ATTEST

Ref. Ares(2020)5974966 - 27/10/2020

WP2

Toolbox specification, support tools and test cases

TSO/DSO coordination mechanisms

D2.4

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 864298.

DOCUMENT CONTROL PAGE

DOCUMENT	D2.4 – TSO/DSO coordination mechanisms
TYPE	Report
DISTRIBUTION LEVEL	Public
DUE DELIVERY DATE	31 / 10 / 2020
DATE OF DELIVERY	26 / 10 / 2020
VERSION	V1.0
DELIVERABLE RESPONSIBLE	ICENT
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DOCUMENT HISTORY

VERSION	AUTHORS	DATE	CHANGES
0.1	Mirna Grzanic ICENT	07 / 07 / 2020	First draft with state-of-the-art review
0.5	Mirna Grzanic, Tomislav Capuder ICENT	02 / 10 / 2020	Final choice of the TSO/DSO coordination scheme for ATTEST
0.9	Mirna Grzanic ICENT	20 / 10 / 2020	Version after reviewers' comments
1.0	André Madureira INESC TEC	26 / 10 / 2020	Final version

Executive Summary

The transition towards green power system puts the focus on improving energy efficiency, higher integration of Renewable Energy Sources (RES) and reduction of CO_2 emissions. In order to ensure secure and efficient system operation, the Transmission System Operator (TSO) faces big challenges due to broader penetration of renewable energy resources with intermittent production. As the required level for flexibility in the system increases, European directives emphasize the importance of providing flexibility from the final consumers and the Distributed Generation (DG). The role of the Distribution System Operator (DSO) in the traditional power system was limited to ensuring reliable and efficient energy supply while safely operating the DG which used to be oversized to remain in stable operation even in the most critical and rare situations. Nowadays, this paradigm is changing and the role of the DSO is expanding: active management and control of DG in the real-time using Distributed Energy Resources (DER) to solve local congestion and voltage problems but also providing flexibility to the system as a whole. To establish an effective market environment for ancillary service procurement from both DSO and TSO, close coordination between system operators is necessary. It is important to ensure that the ancillary service activation from one system operator is not a counteract to the other system operator's need.

The deliverable focused on 5 different TSO/DSO coordination mechanisms in ancillary services procurement and compared them with other proposed coordination schemes in European projects. In Centralized ancillary services market model, the TSO is the only buyer of ancillary services provided from DERs, while the DSO cannot use DER to solve local problems. In Local ancillary services market model, both the DSO and the TSO can use resources connected to DG, while the priority is given to the DSO. The offers not selected in the local market are aggregated and submitted to the global market operated by the TSO. In the Shared balancing responsibility market model each system operator is responsible for their network operation and balancing. Common TSO-DSO ancillary service market model minimizes the total cost of ancillary service procurement due to close collaboration between system operators with one common goal, while the cost is shared between the TSO and the DSO. Integrated flexibility market model opens the door for the market participation to both regulated and deregulated market entities. To ensure market neutrality, independent market operator is required.

Based on detail evaluation of coordination schemes, the hybrid model between Centralized, Local and Shared balancing responsibility market model is chosen and called ATTEST TSO / DSO coordination approach. The TSO has the priority in ancillary service reservation, but unlike in the Centralized ancillary services market model, the DSO can procure ancillary services to solve local problems. Moreover, the DSO is responsible to ensure that reserved capacity of ancillary services in day-ahead (DA) market provided by DER is delivered to the TSO in the real-time (RT).

In ATTEST TSO / DSO coordination approach, DSO shares local flexibility with the TSO. This approach is non-optimal cost-wise for the DSO because the DSO needs to meet operation constraints in DG and also an agreed ancillary service schedule with the TSO. The extra cost incurred by the DSO should be remunerated to some extent by the TSO.

In ATTEST TSO / DSO coordination approach DG constraints are considered in the market clearing, which ensures secure and efficient DG operation in the RT.

ATTEST TSO / DSO coordination approach determines a schedule of ancillary service of each TSO-DSO connection point or local area considering network constraints. The communication and coordination are very precise, but on the other hand, hard to calculate due to challenges in sharing data in a short timeframe, especially in the case with multiple local DSOs.

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Abbreviations and Acronyms

ACRONYM / ABBREVIATION	Extensive form
AB	Advisory Board
AC OPF	Alternating Current Optimal Power Flow
AC SCOPF	Alternating Current Security Constrained Optimal Power Flow
CA	Consortium Agreement
CAPEX	Capital Expenditures
CMP	Commercial Market Player
D	Deliverable
DER	Distributed Energy Resources
DG	Distribution Grid
DSO	Distribution System Operator
EC	European Commission
EU	European Union
EV	Electric Vehicles
FCR	Frequency Containment Reserve
FRR	Frequency Restoration Reserve
FSP	Flexibility Service Provider
GA	Grant Agreement
GCT	Gate Closure Time
HV	High Voltage
HVRS	High Voltage Regulation System
ICT	Information and Communication Technologies
IMO	Independent MO
IP	Intellectual Property
KPI	Key Performance Indicator
LV	Low Voltage
mFRR	Reserve with manual activation
MO	Market Operator
MV	Medium Voltage
MVRS	Medium Voltage Regulation System
MS	Milestone
OLTC	On-Load Tap Changing
OPEX	Operational Expenditures
P	Active power
PC	Project Coordinator
Q	Reactive power
RR	Replacement Reserve
RT	Real-time
SC	Steering Committee
TG	Transmission Grid
TSO	Transmission System Operator
WP	Work Package

1. Introduction

European Union has set ambitious goals in green energy transition. According to amendment to the proposed European Climate Law [1], Europe set an ambitious goal to reduce greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels. Moreover, it is expected to improve energy efficiency for at least 32.5% and to increase production from renewable energy sources in total electricity consumption for at least 32.5%. These goals will bring environmental and health benefits, increase the security of the energy supply, reduce the dependence on energy import and ensure affordable energy for all consumers [2].

Rapid demand growth due to transportation electrification, cooling and heating will result in an increased need for installed capacity. In line with this, it is detrimental to keep increasing the penetration of renewable energy sources and achieve the transition towards clean, sustainable, and competitive energy system. However, due to intermittent nature and variable decentralized production of wind and solar power plants, the power output can greatly fluctuate and therefore exceed or fall behind the demand. This can result in power quality problems, such as frequency disorder, voltage/current harmonics, low power factor, voltage variation or even failure of the grid. High power quality is necessary for achieving stability and high efficiency of the network and ensuring secure and reliable energy supply.

To avoid the identified problems and fully exploit the potential of renewable energy sources, the transition towards smart energy systems is necessary. From both technical and economic perspective, these ambitious goals should be accomplished in a cost-effective way that does not violate power system limits and constraints but keeps the voltage and frequency within limits while satisfying each consumer’s need. To achieve that, significant changes in the current system operation are required in terms of policy changing, low-carbon technologies implementation, data collection and management and communication protocols. Moreover, implementation of different approaches in both transmission grid (TG) and distribution grid (DG) management will be achieved through development of various tools for long-term and day-ahead planning, real-time operation and control together with asset management tools considering energy consumption and generation profiles, ancillary services schedules, smart grid technology, such as on-load tap changing (OLTC) transformers, energy storage devices, controllable distributed generation, flexible loads and electric vehicles. Tools should be defined in detail and based on common standard data interchange protocols to be implemented in a wider toolset in any future system operator’s network management platforms.

Unlike the fit-and-forget approach earlier used in DG planning, which was based on testing all future scenarios and upgrading the network to accommodate the worst-case scenario, active DG management is focused on real-time operation and control. In order to support the increasing demand and renewable energy sources penetration, instead of network reinforcement, the focus should be placed on installation of modern grid technologies, such as battery storage and smart measurement appliances, along with real-time dynamic pricing and provision of ancillary services from a wide range of demand response programs.

Furthermore, establishing a complete coordination between Transmission and Distribution System Operators (TSOs and DSOs) is essential. Distributed generators, energy storage and electric vehicles, all connected to the distribution level, can provide multiple services not only for DG, but also for the entire system. A wide set of tools for network planning and operation with asset management tools incorporated together in a toolbox for Transmission System operator/ Distribution System Operator (TSO/DSO) coordination in an advanced Information and Communication Technologies (ICT) platform will ensure a better use of TG and DG and their capacities. The goal is to satisfy an increase in energy consumption with an optimal deployment of flexibility resources resulting in reduced network investments due to new grid technologies integration.

Besides, optimized TSO/DSO coordination will have a great impact on ancillary service procurement in the market. Distributed resources can provide ancillary services to both the TG and the DG. DSO will exploit DER for local services, while TSO in coordination with DSO will exploit DER for local and cross-border level services.

The activation of ancillary services will be coordinated to avoid technical problems in the grid and to keep the voltage and frequency between the limits in real-time operation. The procurement of conflicting ancillary services in the market will be disabled, i.e. TSO and DSO cannot buy flexibility services in the opposite direction in the same network region. Congestion management should also be performed in coordination between TSO and DSO.

Some of the tools strongly dependent on TSO/DSO coordination which will be developed within ATTEST project are:

1. tool for ancillary services procurement in the day-ahead operation planning stage of the TG through which the TSO procures ancillary services for frequency control, voltage control and congestion management in the day-ahead ancillary services market coordinated with the tool for ancillary services procurement in the day-ahead operation planning of the DG;
2. tool for ancillary services activation in during real-time operation of the TG through which the TSO optimizes the activation of flexibility, provided by both TSO assets and ancillary services procured by the TSO in the day-ahead markets coordinated with the tool for ancillary services activation in real-time operation of the DG;
3. optimization tool for planning the TSO/DSO shared technologies, which will place and size smart grid technologies that will be used for provision of flexibility services at both the transmission and the distribution level, but also for providing a non-asset alternative to transformer, line or cable reinforcement.

Conversely, the increasing number of new devices capable of providing flexibility services, such as electric vehicles (EVs), energy storage, household appliances, distributed generators with real-time monitoring, measurement and control will result in digitalization of the energy sector. The ICT platform developed within the ATTEST project will connect the TSO and DSO databases, including traditional datasets, but also new digitalized data coming from the smart household appliances, weather measurements and predictions, etc. Moreover, the ICT platform will bring together all the tools developed within the project ensuring an efficient TSO/DSO coordination and also enabling access to information from both the distribution and the TG, which will lead to the expected 3% of overall Capital Expenditures (CAPEX) savings and 2% of overall Operational Expenditures (OPEX) savings. Both CAPEX and OPEX savings will be achieved through better network investments planning due to the TSO's access to aggregated flexibility providers connected to the distribution level, which will enable increased efficiency and avoidance of potential network problems. The ICT platform will be composed of the joint TSO/DSO database, the open source toolbox and the TSO/DSO visualization tools.

Finally, the coordination mechanisms will lead to innovative market structures, rules and codes extending the roles of both the TSO and the DSO. From the DSO's perspective, the coordination mechanisms will enable it to participate in the technical validation and procurement of ancillary services traded in the electricity markets. From the TSO's perspective, the coordination mechanisms will enable procurement of ancillary services provided by the smart grid technologies located in both TG and DG s. Additionally, the coordination between the TSO and the DSO will lead to more cost-efficient, reliable, and secure system planning and operation with optimal utilization of resources from both the transmission and the distribution level.

2. Ancillary service

According to [3], ancillary service is a service necessary for the operation of a transmission or distribution system, including balancing and non-frequency ancillary services, but not including congestion management.

Some example applications of non-frequency ancillary service used by TSOs or DSOs include: steady-state voltage control, fast reactive current injections, inertia for local grid stability, short-circuit current, black start capability and island operation capability.

Some ancillary services could be mandatory, whereas others may be procured in the market, or be the result of bilateral trading and tendering. The specific mechanisms used to procure ancillary service, as well as the types of ancillary services available, varies in different countries. The mandatory provision of ancillary services is usually not financially remunerated or payed by the regulated price, e.g., it may be a requirement for the flexible resource to be connected to the grid. Market structures include bilateral contracting and auctions. In typical bilateral contracting, the TSO agrees with the ancillary service providers the quantity and the price for a specific service. Bilateral contracts are long-term. Tendering includes long-duration services, while market trading is used for short-term trading and less standardized products. Tendering and spot markets usually provide the most transparent and fair pricing.

Traditionally, ancillary services used to be procured only from large centralized power plants. Nowadays, the high integration of flexibility resources connected to the DG, the rules and the concept of ancillary services market are strong drivers to allow the new participants to trade ancillary services. However, this is not an easy task, and proper coordination between the TSO and DSOs is required in order to operate both the TG and DG in a secure and efficient way, as well as to avoid violation of DG constraints when procuring the services at distribution level for the TSO network management. There are two main market structure organizations reflecting the coordination between the TSO and the DSO: centralized and decentralized. In the centralized market structure, all flexibility providers offer their service on a single central market, while in the decentralized market structure both local markets and the central market coordinate in ancillary service provision.

Ancillary services markets are divided into reserve and activation markets. In the reserve markets, system operator purchases reserve in advance in order to ensure enough capacity for balancing purposes. In the reserve markets, offers are flexibility availabilities (e.g., a capacity of 1 MW for upward or downward flexibility). Once the capacity to provide ancillary services is procured in the reserve market, the ancillary services can be activated when needed in real time in the activation markets. In activation markets offers are flexibility energy offers. As mentioned, reserve is divided in upward or downward flexibility. An upward flexibility is an increase of power injection in the system resulting from reduced demand or increased generation. A downward flexibility is a decrease of power injection resulting from decreased production or increased consumption.

Some ancillary service markets are coupled geographically, grouping more national markets together. Alternatively, ancillary service markets can be coupled and co-optimized with energy markets or ancillary service markets for different type of service can be coupled together. In order to provide ancillary services in real-time from the flexible resources connected to both transmission and distribution level, a novel market structure with the definition of essential parameters is necessary.

One of the key parameters is timing which consider the time horizon of the market, the time granularity, the gate closure time (GCT), market clearing frequency, maximum full activation time and maximum clearing duration shown in Figure 1 and explained in detail for ancillary service market.

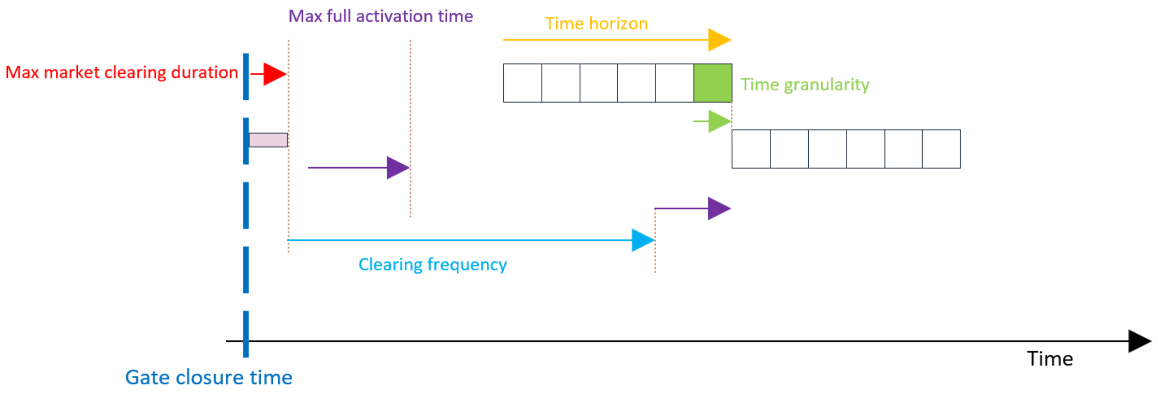

FIGURE 1 – TIMING PARAMETERS

The time horizon of the market (also called delivery window) represents the time period for which offers are made. A long-time horizon is essential for flexibility service providers (FSP) in order to internalize their flexibility constraints in the market. The time granularity represents a fraction of the time horizon, which allows to have detailed information (market bids, needs, etc.) for each time step of the market time horizon (e.g., 1 hour or 15 minutes). The GCT represents the latest time limit for market participants to submit their offers/needs. In ancillary service markets it is important for GCT to be close to real-time because the forecast is more precise shorting the time horizon. More frequent market clearing, which determines how often the market is cleared, allows the forecast improvement. For some AS products, a max full activation time can be specified (i.e., the time required to answer to a dispatch order plus the time required to ramp up/down to the required power level). Typically, a maximum time (maximum market clearing duration) is allowed to the algorithm to clear the market.

Ancillary service market models can consider grid constraints or not in the market clearing process. If the network is strong enough, considering network constraints is not necessary. However, the increasing number of distributed flexibility resources and renewable energy sources will require to consider network constraints as the network is being operated closer to its limits. Several approaches if considering network constraints can be used: full AC power flow, approximated power flow, relaxed power flow which are suitable for different types of network regarding the topology and network characteristics. If the grid model is included in the market clearing algorithm, the bids for flexibility offers submitted it the market must be location specific.

2.1. Frequency control

The main ancillary services used for frequency restoration are [4]:

- Frequency Containment Reserves (FCRs)/Primary Frequency Control: FCR is the first control action to be activated to mitigate rapid frequency drop or rise, usually within a couple of seconds and fully deployed within 30 s, in a decentralized fashion over the synchronous area.
- Frequency Restoration Reserves (FRRs)/Secondary Frequency Control: FRR is the centralized automated control, activated from the TSO in the time interval between 30 s and 15 min from the imbalance occurrence to correct steady-state frequency variations

and flows (e.g., in tie-lines). FRR can be distinguished in reserves with automatic activation (automatic Frequency Restoration Reserves—aFRR) and reserves with manual activation (manual Frequency Restoration Reserves—mFRR).

- Replacement Reserves (RRs)/Tertiary Frequency Control: RR is a manual control meant to restore or improve the security and economy of the system. Typical activation time for RRs is from 15 min after the imbalance occurrence (in Continental Europe) up to hours after.

Minimum bid sizes and procurement entities for providing frequency reserve in European countries are listed in Table 1.

TABLE 1 – FREQUENCY RESERVE IN EUROPEAN COUNTRIES [5]

Country	FCR	aFRR	mFRR	RR
Austria	Generators/Load/Pump Storage/Batteries ≤ 1 MW	1 MW < Generators/Load/Pump Storage ≤ 5 MW	Generators/Load/Pump Storage ≤ 1 MW	No
Belgium	Generators/Load/Pump Storage ≤ 1 MW	Generators/Load/Pump Storage ≤ 1 MW	Generators/Load/Pump Storage ≤ 1 MW	No
Bosnia and Herzegovina	Generators only (no minimum)	1 MW < Generators only ≤ 5 MW	5 MW < Generators/Load ≤ 10 MW	No
Croatia	Generators only (mandatory, no minimum)	Generators only ≤ 1 MW	Generators/Pump Storage / Load	No
Czechia	1 MW < Generators only ≤ 5 MW	1 MW < Generators/Load ≤ 5 MW	1 MW < Generators/Load/Pump Storage ≤5 MW	No
Denmark	Generators/Load/Batteries ≤ 1 MW	1 MW < Generators/Load ≤ 5 MW	5 MW < Generators/Load ≤ 10 MW	No
Estonia	-	No	-	-
Finland	Generators/Load/Batteries ≤ 1 MW	1 MW < Generators only ≤ 5 MW	1 MW < Generators/Load ≤ 5 MW	No
France	Generators/Load/Pump Storage/Batteries ≤ 1 MW	Generators/Pump Storage ≤ 1 MW	5 MW < Generators/Load/Pump Storage ≤ 10 MW	5 MW < Generators/Load/Pump Storage ≤ 10 MW
Germany	MW < Generators/Load/Pump, Storage/Batteries ≤ 1 MW	1 MW <Generators/Load/Pump Storage ≤ 5 MW (90 s < t ≤ 5 min)	1 MW <Generators/Load/Pump Storage ≤ 5 MW (5 min < t ≤ 15 min)	No
Great Britain	Generators/Load/Pump Storage/Batteries ≤ 5 MW	No	5 MW < Generators/Load/Pump, Storage/Batteries ≤ 10 MW	1 MW < Generators/Load/Pump, Storage ≤ 5 MW
Greece	Generators only ≤ 1 MW	Generators only ≤ 1 MW	Generators only	No
Hungary	Generators only ≤ 1 MW	Generators only ≤ 1 MW	No	Generators/Load ≤ 1 MW
Ireland	1 MW < Generators/Load/Pump, Storage/Batteries ≤ 5 MW	No	Generators/Load/Pump Storage ≤ 1 MW	No
Italy	no minimum	-	No	-
Latvia	-	No	Generators only ≤ 1 MW	No
Lithuania	-	No	Generators/Pump Storage (no minimum)	Generators/Load/Pump Storage ≤ 1 MW

Netherlands	1 MW < Generators/Load/Batteries ≤ 5 MW	1 MW < Generators/Load/Batteries ≤5 MW (t ≤ 90 s)	5 MW < Generators/Load ≤ 10 MW	No
Norway	Generators only ≤ 1 MW	5 MW < Generators only 10 MW	Generators/Load ≤ 1 MW	No
Poland	Generators only ≤ 1 MW	Generators only ≤ 1 MW	No	-
Portugal	Generators only (no minimum)	Generators only > 10 MW (90 s < t ≤5 min)	> 10 MW	≤ 1 MW
Romania	1 MW < Generators only ≤ 5 MW	Generators only > 10 MW	1 MW < Generators only ≤ 5 MW	1 MW < Generators only ≤5 MW
Serbia	1 MW < Generators only ≤ 5 MW	Generators only ≤ 1 MW	Generators/Pump Storage ≤ 1 MW	No
Slovakia	Generators only ≤ 1 MW	1 MW < Generators only ≤ 5 MW	1 MW < Generators/Load/Pump Storage ≤ 5 MW	No
Slovenia	Generators only (no minimum)	Generators/Pump Storage ≤ 1 MW (5 min < t ≤ 15 min)	Generators/Load/Pump Storage ≤ 1 MW (5 min < t ≤ 15 min)	No
Spain	Generators only (no minimum)	Generators only > 10 MW (90 s < t ≤5 min)	Generators/Pump storage > 10 MW (5 min < t ≤ 15 min)	Generators/Pump Storage > 10 MW (20 min < t ≤1 h)
Sweden	Generators only ≤ 1 MW	1 MW < Generators only ≤ 5 MW	5 MW < Generators/Load ≤ 10 MW	No
Switzerland	Generators/Load/Pump Storage/Batteries ≤ 1 MW	1 MW < Generators/Load/Pump, Storage/Batteries ≤ 5 MW	1 MW < Generators/Load/Pump, Storage/Batteries ≤ 5 MW	1 MW < Generators/Load/Pump, Storage/Batteries ≤ 5 MW

2.2. Voltage regulation and reactive power supply

The TSO is responsible for voltage regulation in order to ensure stability and avoid the damage of the connected generators or any other units. To regulate the voltage, reactive power support must be injected locally through generating units equipped with Automatic Voltage Regulators (AVRs), tap changing transformers and compensation devices such as Static VAR Compensators (SVCs). Voltage control in Europe is divided in three categories:

- Primary – automatic control, activated within milliseconds and can last up to one minute
- Secondary – centralized automatic, activated one minute after the voltage deviation and can last for several minutes
- Tertiary – 10 to 30 minutes after the voltage deviation.

Voltage regulation in European countries is presented in Table 2.

TABLE 2 – VOLTAGE REGULATION IN EUROPEAN COUNTRIES [5]

Country	Mandatory	Providers	Voltage level	Paid
Austria	Mandatory for power plants in transmission system	Generators/DSO/Wind farms/DSO connected units/Transformers	Transmission/Distribution	Partly
Belgium	All Generating units > 25 MVA must be capable of voltage control	Generators/Wind farms/Transformers	Transmission	Yes
Bosnia and Herzegovina	Mandatory	Generators	Transmission	No
Croatia	All power plants	Generators/Wind farms/Transformers	Transmission/Distribution	Yes
Czechia	All units connected at 220 kV +	Generators/Transformers	Transmission	Yes
Denmark	-	Generators/HVDC/Transformers	Transmission	Partly
Estonia	Mandatory for all plants connected to the main grid	Generators/Wind farms/HVDC/Transformers	Transmission/Distribution	-
Finland	Mandatory for all power plants	Generators/Wind farms/DSO connected units/Transformers	Transmission/Distribution	No
France	Mandatory primary voltage control for all units at transmission level and secondary voltage regulation for all units connected at > 225 kV	Generators/Wind farms/PV/HVDC	Transmission/Distribution	Partly
Germany	Voltage control requirements for plants in both high and medium-voltage	Generators/Wind farms/HVDC/DSO connected units/Transformers	Transmission/Distribution	Partly
Great Britain	Mandatory for all conventional generators and wind farms connected to transmission	Generators/Transformers	Transmission/Distribution	Yes
Greece	Production units (except RES) > 2 MW (comply with technical regulation)	Generators/Transformers	Transmission	No
Hungary	All power plants > 50 MW connected to TG or 132 kV	Generators/Transformers	Transmission/Distribution	Yes
Ireland	-	Generators	-	-

Italy	Mandatory for power units ≥ 10 MVA	Generators/Transformers	Transmission	No
Latvia	Power plants	Generators/ Wind farms/Transformers	Transmission	No
Lithuania	All power plants in transmission	Generators/ Wind farms/Transformers	-	Partly
Netherlands	Mandatory for generators > 5 MW	Generators/DSO/ Industrial consumers/Wind farms/PV/HVDC/DSO units/Transformers	Transmission/Distribution	Partly
Norway	All powerplants	Generators/DSO/ Industrial consumers/Wind farms/PV/HVDC/DSO units/Transformers	Transmission/Distribution	Yes
Poland	All Generating Units and also centrally dispatched units contracted for this service	Generators/ Wind farms/DSO units/Transformers	Transmission/Distribution	Yes
Portugal	All conventional generators	Generators	Transmission	No
Romania	-	Generators	Transmission	No
Serbia	Mandatory for all power plants in TG	Generators/Transformers	Transmission	Yes
Slovakia	Mandatory primary voltage control, secondary voltage control as a paid service at transmission level (400 kV and 220 kV)	Generators/Transformers	Transmission	Yes
Slovenia	Mandatory	Generators/Transformers	Transmission	Yes
Spain	Mandatory service for all power plants > 30 MW connected to the TG	Generators/DSO/ Industrial consumers/Wind farms/PV/HVDC/DSO units/Transformers	Transmission/Distribution	No
Sweden	-	Generators/Transformers	Transmission/Distribution	No
Switzerland	All power plants connected to TG with available reactive power and without compromising the active power	Generators/Transformers/DSO	Transmission/Distribution	Yes

2.3. Black-start

Black-start can be provided by the generator units capable of injecting energy in the system, without external electrical energy supply. Moreover, these units are able to consume and produce reactive power to keep the voltage in the allowed range. These units also serve to facilitate the start-up of other generators, in order to stabilize the operation of power system. Both units connected to TG and DG can provide black-start service, such as pumped storage, interconnections, hydro plants, gas and nuclear units.

Black-start provision in European countries is shown in Table 3.

TABLE 3 – BLACK-START PROVISION IN EUROPEAN COUNTRIES [5]

Country	Mandatory	Voltage Level	Paid by TSO
Austria	Hydro storage power plants. Not mandatory for power plants	Transmission	Yes
Belgium	Not mandatory, provided from gas power plant and pumped storage	Transmission	Yes
Bosnia and Herzegovina	Mandatory	Transmission	No
Croatia	Mandatory for plants connected to TG determined by defense plan (at least two plants in each subarea) Plants connected to DG have the possibility, but not mandatory	Transmission/ Distribution	Yes
Czechia	No obligations to provide black start from any unit	Transmission	Yes
Denmark	Not mandatory	Transmission	Yes
Estonia	Not mandatory, provided by power plants included in restoration plan	Transmission	Yes
Finland	Not mandatory, agreed bilaterally by grid code	Transmission/ Distribution	Yes
France	Not mandatory, provided by nuclear plants	Transmission/ Distribution	No
Germany	Specific contracts	Transmission	Yes
Great Britain	Mandatory	Transmission/ Distribution	Yes
Greece	By predefined power plants	Transmission	Yes
Hungary	Mandatory for power plants > 500 MW connected to TG	Transmission/ Distribution	Yes
Ireland	Mandatory for Northern Ireland for certain plant types	-	-
Italy	Mandatory for power plants defined in restoration plan	Transmission	No
Latvia	Agreements with hydro power plants	Transmission	Yes
Lithuania	Not mandatory	Transmission	Yes
Netherlands	Not mandatory	Transmission/ Distribution	Yes
Norway	Mandatory for power plants with significant impact on reconstruction of network or other critical functions	Transmission/ Distribution	No
Poland	Not mandatory	-	Yes
Portugal	Not mandatory	Transmission	Yes
Romania	Mandatory for power plants included in black start plan	Transmission	No
Serbia	Mandatory for hydro power plants	Transmission	Yes
Slovakia	Not mandatory	-	Yes

Slovenia	Mandatory	Transmission	Yes
Spain	Not mandatory	-	No
Sweden	Contracted with suppliers	Transmission	Yes
Switzerland	adequate number of power stations, qualified for black start and island operation	Transmission	Yes

2.4. Innovative services

Innovative ancillary service markets include new ancillary services and new market participants providing ancillary services [6]:

- New ancillary services: ramping products and fast frequency response by batteries;
- New market participants providing ancillary services: wind turbines providing inertial response, solar PV and utility-scale storage providing voltage support and DER providing frequency and voltage control.

Ramping provided by conventional generators is not classified as a separate ancillary service. It is compensated as a marginal cost in energy market. The problem arises if steep ramping is required leading to increased market price and unfairness to the market players not providing ramping services. To overcome this issue, California Independent System Operator defined ramping as a flexibility product in the balancing market to serve the net load ramping requirements. The pricing is not bid-based, ramping providers are compensated regarding the lost opportunity cost for not providing other services at ancillary service market. The upper bounds for the prices for ramp-up and ramp-down services are set at 247 $/MWh and 152 $/MWh, respectively.

Due to short response time of battery storage units, they are suitable for balancing service provision and frequency response. System operators in the United Kingdom, Australia and Japan use the battery storage for fast frequency response. National Grid in the United Kingdom added eight battery storage units as a new product in the contract for rapid response frequency reserves. In Australia battery storage units are contracted for providing frequency control at the lower price compared to conventional generators resulting in reducing the price of frequency ancillary service by 90 %. In Japan is required that large solar PV projects have to control their energy injection with battery storage in order to satisfy frequency requirements in the grid.

Inertial response is usually provided by large thermal generators and large hydropower plants. However, wind turbines can also provide inertial response during frequency disturbances through a power electronic converter and by reducing or increasing the blade angle to control the power supply, but providing ancillary services by renewable energy sources requires the upgrade of policies and grid codes.

It is important to supply the reactive power from a nearby source in order to avoid network problems, such as voltage deviations and increased losses. The reactive power support can be provided by battery storage or solar panels through solid-state electronic interface or inverters. It is important that grid codes properly define connection requirements and to have incentives that treat reactive power as a separate product.

As problems related to over-voltages and congestion become more relevant with high integration of renewable energy sources at distribution level, more intention is being put on providing local flexibility services from DER.

3. TSO and DSO responsibilities and roles

The responsibility of a TSO is to ensure a secure, reliable and efficient electricity system operation. In accordance with that, TSOs are responsible for ensuring the availability and procurement of ancillary services in order to ensure operational security, including the services provided by demand response and energy storage. Note that in some countries, the role of the TSO is taken by a SO which is in charge of the energy and ancillary markets, and a Transmission Network Operator which is in charge of operating the TG and connecting customers.

Usually TSOs use resources connected to the TG for provision of ancillary services (large conventional power plants, such as nuclear, gas and coal).

TSOs are obliged to procure balancing services and non-frequency ancillary services in transparent, non-discriminatory and market-based procedures from all qualified market participants, including renewable sources, market participants engaged in demand response, operators of energy storage facilities and market participants engaged in aggregation. If the regulatory authority decided that the procurement of non-frequency ancillary services on the market is not cost-efficient, those services can be provided in a different way. In order to promote the uptake of energy efficiency measures and postpone the need for network reinforcement while supporting the efficient and secure TG operation, the regulatory framework must ensure that TSO can procure non-frequency ancillary services from demand response providers or energy storage. This does not apply to fully integrated network components (network components integrated in transmission or distribution system, such as energy storage used only for ensuring a secure and reliable system operation, but not for balancing purposes or congestion management) [7]. The regulatory authority can allow the TSOs to own, develop, manage and operate energy storage if:

- They are fully integrated network components;
- Other parties, following an open, transparent and non-discriminatory tendering procedure that is subject to review and approval by the regulatory authority, have not been awarded a right to own, develop, manage or operate such facilities;
- Other parties could not deliver those services at a reasonable cost and in a timely manner;
- Such facilities or non-frequency ancillary services are necessary for the TSOs to fulfil their obligations to ensure efficient, reliable and secure system operation.

At the DG level, until recently, there were few sources of flexibility. As a result, historically speaking, DSOs do not rely on system services for local voltage control, congestion and balancing. DSO typically use ‘Fit and forget’ approaches to avoid operational problems in the grid through network reinforcement. DSO did not procure flexibility services because it was either not allowed to contract flexibility for DG operation or it did not have any financial incentives as the network reinforcement used to be the most recognized option in dealing with the problems in DG.

But nowadays, the transition towards clean energy system end emergence of ICT is also affecting the provision of ancillary services. The focus is put on ancillary service procurement from distributed sources through active DG management characterized with real time monitoring and control, as well as installation of smart meters. Moreover, the changes are also seen in market development with increased installation of distributed energy resources (DER) and distributed flexibility providers resulting in innovative and diverse possibilities of ancillary services provision. The resources connected to the DG could be sources of flexibility not only for the DSO, but also for the TSO. To balance intermittent production from renewable energy sources connected to the distribution level, different household appliances, energy storage or electric vehicles can provide services to the local grid ensuring voltage control and local congestion management.

DSO can procure the non- frequency ancillary services needed for its system in accordance with transparent, non-discriminatory and market-based procedures, unless the regulatory authority has assessed that the market-based provision of non-frequency ancillary services is economically not efficient and has granted a derogation. The obligation to procure non-frequency ancillary services does not apply to fully integrated network components.

Furthermore, DER will be used for provision ancillary services to the TSO through connection points between TG and DG. In order to ensure a complete coordination between DSO and TSO, real time communication and data exchange between all parties are necessary to ensure the efficient, reliable, secure and the most economic network operation, but also to disable provision of ancillary services in opposite direction from different parties.

TSOs shall exchange all necessary information and shall coordinate with DSOs to ensure the optimal utilization of resources, to ensure the secure and efficient operation of the system and to facilitate market development.

DSOs and TSOs shall cooperate with each other in planning and operating their networks. In particular, DSOs and TSOs shall exchange all necessary information and data regarding the performance of generation assets and demand side response, the daily operation of their networks and the long-term planning of network investments, with the view to ensure the cost-efficient, secure and reliable development and operation of their networks.

DSOs and TSOs shall cooperate with each other in order to achieve coordinated access to resources such as distributed generation, energy storage or demand response that may support particular needs of both the DSOs and the TSOs. This is defined in Article 182: *Reserve providing groups or units connected to the DSO grid* [3]:

“1. TSOs and DSOs shall cooperate to facilitate and enable the delivery of active power reserves by reserve providing groups or reserve providing units located in the distribution systems.

2. For the purposes of the prequalification processes for FCR, frequency restoration reserves (FRR) and replacement reserves (RR), each TSO shall develop and specify, in an agreement with its reserve connecting DSOs and intermediate DSOs, the terms of the exchange of information required for these prequalification processes for reserve providing units or groups located in the distribution systems and for the delivery of active power reserves. The prequalification processes shall specify the information to be provided by the potential reserve providing units or groups, which shall include:

a) voltage levels and connection points of the reserve providing units or groups;
b) the type of active power reserves;
c) the maximum reserve capacity provided by the reserve providing units or groups at each connection point; and
d) the maximum rate of change of active power for the reserve providing units or groups.

3. The prequalification process shall rely on the agreed timeline and rules concerning information exchange and the delivery of active power reserves between the TSO, the reserve connecting DSO and the intermediate DSOs. The prequalification process shall have a maximum duration of 3 months from the submission of a complete formal application by the reserve providing unit or group.

4. During the prequalification of a reserve providing unit or group connected to its distribution system, each reserve connecting DSO and each intermediate DSO, in cooperation with the TSO, shall have the right to set limits to or exclude the delivery of active power reserves located in its distribution system, based on technical reasons such as the geographical location of the reserve providing units and reserve providing groups.

5. Each reserve connecting DSO and each intermediate DSO shall have the right, in cooperation with the TSO, to set, before the activation of reserves, temporary limits to the delivery of active power reserves located in its distribution system. The respective TSOs shall agree with their reserve connecting DSOs and intermediate DSOs on the applicable procedures."

4. TSO/DSO coordination schemes

Five different coordination schemes for procuring ancillary services will be described in detail [8], [9]:

- Centralized ancillary services market model;
- Local ancillary services market model;
- Shared balancing responsibility model;
- Common TSO-DSO ancillary services market model;
- Integrated flexibility market model.

Prequalification, activation, and settlement of flexible resources are similar in all schemes, but the main difference in these schemes lies in the procurement of ancillary services resulting in different roles for each stakeholder and the interaction between these stakeholders.

Several stakeholders are defined in the process of ancillary services procurement: the reserve allocator, the buyer, the seller, the MO and the aggregator. Although the congestion management is not defined as an ancillary service in [7], in the description of proposed coordination schemes, the term ancillary service also includes congestion management. Their roles are divided differently in the processes of ancillary services prequalification, procurement, activation and settlement. System operator, system balance responsible and data manager are responsible for grid operation. System operator (TSO, DSO) is in charge with the operation and management of the physical system. System balance responsible (TSO, DSO) is responsible for demand and generation balance and deviations reduction through reserve activation. Data manager (TSO, DSO, system operator) is responsible for formatting, storage and provision of grid data for each network level. Flexibility feasibility checker (DSO) is in charge in the process of ancillary services prequalification by assessing the potential impact at distribution level from flexibility services provided by DER. Several roles are divided in the process of ancillary services procurement. TSO or DSO as a reserve allocator determines the amount of needed flexibility service. Commercial market player, TSO or DSO can also buy or sell flexibility in the market, while MO is responsible for market operation.

4.1. Centralized ancillary services market model

Regarding the market design, there is a centralized market for ancillary services procurement for resources connected on TG and DG (market bids from flexible resources connected to transmission and distribution level are shown in black arrows in Figure 2). The TSO is a system and a MO, responsible for system operation in real-time and for procurement of ancillary services on the market. In this approach the TSO does not consider DG constraints in the process of ancillary service provision which excludes the DSO from ancillary services procurement and activation by the TSO because the TSO contracts the flexibility directly from resources connected to the DG. No separate local markets exist. Furthermore, the role of the DSO is very limited because the DSO does not use flexibility resources connected to the DG to solve voltage problems or congestion in real time or near to real time. To ensure that the constraints in the DG are not violated, separate process of system prequalification of ancillary services can be executed (blue arrows in Figure 2) in which the DSO communicates the necessary data to the TSO.

The main advantage of this scheme is the straightforward market with low risk of illiquidity. It is very similar to the current ancillary service market in which products are clearly known to all market participants which makes this scheme standardized. The TSO is the MO and the only buyer. Moreover, due to low DSO participation in the ancillary service procurement, the TSO and the DSO are not compelled to share the data, except if the TSO includes DG constraints in the market clearing process.

Costs for market operation are low if the distribution constraints are not considered because only additional communication infrastructure is needed. On the other hand, this limited communication can result in a violation of DG constraints if not considered in market clearing process. The main disadvantage of this approach is that the DSO does not use the resources connected to the DG to solve its local problems.

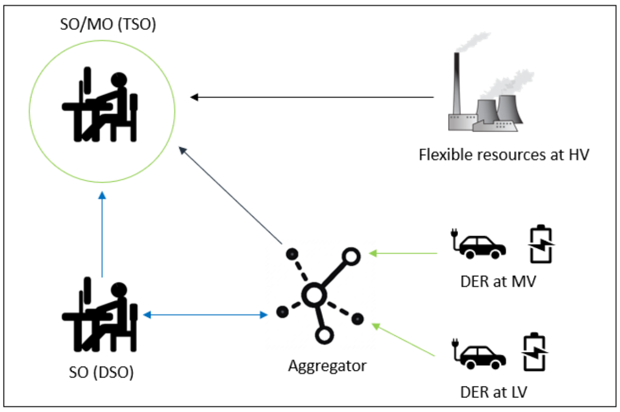

FIGURE 2 – CENTRALIZED ANCILLARY SERVICES MARKET MODEL

Market clearing is performed as follows [9]:

1. The TSO sends the forecast grid state, per market time step, to the MO before the GCT: this includes forecast net nodal power injection (sum of generated power minus sum of withdrawn power at each node), operational limits, grid topology (if modified) and scheduled/agreed flow at the borders.
2. FSPs are flexible resources at HV and distributed resources (DER) at MV and LV. FSPs send bids to the market operator (MO) at TG at nodal resolution.
3. The MO runs the market clearing algorithm, i.e. computes accepted bid quantities and nodal marginal prices (these are only applicable to the TG nodes).
4. The MO transmits market results to the TSO.
5. Finally, the MO dispatches the activated bids of FSPs.

4.2. Local ancillary services market model

This scheme includes two market models: local markets operated by the DSOs (the blue circle in the Figure 3) and a central market operated by the TSO (the green circle). Firstly, the local market is cleared in which the DSO contracts the ancillary services from the aggregator of DER for the local use. The DSO considers DG constraints in the market clearing process and always has the priority (over the TSO) to use the local flexibility resources for congestion management or voltage control in the local DG. When the local market clearing is executed, the TSO procures ancillary services from flexible resources connected to the TG and aggregated services from the DG not procured in the local market. The TSO is responsible only for the central market. This scheme gives the priority to the DSO to use distributed resources for the local network management. It is essential to ensure a real-time communication and data exchange between the DSO and the TSO to avoid the procurement of flexibility services in opposite directions.

This scheme is not in line with current tendencies of harmonization and integration of markets in the EU. The problem arises if each DG has its own separate local market. This can result in limited market liquidity because each DSO acts as an aggregator for its own market because the DSO receives the bids only for the small area. This schemes also implies additional costs for the DSO. Furthermore, in this scheme distributed flexibility providers are spread around different local markets limiting the aggregation of resources under different MOs resulting in the complex process of aggregation and thus in high operation costs of market organization and higher price of ancillary services for both DSO and TSO. When participating in the central market, the DSO needs to aggregate local bids into a format requested by the TSO. The operation of the local ancillary service market organized for the small distribution area may result in the generation curtailment of renewable energy sources and load shedding if the DSO is not able to procure a sufficient amount of the required service. The scheme with multiple local markets can result in different market products for each local market which needs to be harmonized. Each DSO can cause imbalances with the local activation of flexibility services and because of that the DSO is required to communicate its actions to the TSO who is responsible for the entire system balance. The communication is required between all these local markets and the central market which implies the additional investment in communication and ICT infrastructure.

However, the benefits of this type of market fragmentation are very efficient market operation, development of tailor-made products satisfying the needs of the specific market and low risk of violating the network constraints at the distribution level.
To overcome the problem of multiple local markets with the possibility of low liquidity, one more step of aggregation can be included in this scheme: aggregation of all local DSOs who operate different local markets in order to ensure more efficient and lower cost markets which increase the liquidity of the central market.

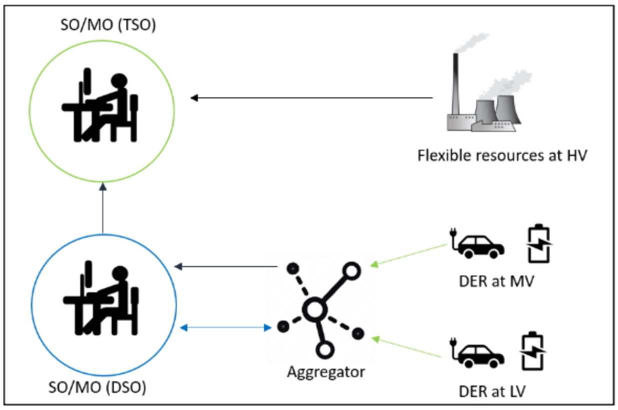

FIGURE 3 – LOCAL ANCILLARY SERVICES MARKET MODEL

The actions in the market are described in following steps [9]:

1. TSO and DSOs send the forecast grid state, per market time step, to their respective MO before the GCT: this includes forecast net nodal power injection over their respective grids, operational limits, grid topology and scheduled/agreed flow at the borders.
2. TG connected FSPs send their bids to the TSO MO at TG nodal resolution, and bids from DG connected resources to the DSO MO, at DG nodal resolution.
3. Each DSO MO runs a “pure” power flow (i.e. without having any bids at disposal) on its subnetwork and checks the presence of over- under-voltages or line congestions. In case any congestions are experienced, the available bids at this subnetwork are then considered in the computation and the local market clearing (i.e. optimal power flow) is performed in terms of quantities. Social welfare is maximized considering nodal active and reactive power balance, bids constraints, operational constraints (line capacities and voltage limits) while trying to avoid unnecessary activations and keep the forecast flow at the HV-MV transformer unchanged. Accepted bid quantities used to solve those congestions and their corresponding activation

costs are stored by the DSO MO for further use. At the same time, forecast net nodal power injection of DSO nodes is updated.

4. Each DSO MO “smartly” aggregates the remaining local market bids into a single aggregated bid which do not counteract with local bids.
5. This aggregated bid is submitted to the TSO MO, before GCT of TSO market (GCT for DSO and TSO markets might, in general, be different).
6. TSO MO runs the market clearing algorithm (same as in Centralized ancillary service market model), i.e. computes accepted bid quantities and nodal marginal prices, having at his disposal all TSO bids together with the aggregated bid coming from the DSOs.
7. The MO transmits market results to the TSO.
8. The MO dispatches the activated bids of TSO FSPs and DSO MO.
9. DSO MO performs the disaggregation of activated DSO bids, by running again the market clearing with a power profile at the TSO/DSO connection point aligned with the activation of the DSO bid required by the TSO.
10. DSO MO transmits market results to the DSO.
11. Finally, the DSO MO dispatches the corresponding DER.

4.3. Shared balancing responsibility model

The shared balancing responsibility model also consists of two markets: a local market operated by the DSO (the blue circle in Figure 4) and a central market (the green circle) operated by the TSO. Both markets are cleared simultaneously. The DSO procures ancillary services for local network management from the aggregator of distributed resources, while the TSO procures the ancillary services from the flexibility resources connected to the TG. The difference between this market model and Local ancillary services market model is that TSO cannot procure ancillary services from distribution level, therefore the DSO is responsible for both the local balancing and the local congestion in the DG following the predefined schedule communicated with the TSO. This schedule disables independent TSO and DSO system operation. Two methods in defining this schedule are possible. The first one implies nominations of balancing responsible parties taking the energy-only market as a base for the scheduled communication. Only one schedule for the entire area operated by the local DSO is required, i.e. details regarding power flow in each TSO/DSO connection point are not necessary resulting in only one aggregated schedule making this method easier for calculation and communication between the DSO and the TSO. However, the lack of this method is not being able to account for real-time or near-to-real-time constraints at TSO-DSO connection points. The second method considers the balancing responsible parties’ nominations and historical forecasts at each TSO-DSO interconnection point, i.e. this method determines a schedule for each TSO-DSO connection point considering network constraints. The communication and coordination are very precise, but on the other hand, hard to calculate due to challenges in sharing data in a short timeframe, especially in the case with multiple local DSOs.

As the DSO is responsible for the local balancing and for the local congestion management, many flexibility resources are required. In the case of multiple DSOs operating in small areas, there are lower possibilities of several resources aggregation into one common bid resulting in low market liquidity if each small part of DG is operated separately. This can result in higher price of the ancillary service. Moreover, curtailment or load shedding can occur if the DSO is not able to procure the required amount of flexibility. However, smaller markets might create better conditions for smaller scaled flexibility sources connected to the DG. As the local markets are separated from the central market operated by the TSO, each local market is obliged to set billing system for balancing responsible parties resulting in higher operational cost of market organization and higher balancing cost due to low market liquidity.

There is also a risk of the total system instability if the DSO is not able to fulfil its balancing responsibilities in the local area.

The TSO has to procure smaller number of ancillary service because it is responsible only for the balancing of the TG - resulting in decrease of total TSO cost. On the other hand, the cost of the DSO will increase drastically which will potentially be reflected on end-user DG fee.

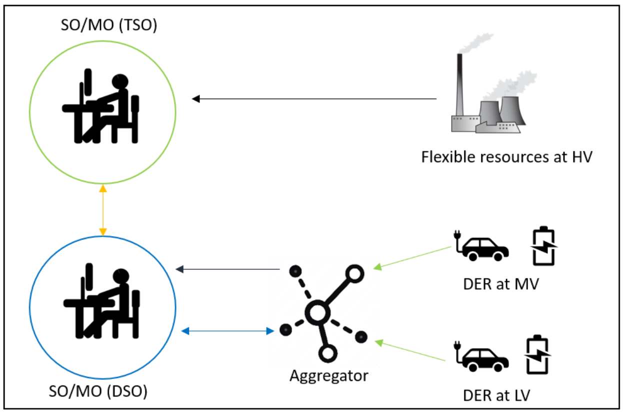

FIGURE 4 – SHARED BALANCING RESPONSIBILITY MODEL

Market actions in this scheme are following [9]:

1. TSO and DSO agree upfront in defining a schedule for the exchange of power at each primary substation (TSO/DSO connection point).
2. TSO and DSOs send the forecast grid state, per market time step, to the TSO and DSO MO, respectively, before the GCT: this includes forecast net nodal power injection, operational limits, grid topology and scheduled/agreed flow at the borders.
3. FSPs send bids coming from TG connected resources to the TSO MO, at TG nodal resolution, and bids from DG connected resources to the DSO MO, at DG nodal resolution.
4. TSO MO and DSO MO run their market clearing algorithms, i.e. compute accepted bid quantities and nodal marginal prices trying to maximize social welfare taking into account nodal active power balance at MO and DSO MO level, bids constraints, operational constraints (line capacities, and voltage limits for DSO MO) at MO level while respecting the agreed schedule at TSO/DSO connection point and trying to avoid unnecessary activations.
5. TSO MO and DSO MO transmit market results to the TSO.
6. Finally, TSO MO and DSO MO dispatch the activated bids from FSPs.

4.4. Common TSO-DSO ancillary services market model

This model has only one common market (the purple circle in Figure 5) for resources connected to both transmission and distribution level. This market is operated jointly from both the DSO and the TSO ensuring the optimized system operation as a whole without prioritizing the DSO nor the TSO. In other words, the DSO uses distributed resources for local DG management, while the TSO uses flexibility resources connected to both TG and DG resulting in the most economical solution for the entire system. There are two possible scenarios of this market model: centralized one (possible extension of Centralized ancillary service market model) including a common market platform or decentralized one (possible extension of the Local ancillary service market model) which consists of multiple local markets connected to a central market. In the centralized solution, both the DSO and TSO share the operational market costs (which is different from the Centralized market model in which the TSO is the only one bearing the cost) resulting also in reduction of total grid costs of each system operator. It is important to determine how these costs will be shared among them. As the DSO and the TSO are responsible for the market operation to increase the efficiency of the system performance, a clear definition of processes in the ancillary service provision and communication between system operators should be defined. It is also possible to include the third party as a MO which will be under the supervision of system operators. The DSO does not have a priority in procuring flexibility services from the distribution level, both the TSO and the DSO can use distributed resources to operate the system in the most efficient and economical way. Structure of bids submitted to the market might be less complex compared to bids offered directly to the TSO and aggregation can combine the resources from the areas operated by different DSOs making the central market (which is also the only one) organization easier with the standardized products. The DG constraints are included in the market clearing which ensures that the provision of ancillary service connected to the DG does not violate the DG constraints.

On the other hand, a decentralized solution is more expensive compared to the centralized one because there is a low possibility of ancillary service aggregation in small local markets operating separately. This can result in higher cost of the required market service, low liquidity and less possibilities to aggregate several resources into one common bid due to fragmented markets.

Additional infrastructure for the communication between the DSO and the TSO is required in both scenarios due to their close collaboration and required data exchange where the focus is on security and privacy of data.

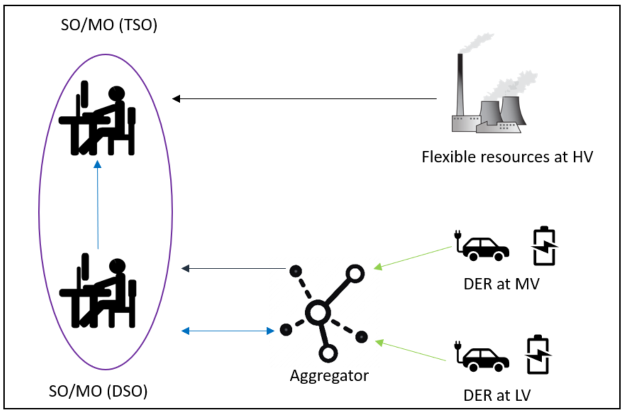

FIGURE 5 – COMMON TSO-DSO ANCILLARY SERVICES MARKET MODEL

Following steps are executed in the market [9]:

1. TSO and DSOs send their forecast grid state, per market time step, to the common MO before the GCT: this includes forecast net nodal power injection (sum of generated power minus sum of withdrawn power at each node), operational limits, grid topology and scheduled/agreed flow at the borders.
2. FSPs send bids coming from both TG and DG resources to the MO, at nodal resolution.
3. The MO runs the market clearing algorithm, i.e. computes accepted bid quantities and nodal marginal prices maximizing social welfare while considering nodal active and reactive power balance, bids constraints and operational constraints while trying to avoid unnecessary service activations.
4. The MO transmits market results to the TSO and DSOs.
5. The MO dispatches the corresponding FSPs.

4.5. Integrated flexibility market model

This market model implies that flexibility procurement is opened for both regulated participants (system operators) and deregulated participants (commercial market players) allowing the direct competition between them under the same conditions, i.e. deregulated participants can be both sellers and buyer of ancillary services. The role of an independent MO is to ensure the neutrality while having the influence in data management and market settlement. The flexibility resources in this market model will be allocated according to the highest payment incentivizing the demand side to be more competitive. It is also important to incentivize that participants support system operation to ensure that system operators get the requested ancillary services.

The main advantage of this market model is that all flexibility services are offered in one market which increases the possibilities of desired service procurement for all market participants resulting in high market liquidity and lower prices of ancillary services. As deregulated market players have the possibility to participate in the ancillary service market in real-time or near real time to balance their position, the trade on day-ahead and intra-day market could be either decreased or fragmented in the smaller volumes. The increase of ancillary service market liquidity is also affected by the fact that system operators can resell the unneeded ancillary service previously contracted on the market, but also to buy the unneeded service from the market player selling it. Moreover, the aggregation can use distributed sources connected to different local areas because all flexibility is traded in one market. It is very important to define how much the ‘reselling price’ can be. Balancing responsible parties can lower their imbalance penalties because they can correct their balancing position closer to real time which can lower the intra-day market liquidity. System operators have lower needs for ancillary service procurement since balancing responsible parties are involved in the balancing service procurement. Moreover, the operational market costs are shared among large number of market participants resulting in lower individual cost. The DG constraints are included in the market clearing process, while all market participants have the same priority in procuring ancillary service form the resources connected to the DG.

As both regulated and deregulated players participate in this market, an independent MO is essential to ensure the market neutrality. This MO can be an entity already involved in day-ahead or intra-day market operation. The responsibility of the independent ancillary service MO to the system operators and commercial market parties should be clearly defined, especially for the system prequalification and the bids blocking process where the DSO and independent MO may be in conflict.

As the system operator closely collaborate with the independent MO, the additional ICT and infrastructure is needed. It is important to establish the platform where the DSO and the TSO can share their data with the MO in the most secure and private way.

As the TSO is responsible for the system balance and stability, it needs to have access to the required ancillary service which might be limited due to deregulated market players buying actions. The lack of the Integrated flexibility market model is that the TSO might need to procure additional ancillary services outside the market to ensure the secure and efficient system operation. Procuring ancillary service outside the market can decrease the market liquidity. This can be solved in installation of balancing settlement mechanism which gives specific incentives to deregulated players to buy the volumes not harmful for the operation of the system. On the other hand, the TSO can also be exposed to the risk of procuring more resources on the market than actually needed just to be sure that it will be able to safely operate the system.

The competition for the same resource can increase the price of the service, or even worse, the DSO or the TSO can activate the service in the opposite direction which can harm the other system operator's network resulting in high grid operation cost billed in increased end-user's distribution and TG fee. Integrated flexibility market model is shown in Figure 6.

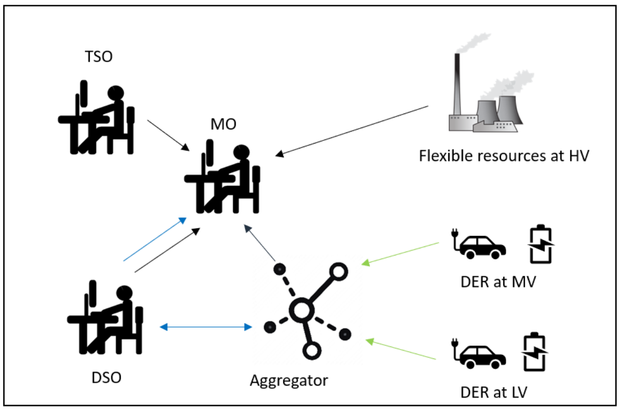

FIGURE 6 – INTEGRATED FLEXIBILITY MARKET MODEL

5. Computational effort

When it comes to computational tractability, the qualitative assessment of the computational complexity of each TSO-DSO coordination scheme is summarized as follows:

a) Centralized ancillary service market — less complex to model because only TG is considered, while DGs constraints are not used.
b) Local ancillary services market — has intermediate complexity because of parallel optimizations, but smart aggregation induces some complexity while biding from the local markets in the central market.
c) Shared balancing responsibility market — very simple because the model does many optimizations in parallel, but requires many power platforms.
d) Centralized common TSO-DSO ancillary service market — extremely difficult because the model uses both full TG and DG for single market clearing problem.
e) Integrated flexibility market — extremely difficult because the model uses both full TG and DG.

6. DG constraints

The increasing growth in renewable energy resources and the activation of flexibility resources connected to the DG can result in violating the DG limits. The question arises regarding consideration of DG constraints in the ancillary service market clearing procedure. Four possible solutions are considered in Smart Net project [10]:

1. Constraints in DG are neglected, as it is the current practice in the most European countries. Moreover, in the Centralized ancillary service market model the DG constraints are not considered, the DSO does not use flexibility resources connected to the DG, while the TSO procures ancillary services directly from the resources at the distribution level. This solution is acceptable for over-dimensioned DGs in which violating network constraints in not questionable. In this solution the interaction between the TSO and the DSO is not necessary.
2. The DSO is involved in the dynamic process of system prequalification which can also be the practice in Centralized ancillary service market model. The DSO preforms multiple analyses to investigate the impact of providing flexibility service from the specific distributed resource on the DG. If the DG constraints are not violated, the DSO gives the approval to the specific resource for participating in the ancillary service market.

   The benefits of this solution are low implementation cost and increased grid observability due to consideration of DG constraints. Moreover, this solution gives an indication to flexible resources in case they are located in the constrained area and thus incentives the DSO to invest in that part of the grid to unlock the flexibility potential.

   The possible lacks are very conservative safety margins in DG operation and need for precise forecasts of future grid load and production from renewable energy sources.
3. The DSO is responsible for system prequalification and involved in the process of blocking the activation of flexible resources in manual iterative process after the clearing of the market if the constraints in the DG are violated. If the DSO determines that provision of ancillary service violates the network constraints, the bid is blocked, and the market is cleared again. The disadvantages of this solution are convergence of the iterative procedure in the process of flexibility assessment in the short time period, issues with transparency, uncertainty regarding unclear base on which the DSO could block the activation of flexibility service and postponed final market clearing due to multiple possibilities of bids blocking. On the other hand, positive sides of this solution are simple mathematical model that always checks DG constraints and increase of the grid observability.
4. DG constraints are included in market clearing algorithm which ensures that any provision of flexibility service will not violate DG constraints. The main problems with this solution are mathematical models with all constraints in the process of the market clearing which is hard to integrate and solve and secure and private data exchange if the DSO is not the MO. However, this model always respects the constraints in the DG, DSO is the neutral market participant and operational process is relatively light. If continuous market set-up is considered, this solution is not the optimal one because the grid constraints should be checked every time when the bid is submitted.

   The Local ancillary service market model, the Shared balancing responsibility model and the Common TSO-DSO ancillary service model should be based on this solution because in these approaches the DSO is a MO and there is no problem with security and privacy of data exchange with the third party.

7. Roles of market participants in processes of grid operation, prequalification, procurement, activation, and settlement

7.1. Grid operation

The roles concerning grid operation in each coordination scheme is shown in Table 4, giving the overview of responsibility for system operation, balancing and data management. The abbreviations in brackets stand for responsibility of the system operator either DSO or TSO for TG or DG.

Regardless of the coordination scheme, the system operators should be responsible for reliable and safe operation of the grid, as seen in the first row in Table 4. The TSO is responsible for balancing of the entire system, including both TG and DG in each coordination scheme, except in Shared balancing responsibility model in which the DSO is responsible for balancing DG. Both TSO and DSO are responsible for their data management, i.e. collection, storage, access, sharing with other system operator. In Integrated flexibility market model, as the independent MO (IMO) is responsible for market operation, the access to DSO and TSO data should be enabled through secure and private data exchange mechanisms.

TABLE 4 – ROLES REGARDING GRID OPERATION FOR EACH COORDINATION SCHEME

Role	Centralized AS market model	Local AS market model	Shared balancing responsibility model	Common TSO-DSO AS market model	Integrated flexibility market model
System Operator	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)
System Balance Responsible	TSO (TG; DG)	TSO (TG; DG)	TSO (TG) DSO (DG)	TSO (TG; DG)	TSO (TG; DG)
Data Manager	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG) IMO

7.2. System prequalification

In each coordination scheme the DSO is responsible for system prequalification of DG. The system prequalification checks the impact of specific flexibility service activation on the DG.

The role of the DSO is to analyze possible scenarios of ancillary services provision and investigate their impact on the DG. However, the TSO can also be part of the prequalification and preform the assessment of ancillary services provision on DG, while the DSO needs to ensure that the TSO has access to all the necessary data.

Prequalification process is very similar for centralized (Centralized AS market model, Common TSO-DSO AS market model – centralized and the Integrated flexibility market model) and decentralized market models (Local AS market model, Shared balancing responsibility model and the Common TSO-DSO AS market model – decentralized). The main difference is in the actor responsible for the market operation. The prequalification process is performed in 8 steps [10]:

1. DER owner requests the technical prequalification from the certified body.

2. Certified body verifies technical characteristics of DER, validates the technical prequalification and sends it to the DER owner.
3. The aggregator is responsible for DER aggregation.
4. Seller requests the system prequalification from the MO.
5. The MO communicates the request for system prequalification to the flexibility feasibility checker (DSO).
6. The flexibility feasibility checker analyses the impact of distributed flexibility resources on local DG.
7. The flexibility feasibility checker sends the response of system prequalification assessment to the MO.
8. The MO sends the system prequalification assessment to the seller.

7.3. Procurement

In the process of ancillary services procurement, the roles reserve allocator, buyer, seller, MO and aggregator differ among coordination scheme as shown in Table 5.

In each coordination scheme both system operators determine the required flexibility service for the safe grid operation, TSO for TG and DSO for DG. The exception is Centralized ancillary service market model in which only the TSO schedules ancillary services, while the DSO does not use distributed resources for voltage control or congestion management, i.e. the DSO does not participate in ancillary service procurement at all. The TSO is responsible also for frequency control and stable system operation in each coordination mechanism, except in the Shared balancing responsibility market model in which the DSO is responsible for balancing on the distribution level.

In Local ancillary service market, the DSO has the priority in flexibility services allocation, while in Common TSO-DSO ancillary service market model the provision of flexibility services is in line with cost minimization for the entire system, i.e. for distribution and transmission level. On the other hand, in Shared balancing responsibility model the TSO can procure ancillary services only from resources connected to TG, while the DSO procures the ancillary services from distributed resources. In Integrated flexibility market model, commercial market players (CMP) can also participate in ancillary services market and compete for the flexibility together with system operators.

The flexibility services are provided from commercial market players connected to the TG (e.g. power plants) and the DG (distributed flexibility resources, such as energy storage). In the Integrated flexibility market model, both the DSO and the TSO can also sell the ancillary services previously purchased in the market to reduce the network cost or increase market liquidity.

The role of MO differs because of different market design in coordination schemes. The TSO operates the common ancillary service market with the services provided from distribution and transmission level. In the Local ancillary service market model and in the Shared balancing responsibility model, the TSO is responsible of the ancillary service market operation for transmission level, while the DSO is responsible for the local market for ancillary services operation. In the Common TSO-DSO ancillary services market model, the TSO and the DSO are operating in coordination to minimize the cost for the entire system and ensure the most efficient system operation. In the Integrated flexibility market model, IMO is in charge of market operation and ensures the neutrality as the market is opened for ancillary service procurement for both regulated and deregulated market players.

FSPs or aggregators employ the flexibility resources connected to the DG. However, in the Local ancillary service market model and in the Common TSO-DSO ancillary service market model, the DSO aggregates the aggregation bids from the local ancillary service markets and sends them the TSO ensuring that all constraints in the DG are not violated.

TABLE 5 – ROLES REGARDING ANCILLARY SERVICES PROCUREMENT FOR EACH COORDINATION SCHEME

Role	Centralized AS market model	Local AS market model	Shared balancing responsibility model	Common TSO-DSO AS market model	Integrated flexibility market model
Reserve Allocator	TSO (TG; DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)
Buyer	TSO (TG; DG)	TSO (TG; DG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG; DG) DSO (DG)	TSO (TG; DG) DSO (DG) CMP (TG; DG)
Seller	CMP (TG; DG)	CMP (TG; DG)	CMP (TG; DG)	CMP (TG; DG)	TSO (TG; DG) DSO (DG) CMP (TG; DG)
MO	TSO (TG; DG)	TSO (TG) DSO (DG)	TSO (TG) DSO (DG)	TSO (TG; DG) DSO (TG; DG)	IMO (TG; DG)
Aggregator	CMP (TG; DG)	CMP (TG; DG) DSO (DG)	CMP (TG; DG)	CMP (TG; DG) DSO (DG)	CMP (TG; DG)

The procurement process is different for each coordination scheme. The procurement in the Centralized AS market model is described in 6 steps [9]:

1. The reserve allocator (TSO) determines the volume of each ancillary service to be procured.
2. The buyer (TSO) communicates the volumes to the MO (TSO).
3. The seller sends aggregated bids from both transmission and distribution level to the MO (TSO).
4. DSO communicates DG constraints to MO if the DG constraints are considered in market clearing process.
5. The MO (TSO) clears the market and communicates results to the DSO.
6. DSO checks if the local constraints are violated and blocks the activated bid if necessary. The blocking is communicated to the MO (TSO) and the step 5 is repeated. This step is relevant only for the case in which the DSO is involved in the process of blocking the cleared marked bid that violets network constraints (solution 3 in considering network constraints).

The steps of procurement are different in decentralized market models. The procurement is performed in the Local ancillary service market model as follows:

1. Reserve allocator (DSO) calculates volumes of local flexibility to be procured via the local market for local use.
2. The buyer (DSO) communicates the required volumes to the MO (DSO).
3. Reserve allocator (TSO) calculates volumes of required ancillary service for the entire system.
4. The buyer (TSO) communicates volumes to the MO (TSO).
5. The seller (CMP) sends aggregated bids of flexibility connected at the TG to central market (TSO) and then aggregated bids of flexibility connected at the DG to local market (DSO).
6. The DSO communicates the constraints of DG to the central MO (TSO).
7. MO (DSO) clears the local market taking into account the constraints in the DG.
8. MO (DSO) or the aggregator aggregates non- selected bids and sends them to the central market (TSO).
9. The TSO as the central MO clears the central market.

10. The TSO communicates cleared central bids to the seller (CMP) and cleared local bids to the local MO (DSO) or the aggregator.

In the Shared balancing responsibility model, the procurement of ancillary services is performed in six steps:

1. System operators (DSO and TSO) agree to exchange ancillary service profiles.
2. The reserve allocator (TSO) calculates the required reserve that needs to be bought from the central market. DSO as the local reserve allocator calculates volumes of ancillary service required for the local use from distributed flexibility providers.
3. The buyer (TSO) communicates volumes to the MO (TSO), while the DSO as the local buyer communicates volumes to the MO (DSO).
4. Seller (CMPs) sends aggregated bids from resources connected to the TG to the central market (TSO) and aggregated bids from resources connected to the DG to the local market (DSO).
5. The TSO communicates TG constraints to the central market, while the DSO communicates DG constraints to the local market.
6. The TSO clears the central market, while the DSO clears the central market.

In Common TSO-DSO AS market model both system operators determine the required flexibility service for the safe grid operation, TSO for TG and DSO for DG. Both the TSO and the DSO can purchase ancillary services from the distributed resources. In Common TSO-DSO ancillary service market model the provision of flexibility services is in line with cost minimization for the entire system, i.e. for distribution and transmission level. The flexibility services are provided from commercial market players connected to TG (e.g. power plants) and DG (distributed flexibility resources, such as energy storage). In the Common TSO-DSO ancillary services market model, the TSO and the DSO are operating in coordination in order to minimize the cost for the entire system and ensure the most efficient system operation. The steps of procurement in the Common TSO-DSO ancillary services market model is described in 5 steps:

1. Reserve allocator (DSO) calculates volumes of local flexibility for local use, while the TSO determines the volume of each ancillary service to be procured for TG.
2. The buyers (TSO and DSO) communicates the volumes to the market.
3. The seller sends bids from both transmission level and aggregated bids from distribution level to the MO (TSO and DSO).
4. MOs (TSO and DSO) clear the Common market considering the constraints in the DG.
5. The MOs (TSO and DSO) communicate cleared bids to the seller (CMP).

7.4. Activation

During the market clearing process, the adequate bids are selected, and the services are either reserved in the capacity market or activated in activation market in order to provide the requested ancillary service. Table 6 shows the adopted roles regarding the activation of ancillary services for each coordination mechanism.

TABLE 6 – ROLES REGARDING ANCILLARY SERVICES ACTIVATION FOR EACH COORDINATION SCHEME

Role	Centralized AS market model	Local AS market model	Shared balancing responsibility model	Common TSO-DSO AS market model	Integrated flexibility market model
Flexibility Dispatcher	TSO (TG; DG) CMP (TG; DG)	DSO (DG) TSO (TG; DG) CMP (TG; DG)	TSO (TG) DSO (DG) CMP (TG; DG)	TSO (TG; DG) DSO (DG) CMP (TG; DG)	IMO and TSO (TG; DG) DSO (DG) CMP (TG; DG)

The activation process is different for each coordination scheme. The activation in the Centralized AS market model is described in 2 steps [10]:

1. MO or flexibility dispatcher (TSO) communicates the results of market clearing to the buyer (TSO) and to the seller (distributed resources).
2. The aggregator or flexibility dispatcher activates the distributed resources according to the cleared bids in the market.

The steps of ancillary service activation in decentralized market model for the Local ancillary service market model are similar to the centralized scheme:

1. MO, aggregator or flexibility dispatcher (DSO) communicates market results to the seller (CMP) and system operator (DSO).
2. The aggregator or flexibility dispatcher activates the selected bids.

The activation of ancillary services in the Shared balancing responsibility model is divided in two steps:

1. MO (TSO) communicates central market results to the seller (CMP) and to the TSO as a system operator. The market results include both local and system flexibility. Moreover, the DSO as the MO communicates the local market results to the seller (CMP) and DSO as a system operator.
2. Aggregator or flexibility dispatcher activates the distributes resources for providing selected ancillary services.

7.5. Settlement

The responsibility for reading, storing and sharing data measurement is shown for each coordination mechanism in Table 7. The TSO is responsible for measurement data on the transmission level, the DSO for distribution level, while each CMP is responsible for measurements regarding the activation of flexibility resources.

TABLE 7 – ROLES REGARDING ANCILLARY SERVICES SETTLEMENT FOR EACH COORDINATION SCHEME

Role	Centralized AS market model	Local AS market model	Shared balancing responsibility model	Common TSO-DSO AS market model	Integrated flexibility market model
Metered Data Responsible	TSO (TG) DSO (DG) CMP (TG; DG)	TSO (TG) DSO (DG) CMP (TG; DG)	TSO (TG) DSO (DG) CMP (TG; DG)	TSO (TG) DSO (DG) CMP (TG; DG)	TSO (TG) DSO (DG) CMP (TG; DG)

The settlement process is different for each coordination scheme. The settlement in the Centralized AS market model is described in 5 steps [10]:

1. The actor responsible for data measurement (DSO) communicates the measurements to the MO (TSO).

2. The actor responsible for data measurement (TSO) communicates the measurements to the MO (TSO).
3. The MO (TSO) communicates the measurements to the TSO.
4. The TSO corrects the perimeter of balancing responsible parties affected by activation of ancillary services.
5. The MO (TSO) performs financial settlement of flexibility activation for resources connected at distribution and TG and sends it to the aggregator.

The steps in the processes of procurement, activation and settlement differ among the coordination schemes due to different entity acting as a MO. As the MO in the Centralized AS market model is the TSO, in the Common TSO-DSO ancillary service market model are both TSO and DSO in coordination and in the Integrated flexibility market model the independent MO, the steps including the MO are different (steps 2, 3, 4, 5, 6 in the process of procurement, step 1 in the process of activation, and steps 1, 2, 3 and 5).

Moreover, the roles of buyers and sellers are different. In the Centralized AS market model, the TSO is the only buyer and CMPs are the only sellers. In the Common TSO-DSO AS market model both TSO and DSO are buyers and the sellers are CMPs. In the Integrated flexibility market model both TSO and DSO are buyers and sellers. These differences affect the selling step (step 3 in the procurement process) and the buying step (steps 1 and 2 in procurement and step 1 in activation process).

The settlement process for the Local ancillary service market model is described in the following steps:

1. The actor responsible for data measurement (DSO) communicates the measurements to the MO (DSO).
2. The MO (DSO) communicates the measurements to the DSO as the system operator.
3. The MO (DSO) communicates the measurements to the TSO as the system operator.
4. The actor responsible for data measurement (TSO) communicates the measurements to the MO (TSO).
5. The MO (TSO) communicates the measurements to the TSO as the system operator.
6. TSO as the system operator corrects the perimeter of balancing responsible parties affected by ancillary service activation.
7. The MO (TSO) performs financial settlement of flexibility activation from resources connected at TG.
8. The MO (DSO) performs financial settlement of flexibility activation from resources connected at DG.

The procedure of procurement, activation and settlement is similar in Decentralized common TSO-DSO ancillary service market model. As the DSO does not clear the market, the step number 7 is not performed in the procurement process. On the other hand, in the step 8 the DSO aggregates bids together in one offer while considering the constraints in the DG. The TSO receives the aggregated offer from the DSO, clears the market, chooses the desirable bids and activates the resources connected to the DG.

The settlement process in the Shared balancing responsibility model is divided in 4 steps:

1. Both actors responsible for data measurement, the TSO and the DSO, communicate measurements to the MO (TSO and DSO).
2. MOs, both the TSO and the DSO communicates the measurements to the system operators (TSO and DSO).

3. The TSO as a system operator corrects the perimeter of balancing responsible parties affected by activation of resources connected to the TG. The DSO as a system operator corrects perimeter of balancing responsible parties affected by activation of resources connected to the DG.
4. MOs, the TSO and the DSO, performs financial settlement of flexibility activation of resources connected to the TG and DG.

In the Common ancillary service market model, the TSO is responsible for reading, storing and management of measurement data on the transmission level, the DSO for distribution level, while each CMP is responsible for measurements regarding the activation of flexibility resources.

The settlement process in the Common TSO-DSO ancillary services market is described in four steps:

1. The actors responsible for data measurement (TSO and DSO) communicate the measurements to the MO (TSO and DSO).
2. The MOs (TSO and DSO) communicates the measurements to the TSO.
3. The TSO corrects the perimeter of balancing responsible parties affected by activation of ancillary services.
4. The MOs (TSO and DSO) performs financial settlement of flexibility activation for resources connected at distribution and TG and sends it to the aggregator.

7.6. TSO-DSO ancillary services

Compared to traditional power system in which ancillary services could be provided only from the conventional generators connected to TG, today the focus has been put on providing ancillary services from resources connected to DG. In order to achieve safe, reliable, and cost-efficient use DER, coordination between system operators is necessary. Ancillary services from DER are described below.

7.6.1. Frequency control

Frequency Containment Reserves (FCR) are the fastest reacting reserves and first to be activated when a disturbance occurs. Frequency Restoration Reserves (FRR) means the active power reserves available to restore system frequency to the nominal value and for synchronous area consisting of more than one load-frequency control area to restore power balance to the scheduled value. Replacement reserve (RR) means the active power reserves available to restore or support the required level of frequency restoration reserve (FRR) to be prepared for additional system imbalances, including generation reserves.

As the TSO is the only buyer of the services for frequency control to maintain the frequency of the grid, there is no need for forming local markets. Centralized coordination schemes are relevant for frequency control procurement.

In the Centralized market model, the DSO does not use flexibility resources connected to the DG to solve local problems and thus the role of the DSO is very limited. The DSO participates in the prequalification process in which assesses the impact of specific flexibility service on the DG. As the market for the frequency control is a capacity market, during the process of prequalification, the DSO can forbid the participation of flexibility provider on a market if the provision of the service violates the constraints in the DG. On the other hand, if the grid is strong enough, it would be possible to omit the control of grid constraints violation making the process of ancillary service procurement cheaper. This implies that active DG management, i.e. DG control in real-time is not performed. However, the DSO could determine the range of droop control settings. This is the reaction of the flexible resource, dependent on an external signal optimized based on both local grid situation and total system need.

The Centralized common TSO-DSO ancillary service market is very similar to the Centralized ancillary service market model. The main difference is in droop control settings, i.e. in the Centralized ancillary service market model these drop control settings are determined once, while in the Centralized common TSO-DSO ancillary service market on regular base resulting in more resources participating in the market due to dynamic checking of grid constraints violations.

7.6.2. Voltage control

To ensure efficient and reliable system operation, system operators should put focus on voltage control, improving system security and quality of electricity supply.

The ancillary service for voltage control can be procured in the Local ancillary service market model, the Shared balancing responsibility model and the Common TSO-DSO ancillary service market model.

In the Local ancillary service market model, the TSO can procure reactive power from the DSO offers or from the central market where resources connected to the TG compete.

As the DSO and the TSO participate in joint cost minimization in the Common TSO-DSO ancillary service market model, the DSO will provide the ancillary service even at the possible cost of additional losses.

In the Shared balancing responsibility model, the DSO uses the flexibility of local resources procured on the local market to fulfil its responsibilities on behalf of the TSO according to the predefined schedule set by the TSO.

The provision of reactive power for voltage control is performed in three steps:

1. The TSO require from the DSO to provide voltage control by defining a reactive power set point for a specific period. The set point can be a value of reactive power, a value of tan(ϕ) or an active/reactive power area.
2. The DSO evaluates the flexibility resources in order to check if required service can be provided or sets the maximum value that can provide and communicates the information back to the TSO.
3. The TSO schedules the flexibility resources and sends the information to the DSO.

8. Market organization

Ancillary service markets can be organized as discrete auctions or continuous market. Continuous market and discrete auction markets with a high auction frequency might have low liquidity, but the main advantage is a possibility for trading at any moment before the gate closure. Furthermore, as the TSO is responsible for the system security and stability and needs to buy reasonable amount of flexibility service in the advance, commercial market players would set high prices for the bids further away from gate closure in the continuous market. The best solution is a discrete market with high frequency of auctions.

Market clearing example is shown in Figure 7. Different flexibility providers bid their prices and quantities, while the MO clears the market with the required, inelastic request from the system operators.

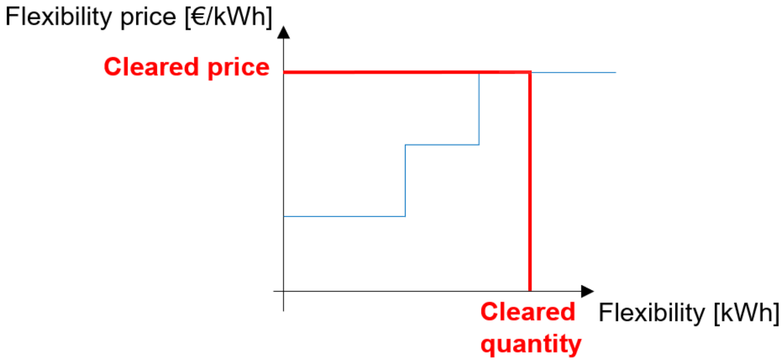

FIGURE 7 – MARKET CLEARING EXAMPLE

There are two possible resulting prices: bid price (pay as bid) or cleared price (pay as cleared). In pay as bid pricing mechanisms all activated flexibility providers are paid based on their bidding price which makes the process simple and clear. However, the lack of this pricing method is that market participants may not bid the price which reflect their real cost. On the other hand, in the pay as clear pricing mechanism all activated flexibility providers receive the same price per kWh. The cleared price is the bid price of the most expensive activated flexible service.

Pay as bid pricing introduces inefficiency in the market. If the generators do not bid their marginal cost and try to predict the market price, total cost-minimizing merit order dispatch cannot be assured. Moreover, prediction of a market price is a complex procedure and requires expensive data analyses which are affordable only to large players who can afford them. In other words, pay as bid pricing rewards good guess, but which could be extremely expensive. In competitive markets all participants have the incentive to bid their marginal price. Pay as bid pricing does not result in one single transparent price. However, imperfect competition can be a disadvantage of pay as cleared pricing. Suppliers with market power have incentives to reduce supply that could otherwise be profitably operated. The reduction of supply can increase the market clearing price and the profit of infra-marginal units.

8.1. Market models for balancing and congestion management

According to [11], three market models for balancing and congestion management regarding separate or combined merit order list can be distinguished. Regarding the availability of locational information on the balancing market, two different approaches lead to three market models for balancing and congestion management.

8.1.1. Combined balancing bids and congestion management

In this market model, the balancing market has the access to the information about DER bids and these balancing bids can also be used for the congestion management in the DG. The market coordination is shown in Figure 8.

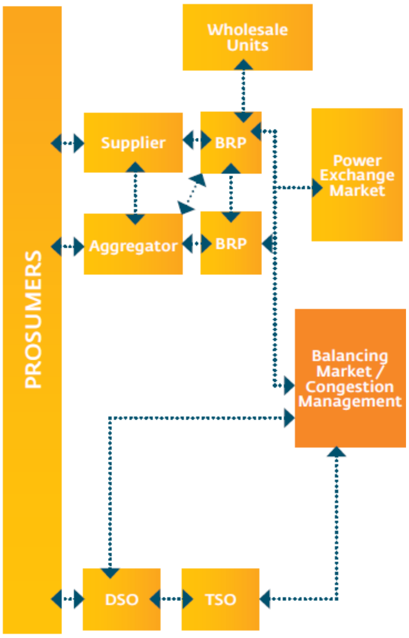

FIGURE 8 – COMBINED BALANCING BIDS AND CONGESTION MANAGEMENTS

The main advantages of this model are high liquidity, easy access for existing market parties and a single-entry gate, low price of congestion management bids due to merging with balancing market.

The disadvantage of the proposed model lies in complexity of governance, implementation and performance. Moreover, the problem is mixing balancing and congestion management cost due to different settlement rules.

8.1.2. Combined TSO and DSO congestion management

On the other hand, in this approach the balancing market is aware of the local information, but the balancing bids cannot be used for local congestion management or the balancing market is completely unaware of the local situation, however the bids for congestion management from the TSO and the DSO can be combined. The process is shown in Figure 9.

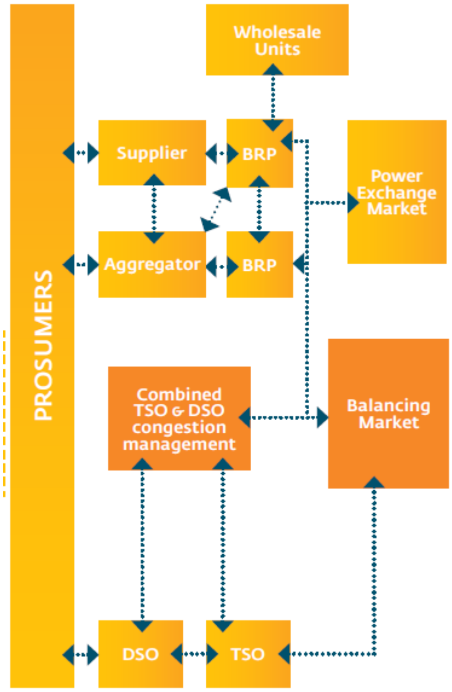

FIGURE 9 – COMBINE TSO AND DSO CONGESTION MANAGEMENT

The main advantages are that more flexibility and competition lead to lower cost, there is no need for the coordination of market parties between two congestion management process, the coordination between TSO and DSO is more efficient.

The disadvantages are shared governance, higher costs for congestion bids compared to Combined balancing bids and congestion management and the TSO and the DSO need to agree on product specifications which may differ between them.

8.1.3. Separate TSO and DSO congestion management

In this market model, the balancing market has no access to the local information and the bids for congestion managements cannot be combined. The model is demonstrated in Figure 10.

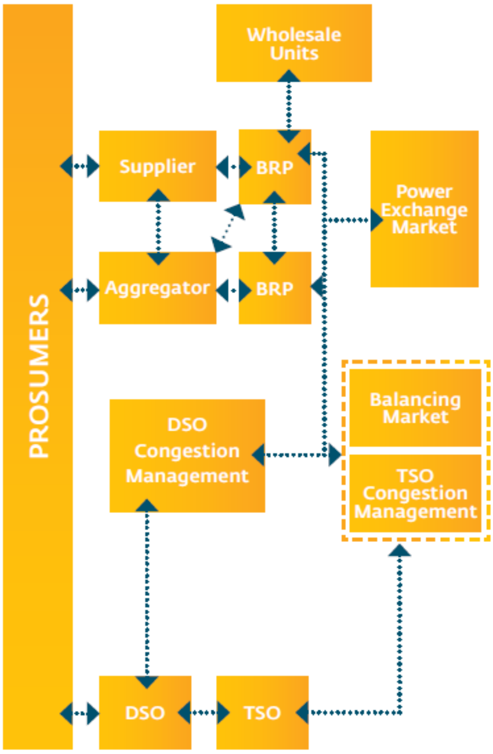

FIGURE 10 – SEPARATE TSO AND DSO CONGESTION MANAGEMENT

The main advantages of this model are clear division between the balancing and congestion management and separated governance, clear congestion management costs and low entry barriers for small local market parties.

The disadvantage of separate TSO and DSO congestion management is small liquidity in local markets which may result in high prices because the entities can participate only in the TSO or DSO congestion management market. Moreover, 'locking' the resources in local market makes them unavailable for other market services. The coordination between system operator is more difficult in this approach compared to combined and separate TSO and DSO congestion management. Furthermore, possible extra interfaces for market parties due to separate bidding systems (either for transmission or distribution level) might be required.

8.2. Counterbalancing congestion management actions

Providing flexibility services in order to solve system imbalance can result in negative portfolio imbalance. If the market participants cannot solve it, the imbalance can be counteracted by the service provider, by the system operators using flexibility product or by the TSO (in all cases). The cost efficiency can be improved if two separate completions on upward and downward bids exist. Day-ahead and intra-day corrections are more suitable for FSPs, while real-time corrections for system operators.

8.3. Coordination between balancing and congestion management

If balancing and congestion management are fully separated, as in separate and combine TSO and DSO congestion management, flexibility providers choose the market process in which they want to bid. They are-self responsible for preventing the double action in opposite direction, otherwise they will be penalized.

If the market processes are coordinated or combined, the coordination is performed by the party which is in charge of market operation. Flexibility providers can submit their bids only once and it is determined where the bid is most useful. This coordination can be done in the commercial (operated by MO) and regulated domain (operated by the system operator).

Two possible approaches can be adopted in the coordination between balancing and congestion management: skipping bids or co-optimization. Skipping bids refers to non-activation of the balancing bid that would cause the congestion. The problematic bid is skipped and the following cheapest bid is activated. On the other hand, co-optimization includes an overall assessment of congestion and balancing bids resulting in avoiding counter activation and double activation.

9. Provision of the services in each coordination scheme

The provision of several ancillary services can be divided in several steps: prequalification, procurement, activation and settlement in each coordination scheme [10]. The focus was put on providing several flexibility services from the resources connected to the DG to the TSO: frequency restoration/frequency control (aFRR, mFRR and RR), congestion management and voltage control. Moreover, the use of flexibility resources was investigated also for local congestion management performed by the DSO. Table 8 presents which ancillary service is feasible for described coordination mechanisms. Providing balancing and congestion services is possible in each coordination market model, but frequency and voltage control are not possible for some coordination schemes.

TABLE 8 – FEASIBILITY OF EACH SERVICE PROVISION FOR DIFFERENT COORDINATION MECHANISMS

	Congestion management	Frequency control	Voltage control
Centralized AS market model	+	+	-
Local AS market model	+	-	+
Shared balancing responsibility model	+	-	+
Common TSO-DSO AS market model	+	+	+
Integrated flexibility market model	+	-	-

Voltage control is used by both the DSO and the TSO. Since in the Integrated flexibility market model both regulated and deregulated market participants can participate, this scheme is not relevant for voltage control procurements because only system operators would bid for the services (systems operators would be only buyers).

Moreover, as the frequency control is the responsibility of the TSO, the Local ancillary service market model and the Shared balancing responsibility model are not relevant for this service because the DSO would not procure it and DER connected on the DG level cannot provide services to the TSO.

The Centralized ancillary service market model is not applicable for voltage control because the TSO would not be able to control the voltage with direct activation of resources connected to the DG.

As it can be seen from Table 8, the Common market model enables the provision of all ancillary services.

10. Regulatory barriers

It is of significant importance to remove all the barriers for the participation of distributed resources in the ancillary service market in order to have transparent market with increased liquidity and more flexibility options.

Directive (EU) 2019/944 of the European parliament and of the council of 5 June 2019 on common rules for the internal market for electricity and amending Directive 2012/27/EU [7] defines the roles and responsibilities of the DSO in the Article 31:

"The DSO is responsible for the procurement of products and services which are necessary for the efficient, reliable and secure operation of the distribution system in objective, transparent and non-discriminatory way and in coordination with the TSO and other market participants. The DSO shall procure the non-frequency ancillary services in transparent, non-discriminatory and market-based procedure, unless the regulatory authority has assessed that the market-based provision of non-frequency ancillary services is economically not efficient and has granted a derogation. The provision of non-frequency ancillary services shall include the participation of all qualified market participants, renewable energy resources, demand response providers, operators of energy storage units and market participants engaged in aggregation. DSOs shall cooperate with TSOs for the effective participation of market participants connected to their grid in retail, wholesale and balancing markets."

Moreover, the roles and responsibilities of the DSO and the TSO should be expanded. Today, the DSO does not contract flexibility service to solve local network problems because of the DSO cost structure in which ancillary service procurement is not refunded because it is not considered as operational expenses. It is of the outmost importance to remove that barrier in the regulatory policies to ensure the profitability of ancillary service procurement in the DG management. To overcome this issue, Article 32 in [7] suggests a new regulatory framework in each Member State to allow and provide incentives to DSOs to procure flexibility services in their operating area to improve efficiencies in the operation and development of the distribution system. The procurement of ancillary services should be in a non-discriminatory, transparent and market-based procedure and the framework shall ensure this procurement from distributed generation, demand response or energy storage. The information exchange and coordination between TSO and DSO is necessary in order to ensure the optimal utilization of resources, secure and efficient system operation and facilitate market development. DSOs shall be adequately remunerated for the procurement of such services to allow them to recover at least their reasonable corresponding costs, including the necessary information and communication technology expenses and infrastructure costs. The network development plan shall also include the use of demand response, energy efficiency, energy storage facilities or other resources that the DSO is to use as an alternative to system expansion. The network development plan should be established in coordination with all relevant system users and the TSO.

However, DSOs still do not use flexibility from DER, while the provision of these services to the TSO is still very limited. In order to overcome these issues, the DSO needs to investigate the economic incentives to use the local flexibility. In order to efficiently use the flexibility from the resources connected to the DG, the coordination between TSO and DSO needs to ensure that actions taken from one system operator does not have a negative impact on DG and TG. The rules for aggregation, market product definition and market mechanisms must be established and clearly defined [12].

European directives emphasize the importance of coordination between DSOs and TSOs [7]. Their cooperation shall be established in all stages, from planning to operation. The information exchange between system operators should include performance of generation assets, demand response, long-term planning of network investments in order to ensure the cost-efficient, secure and reliable development and operation of TG and DG. Moreover, coordinate usage of resources connected to the DG can satisfy both TSO's and DSOs' needs. Regulations regarding reserve providing groups or units connected to the DG is detailly elaborated in Chapter 3.

However, the DSO cannot participate on the market as both the service provider and the MO at the same time (the DSOs cannot buy or sell the service provided by them) [13].

System operators are not allowed to own or operate energy storage units because energy storage units should be competitive and market-based. However, the energy storage unit as a fully integrated network component is essential for the system operator to ensure reliable and secure network operation, and thus it cannot be used for congestion management or balancing. Moreover, a special case in which the regulatory authority may allow the DSO to own the storage unit must fulfill several conditions: other entities in transparent and non-discriminatory tendering procedures have not been awarded a right to own, develop, manage or operate energy storage or other possible flexibility providers, or could not deliver these services at a reasonable cost and in a timely manner.

The establishment of joint DSO-TSO optimization for the Common TSO-DSO ancillary service market model is crucial in order to minimize the total cost for both the TSO and the DSO while considering the investment in the new units or network reinforcement and flexibility service provision from resources connected to both TG and DG. It is also important to extend the role of the DSO from the system operator to an aggregator who acts on behalf of the TSO to support the implementation of the Local ancillary service market model and the Common TSO-DSO market model. Moreover, it is not regulated by the low that DGs constraints should be respected. To ensure system prequalification and active blocking, this regulatory barrier should be removed.

Regarding regulatory barriers, in the Centralized AS market model no process for prequalification or active blocking of bids by DSOs is defined by law. In the Local ancillary service market model, there is no cost remunerations for DSOs who contract flexibilities and the DSO is not allowed to be an aggregator on behalf of the TSO. When it comes to balancing responsibility, nowadays the TSO is the only entity responsible for system balance, which has to be changed for the Shared balancing responsibility model. Moreover, the DSO, as flexibility contractor, does not have any cost remuneration. In the Common TSO-DSO ancillary service market model, there is no common cost objective for TSOs and DSOs; the DSO is not remunerated for the flexibility and the DSO is not allowed to be an aggregator on behalf of the TSO. Commercial market players are not allowed to participate in ancillary service market which is the main barrier in the organization of the Integrated flexibility market model. Moreover, there is no cost remuneration for DSOs who contracts flexibilities, no process for prequalification or active blocking of bids by DSOs defined by law and allowing TSOs and DSOs to resell previously contracted flexibility to the market.

The Centralized ancillary service market model is the closest to adoption due to the lowest number of regulatory issues. Moreover, this coordination scheme is very similar to the already existing ancillary service market organization.

11. Projects

In the light of ongoing TSO-DSO coordination schemes issues a number of EU funded project introduced different TSO-DSO coordination schemes suitable for the exiting ancillary services market models within the EU. Table 9 presents an overview of the most relevant EU funded projects that to some extent analyzed coordination schemes between TSOs and DSOs. In-detail analysis of the project results is provided in the following subsections.

TABLE 9 – OVERVIEW OF THE MOST RELEVANT EU FUNDED PROJECTS

Project	Project description
SmartNet (H2020)	This project aims at providing architectures for optimized interaction between TSOs and DSOs in managing the exchange of information for monitoring, acquiring and operating ancillary services (frequency control, frequency restoration, congestion management and voltage regulation) both at local and national level, taking into account the European context.
FutureFlow (H2020)	FutureFlow links interconnected control areas of four TSOs of Central-South Europe which today do face increasing challenges to ensure transmission system security: the growing share of renewable electricity units has reduced drastically the capabilities of conventional, fossil-fuel based means to ensure balancing activities and congestion relief through redispatching. Research and innovation activities are proposed to validate that consumers and distributed generators can be put in a position to provide balancing and redispatching services, within an attractive business environment.
INTERFACE (H2020)	The INTERFACE project will design, develop and exploit an Interoperable pan-European Grid Services Architecture (IEGSA) to act as the interface between the power system operators (TSO and DSO) and the customers and allow the coordinated operation of all stakeholders to use and procure common services.
CoordiNET (H2020)	The purpose of CoordiNET is establish different collaboration schemes between TSOs (TSOs), DSOs (DSOs) and consumers to contribute to the development of a smart, secure, and more resilient energy system. Special emphasis will be on the analysis and definition of flexibility in the grid at every voltage level ranging from the TSO and DSO domain to consumer participation.
SmarterEMC2 (H2020)	The goal of the project is to provide ICT tools and solutions compatible with standardization activities in Europe. The focus of the project is put on ICT tools implementation which support both RES integration and Customer Side Participation. The tools consider the SGAM architecture and the future structure of the DG. The project supports standardization by proposing adaptation to data models of market-oriented standards (IEC 62325-351) and field level standards (IEC 61850).

TDX-ASSIST (H2020)	This project aims to design and develop novel Information and Communication Technology (ICT) tools and techniques that facilitate scalable and secure information and data exchange between TSOs and DSOs.
EU-SysFlex (H2020)	The project is focused on integration of large-scale renewable energy sources. It will identify the problems and investigate possible solutions in providing assistance to system operators and present novel market approaches in the system with high integration of renewable energy sources including regulatory barriers, data management and integration of new devices.
evolvDSO (FP7)	The goal of the project is to define and develop the roles of DSO in the future system with the different integration level of DER. The innovative tools and methods are related to planning, operation scheduling, real-time operation and maintenance in the DG.
CROSSBOW (H2020)	The project's goal is to propose the shared use of resources to foster cross-border management of variable renewable energies and storage units, enabling a higher penetration of clean energies whilst reducing network operational costs and improving economic benefits of clean energies and storage units.
InterFlex (H2020)	The project aims to develop new solutions for broader integration of DER and prepare the power system for new consumers, such as electric vehicles.
GOFLEX (H2020)	The project's goals are to accelerate the GOFLEX technology in Europe and establish a market for distributed flexibilities and automated dynamic pricing in order to improve the secure energy supply.
FlexPlan (H2020)	The focus is put on establishing a new grid planning methodology that considers the opportunity for introducing new types of flexibility as an alternative to traditional network planning approach which includes investments in the grid.
EUniversal (H2020)	The focus of the project is put on the potential of electricity grids to lead the energy system transition towards green power systems. New solutions deal with the challenges related to flexibility, grid observability and controllability, market mechanisms and interoperability in a holistic way covering the technological aspects by linking smart and integrated services and tools for DG with market mechanisms.

11.1.SmartNet

In Smart Net project, three different pilots were investigated. The first pilot in Italy used centralized ancillary services market. The second pilot in Denmark used Common TSO-DSO ancillary services market, while the third pilot in Spain used shared balancing responsibility ancillary services market model.

In the first project, hydro power plants were used as distributed flexibility providers for voltage and frequency control for TSO, while the main focus of the project was put on information aggregation for TSO, TSO-DSO communication and assessment of DER capability to participate in markets.

In the second project, the focus was put on DSO congestion management and TSO frequency control through pumps for hot water in indoor swimming pools in rental house while trying to evaluate price signals from aggregators in order to obtain flexibility from distributed sources and to establish communication chain from market to distributer sources via aggregators.

In the third project, backup batteries for radio-based stations used in mobile phone communications were used for DSO congestion management and frequency control. The goal of the project was to monitor DG, to create and operate local flexibility markets and asses the base station to provide services in network operation.

11.1.1. The pilot project in Italy

The pilot project was located in South Tyrol, in the Ahrntal Valley. This region has a big hydropower potential for electricity production which is manifested during the summer as an overgeneration exceeding the local load and resulting in the reverse power flow. 132 kV and 20 kV voltage levels were included in the project. Two hydro power plants are connected to the HV substation (total installed capacity of 43 MW), while 23 smaller hydro power plants with total installed capacity of 29 MW to the MV level. This area is characterized with 5 DSOs operating the local DGs. Each DSO supplies a small number of consumers through hydro power plants connected to the DG. Demand at the interconnection points at the lower voltage level of HV/MV substations can be characterized as a power consumption of 17 MW. Big number of hydro power plants with high generation potential connected to the distribution level cause reverse active power flow from distribution to the TG almost during the whole year.

According to the described situation in the pilot project, the goal of the project was to install two real-time monitoring devices of in order to implement and investigate the potential of hydro power plants providing ancillary services for coordinated voltage regulation and the power/frequency regulation (automatic frequency restoration reserve, aFRR). The proposed coordination TSO-DSO scheme is the Centralized ancillary services market model operated by the TSO. The devices were installed in the HV part of the substation to control the reactive power of the two hydro plants directly connected to the HV level (High-voltage regulation system, HVRS) and in the DSO operation centre to allow monitoring and control of RES connected to the HV/MV transformers of the primary substation (Medium-voltage regulation systems, MVRS). HVRS was installed to test the coordinated voltage regulation provided by the hydropower plants connected to the sub-transmission grid. MVRS was installed for testing the computation of the dynamic capability of the aggregation of power plants connected to the DG, the voltage and the power/frequency regulation provided by the aggregation of hydropower plants connected to the DG. Moreover, 28 meters were installed for collecting measurements in 23 power plants and 5 connection points. 16 of them were installed at the connection point between the power plant and the grid to monitor the active and reactive power exchange, while 7 of them were installed at the terminal of the generator.

When it comes to regulatory policies in Italy, the voltage regulation has a hierarchical structure and only big power plants with specific devices capable of providing reactive power service and connected to the TG can provided secondary voltage regulation. To overcome this barrier, the HVRS device was installed to enable providing voltage control from hydropower plants connected to the DG. The communication between the TSO as the ancillary service buyer and the hydropower plants as the ancillary service provider is achieved through reactive power data exchange. The HVRS computes and sends the reactive power availability from the four generators to the TSO. The TSO is in control of the generators through a reactive power or voltage set points of HV part of the substation sent to the power plants. These set points can be in range between zero and 100% which characterizes the over-excitation condition requiring from the hydropower plants to generate reactive power to increase the voltage. On the other hand, if the set points are in the range between -100% and 0 (under-excitation condition) the hydropower plants need to reduce the voltage by absorbing the reactive power. The second approach includes set points as the optimal voltage value in kV. Based on the difference between the voltage set point and real-time voltage measurement, which is reflected as an error, the HVRS converts the set point in a reactive power command taking into account the correlation between the production/consumption of reactive power and the voltage error. Even though some delays and overshoots in the hydro power plants response have been experienced, the HVRS was a successful device in coordination between the TSO and reactive power exchange of hydro power plants as an ancillary service provider.

MVRS calculates the dynamic capability of the aggregated distributed generation defined by the active and reactive power limits. These limits are used for informing the TSO if the active and reactive power can be activated for ancillary service provision. In order to calculate the maximum available capability while taking into account the nominal capability of each power plant, the operational status and the constraints of the grid, load flow calculations are run continuously. The ancillary service can be provided only if its activation does not violate any of DG constraints. If the violation is detected, the MVRS takes actions on hydro power plant central regulators or on the transformer's tap changers making this approach monitored and controllable in real-time in order to respect DG constraints. After the calculation of the dynamic capabilities, hydro power plants are allowed to participate in voltage and power/frequency regulation. The MVRS's voltage regulation is similar to HVRS approach. The reactive power exchange of distributed hydro power plants is controlled in order to regulate the HV side of the MV/HV transformer at the primary substation. This reactive power control can reduce the waste of reactive power reserve. Moreover, it is very important to point out that this approach allows the control of power flow and ensures that DG constraints are not violated, even though the TSO is not directly involved in the operation of this part of the grid.

In Italy, aFRR can only be provided by programmable power plants greater than or equal to 10 MW and connected to the HV grid, while RR can be provided by DER which enables the MVRS to participate in the power/frequency regulation. However, this pilot project tested the provision of aFRR from aggregated hydro power plants connected to the DG as described in the following sentences. The national regulator sends a tele-signal to the MVRS every 4 seconds, while each hydro power plant determines the active power band available for regulation in order to change the active power production around the programmed value. This programmed value was defined as the last active power measurement before the start of the test due to absence of the market baseline. The deviation from the nominal frequency is taken into account in the set point calculation. The values can range between 0 and 100%. If the set point is 0 as the lower limit of the band, to reduce the generation the minimum production power is made available for downward service. If the set point is 50, no activation is needed because it is in the line with the programmed production. Finally, if the set point is equal to 100 as the upper limit of the band, the maximum production power is made available for upward service in order to increase the generation. However, the hydro power plants are used only for the downward reserve in order to avoid maintaining a margin between the operating point and the maximum production. The results show that hydro power plants connected to the DG were able to provide more than 6 MW of the service. On the other hand, some significant problems were detected, such as delays in the communication and the inaccurate regulation of the power plant governor resulting in the dynamic response not complied with the technical requirements of the service. When it comes to the reliability and the quality of the regulation at the interconnection point, they are affected by different uncontrollable and unforeseeable elements in the grid, and not only by the performance of the hydro power plant.

Main conclusions derived in this pilot projects regarding different aspects are described below.

Even though the same communication protocol was adopted between the TSO, the substation automation system, the HVRS and the control systems in hydro power plants, the difference between devices from different manufacturers were distanced. The availability and reliability of the telecommunication network is essential respecting safety and quality standards required from the TSO. The technical results of the project show the benefits of HVRS implementation due to the fact that the TSO was able to use the reactive power control of different plants connected to the same substation in order to securely and efficiently operate the network. The local equipment in the DG is needed to reduce the delays and overshoots in the power plants response to requested reactive power change. As the grid is resistant against the activation in the sub-TG and renewable sources are limited in ancillary service provision due to their technical characteristics, the impact on the grid voltage is not comparable to the current practice in which the voltage regulation is provided by traditional power plants.

It is important to have a real-time monitoring in the DG in order to safely control distributed resources to ensure the network operation without violating the constraints. The problem occurs with different time stamps in the process of monitoring ancillary services and measurements updating. The aggregated measurements are updated every 20 seconds at the interconnection point, while the monitoring for the provision of ancillary service is sending the set point every 4 seconds which results with not verified aggregated response. Moreover, the response of renewable power plants is not consistent with the requirements of the services in terms of delay and accuracy which requires the improvement of the technical performance and the capabilities of distributed resources. Also, the availability of RES capability to provide the ancillary service is questionable due to their intermittent nature. It is necessary to make a production plan together with the other source of flexibility which is programmable and controllable. However, the approach demonstrated in this pilot project presents the provision of ancillary services from distributed resources without violating DG constraint with real-time power flow calculations. The local voltage control resulted in improved voltage profiles in the DG through the reactive power regulation in the resources connected to the DG. Moreover, the results of the project demonstrate the successful TSO-DSO coordination in reactive power exchange, but it also highlights the importance of improving the dynamic response of power plants in order to satisfy the requirements for ancillary service provision.

11.1.2. The pilot project in Denmark

Two different control mechanisms can be distinguished. The direct control implies that the signal sent from the aggregator requests the service from the flexibility resource (to be turned off or on). The indirect control used in Denmark is based on an economic optimization performed by the flexibility resource which can decide if it wants to provide the required service or not. The Danish pilot used Smart-Energy Operation-System (SE-OS) to integrate the top-down one-way communication from aggregators to distribute resources using price-based control method. A control signal can be a price or a penalty reflecting the real time CO_2 footprint. The optimization function can be modelled as cost and emission minimization or energy efficiency maximization.

When the market is cleared, the MO sends the information about prices and accepted bids to an aggregator. As this approach is based on the indirect control with one-way communication, the price signal is sent from an aggregator to flexibility resources, affecting the whole load of the flexibility resource during the time of the activation. As the flexibility owners can decide either they want to provide the service or not, it is important that the price control signal economically stimulates the resources to reduce or increase the consumption. There is no feedback requested from the DER side. Each flexibility resource runs the cost optimization continuously with the received price signal for every time interval. The aggregator must predict the response from the DER based on a given price signal calculated in flexibility function which estimates the response on historical data.

Model predictive control and short-term simulations of pool temperatures are modelled with the grey-box. Compared to the black or the white box modelling, in the grey-box formulation, the state of the model can be estimated and simulated in the real-time, parameters can be estimated based on real-time data and risk measures can be taken into account with specification of the uncertainty of the evolution of the states. The Danish pilot uses the flexibility of indoor swimming pools in summerhouses. Multiple requirements are necessary for establishing the model: technological requirements, availability of meteorological data, having access to the electricity market price data (MO), real-time data from flexibility providers, visualization tools and having a reliable communication network.

The results of the project show that energy flexibility can reduce the $C0_2$ emission for at least 10% and utility bill for 8-12%. The indoor pool heating is turned on when the CO_2 intensity is low. These savings sometimes cannot be sufficient for small consumers and it is of significant importance that regulation encourages the provision of ancillary services with tax break or lower electricity tariffs.

11.1.3. The pilot project in Spain

The goal of the pilot project in Spain was to demonstrate the ability of providing AS to DG from small-scale DER. In order to compensate DER for their services, shared balancing responsibility market model was organized on a software platform. In order to establish a successful communication between the DSO and the TSO, the energy exchange profile at the TSO-DSO interconnection point has to be defined making both of them responsible to follow the schedule, while taking care of congestion in their part of the grid.

Radio base stations for mobile phone communications in this pilot project were equipped with backup batteries to keep the communication service available in the case of electricity failure. Moreover, these batteries can supply the stations for at least two hours after the blackout.

The focus was put on solving congestion problems in DG and keeping the predefined schedule at a virtual TSO-DSO interconnection point in a simulated grid model based on the real grid model (there were no real congestion problems in the observed part of the grid). The real network was modified by adding additional DER and increasing consumptions to cause the congestion and to simulate flexibility service activation with simulated market prices.

Three main innovations derived in the project are: execution time, aggregation model and mathematical model of market clearing operated by the DSO as a MO which takes into account DG constraints and flexibility bids. The execution time was set to 5 minutes, i.e. close to real-time with high accuracy.

The pilot results show that the DSO is capable of keeping the predefined energy exchange profile at the TSO-DSO interconnection point while avoiding congestion in the observed part of the grid by exploiting the flexibility of backup batteries without investing in network reinforcement. The DER in this project were able to provide only the upward balancing (demand reduction), but not downward balancing. It is important that DSO monitors the system even at consumer level in LV network. Moreover, the novelty of this project was considering the network constraints in the real time, unlike other approaches which solve technical problems when the marked is cleared. The results show that presented business case is beneficial for DER owners and also for the DSO which can use the aggregated backup batteries for local congestion.

11.2. FutureFlow project

In FutureFlow project four European TSOs of Central-Eastern Europe (Austria, Hungary, Romania, Slovenia), associated with electricity suppliers, IT providers and renewable electricity providers collaborated closely together in the design of a unique regional cooperation scheme. The main goal of the proposed regional cooperation scheme is to open Balancing and Redispatching markets to new sources of flexibility. Furthermore, the intention of this cooperation scheme is also to ensure that new sources of flexibility act on such markets competitively. In that regard, aggregation platform was developed to enable flexibility providers, i.e. distributed generators and commercial and industrial consumers providing demand response (DR), to provide competitive offers for FRR. In this scheme suppliers act as flexibility aggregators and pool the resources in order to provide the products required by the TSO. Furthermore, a common activation function was implemented into techno-economic model to enable cross border integration of such services. By and large, the proposed Regional and Redispatching platform can be considered as Common TSO-DSO ancillary service market model with emphasis on decentralized scenarios.

The main tasks of the FutureFlow project are illustrated in Figure 11.

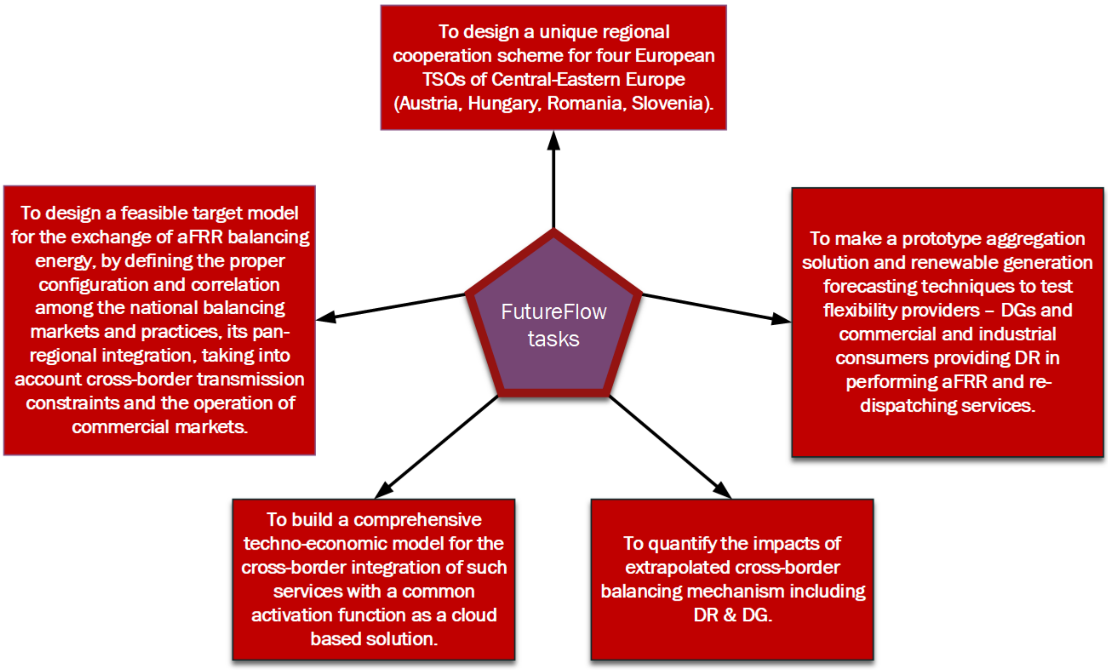

FIGURE 11 – FUTUREFLOW PROJECT MAIN TASKS [14]

As a part of FutureFlow project SAP developed and built the regional balancing and redispatching platform using a scalable architecture. Furthermore, the platform is deployed in the SAP Cloud Platform. The main functionalities that are integrated in the platform are redispatch simulation tool and real-time balancing system. A database is also integrated in the platform that stores all the received data or the data generated in the real-time balancing system. During the balancing procedure TSOs involved in the project send XML-encoded data via an API over MQTT over Secure Web Sockets. A graphical user interface (GUI) in a form of a web page is available not only before gate-closure-time but also during real-time operation for TSOs to take corrective action. In addition, the redispatch tool is also available via GUI. The main purpose of this tool is to use received inputs uploaded from user files, run redispatching procedure and export the results of redispatching. Since security questions are vitally important all communication channels to the SAP Cloud Platform are secured with transport layer security. Since FutureFLow is also a development project the outcome of the project will include prototype solutions applicable in practice. In that regard a field tests involving control areas of the four TSOs that are partners in the project were carried out.

Figure 12 illustrates the overall architecture of the regional and redispatching platform introduced in the FutureFlow project. The architecture of this platform will serve as a good starting point for the development of the ATTEST toolbox.

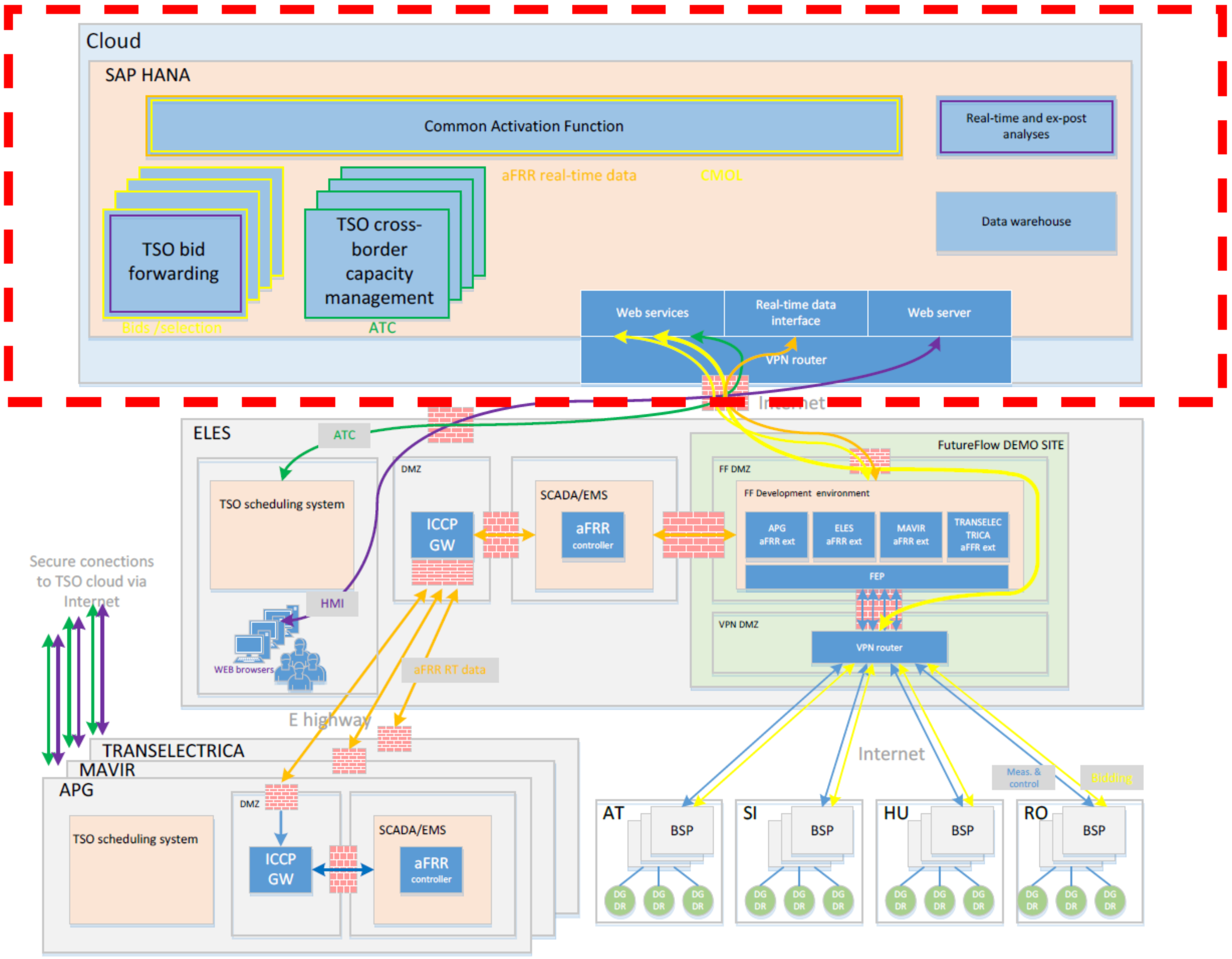

FIGURE 12 – FUTUREFLOW OVERALL ARCHITECTURE [14]

11.3. INTERFACE - TSO-DSO-Consumer INTERFACE aRchitecture to provide innovative grid services for an efficient power system

INTERFACE project main goal is to design, develop and exploit an Interoperable pan-European Grid Services Architecture (IEGSA) to act as the interface between TSOs, DSOs and the customers. IEGSA will allow seamless and coordinated operation of all stakeholders to use and procure common services. In that regard, the project main technical and operational objectives are listed as follows:

- To design IEGSA that will connect market platforms in a transparent, non-discriminatory manner and will allow a pan-European electricity exchange that links wholesale and retail markets and enables trading of energy services;
- To design, develop and deploy a reference IT infrastructure;
- To test state-of-the-art digital technologies, e.g. blockchains and IoT, for peer to peer energy transactions that promote local markets and smart asset management;
- To mitigate congestions and activate local flexibility resources for system balancing services through innovative platforms, operated by TSOs and DSOs in a coordinated manner;
- To promote the integration of DER into the electricity markets, demonstrating mechanisms and platforms leading to the establishment of a seamless pan-European Market empowering all market participants to provide energy services in a transparent and non-discriminatory way;
- To demonstrate the IEGSA components and architecture and the relevant IT infrastructure;

In order to design IEGSA architecture an analysis of existing tools and services was conducted to provide in-depth insights on the various developments of tools and services used by different operators and other actors of the energy value chain for data collection and delivery. In that context, different tools and services were listed and analyzed to ensure that their use through IEGSA satisfies the transparency needs of new actors, e.g. DER, Prosumers, ESCOs and DSOs.

In this analysis services were divided into services provided by the TSOs and DSOs and the services utilized by the TSOs and DSOs. Services provided by the TSOs and DSOs are DataHub and flexible grid connection contracts. DataHub is an emerging service provided by TSOs, DSOs or third parties to collect and share smart meter data. The main idea behind this service is that actors responsible for metering submit metering data to DataHub where it becomes accessible for the relevant actors. The main intention of using a flexible grid connection contract is to avoid or postpone grid reinforcements while enabling a connection to a new customer who is willing to behave in a flexible way. TSOs use flexibility services in frequency control and reserves, balancing of power system, capacity reserve, voltage control and congestion management, while at the same time DSOs are utilizing flexibility services in congestion management and voltage control. In addition, the analysis made in this project provided in detail overview of the ancillary services available in the European countries. Parameters of the following standard reserve products with emphasis on different European TSOs were analyzed:

- Frequency Containment Reserve;
- Frequency Restoration Reserve;
- Restoration Reserve;
- Black start capability;
- Reactive power and voltage control.

In addition, an overview of the international co-operations for provision of ancillary services was also provided. Table 10 gives an overview of the platforms for activation of ancillary services.

TABLE 10 – INTERNATIONAL CO-OPERATIONS [15]

	Platform	
Primary control	**Primary Control Reserve (PCR)** is a cooperation for primary control procurement on a Central Clearing System (CCS) platform.	
Secondary control	**International Grid Control Cooperation (IGCC)** realizes imbalance netting to avoid simultaneous activation of reserves in opposite direction. As a consequence of that it reduces the volume of control reserve activation that leads to cost reduction. The procurement of control power stays at national level.	**PICASSO** is a common platform for aFRR activation. This platform will probably replace IGCC. The main intention of this platform is to realize a common merit order list for aFRR activation in order to minimize the control energy cost on European level.
Tertiary control	**Manually Activated Reserves Initiative (MARI)** is envisioned as a common platform for mFRR activation. The procurement of the mFRR will stay under national regulation but the product has to unified in the member states.	**TERRE** is a central clearing platform for RR in Europe. The RR provision and procurement will take place at national level. The TSOs involved in this project are developing an IT platform and optimization algorithm called LIBRA to realize this.

In general, services provided or utilized by the TSOs and DSOs may be realized as mandatory requirement, as a voluntary bilateral contract, or as a market-based solution. Provision of metering data is a good example of a mandatory services of the TSOs and DSOs. Furthermore, market-based solutions are more common choice for services on national or international level. Reserves, balancing, and congestion management are typical examples of services that are commonly organized as a market-based solution. When it comes to congestion management and voltage control TSOs and DSOs usually use power system simulation and analysis tool that allows them to perform a wide variety of analysis functions, e.g. power flow analysis, short circuit calculation, contingency analysis, optimal power flow, transient stability analysis, voltage stability, etc. ENTSO-E Communication and Connectivity Platform (ECCo SP) platform enables communication between business applications, and it is mainly used to ensure data exchange between TSOs. ECCo SP consists of two components:

- ECP (Energy Communication Platform) – this platform provides message delivery capabilities with security, compliant with technical specification IEC 62325-503 for transparent message exchange;
- EDX (Energy Data eXchange) - its distributed messaging system allows the transfer of messages between ECCo SP network participants, support the integration through MADES, FTP, AMQP or web-services.

Since market tools will also be integrated within IEGSA platform a special emphasis, in the analysis conducted within this project, was placed on market tools, in particular on XBID program.

XBID is a platform that enables continuous intraday cross-border trading across Europe. The platform is designed as a common IT system with one Shared Order Book (SOB), a Capacity Management Module (CMM) and a Shipping Module (SM). Therefore, the orders submitted by market participants for continuous matching in one country can be paired with orders similarly submitted by market participants in any other country within the project’s reach. This will always be realized under the assumption that transmission capacity is available. XBID supports both explicit and implicit continuous trading. The structure of intraday-cross border market is illustrated in Figure 13.

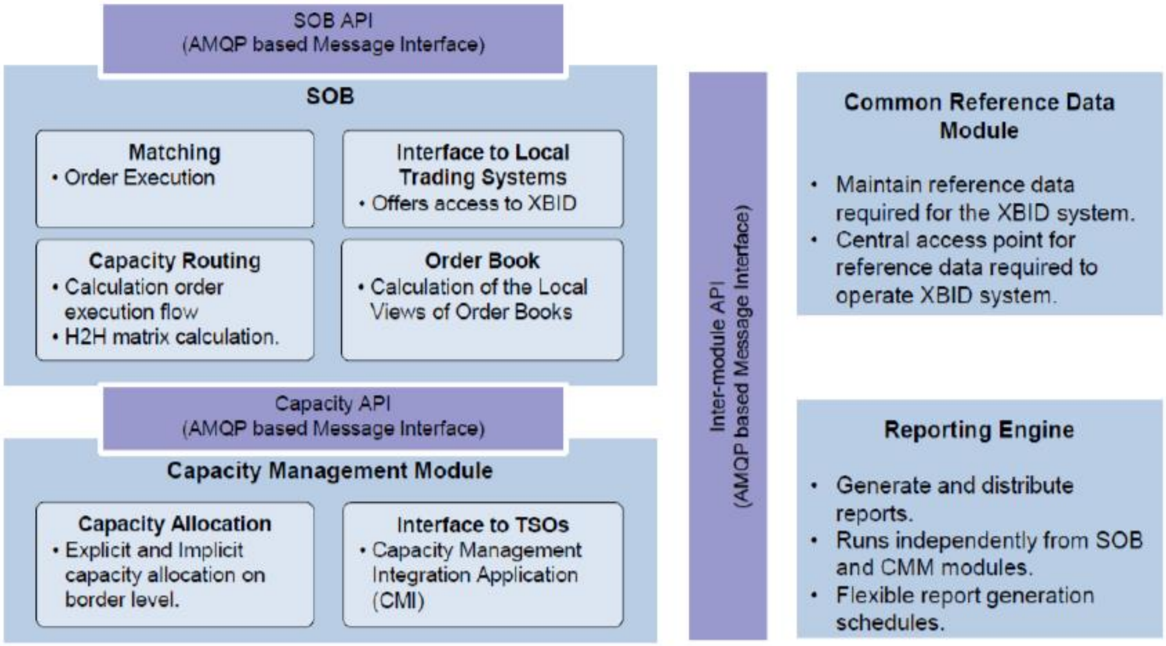

FIGURE 13 – STRUCTURE OF INTRADAY CROSS-BORDER MARKET [15]

11.4.CoordiNET

In CoordiNET project the main goal is to introduce different collaboration schemes between TSOs, DSOs and consumers to contribute to the development of a smart, secure, and more resilient energy system. The project is specially focused on the analysis and definition of flexibility in the grid.

The CoordiNET main objectives are listed as follows:

- Contribute to a smart, secure, and more resilient energy system through demonstrating cost-efficient models for electricity network ancillary services that can be scaled up to include networks operated by other TSOs and DSOs;
- To opening up significant new revenue streams for consumers and generators to provide grid services;
- To increase the share of RES in the electricity system.

The project will demonstrate how DSOs and TSOs by acting in a coordinated manner can provide favourable cooperating conditions to all actors while at the same time removing obstacles to participation for customers and small-scale market players connected to DGs. In that regard, the project provided a detail overview of different coordination schemes between TSOs and DSOs. Based on the coordination schemes introduced in SmartNet project seven groups of coordination possibilities have been identified in the CoordiNET project. The proposed coordination schemes are service-agnostic so that they can be applied to different services or even a combination of services, always maintaining a SO-viewpoint. An overview of the coordination schemes considered within the CoordiNET project is provided in the Table 11.

TABLE 11 – CATEGORIZATION STRUCTURE OF COORDINATION SCHEMES CONSIDERED WITHIN COORDINET PROJECT [16]

	Which SO-needs will be addressed?	Which stakeholder buys the flexibility to answer the considered needs?	How many markets are considered?	Does the TSO have access to DER?
Local Market Model	Local need	DSO	1	NA
Central Market Model	Central need	TSO	1	Yes or No
Common Market Model	Local and central need	DSO and TSO	1	Yes
Multi-level Market Model			>1	Yes
Fragmented Market Model				No
Integrated Market Model		DSO, TSO, and commercial parties	1	Yes
Distributed Market Model	Local need	Peers	>1	NA
	Local and central need			

Additionally, the project analyzed alternative coordination schemes. Table 12 gives an overview of existing alternative coordination scheme compared to the corresponding SmartNet scheme. Table 12 focusses on coordination schemes that are different from the SmartNet project schemes. It indicates to which SmartNet project scheme the coordination scheme discussed resembles, and then details how it differs from the indicated scheme. The result of Table 12 is an overview of possible extensions to or different highlights of the existing SmartNet coordination schemes.

TABLE 12 – OVERVIEW OF ALTERNATIVE COORDINATION SCHEMES [16]

Alternative coordination scheme	Corresponding SmartNet scheme	Differences from SmartNet scheme
Total TSO model	Central market model	• TSO has full observability of all grids and performs a whole-system optimization at both grids
Minimized or minimal DSO model	Central market model	• DSO is responsible for the physical coordination of the TSO dispatch of DER according to the DG state
Market DSO model C1 (and C2) or Total DSO model	Central market model with elements of local market model (and the shared balancing market model)	• DER are aggregated to a minimum size to participate in the TSO economic dispatch or wholesale market • DSO provides coordination among DER aggregators within local distribution area; or DSO is a (technical) aggregator • DSO autonomously operates its network and distributed RES below the T-D interface
Full integration market model	Central market model	• TSO takes physical DG constraints into account in the procurement process • Central market could also be operated by a new MO
System Balancing Cost Allocation based on the Cost-Causality Principle	Shared Balancing Responsibility Model	• The coordination scheme proposes an alternative for the pre-defined schedule. It focusses on a cost-causality principle for the DSO in which the user pays a use of

		system charge depending on his side-effects on system balancing.
Enhanced Bulk Balancing Authority (BA) Model variant A	Centralized market model	• The DSO provides the system BA (system balancing authority) with complete information regarding the status of the DG. • The BA accounts for all distribution system conditions • The BA dispatches all resources
Enhanced Bulk BA Model variant B	Centralized market model	• Same as variant A, but BA dispatches orders to the DSO who executes them
Hybrid model	Common TSO-DSO market model – decentralized variant	• BA and DSO share balancing responsibility • The actor with the highest marginal value will execute, and the other will settle for a sub-optimal and feasible order
Separated TSO and DSO congestion management	Local Market Model	• DSO Congestion Management is separated from TSO congestion management and balancing
Combined TSO and DSO congestion management, with separated balancing	Common TSO-DSO market – decentralized variant	• Congestion management market for TSO and DSO needs • Streamlining the needs regarding market process and rules
Combined balancing and congestion management for all system operators together	Common TSO-DSO market - centralized variant	• This alternative CS encompasses the common market model, but it goes into more detail on locational information, emphasizing the combination of bids and actions on balancing and congestion management in a market-based process
Single Flexibility Market Place	Common TSO-DSO market – centralized variant	• Bids can be distinct for balancing and congestion management, but could also be the same • Locational information is included for congestion management in relevant areas • Activation can be performed directly from the SOs or from the flexibility marketplace, depending on the adopted implementation decisions
Sequential Design, TSO-DSO Mechanism, and TSO-DSO-Retailer Mechanism	Integrated Flexibility Market Model	• No fundamental change from the core assumptions of SmartNet model, but focus on alternative sequences / options in which flexibility could be procured
Regional Reserve Market Plus	Centralized market model	• Products are expanded with a geographical component • DSO has access to the platform for own congestion management if he provides information to the TSO
Cascade model	Local Market Model	• The remaining resources of the local market for congestion management are not offered to the TSO • Platform can also be operated by independent third party
Regional Intraday Plus market	Integrated flexibility market model	• Regional or local characteristics will be included in products on the regular Intraday-market (wholesale)

		- There is an integration of products (energy for balancing responsible party and energy for congestion management)
New flexibility platform	Common Market Model	- Flexibility platform exclusively for network congestion management (one product for both TSO/DSO) - Operated by an independent platform operator

11.5.Smarter Grid: Empowering SG Market Actors through Information and Communication Technologies (SmarterEMC2)

The goal of SmarterEMC2 is to implement tools that support the integration of consumers through Demand Response services and the integration of distributed generation units through Virtual Power Plants. The tools developed within the project will be based on Smart Grids Architecture Model (SGAM) as well as on the paradigm change in the management of the DG. The project explores whether the existing telecommunication infrastructure is sufficient to support in mass scale the emerging business models and Smart Grid services. Since TSO-DSO coordination mechanisms depend on the communication infrastructure the project findings in that context will be important.

Figure 14 illustrates the main tasks of the SmarterEMC2 project.

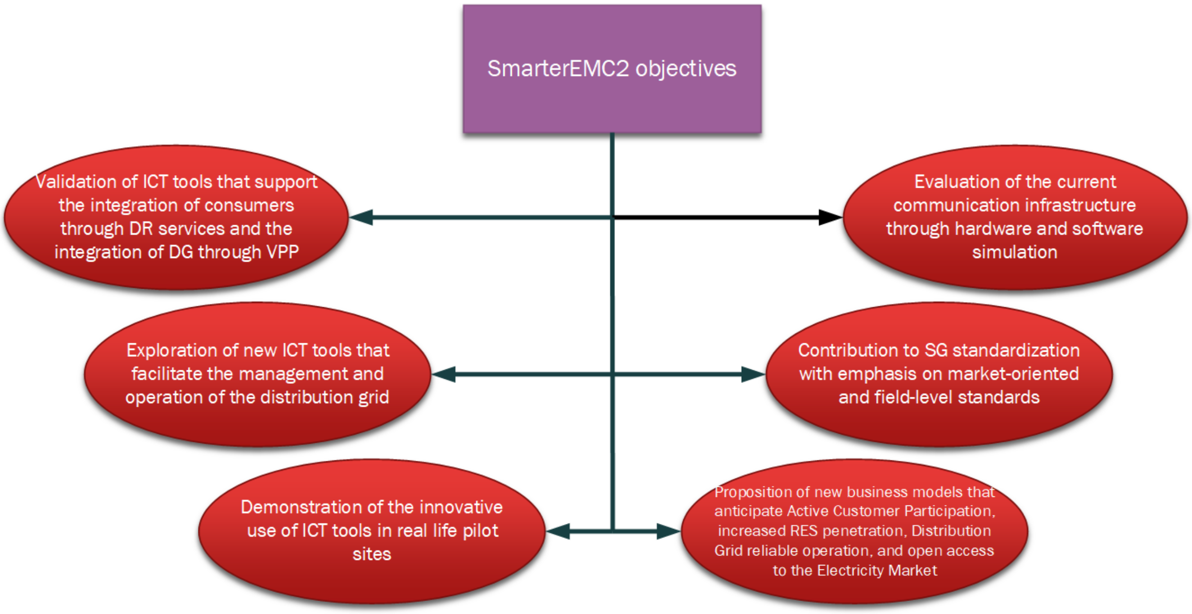

FIGURE 14 – SMARTEREMC2 PROJECT OBJECTIVES

Figure 15 presents high level conceptual architecture of the ICT tools developed in the project. Entire architecture introduced in the project is composed of different components, with interfaces to each other and to external systems.

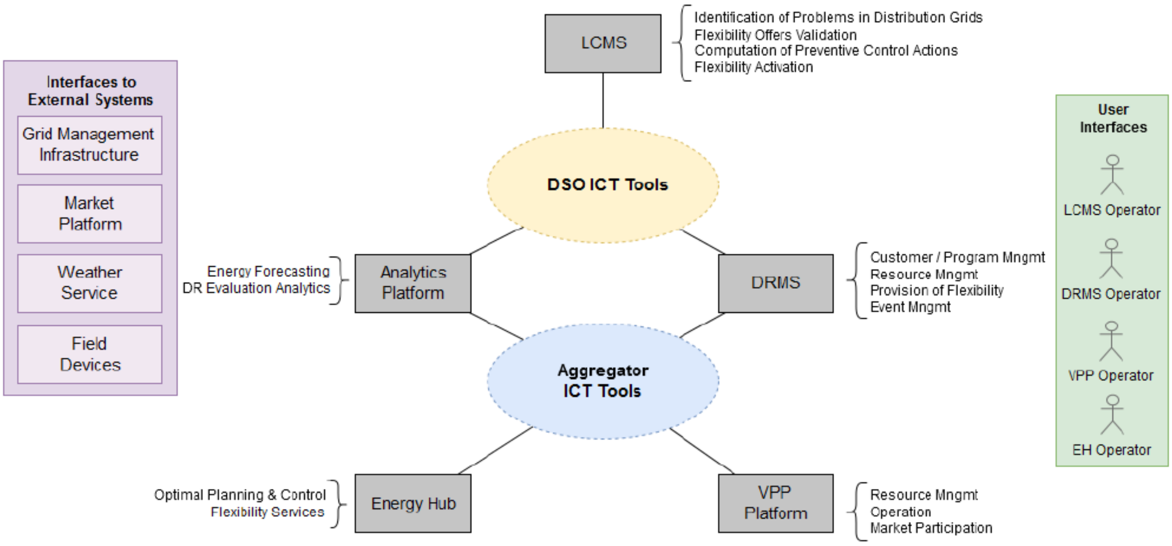

Figure 15 – SmarterEMC2 High Level Conceptual Architecture [17]

In Figure 15 VPP Platform represents a set of ICT tools that enables the operation of a number of components connected to the DG as an aggregated single entity, while Demand Response Management System (DRMS) is utilized for the provision of demand response services and realization of communications with DR resources. Furthermore, Energy Hub (EH) is a system that associates a certain number of prosumers with an objective to optimize local energy flows and minimize the economic costs. Local Congestion Management System (LCMS) are set of management and control tools that support the operation of a DSO for the specific case of solving local constraints in the DG in coordination with market participation. Analytics Platform (AP) provides a set of tools for energy forecasting related to consumption or RES production, the calculation of evaluation metrics, as well as visualization tools.

11.6.Coordination of Transmission and Distribution data eXchanges for renewables integration in the European marketplace through Advanced, Scalable and Secure ICT Systems and Tools (TDX-ASSIST)

The goal of TDX-AASIST project is to design and develop novel ICT tools and techniques to facilitate scalable and secure information systems for data exchange between TSOs and DSOs [18], [19] and [20]. Three novel aspects of ICT tools and techniques developed in this project are scalability, security and interoperability. The term scalability refers to ability to deal with new users and large volumes of information and data, while the security is the protection against external threats and attacks. Interoperability stands for information systems and data exchange based on international standards.

Figure 16 shows the smart grid architecture model's perspective. Each layer is represented with the Smart Grid Plane in which x and y axes define domains (generation, transmission, distribution, DER, customer premises) and zones (process, field, station, operation, enterprise and market). The z axe shows five different Interoperability layers and the interaction between them: business objectives and processes, functions, information exchange and models, communication protocols, and components.

The project specified TSO-DSO information exchange interfaces for highly automated information exchange and network analysis based on Use Case analysis and IEC 61970/61968/62325 standards and information exchange between DSOs and market participants based on Use Case analysis and IEC 61850/62325 standards to support highly automated information exchanges.

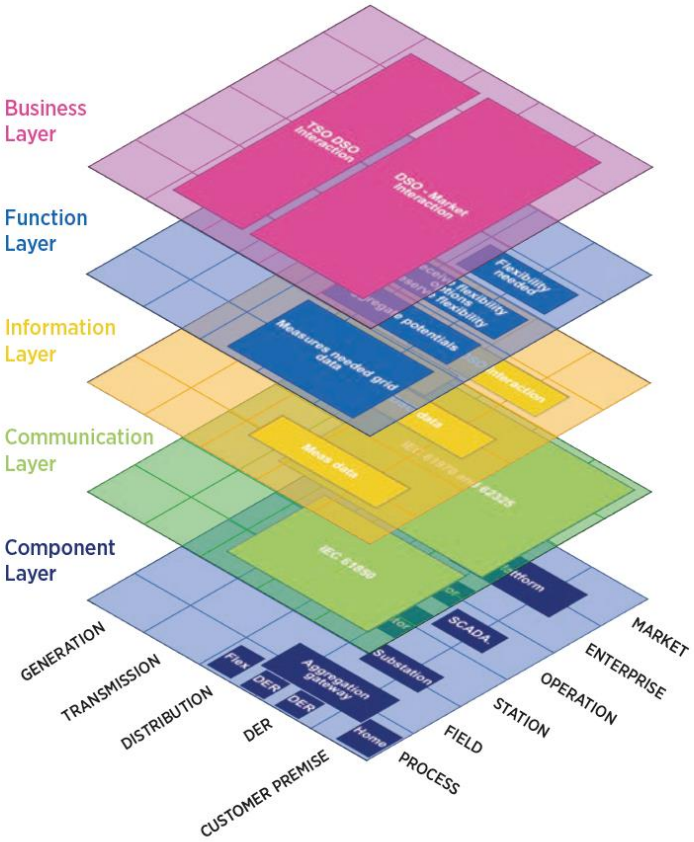

FIGURE 16 – TDX-ASSIST FROM THE SMART GRID ARCHITECTURE MODEL'S PERSPECTIVE

The project addressed 13 scenarios of DSO's interaction in the market regarding different distributed generation technologies, the level of their penetration and contributions in the DSO market. The DSO's market scenarios are described below:

- DSO acting as a data manager: Collecting, providing and processing raw data from DSO level (IED data, contracts data, metering data);
- Contracting different flexibility services at DSO level at different timeframes;
- Activating different flexibility services at DSO level at different timeframes;
- Enabling new products for energy markets, facilitate market development;
- Providing data management services based on regulated services environments;
- Operation, roll-out and de-commission as well as governance of a smart metering infrastructure for third parties;
- Creating new operational paradigms for network connection;
- Providing metering and service provision monitoring infrastructure for future EV;
- Managing electricity grid congestion;
- Balancing supply and demand;
- DG, TG, real-time operation;
- Enacting Operational planning activities for DSO, Municipalities and conceding agencies in close relationships;
- Making the necessary network design evolutions in consistency with appropriate functional improvement of operational planning.

The project developed the New Interval Constrained Power Flow Tool for the TSO-DSO coordination. It aggregates the flexibility in the DG and estimates the active and reactive power flow exchange at the interconnection points between TG and DG. The tool requires data describing network equipment's and technical operational limits, bus voltage and branch loading, capacitor/reactor banks, OLTC, DER, limits of reactive power dispatch of DER, limits of reactive power exchange between TSO/DSO, network topologies and flexibility ranges and costs.

The goal of the New Sequential Optimal Power Flow Tool is to reduce the flexibility operational costs and assure the proper function of the network. The tool defines the optimal scheduling of reactive power flexibilities to meet the desired profile at the TSO-DSO connection point taking into account uncertainty of RES production.

The project defines several business cases regarding TSO and DSO responsibilities and different kind of information exchanges:

1. Activation of DSO-connected resources for balancing purposes in market environment
    - Data exchange between TSO, DSO and BSP;
    - Information exchange between the TSO and DSO when the TSO profits of DSO demand response mechanisms (e.g. Conservation Voltage Reduction) for mFRR and in some cases also for aFRR balancing service.
2. Coordination of distributed flexibility services in a market place
    - Information exchanges between TSO, DSO, Flexibility Operators and MO necessary for procurement of flexibility provided by DER.
3. and 4. Optimize active power management by the System Operator for congesting management purposes
    - The interactions between the TSO and DSO to optimally manage the congestion constraints with activation of flexibility providers connected to DG in day-ahead, intra-day and real-time.
5. and 6. Optimize reactive power management by the TSO and DSO for Voltage control purposes
    - Information exchanges between TSO and DSO to optimize reactive power management actions at each primary substation for voltage control with existing resources connected to the DG.
7. Coordination of operational planning activities between TSO and DSO
    - Exchange of operational planning data (foreseen connection state, scheduled maintenance actions and electrical characteristics of specific lines) between the TSO and the DSO 72 hours ahead, being refreshed every 24 hours.

8.1. Optimize work programs (TSO, DSO, and SGU works)
    - Requirements concerning exchange of information between the TSO/DSO and SGUs in each time-horizon to assure the works planning considering the forecasted generation and consumption and a technical validation.

8.2. Coordination between TSO and DSO for DG reconfiguration
    - Information exchanges between TSO and DSO to avoid possible DSO current constraints during a network reconfiguration.

9. Coordination of long-term network planning between TSO and DSO
    - Information exchange between TSO and DSO necessary for preparation of long-term power network investment, expansion and reinforcement plans in order to provide long-term network stability and robustness in light of modern challenges.

10. Improve system real-time supervision and control through better coordination (TSO, DSO and SGUs)
    - ➢ The necessary real-time information exchange between TSO and DSO, periodic updates of TSO and DSO observability area.
11. Improve fault location close to the TSO-DSO interface
    - ➢ Improving the location of faults at distribution lines, close to the interface with the TG.

11.6.1. Coordination of distributed flexibility services in a marketplace

Four coordination schemes are explored in the project and correlated with described SmartNet coordination schemes in Table 13.

TABLE 13 – TDX-ASSIST COORDINATION SCHEMES

TDX-ASSIST	SmartNet
TSO procures the flexibility services and the DSO should validate their activation	Centralized AS market model
DSO procures the flexibility services and provides the forecasted load/generation by primary substation	Shared balancing responsibilities market model
Coordination mechanism between local and national market	Local AS market model
TSO and DSO procure flexibility services in a single flexibility market	Common AS market model

11.7.EU-SysFlex

Two different approaches in ancillary services procurement have been investigated: market-based and regulated. Market-based approach can be centralized or decentralized in which the optimization is required and distributed principle which does not require optimization. Regulated type of market organization requires optimization and can be both centralized and decentralized.

The regulated organization refers to the ancillary service provision which is mandatory for specific type of resources. On the other hand, marked-based organization includes market participation of different kind of FSPs. In a centralized market-based organization all flexibility providers bid on a single market which includes distribution and TG constraints. The cleared bids are the result of joint market clearing which serves both to the TSO and the DSO. Grid constraints can be included also through bids that reflect and don not harm network constraints. The MO (optimization operator) can be either the TSO or the DSO or a third party. In decentralized market-based organization two separated algorithms for ancillary service provision exist. The TSO is responsible for TG, while the DSO for DG. Two algorithms require coordination in order to avoid the activation in the opposite direction, i.e. activated bids from distribution level that can harm TG. In the distributed organization, as the last type of market-based organization, high number of FSPs and buyers are represented as peers. The peer is defined as a market-entity which owns or operate an asset which is qualified for the service provision.

Four steps are defined in ancillary service provision:

1. Prequalification – the goal of this step to ensure that each ancillary service satisfies technical, financial and communication requirements which are required for market participation. Moreover, the process of prequalification can be used for checking if any of possible activated

service result in congestion. Prequalification process is divided in 3 phases: request for market prequalification, products and grid prequalification. In the first phase, MO checks if the applied FSP qualify as an ancillary service provider. If the MO approves FSP feasibility, in product prequalification SO runs predefined test cases with provided flexibility options to check if the flexibility source can actually deliver the product. In the final phase in grid prequalification, the SO checks if activated flexibility result in congestion.

2. Procurement of capacity and energy products – this step includes market bidding and market clearing. FSP submit their bids to the MO who validates the offers and sends them to optimization operator (OO). Optimization operator also receives the requests from system operators. Having all bids from FSP and required flexibility needs from SOs, OO selects the activated bids with minimal cost which satisfy the technical constraints in the network.
3. Activation of flexibility – can be automatic or manual. In automatic activation, flexibility service can be triggered by an automatic signal sent by SO or self-activated by network state. Manual activation is determined by MO or SO when necessary and then delivered by flexibility provider.
4. Settlement – this step includes measurement data management and financial settlement between buyers and sellers.

The project also detailly describes the differences between regulated and market-based ancillary service provision for each product:

1. Frequency control products:

   In some countries it is required from conventional power plants to provide FCR, which can block new entities, such as distributed resources, for competing for ancillary services. As the TSO is the only entity responsible for frequency control, centralized market-based organization is the most suitable environment for frequency control procurement.
2. Inertia:

   As the decommission of synchronous power plants will be done in upcoming years, it is very important to ensure the sufficient inertia in the system. Regulated provision of this service is necessary to ease the decommission of synchronous generators, but market-based provision is preferred.
3. Voltage control products:

   The grid codes define that mandatory requirements from the generators in the case of voltage control which is not compensated properly. Both market-based and regulated approaches are desirable. If a problem occurs in a small cloacal area, due to insufficient number of possible flexibility providers, this can be solved with regulated approach. On the other hand, marked-based solution is desirable when the market liquidity satisfy the system needs.
4. Congestion management products

   Market-based procurement of congestion management products is desirable, but also if the market liquidity is poor due to insufficient local flexibility providers, mandatory and regulated participant can be a viable option, but with proper remuneration.

Moreover, the project gave a comprehensive comparison of advantages of centralized and decentralized ancillary service provision.

1. Centralized optimization: there is less coordination needed between the roles, the results of market clearing can be fully optimal, one optimization operator with one set of rules for IT requirement and process organization due to only one central market.
2. Decentralized optimization: sequential optimization for different voltage levels, easier to match local needs, less data processed which makes optimization algorithm simpler, high resilience due to decentralized markets which ensures separation of data in case of any interruptions and failures.

The project concluded that the performance difference between centralized and decentralized optimization can be minimized if the optimization is performed close to real-time and the operation of DG is flexible enough to ensure that the allocation of distributed flexibility providers can be corrected to satisfy both transmission and distribution requirements. Moreover, the centralized option results in optimal allocation of all flexibility resources, but the problem is computational effort and central entity need for overall control.

Different types of joint ancillary services procurement exist:

1. Coordinated procurement by TSOs and DSOs – the buying process is independent from each other, but TSOs and DSOs coordinate to jointly procure the flexibilities for each scarcity.
2. One product for solving more than one scarcity – each system operator uses the same bids for different services (e.g. mFRR and voltage control or congestion management).
3. Procurement of two or more products – e.g. the use of active and reactive power bids to solve both voltage problems and congestion.

The focus in the project was put on the joint procurement of the mFRR and congestion management products for both DSO and TSO. The similarity of mFRR and congestion management is that both are controlled with increase or decrease of active power with the flexibility activation time of 15 minutes and duration of more than 15 minutes. Moreover, if both problems would be solved jointly, less flexibility could be used. This is already used in Great-Britain Balancing Mechanism and French Balancing mechanism. In line with this, three potential products were proposed: long-term products, slow products and fast products [21], [22].

11.8.evolvDSO

evolvDSO project focused on development of two tools for supporting the cooperation between the TSO and the DSO: the Interval Constrained Power Flow (ICPF) tool and the Sequential Optimal Power Flow (SOPF) tool [23].

ICPF tool estimates the range of flexibility in primary substations. Flexibility providers connected to the DG are aggregated (demand response, flexible distributed generation, reactive power control from the DSO assets) and evaluated from technical and economic perspective. The goal of this tool is to approximate a feasible region of active and reactive power exchanged at primary nodes. This information helps the TSO do determine from which primary node can request the flexibility service. The tool defines how much flexibility the TSO can activate in each hour from each primary node.

Different types of flexibility services from the DSO side can be provided:

1. Mid-term bilateral flexibility contracts – annual flexibility tenders between TSO and flexibility operators and other flexibility providers

2. Non-firm connection contracts – large consumers and power plants which will accept the curtailment in order to get connection license to the DG
3. Flexibility bids at the level of MV/LV nodes from local demand response aggregators
4. Controllable resources connected to the DG and owned by the DSO, e.g., capacity banks, on-load tap changers (OLTC).

Flexibility range is determined in 3 steps:

1. The TSO receives all information about flexibility resources (offers, their status, mid-term bilateral flexibility contracts, non-firm connection contracts) from secondary substations and MV levels. These data will be used to determine minimum and maximum flexible values of active and reactive power in each node of MV network. The TSO also receives forecasted net-load data for DG.
2. The execution of flexibility estimation algorithm, as shown in Figure 17.

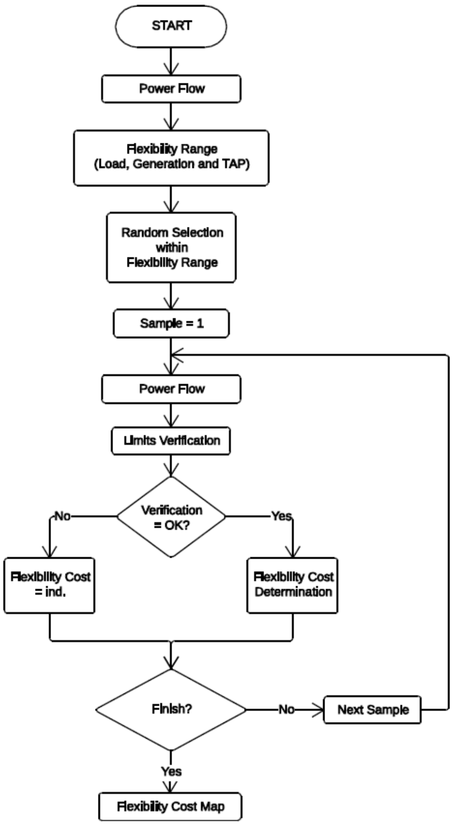

FIGURE 17 – FLEXIBILITY ESTIMATION ALGORITHM – FLOWCHART

3. Information regarding range of flexibility is sent to a TSO-DSO common data sharing platform which is later used for TSO activation of flexibility resources connected to DG or setting the values of active and reactive power on primary substation. SOPF tool minimizes the cost of activated flexibility services from distributed resources. Optimal volumes are determined through network reconfiguration with voltage and reactive power control which lie in feasible region obtained with ICPF tool.

11.9.CROSS BOrder management of variable renewable energies and storage units enabling a transnational Wholesale market

CrossBow project emphasizes the importance of information exchange, not only between system operators, but also between the DSO and small scale flexibility providers and distributed generation [24]. It gives an overview of TSO/DSO coordination in several countries in Europe: Croatia, Serbia, Bosnia and Herzegovina, Montenegro, Romania, North Macedonia and Greece.

The project proposed several use cases for the cooperation between the TSO and the DSO. The first ones focus on enhancing the visibility of the grid. In order to ensure observability, granularity and transparency of data, the data exchange between the system operators should be improved. Moreover, the project emphasizes the importance of detailed grid information regarding power flows in DG and modelling dynamics in DG in the process of planning and predicating. Several case studies defined in the project related to information exchange are listed below:

- HLU5-UC01 “TSO-DSO cooperation for voltage control-congestion management via distributed storage systems”
- HLU5-UC02 “HLU5-UC02 Frequency regulation by VSP coordination”
- HLU5-UC02 “HLU5-UC02 Voltage regulation by VSP coordination”
- HLU5-UC02 “HLU5-UC02 congestion mitigation by VSP coordination”
- HLU6-UC06 “TSO-DSO cooperation for voltage control-congestion management via demand response”
- HLU8-UC06 “API: VPP integration with TSO”

The second group of use cases focuses on congestion management in DG utilizing voltage or power flow control or network reconfiguration. Voltage control can be passive or active. Passive voltage control is increasing the conductor size and connecting generation, while active voltage control refers to controllable resources, such as on-load tap changers (OLTCs), active and reactive capability of distributed generation. Power flow control can be done with Flexible AC transmission systems (FACTS), distributed generation, load shedding, generation curtailment and demand shifting through flexible demand or energy storage. Network reconfiguration is used to reduce power losses, improve voltage profile and power balancing or in congestion management. Under this project, Common TSO-DSO ancillary service market model is adopted.

System operators need to ensure that all participants have an open access to all markets. Generation units, demand and storage units should be able to participate in both energy market and ancillary service market. The market participation of small units will require aggregation regardless the connection point in order to achieve the full potential of aggregated flexibility. A single market for flexibility and balancing is preferable in order to avoid market fragmentation. Moreover, to achieve a simple process of engaging consumers in providing flexibility services, administration should not be complicated. All markets rules should be transparent, providing ancillary services should be in line with finding the most economical solution, the privacy in data collection must be ensured and cost allocation must be fair and consistent. Several use cases are defined connected to analyze the market participation of resources connected to the DG:

- HLU5-UC05 “Market participation”
- HLU8-UC05 “API: VPP integration with Market”
- HLU9-UC02 “System market platform for Balancing Market”

Furthermore, one of the main problems that the project will address is how to allow a higher penetration of RES into the grid. A virtual storage plant presents the aggregation of energy storage units from the system operator's point of view. Use cases for promotion and adoption of virtual storage plant which will be used to provide frequency support, voltage regulation, improve cross-border power transfer and enhance RES penetration are listed below:

- UC1: "TSO-DSO cooperation for voltage control and congestion management"
- UC2: "Frequency support by VSP coordination"
- UC3: "Voltage support by VSP coordination"
- UC4: "Congestion mitigation by VSP coordination"
- UC5: "Market participation"

11.10. InterFlex

InterFlex project investigates how the use of local flexibilities can reduce congestion in the grid and increase the resilience. The new business model for the DSO lies in avoided cost for grid management. DSO procures the flexibility on local flexibility market and is responsible for congestion management in DG, but also for balancing in case of island operation.

InterFlex project does not focus on the coordination between the TSO and DSO, however the aggregators can potentially participate and submit their bids to both DSO and TSO markets. The DSO will request the flexibility based on local problems. The project developed the price for flexibility as a grid tariff reflecting the savings when the local flexibility is used. The required flexibility can be acquired by flexibility trading on a local scale with the focus on long/mid-term and day-ahead forecasts. The energy storage can be owned by the DSO and by commercial market player. The combined ownership is also investigated depending on the system needs. The challenges arisen in this project refer to the local market liquidity: there should be an economic interest for the local aggregators to participate in flexibility market, flexibility products must be clearly defined and compatible with the TSO and DSO needs. The projects put the focus on the use of local flexibility by the DSO. Six demo sites are included in the project: two in Sweden, one in Germany, Czech Republic, The Netherlands and in France [25].

11.11. GOFLEX

The project GOFLEX has 3 pilot locations: Germany, Switzerland and Cyprus. The demo site in Germany involves around 50 residential prosumers, 25 flexible residential consumers and 2 commercial customers. Each participant will be equipped with intelligent measuring equipment for local storage of data and automated trading of energy and flexibility. The project will develop new products and services according to the consumers' needs. The main goal for German demo site is 100% renewable energy supply. On the other hand, the demo site in Cyprus tests the microgrid including the university buildings in order to explore the flexibility provision by public sector. This flexibility will be established through the combination of PV production, consumption and energy storage. The second pilot project on Cyprus includes 20 dispersed consumers equipped with a specific home energy management system to control and trade the energy and flexibility. The pilot project in Switzerland aims to minimize the balance for the DSO to reduce corrective cost by using demand side management and reduce peak loads.

Three different approaches are demonstrated in the project with the goal of global cost minimization in avoiding the congestion. In the first approach the DSO system becomes a "cellular" subsystem of the TSO (the DSO is responsible for balancing the DG subordinated with the TSO's overall responsibility). In the third approach 4 structures are distinguished: a balance group, a sub-balance group, a local energy community and a local micro-grid system which enables the introduction of different local markets and differ offers from various range of flexibility providers. In the third approach a prosumer becomes the smallest entity able to participate in the market either alone or aggregated into large offer.

The TSO procures the flexibility on the TSO reserve market, while the DSO is the only buyer on the local flexibility market. The DSO is responsible for the congestion management in the DG and also for local grid balancing. As the flexibility markets are organized on different levels for the TSO and DSO, the cooperation between system operators is done through parental responsibility of TSO for its DSOs. The cooperation between DSOs is executed by competitive bids of involved DSOs for energy flexibility. The dynamic price of flexibility is determined based on actual conditions in the grid and avoided cost principle of the user of energy flexibility. The flexibility can be acquired by DSO or TSO by flexibility trading on the local or regional market close to the real time and based on actual or short-term predictions of the network state.

Two types of trading are investigated: direct trading of individual prosumers and delegated trading of groups of prosumers with a collective business strategy. The main challenges in the project was the definition of remuneration model correlated with the avoided costs. The network fee should be split between the TSO and the DSO according to the share of congestion and balancing services. There is also a kind of “insurance policy” which remunerates the TSO if the DSO is not able to solve the problem locally.

11.12. Flexibility to support GRID PLANNING (FlexPlan)

FlexPlan gave a comprehensive review about the compliance of network planning tool with EU overall strategies and regulatory conditions [26]. The deliverable focused on procedures for TSO-DSO interactions during planning: priority, iteration, sharing of information and models, present practices for TSO-DSO interactions, priorities in sharing resources between system operators, responsibilities for congestion management and balancing, roles and responsibilities related to network expansion planning, Incentivization mechanisms for flexibility resources, etc.

The project described the present practice for TSO-DSO interconnections for two TSOs and four DSOs. Portuguese TSO REN has regular planning meeting with the DSO and uses quality of supply to the load of the DSO and minimization of active power losses. REN shares with the DSO grid data and not models. Slovenian TSO ELES does not acquire any network data from the DSO. They communicate about network expansion, planned new substations, consumption for each substation, distributed energy generation expansion and reconstructions on distribution level. ENEL shares with the TSO the annual development plan with the interventions for the following 3 years in order to increase the reliability of the network with coordinated planning and constructions of elements in both TG and DG. Iberdrola submits transmission development proposals and provides any information that may be needed for TSO technical studies development. Netz Niederoesterreich puts the focus on national Network Development plan in coordination with the TSO. They share 110 kV network data to get a parallel network flow calculation. In Lithuania TSO and DSO share primary substation's HV and MV measurements data. In Italy under the resolution 36/2020 DSOs will start collecting and transmitting to the TSO real-time data related to distribute generation resources connected to DG.

12. TSO/DSO planning strategies for CAPEX reduction

The future power systems will be faced with an increasing demand, but also with high integration of renewable energy sources. Green energy polices suggest putting the focus on final consumers willing to shift their load when simulated with the desirable price signals in order to provide ancillary services to the system operator (balancing, voltage control, congestion management). This chapter will describe how successful coordination between TSO and DSO in DER operation can reduce or postpone network investments.

At planning level, the TSO/DSO coordination mechanisms will reduce CAPEX of the planning strategies and optimize the utilization of the smart grid technologies located in both TG and DG. The reduced CAPEX cost will have a significant impact on final consumers' electricity bill reduction due to reduced network charges. In order to reduce CAPEX, several tools will be developed in the ATTEST project in the planning module:

- Optimization tool for DG planning;
- Optimization tool for TG planning;
- Optimization tool for planning TSO/DSO shared technologies.

The transition towards green energy systems shifted the DSOs paradigm in DG planning, operation and control. In the passive approach the DSO played the important role only in the planning stage in order to ensure secure and reliable DG operation. On the other hand, Active DG Management (ADNM) requires real-time monitoring and control to ensure the quality of energy supply to all final consumers in the system with high integration of RES satisfying all technical constraints. In order to ensure the goals of clean energy transition, high penetration of RES will require additional investments in the current infrastructure. However, this can be either postponed or reduced with ADNM and TSO-DSO coordination. Instead of physical network reinforcement, the existing potential of final consumers should be exploited. On the other hand, to ensure close collaboration between the DSO and TSO, additional ICT infrastructure is required.

With DER deployment in the area with growing integration of RES and increase in demand, DSO can postpone the investment in network reinforcement. According to [27], if considered in the grid planning phase, but also in operation, the demand response can effect both CAPEX and OPEX. Demand response can participate in peak reduction in the network and reduce the need for additional infrastructure, while the reduction of technical losses with the local balancing can have an impact on OPEX reduction if high cost of losses is considered. Demand response reduces the difference between the local demand and distributed generation and thus reduces the need for the network upgrading.

The procurement of some AS by DSO/TSO should reflect CAPEX and OPEX cost. EnerNOC estimated the avoided network costs, if the demand response programs were adopted, with the capability to integrate additional 500 MW of demand [28]. In the South West Interconnected System (SWIS) in Australia the results of the demand response analysis presented in Table 14 show the avoided cost for the period of 10 years.

TABLE 14 – AVOIDED COSTS

	Marginal avoided cost ($million/MW)	Total avoided cost assuming 500 MW of DR ($million/MW)	Avoided cost assuming 500 MW of DR, per energy user ($)
Transmission and distribution	2.05	1025	967

To ensure more efficient operation of DG, the tool described in [29] presents the usage of energy storage that assist the DSO in CAPEX and OPEX minimization. Four different methods for DG planning were considered to demonstrate the avoided costs. The investment cost for initial passive scenario was 466 k€ (the planning period is 5 years). The size of observed area is 22 MV nodes. The rest of the cases and total costs are listed below:

- ADNM – PQ control of distributed generation: 440 k€
- ADNM - demand side response: 280 k€
- Control of energy storage to reduce losses or defer network investments: 282 k€
- ADNM – energy storage: 34 k€

13. Current practice

Today only a small number of DSOs participate in the demand flexibility programs (demand side management or demand response). According to [30], among 99 DSOs in Europe which participated in the survey and are supplying more than 100 000 consumers, almost 57% of them do not use any kind of demand response, demand side management or flexibility programs. 15% of DSOs who participate in the flexibility service procurement use it to alleviate constrained network, 14% for ripple control and 3% for mass remote control. However, several DSOs not participating in these programs have the intention to include them (they have already participated in pilot projects and have used these programs for demonstration purposes or collaborate with the TSO which runs such programs).

The comprehensive review of business models for ancillary service procurement by DSOs is shown below. Market-based approaches are listed in Table 15, contractual obligation with periodic remuneration for the service or network fee reductions in Table 16Table 16 and price-based ancillary service procurement handled by aggregators as intermediaries between DSOs and grid users in Table 17.

TABLE 15 – FLEXIBILITY SERVICE MARKET PLATFORMS

Country	Project	Description	References
Netherlands	GOPACS	An intermediary between the network operators and flexibility service markets, it enables DSOs to procure ancillary services in the same markets as balancing responsible parties. Currently four Dutch DNOs are part of the platform. It is connected to the Dutch intraday trading platform (ETPA), with plans for connecting to other market platforms as well. It is mostly used for congestion management. To ensure balance in the TG remains undisturbed, for each congestion two symmetrical bids are placed – the first one for the decrease of load in the congested area and the second one for the increase outside of it.	[31], [32]
United Kingdom	Piclo Flex by Open Utility	Trading platform where DSOs can procure standardized flexibility services from grid users or aggregators. Currently, six UK DSOs procure flexibility services through this platform. For each service, DSOs can specify type of power (active or reactive), duration, etc. The same company offers P2P trading platform Piclo Match as well.	[31], [33], [34], [35]
Germany	Enera	A mobile trading platform that also provides the consumers with an overview of their energy consumption. It is deployed in Northern Germany with an aim of minimizing wind energy curtailment. Network operators place requests for congestion management and consumers place offers for load increase or decrease. It is operated on the intraday timescale.	[31]
Germany, Norway	NODES	Flexibility trading platform developed by a Norwegian utility and Nordpool. It offers to DSOs possibility to model local networks and submit them as local markets to the platform. Current demos are in Norway where investment deferral is the main use case, and Germany where the main use case is RES curtailment mitigation. The platform also enables TSO-DSO coordination.	[31], [36]
Denmark	EcoGridEU	FP7 funded project that developed real-time balancing market concept at the distribution level. The concept was demonstrated on the island Bornholm in Denmark and was later incorporated into NordPool DK2 market zone.	[35], [37]

TABLE 16 – CONTRACT-BASED DSO ANCILLARY SERVICE PROCUREMENT

Country	Project	Description	References
Slovenia	Flex4Grid	DSOs were allowed by the Regulator to develop experimental Critical Peak Pricing tariffs called “Kritična konična Tarifa” (KKT) with an aim to test possibility of peak power reduction within DGs. Network tariffs are lower for the consumers on KKT contracts than for the rest. There can be up to 50 peak pricing events during a year, during which tariffs are circa 10 times higher than normally. Consumers are notified at least 24 hours before the event through a web page, via email and through a mobile app.	[38], [39]
United Kingdom	Electricity North West Demand Side Response	In the UK, DSOs have an obligation to help maintain frequency between 49.5 and 50.5 Hertz. To ensure this, Electricity North West offers contracts to commercial and industrial consumers who can join their VPP portfolio and be managed by them directly. This management consists of turning down consumption for up to 30 minutes, while financial compensation depends on the available power to be shedded/shifted. There are about 6 events yearly per consumer.	[40]
United Kingdom	UK Power Network flexibility service tenders	UK Power Networks, a DSO, hold tenders through Piclo Flex platform twice yearly where they procure three types of services from consumers connected to HV or LV network. The consumers enter into contract with the DSO who can schedule their service monthly or weekly. Minimum bids are 10 kW, lasting for at least 30 minutes. They are remunerated for the service monthly and are also eligible for performance-based deductions.	[41]
United Kingdom	Power Potential	A unique project aimed at developing a reactive power market for UK’s DSOs. The project is in the trial period, slowed down during COVID-19 pandemic. The participating grid users will have to provide voltage droop control during a set period. The project is led by UK Power Network. The services will be provided by contractually obliged grid users who will be paid for availability, similar to the active power services procured by the same DNO.	[42], [43], [44], [45]

TABLE 17 – AGGREGATOR-BASED DSO ANCILLARY SERVICE PROCUREMENT

Country	Project	Description	References
Netherlands	EnergieKoplopers	Flexibility services trading platform was developed to enable trade between distributed flexibility resources and aggregators. The platform, based on USEF guidelines, helped the DSO, Liander, to demonstrate possibility of peak power reduction through local electricity market.	[46], [47]
United Kingdom	Moixa Gridshare for Northern Powergrid	Gridshare is an aggregator platform developed by firm moixa to enable virtual power plants to provide flexibility services to the DSOs. DSO communicates with the aggregator, sending information on grid constraints and the aggregator communicates with batteries placed at the consumers premises, managing the consumption. Main results of this project are peak load reduction on the local substation, enabling integration of local PV plants and ensuring electricity bill savings for the participating households.	[48]

14. ATTEST solution for TSO/DSO coordination mechanism

The summary of each coordination scheme is described below.

The Centralized ancillary service market model is the most similar to the current market organization and supports standardized processes. It is the most efficient market if the TSO is the only buyer, and offers the lowest operational cost. The main disadvantage of this scheme is that the DSO is not involved in the market, only in system prequalification, and cannot purchase ancillary services for local use. Moreover, constraints in the DG are not considered in the process of market clearing.

On the other hand, in the Local ancillary service market model, the DSO has the priority for ancillary service procurement from the resources connected to the DG, i.e. local market is cleared firstly taking into account DG constraints, and not-selected offers are bided in the central market (single aggregated bid which do not counteract with local bids). The problem is the existence of multiple local markets limited to the small distribution area which might have the risk of low flexibility sources aggregation resulting in low market liquidity.

In the Shared balancing responsibility model, clear boundaries are defined for each system operator responsibilities. The TSO is responsible only for balancing and operation of TG and cannot procure ancillary services from DER (only from the resources connected to TG), while the DSO has the same responsibilities for the DG. The TSO will need to procure the lower amount of ancillary services but balancing responsible parties may pay higher imbalance penalties due to low local market liquidity and high ancillary service price. The coordination schemes between the DSO and TSO must be established not to jeopardize the system stability.

In the Common TSO-DSO ancillary service market model decentralized and centralized scenarios are possible. This scheme minimizes the total cost of ancillary service procurement due to close collaboration between system operators, while the cost is shared between the TSO and the DSO.

In the Integrated flexibility market model, the participation is opened for regulated and deregulated market entities making the market very liquid with competitive prices. As the commercial market players can participate in the market, balancing responsible parties can reduce their imbalances in real time or near to real time. To ensure the market neutrality, independent MO is necessary, while system operators are mandatory to share their data. This scheme can lower the intra-day market liquidity because commercial parties are allowed to trade in the ancillary service market which is closer to the real-time.

Taking into account the detail description of each coordination scheme, evaluating all the benefits and the risks and in line with the project proposal, the choice in ATTEST project is a hybrid model between Centralized ancillary service market model, Local ancillary market model and Shared Balancing Responsibilities model which will be described in detail and called **ATTEST TSO / DSO coordination approach**.

In the Centralized ancillary service market model, the TSO is the only buyer of the service. Unlike this approach, in ATTEST TSO / DSO coordination approach the DSO can use local flexibility resources, but the TSO has the priority.

In ATTEST TSO / DSO coordination approach DSO shares local flexibility with the TSO. This approach is non-optimal cost-wise for the DSO because the DSO needs to meet operation constraints in DG and also an agreed ancillary service schedule with the TSO. The extra cost incurred by the DSO should be remunerated to some extent by the TSO.

In ATTEST TSO / DSO coordination approach **DG constraints are considered** in the market clearing which ensures secure and efficient DG operation in the real-time.

ATTEST TSO / DSO coordination approach determines a schedule of ancillary service of each TSO-DSO connection point or local area considering network constraints. The communication and coordination are very precise, but on the other hand, hard to calculate due to challenges in sharing data in a short timeframe, especially in the case with multiple local DSOs.

Because of the market fragmentation, the possibility of the aggregation of resources located in the same area can be limited which can result in low market liquidity. This can also lead to high price for specific ancillary service due to reduced market competition. However, if flexibility bids are aggregated in the entire area operated by the same DSO, the specific ancillary service will be provided in the required volume resulting in a high liquid market with low ancillary service prices.

The additional infrastructure for the communication between the DSO and the TSO is required due to their close collaboration and required data exchange where the focus is put on security and privacy of data. Access to sensitive data will be granted according to specific roles and privileges. Each system operator is responsible for measurement collection, load and generation forecast, flexibility resources characteristics and availability, connection points power flow prediction and real-time observation. It is highly important to ensure a safe data storage and exchange with an easy access for the system operators. The ICT TSO-DSO platform should be established with different tools for DG and TG planning in long term and midterm, operation in day-ahead and real-time framework together with asset management tool in order to minimize investment and operational network cost, increase the reliability and quality of the service and decrease the environmental impact. The ICT platform must be compliant with the relevant established standards (such as IEC 61968/61970, IEC 61850, IEC 62746).

14.1.Optimization model

The optimization model is divided in 4 tools:

- Tool for ancillary services procurement in day-ahead operation planning of the DG;
- Tool for ancillary services procurement in day-ahead operation planning of the TG;
- Tool for ancillary services activation in real-time operation of the DG;
- Tool for ancillary services activation in real-time operation of the TG.

ATTEST TSO/DSO coordination approach is divided in day-ahead and real-time operation in which active and reactive bids are decoupled, but provision of the service related to active and reactive power is part of one tool executed in two steps.

Day-ahead ancillary service market is cleared after the closure of the day-ahead energy market. The result of the day-ahead energy market is taken into account when TSO and DSO agree on day-ahead active power P^{DA} and corresponding reactive power Q^{DA} exchange at their interface.

Flexibility providers connected to the DG submit their bids to the DSO. Due to complexity of pricing mechanism for the coupled P-Q bid, bids for active and reactive power are decoupled and independently submitted to the DSO with the constant cost per bided unit of energy. In day-ahead operation planning, DSO calculates the range of active and reactive power from submitted bids which does not harm DG constraints and can be offered to the TSO. This process is divided in two steps: firstly, for active power bids, and then for reactive power bids with agreed/fixed active power exchange profile at the TSO-DSO interface. When the DSO approves the bids, they are submitted to the global market. The TSO clears the global market determining the required flexibility and sends the reservation capacity to the DSO. Agreed power flow at day-ahead stage at the TSO-DSO interface will be in range [P^{DA}-P^{down}*,P^{DA}+P^{up}*] and [Q^{DA}-Q^{down}*,Q^{DA}+Q^{up}*], where P^{down}* and P^{up}* are the maximum values of down and up reserved ancillary services of active and Q^{down}* and Q^{up}* of reactive power (maximum value of ancillary services reserved at day-ahead stage which can be activated in the real-time).

After clearing the global ancillary service market and setting active and reactive power flow exchange at the day-ahead stage at the TSO-DSO interface, the DSO clears the local market in order to solve local problems with the respect of agreed P^{down}*, P^{up}*, Q^{down}* and Q^{up}* and dispatches local flexibility providers.

In the process of real-time activation of day-ahead reserved ancillary services, the TSO runs OPF to determine how much of reserved capacity (P^{down}*, P^{up}*, Q^{down}* and Q^{up}*) is required in real-time. These values of active and reactive power P** and Q** can be in range from 0 to P^{down}*/P^{up}* and from 0 to Q^{down}*/Q^{up}* reserved on the day-ahead ancillary service market. The TSO sends the desired active and reactive bids P** and Q** to the DSO. The DSO runs OPF in real-time with the fixed P** and Q** values at the TSO/DSO interface and clears the local real-time (RT) market making sure to satisfy DG constraints.

Detail description of ATTEST TSO/DSO coordination approach in the process of ancillary service procurement is presented in Section 14.2 for day-ahead reservation and in Section 14.3 for real-time activation.

14.2. Reservation of active and reactive power services at day-ahead operation planning

Detail description of active services reservation in day-ahead operation planning in ATTEST TSO/DSO coordination approach is described in three steps and illustrated in the Figure 18.

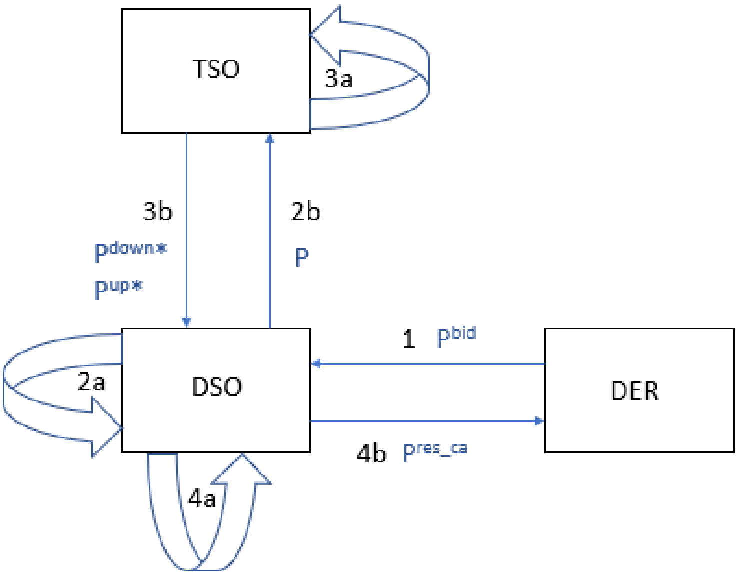

FIGURE 18 – RESERVATION OF ACTIVE POWER SERVICES AT DAY-AHEAD OPERATION PLANNING

1. Submission of DER bids to the DSO - independent active P^{bid} and reactive Q^{bid} bids and their associated cost. Two different bids for both active (up and down bids with corresponding cost) and reactive power (inductive and capacitive with corresponding cost) are considered.

2. a) The DSO calculates via Alternating Current Optimal Power Flow (AC OPF) active power flow range and cost at TSO-DSO interface given the P of DER such that the DSO network constraints are met.

   b) The DSO submits P flow range bids capability to global P market run by TSO.

3. a) The TSO determines the required flexibility in global market clearing to remove congestion through Alternating Current Security Constrained Optimal Power Flow (AC SCOPF) including active power flow ranges provided by DSO. TSO also determines the values of reserve for frequency control.

   b) The TSO sends to the DSO $P^{down}*$ and $P^{up}*$. The optimal active power flow at TSO-DSO interface can be in range [P^{DA}-$P^{down}*$,P^{DA}+$P^{up}*$]. If the TSO does not require any service from DER, the active power flow at the TSO-DSO interface will be equal to day-ahead energy schedule P^{DA}.

4. a) DSO clears the local market in order to solve local problems with the respect of agreed $P^{down}*$, $P^{up}*$.

   b) DSO sends the request for active power capacity reservation P^{res_ca} to DER (from both global and local market).

The reservation of reactive power services in day-ahead operation planning is demonstrated in Figure 19.

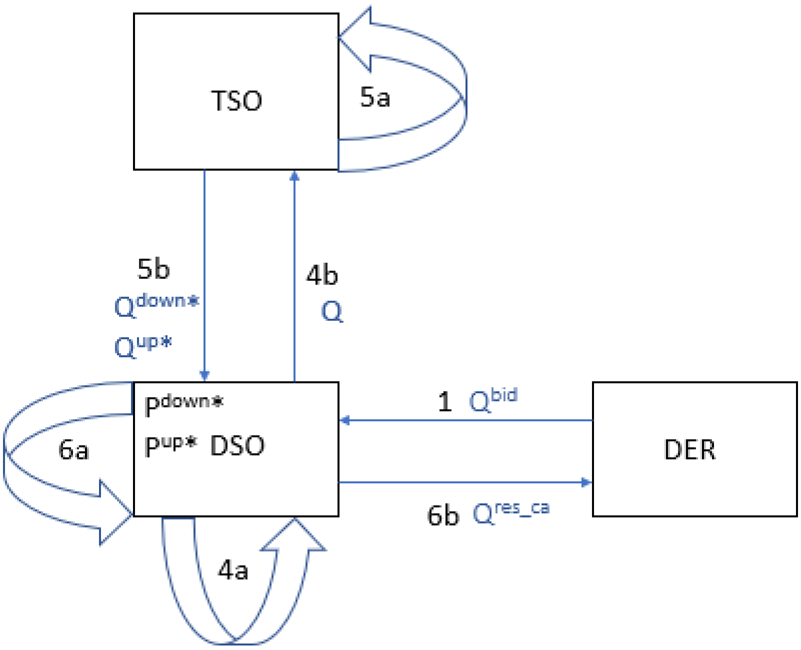

FIGURE 19 – RESERVATION OF ACTIVE POWER SERVICES AT DAY-AHEAD OPERATION PLANNING

4. a) The DSO calculates via AC OPF the Q flow range and cost at TSO-DSO interface Q bids of DER with fixed $P^{down}*$ and $P^{up}*$ values provided by the TSO such that the DSO network constraints are met.

   b) The DSO submits Q flow range bids capability to global Q market run by TSO.

5. a) The TSO determines the required flexibility to satisfy voltage constraints through AC SCOPF including Q flow ranges provides by DSO.

   b) The TSO sends $Q^{down}*$ and $Q^{up}*$. The optimal reactive power flow at TSO-DSO interface can be in range [Q^{DA}-$Q^{down}*$,Q^{DA}+$Q^{up}*$]. If the TSO does not require any service from DER, the active power flow at the TSO-DSO interface will be equal to day-ahead energy schedule Q^{DA}.

5. a) DSO clears the local market in order to solve local problems with the respect of agreed $P^{down}*$, $P^{up}*$, $Q^{down}*$ and $Q^{up}*$.

   b) DSO sends the request for active power capacity reservation P^{res_ca} to DER (from both global and local market).

6. a) DSO clears the local market in order to solve local problems with the respect of agreed $Q^{down}*$, $Q^{up}*$, $P^{down}*$, $P^{up}*$.

   b) DSO sends the request for active power capacity reservation Q^{res_ca} to DER (from both global and local market).

14.3.Activation of active and reactive power services in real-time operation

The activation of active and reactive power services in real-time operation is shown in Figure 20:

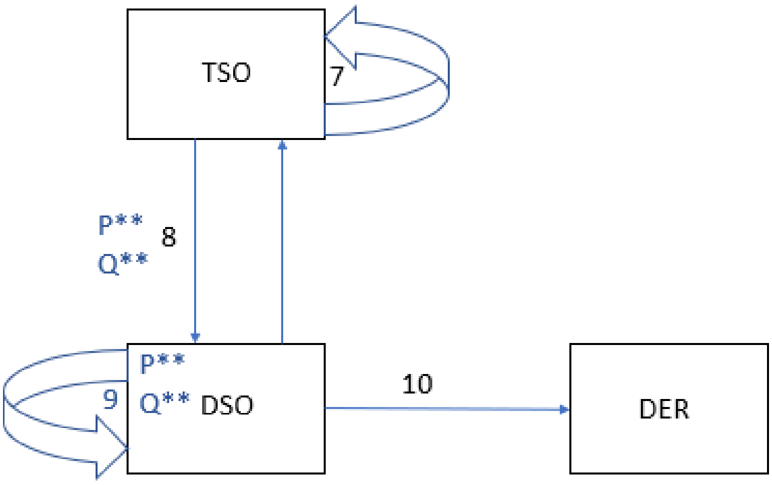

FIGURE 20 – ACTIVATION OF ACTIVE AND REACTIVE POWER SERVICES IN REAL-TIME OPERATION

7. The TSO runs OPF in RT and determines the required ancillary service P** and Q**.
8. The TSO sends to the DSO the desired active power P** and reactive power Q**.
9. The DSO runs RT OPF with the fixed P** and Q** values at the TSO/DSO interface and clears the local RT market making sure to satisfy DG constraints.
10. The DSO activates flexibility providers.

14.3.1. Grid operation

The roles concerning grid operation for ATTEST TSO/DSO coordination approach is shown in Table 18. The TSO is responsible for balancing for the entire system, including both transmission and distribution. Both TSO and DSO are responsible for their data management.

TABLE 18 – ROLES REGARDING GRID OPERATION FOR ATTEST TSO/DSO COORDINATION APPROACH

System Operator	System Balance Responsible	Data Manager
TSO (TG) DSO (DG)	TSO (TG; DG)	TSO (TG) DSO (DG)

14.3.2. Procurement

The roles in ancillary services procurement for ATTEST TSO/DSO coordination approach is shown in Table 19.

TABLE 19 – ROLES IN ANCILLARY SERVICES PROCUREMENT FOR ATTEST TSO/DSO COORDINATION APPROACH

Reserve Allocator	Buyer	Seller	Aggregator	Market Operator
TSO (TG) DSO (DG)	TSO (TG; DG) DSO (DG)	CMP (TG; DG)	CMP (TG; DG) DSO (DG)	DSO TSO

In ATTEST TSO/DSO coordination approach both system operators determine the required flexibility service for the safe grid operation, TSO for TG and DSO for DG. Both the TSO and the DSO can purchase ancillary services from the distributed resources. The TSO has the priority in flexibility services procurement.

The flexibility services are provided from commercial market players connected to TG (e.g. power plants and demand response) and DG (distributed flexibility resources, such as energy storage, demand response programs or distributed generators).

14.3.3. Settlement

The TSO is responsible for reading, storing and management of measurement data on the transmission level, the DSO for distribution level, while each CMP is responsible for measurements regarding the activation of flexibility resources.

The settlement process in ATTEST TSO/DSO coordination approach is described in four steps:

1. The actors responsible for data measurement (TSO and DSO) communicate the measurements to the MO. Both TSO and DSO are market operators. TSO is in charge for global market, while the DSO for local market.
2. The MOs communicates the measurements to the TSO.
3. The TSO corrects the perimeter of balancing responsible parties affected by activation of ancillary services.
4. The MO performs financial settlement of flexibility activation for resources connected at distribution and TG and sends it to the aggregator.

14.3.4. Information exchange

Several types of information between flexibility providers and system operators [19], [49] should be exchanged:

- Regulation up and down power,

- Starting and ending time of the service,
- Minimum and maximum duration interval,
- Points of activation,
- Prices,
- TSO’s and DSOs’ margins (margin to activate the regulation up and down offers for a region (group of TSO/DSO connection points) and for each period),
- Values of forecasted consumption/generation by period and primary substations for the next day
- Value of active and reactive power flow at each TSO/DSO connection point.

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