.148856	20.148856	6.044657	5.927274
3	1	17	115.042517	15.042517	4.512755	4.425120
4	1	18	111.546547	11.546547	3.463964	3.396696
5	1	19	106.023224	6.023224	1.806967	1.771877

For testing the models on the case study, several scenarios should be implemented. In the following, there are some scenarios :

Scenario	Definition	Transmission FSP	Distribution FSP
Scenario 1	**High number of FSPs, All buses contain FSPs**	**5**	**12**
Scenario 2	**Medium number of FSPs, Some buses contain FSPs**	**4**	**6**
Scenario 3	**Low number of FSPs, A few buses contain FSPs**	**2**	**4**

	Variant 1*	Variant 2**	Variant 3*	Variant 4**
$p_{f,\mathrm{h}}^{U}, p_{f,\mathrm{h}}^{D}$	$p_{f,\mathrm{h}}^{U} > p_{f,\mathrm{h}}^{D}$	$p_{f,\mathrm{h}}^{U} > p_{f,\mathrm{h}}^{D}$	$p_{f,\mathrm{h}}^{U} > p_{f,\mathrm{h}}^{D}$	$p_{f,\mathrm{h}}^{U} > p_{f,\mathrm{h}}^{D}$
$p_{f.\mathrm{h}}^{TSO.U.D}, p_{f.\mathrm{h}}^{DSO.U.D}$	$p_{f.\mathrm{h}}^{TSO.U.D} > p_{f.\mathrm{h}}^{DSO.U.D}$	$p_{f.\mathrm{h}}^{TSO.U.D} < p_{f.\mathrm{h}}^{DSO.U.D}$	$p_{f.\mathrm{h}}^{TSO.U.D} > p_{f.\mathrm{h}}^{DSO.U.D}$	$p_{f.\mathrm{h}}^{TSO.U.D} < p_{f.\mathrm{h}}^{DSO.U.D}$
$p_{int,\mathrm{h}}^{U,D}$	$p_{int,\mathrm{h}}^{U,D}=0$	$p_{int,\mathrm{h}}^{U,D}=0$	$p_{int,\mathrm{h}}^{U,D}=p_{\mathrm{VC,h}}^{U,D}$	$p_{int,\mathrm{h}}^{U,D}=p_{\mathrm{VC,h}}^{U,D}$

General Assumptions:

Every single FSP can provide both downward and upward flexibility (equally)

The price and quantity of each FSP are constant for different hours.

There is no inter-temporal constraints

Upward price={200, 120} , Downward price={150,90}

Capítulo 5. ANÁLISIS DE RESULTADOS

Comparing the result of the first scenario, variant 1 for the three coordination schemes, following results are obtained:

Scenario 1 Variant 1	DSO procurement		TSO procurement		Whole system	
	Total Quantity	Total Price	Total Quantity	Total Price	Total Quantity	Total Price
Common Market	33,29	3995,28	500,00	75582,35	533,29	79577,63
Multilevel Market	33,29	3995,28	514,93	77412,34	548,23	81407,62
Fragmented Market	33,29	3995,28	471,72	81720,34	505,023	85715,62

Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. the DSO procurement cost is equal for all the market models. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs. In this case, since the interface flow is zero, the distribution network causes an imbalance in transmission network by violating the interface flow, and as the result the TSO should solve the imbalance and consequently undergoes an additional cost.

Comparing the result of the first scenario, variant 3 for the three coordination schemes, following results are obtained:

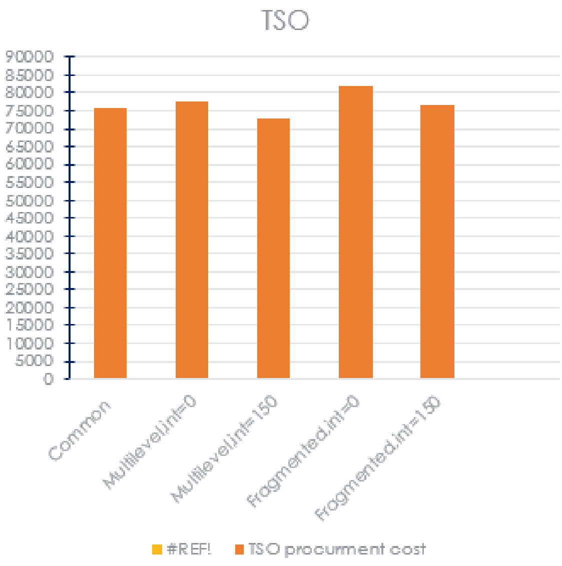
Scenario 1 Variant 3 Interface price	DSO procurement		TSO procurement		Whole system	
	Total Quantity	Total Cost	Total Quantity	Total Cost	Total Quantity	Total Cost
Common Market	33,29	3995,28	500,00	75582,35	533,29	79577,63
Multilevel Market	45,37	8264,76	495,53	72734,93	540,90	80999,69
Fragmented Market	45,37	8264,76	460,32	76844,08	505,69	85108,84

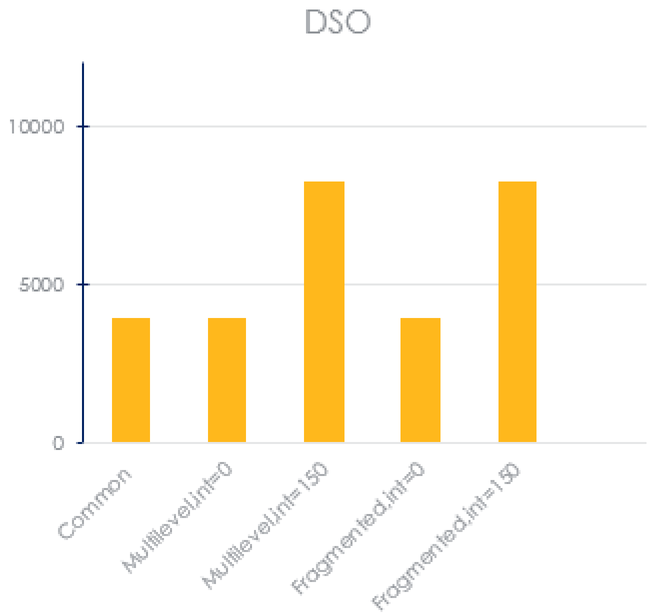
Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. The DSO procurement cost is equal for multilevel and fragmented and is higher for the common market. The reason why is that in multilevel and the fragmented market, DSO must pay penalty, as it caused an imbalance to the transmission network by violating the interface flow. On the other hand, the TSO will receive this penalty from the DSO, and even if it will be in charged of solving the imbalance, TSO will not undergo any additional cost. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs.

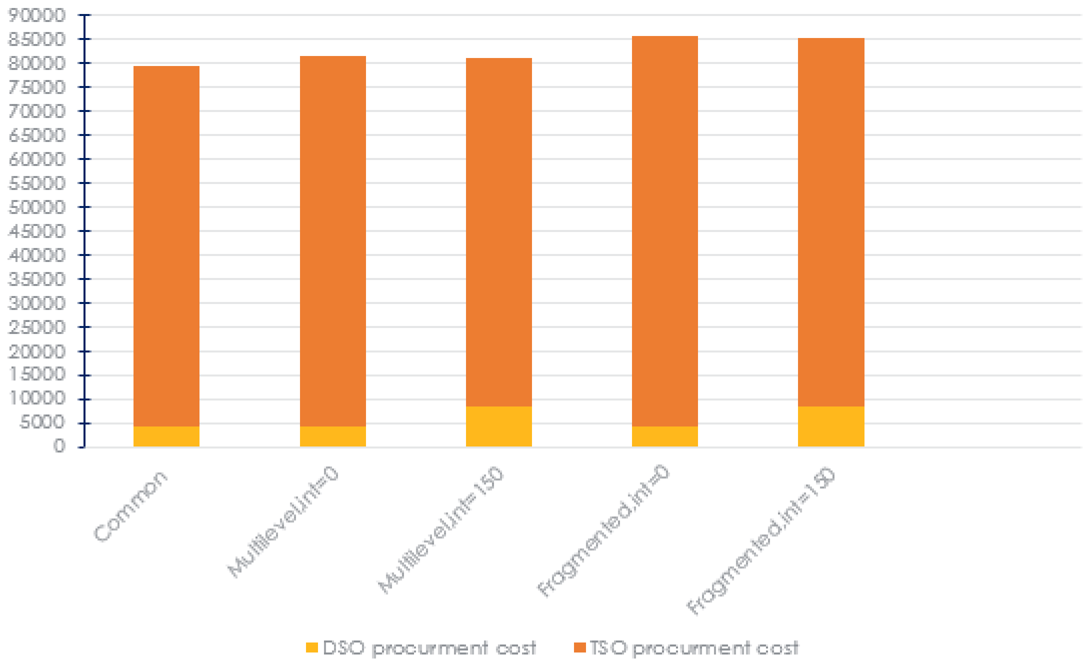
Having look at the following bar chart, it is clear that having the interface cost, cause a increment in the DSO cost in the multilevel and the fragmented market, as the DSO has to pay the cost of violating the interface.

Moreover, the TSO cost decreases, as the TSO receives the penalty from the DSO, and even if it solves the imbalance, its cost is already paid by DSO.

Looking at the following bar chart, it is obvious that the price for the common market is the least among all. Moreover, imposing the interface price does not change the total system price significantly for multilevel and fragmented market model.

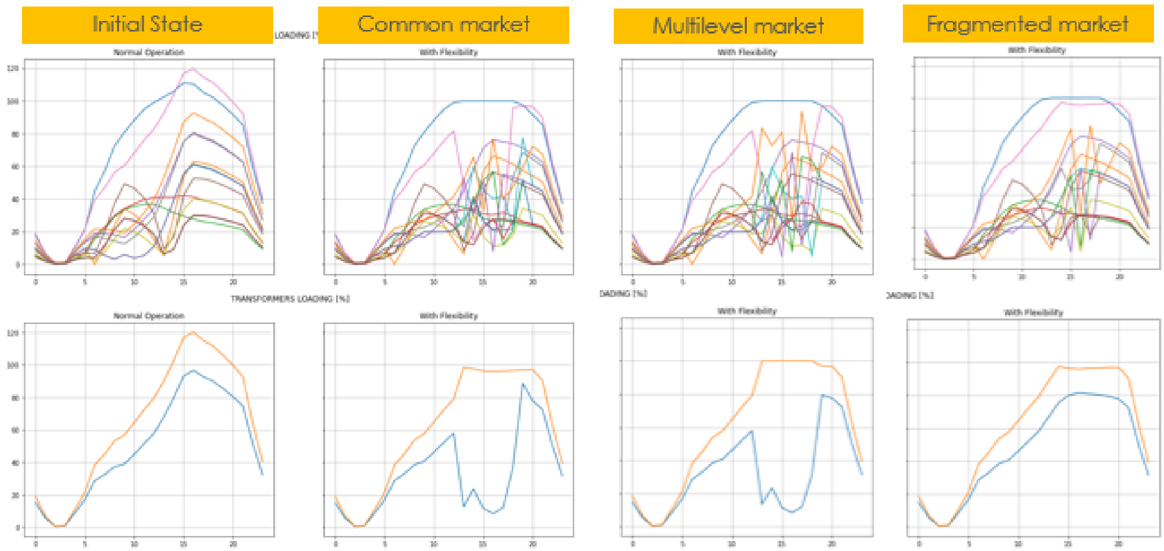






Comparing the line flow graphs after market clearing, it shows that all the coordination schemes are able to solve the congestion perfectly.

As we see for the common and multilevel market, the market procures a large amount of power from the distribution resources, and it causes a large decrement in the transformer loading. Moreover, since the scenario is associated to high number of FSPs, it procures energy from different FSPs (their price is lower).



Comparing the result of the first scenario, variant 3for the three coordination schemes, following results are obtained:

	Distribution network		Transmission network		Whole system	
	Total Quantity	Total Price	Total Quantity	Total Price	Total Quantity	Total Price
Common Market	33,29	3995,28	479,86	76517,54	513,15	80512,82
Multilevel Market	33,29	3995,28	499,32	77884,89	532,62	81880,17
Fragmented Market	33,29	3995,28	471,72	81720,34	505,023	85715,62

Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. the DSO procurement cost is equal for all the market models. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs. In this case, since the interface flow is zero, the distribution network causes an imbalance in transmission network by violating the interface flow, and as the result the TSO should solve the imbalance and consequently undergoes an additional cost.

Comparing the result of the first scenario, variant 3 for the three coordination schemes, following results are obtained:

	Distribution network		Transmission network		Whole system	
	Total Quantity	Total Price	Total Quantity	Total Price	Total Quantity	Total Price
Common Market	33,29	3995,28	479,86	76517,54	513,15	80512,82
Multilevel Market	45,37	8264,76	482,15	73704,06	527,52	81968,82
Fragmented Market	45,37	8264,76	460,32	76844,08	505,69	85108,84

Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. The DSO procurement cost is equal for multilevel and fragmented and is higher for the common market. The reason why is that in multilevel and the fragmented market, DSO must pay penalty, as it caused an imbalance to the transmission network by violating the interface flow. On the other hand, the TSO will receive this penalty from the DSO, and even if it will be in charged of solving the imbalance, TSO will not undergo any additional cost. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs.

Having look at the following bar chart, it is clear that having the interface cost, cause a increment in the DSO cost in the multilevel and the fragmented market, as the DSO has to pay the cost of violating the interface.

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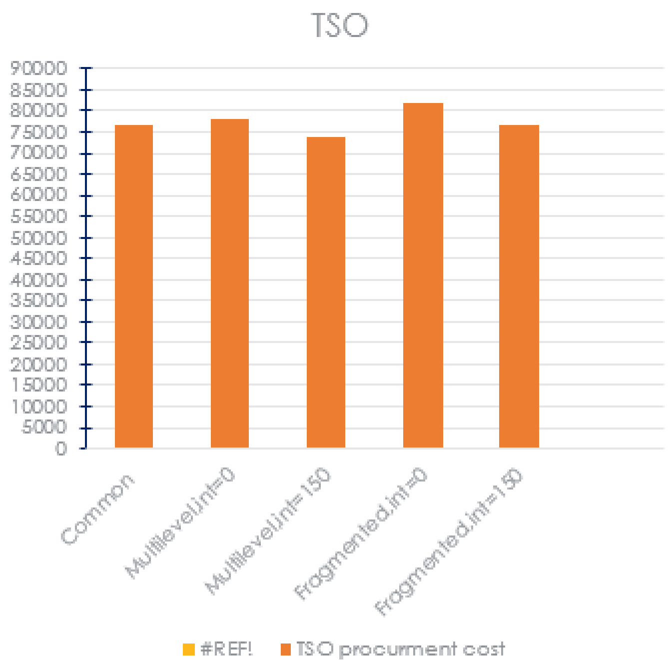
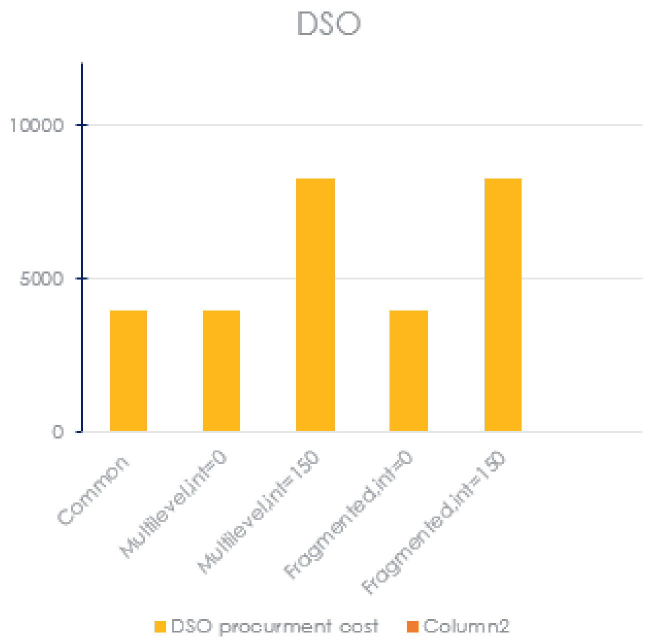
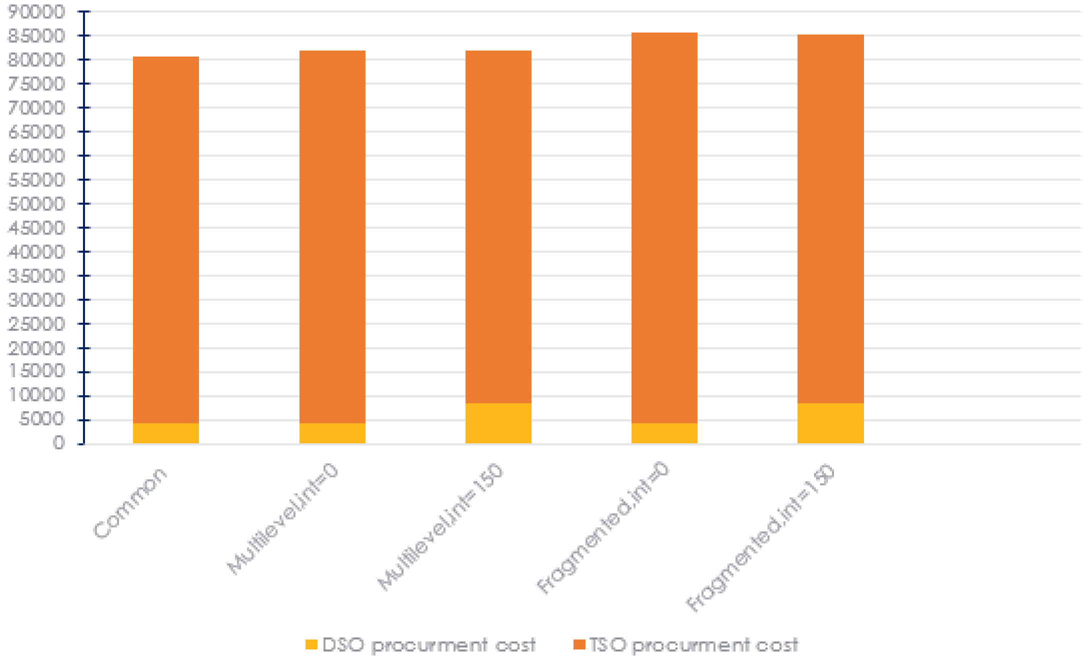


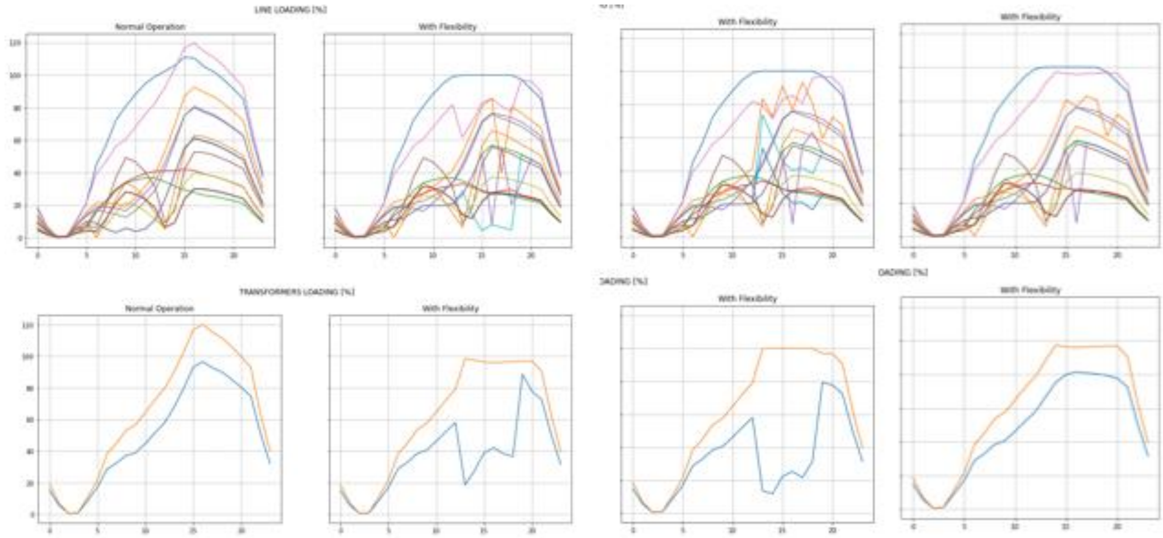


Looking at the following bar chart, it is obvious that the price for the common market is the least among all. Moreover, imposing the interface price does not change the total system price significantly for multilevel and fragmented market model.



Comparing the line flow graphs after market clearing, it shows that all the coordination schemes are able to solve the congestion perfectly.

As we see for the common and multilevel market, the market procures a large amount of power from the distribution resources, and it causes a large decrement in the transformer loading. Moreover, since the scenario is associated to high number of FSPs, it procures energy from different FSPs (their price is lower).



Comparing the result of the first scenario, variant 3for the three coordination schemes, following results are obtained:

	Distribution network		Transmission network		Whole system	
	Total Quantity	Total Price	Total Quantity	Total Price	Total Quantity	Total Price
Common Market	33,29	3995,28	408,4	112,609,73	441,69	116605,01
Multilevel Market	33,29	3995,28	448,15	100664,41	481,44	104659,69
Fragmented Market	33,29	3995,28	425,22	102630,36	458,52	106625,64

Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. the DSO procurement cost is equal for all the market models. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs. In this case, since the interface flow is zero, the distribution network causes an imbalance in transmission network by violating the interface flow, and as the result the TSO should solve the imbalance and consequently undergoes an additional cost.

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	Total Quantity	Total Price	Total Quantity	Total Price	Total Quantity	Total Price
Common Market	33,29	3995,28	408,4	112609,73	441,69	116605,01
Multilevel Market	45,37	8264,76	430,70	96071,43	476,07	104336,19
Fragmented Market	45,37	8264,76	413,59	97856,04	458,96	106120,80

Having look at the total cost, the common market has the lowest cost for flexibility procurement. However, the fragmented market is the one which procures the least quantity of flexibility. The reason why the common market procures higher flexibility services with the lower cost, is that in common market, the cheap distribution resources can be utilized. Since the sensitivity of the congested lines in transmission network with respect to FSPs in distribution network is lower than the one in the transmission network, the common market will procure more flexibility. The same concept can be applied for the multilevel market, as the transmission-level market can procure the uncleared forwarded bids of distribution-level market along with transmission level bids. The DSO procurement cost is equal for multilevel and fragmented and is higher for the common market. The reason why is that in multilevel and the fragmented market, DSO must pay penalty, as it caused an imbalance to the transmission network by violating the interface flow. On the other hand, the TSO will receive this penalty from the DSO, and even if it will be in charged of solving the imbalance, TSO will not undergo any additional cost. However, the TSO pay less in case of common market, as it procures flexibility from the distribution FSPs.

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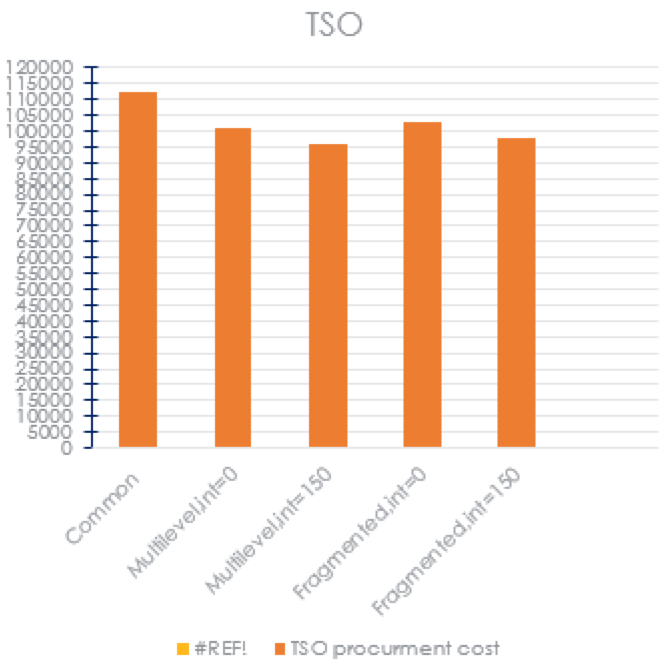
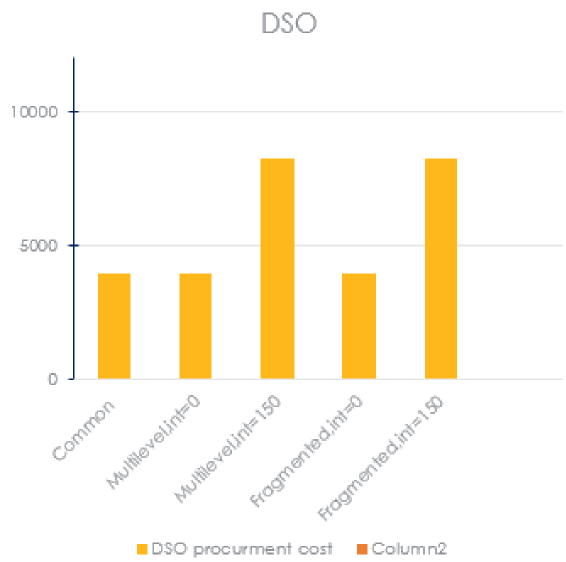
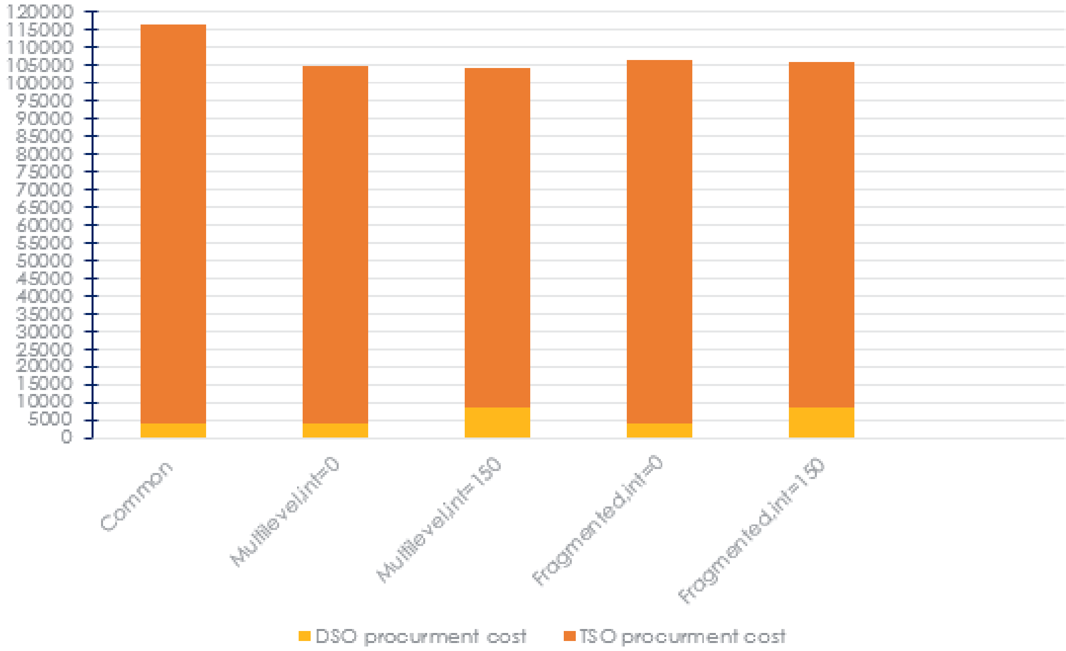




Looking at the following bar chart, it is obvious that the price for the common market is the least among all. Moreover, imposing the interface price does not change the total system price significantly for multilevel and fragmented market model.



Comparing the line flow graphs after market clearing, it shows that all the coordination schemes are able to solve the congestion perfectly.

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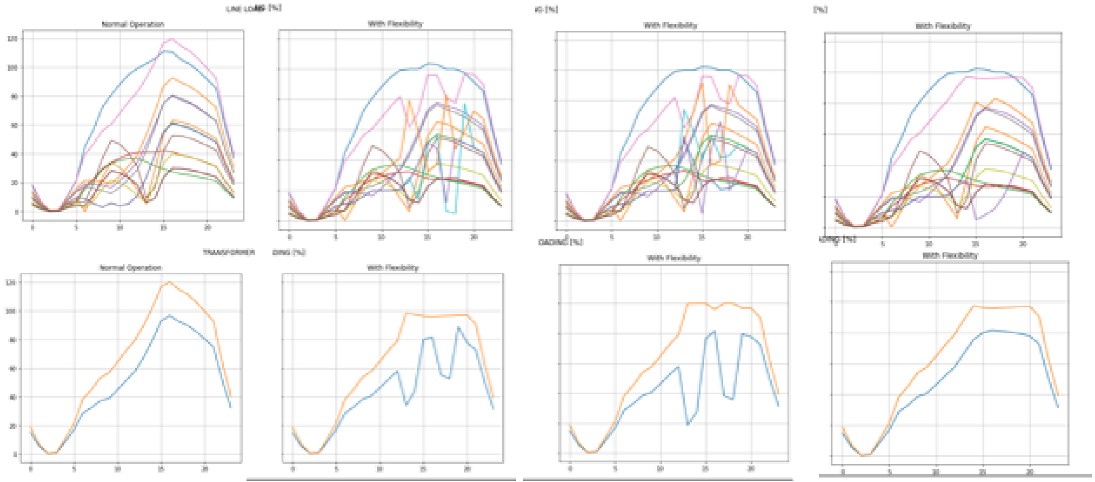


Congested line		Line 0
Hours	15	16
Non-supplied energy (MW)	13.174140	11.544050

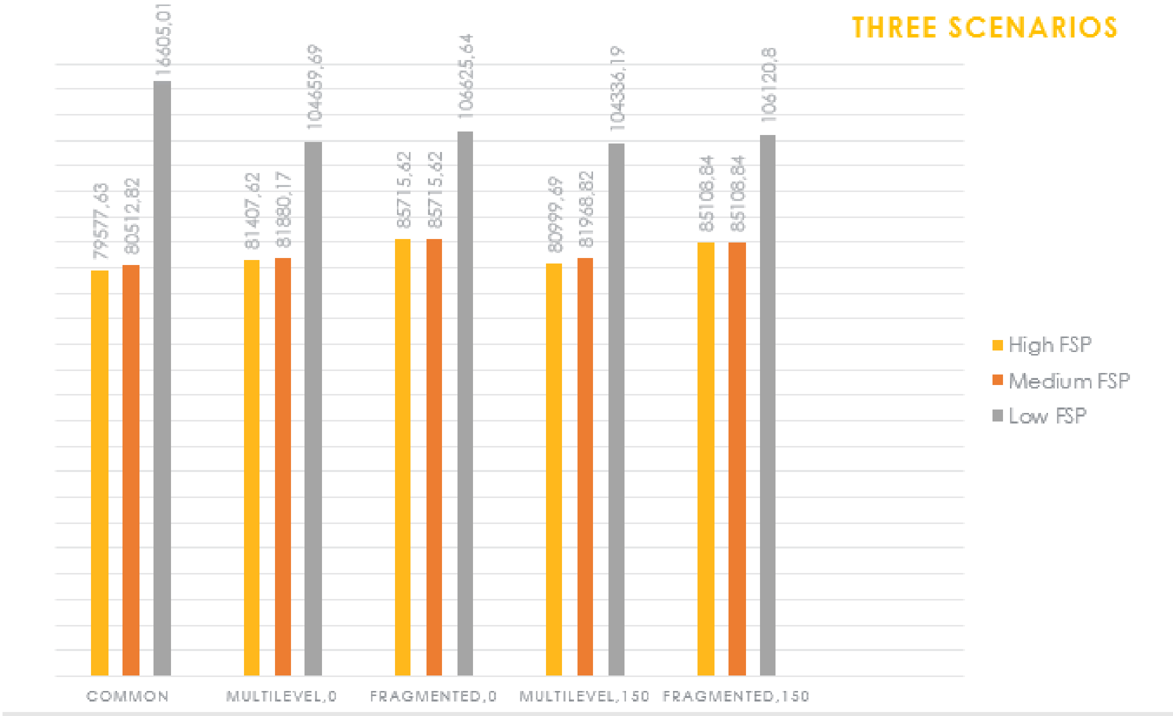
Congested line		Line 0
Hours	15	16
Non-supplied energy (MW)	8.336814	6.801575

Congested line		Line 0
Hours	15	16
Non-supplied energy (MW)	9.115007	6.801575

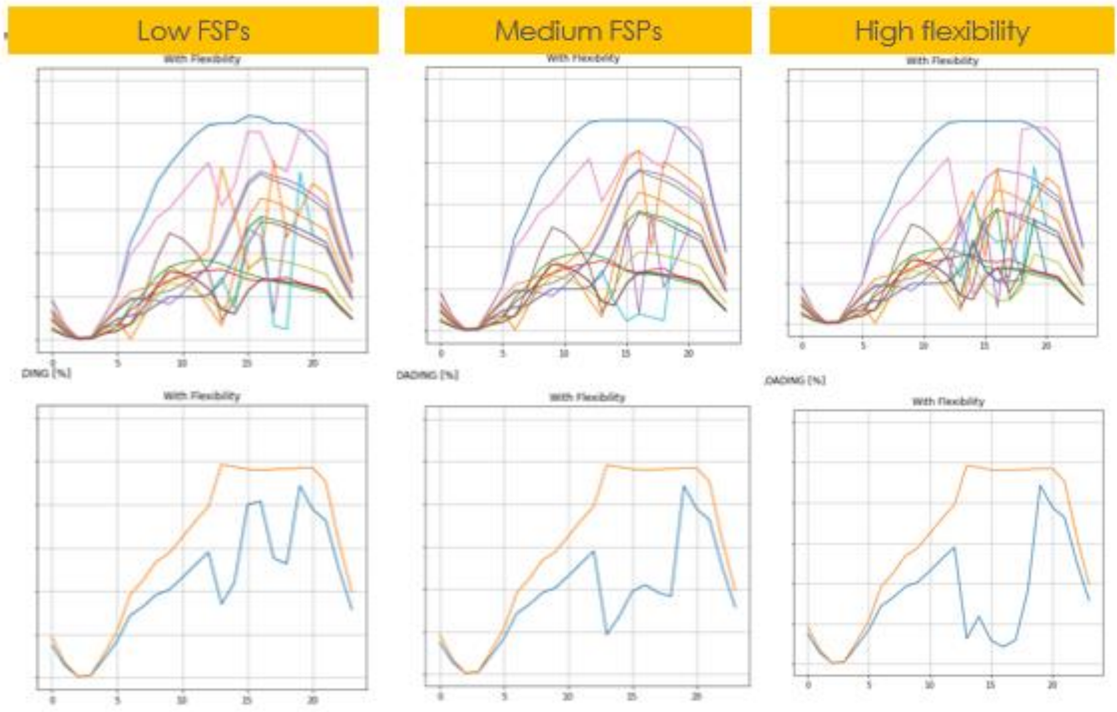
Here it shows that the common market has the largest non-supplied energy among all.

In this case, due to the location of the FSPs, and their capacity, as well as the price of the flexibility, and so case dependent.

In the following there is the comparison of each model in different scenario



As shown in the following graph, the load flow after common market clearing is depicted:


Low FSPs
Medium FSPs
High flexibility
With Flexibility

Capítulo 6. CONCLUSIONES Y TRABAJOS FUTUROS

Analyzing the results come from different scenarios, we are able to answer the research questions.

Having look at the results extracted from different defined scenarios; we can compare the market models from different aspects. From the point of view of the "Total procured flexibility quantity", in general, the fragmented market has the lowest procured amount, which does not imply that this market model is the most cost-efficeint one. The reason why that the fragmented market procures less energy, is that it must procure the flexibility from its own network from the resources near to the congested area. As an illustration, in transmission-level market of the multilevel market, the market operator can procure the flexibility from the far distribution resources, and since the sensitivity of the congested area in transmission network is not significant with respect to the distribution network bus, the procured flexibility will be more costly. So, in general, the multilevel market has the highest flexibility procurement. From the point of view of "Total procured flexibility cost", in almost all scenarios the total cost for the common market is lower among all other variants. The common market is the cheapest, as it only operates one single market clearing. In the common market model, the market have access to all the resources of the network, and the liquidity and the competition is higher, and this cause to have a lower clearing price for the resources. Moreover, since there is only one market, there is no other market to impose the imbalance. In the second ranking of the most efficient market model, the Multilevel market can be placed. Specifically, in scenarios at which the DERs are cheaper than the transmission resources, the multilevel is cheaper than the fragmented. However, in general, the price for multilevel is equal or cheaper than fragmented.

Having the price imposed for the interface, makes the distribution-level market to make a trade off the price of its own downward bids and the interface price. If the price of the interface is lower than the downward flexibility of distribution-level market, the DSO tends to impose the imbalance in transmission network, and TSO by procuring downward flexibility should solve the problem. However, when the interface price is higher than downward flexibility bids of the distribution-level market, the DSO decides on procuring the downward flexibility from its own grid to balance its network. Having the second case, guarantee a better cost sharing between system operators.

Having defined three scenarios, with high, medium, low FSPs, one can conclude that having high number of FSPs can guarantee of supplying all the congested areas. However, the management and activation of these resources should be in a way to avoid any sharp change in the line flow. So, defining the inter-temporal constraints, having the FSPs with different price can help to mitigate these issues. Moreover, in reality, having high number of FSPs increase the liquidity and competition and the price will be lower. Also, it should be noted that the high FSPs sometimes can cause to have a reverse power flow, which should be taken into consideration.

Having low number of FSPs, not only decrease the liquidity and the competition in the market, but also it may cause to failure in solving the congestion. Having low number of FSPs can cause to have a higher price in the market, and since there is a lack of available power, some congestion areas may be unsupplied.

So, regarding these conclusions, the possibility of reverse power flow should be studied. Moreover, the loss of the system in the market should be considered in a way to avoid any mismatch between the procured flexibility, and the congested point need. On the other hand, the meshed distribution network using reconfiguration should be studied. Furthermore, the down-limit of the transformer should be investigated. Finally, the inter-temporal constraints should be considered. And the constraints of having storage as the FSP should be noted.

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