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ICT architectures for TSO-DSO coordination and data exchange: a European perspective

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***Abstract*— The coordination between system operators is a key element for the decarbonization of the power system. Over the past few years, many EU-funded research projects have addressed the challenges of Transmission System Operators (TSO) and Distribution System Operators (DSO) coordination by implementing different data exchange architectures. This paper presents a review of the ICT architectures implemented for the main coordination schemes demonstrated in such projects. The main used technologies are analyzed, considering the type of data exchanged and the communication link.**

Finally, the paper presents the different gaps and challenges on TSO-DSO coordination related to ICT architectures that must still be faced, paying especial attention to the expected contribution of the EU-funded OneNet project on this topic.

***Index Terms*—TSO-DSO coordination, ICT architecture, IEC protocols, transmission system operator, distribution system operator, data exchange.**

I. Introduction

The digitalization of the power systems is a key driver of the energy transition, enabling the technical and market integration of distributed energy resources (DERs). The complexity of this integration and the increasing volume of available data make necessary to develop and implement communication architectures that are efficient and interoperable to exchange information between the different actors of the power system.

In Europe, better cooperation between the Transmission System Operator (TSO) and the Distribution System Operator (DSO) for the overall system optimization is identified as of great importance [1]. Consequently, many EU-funded research projects have focused on the coordination between TSO and DSO, developing data platforms and architectures so that the system operators can exchange data and coordinate their actions efficiently and reliably [2].

In this context, the EU H2020 on-going project OneNet [3] stands out aiming to create a scalable and replicable architecture that enables the operation of the whole European electrical system as one (i.e., “One Network for Europe”). To achieve this, the OneNet architecture aims to be fully interoperable for enabling the connection of the different existing platforms and systems, including the ones developed in recent EU projects, which use different Information and Communication Technologies (ICT).

In the last few years, academic literature has mainly focused on the business and functional aspects when addressing TSO-DSO coordination [4]–[8]. Nevertheless, the ICT component is becoming more relevant, as the standardization and interoperability level of the ICT systems deployed will deeply affect the final cost of implementation of a TSO-DSO coordination scheme [9].

Regarding ICT, [10] presents a general ICT architecture for data exchange using commonly used protocols in the European TSO-DSO context. However, the ICT advances made by different European projects in the last few years are not included. In addition, [10] identifies the use of client/server and publish/subscribe protocols, but without discussing the types of data or communications links that could make use of each of these types of communications.

Reference [11] mainly focuses on reviewing how different European projects have implemented CIM and which gaps are still present for interoperability. However, the review does not include the communication layer of the Smart Grid Architecture Model (SGAM); the systems and protocols implemented by each project are also of the utmost importance for interoperability.

Finally, reference [12] presents a description of each data exchange in a TSO-DSO scheme, describing the type of data, the importance, the time domain, and source/user of the data. Nevertheless, the communication protocols and standards for each data exchange are not discussed.

In order to achieve an effective TSO-DSO data exchange, a previous exchange of the information about data models, protocols, platforms, etc. that can be used is needed. TSOs, DSOs, and service providers need to agree on the communication protocols and increase the interoperability of their systems.

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To facilitate this process, this paper provides an overview of the developments made so far by five EU H2020 projects regarding ICT architectures (i.e., communication and information layers of the SGAM) for TSO-DSO coordination: SmartNet [13], CoordiNet [14], TDX-Assist [15], INTERRFACE [16], and EU-Sysflex [17]. The architectures implemented in different demos are analyzed, discussing the adequacy of two alternative types of protocols (publish-subscribe, and client-server) for different data exchanges, and considering the underlying market coordination scheme, so that common approaches, gaps, and challenges are discussed. Future developments, such as those carried out by the OneNet Project to address those challenges, are also included.

This paper is organised as follows. Section II gives an overview of power actors and their interaction, which determines the implemented coordination scheme. Section III introduces the main coordination schemes proposed in the literature. Section IV discusses the data types and requirements involved in the data exchanges between power actors. In Section V, the ICT architectures of the different EU-funded projects are reviewed. Section VI analyses and compares the main protocols and standards used in the demos of such architectures and identifies common approaches. Section VII summarises current challenges and expected contributions in ICT architectures for DSO-TSO coordination, paying special attention to the BRIDGE initiative and the expected developments of the OneNet project. Finally, section VIII concludes.

II. General Overview of Power Actors and their Interaction

The correct operation of power grids is achieved thanks to the cooperation of the different actors. The Smart Grid Conceptual Model (SGCM) developed by NIST [18] presents the interaction of up to seven power systems actors' domains: markets, operations, services provision, transmission, distribution, generation, and customer domain. Since, in Europe, TSOs and DSOs usually own the grid they operate, the operations, transmission, and distribution domains can be merged under the figures of the System Operators (SOs). In addition, the generation domain can be divided into bulk generation and DER. This last one is considered as a customer by the DSOs. Considering this, the main actors involved in the power sector and their communication and electrical flows are shown at a high level in Fig. 1. In this figure, the *service provider* actor refers to any entity that provides energy-related services such as energy and flexibility trading, balancing, DER aggregation, among others.

Fig. 1 summarises the interactions considered and analysed by the EU projects reviewed in this paper. Although these interactions can be studied according to the five layers (business, function, information, communication, and component) defined in the Smart Grid Architecture Model (SGAM) [19], this paper focuses on the information (i.e., data models) and communication (i.e., protocols) layers of the architectures proposed by the reviewed projects.

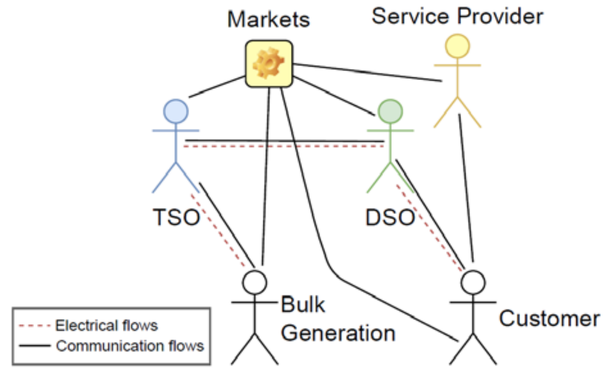

Fig. 1. High-level interaction of the main power grid participants. Conceptual model. Based on the Smart Grid Conceptual Model developed by NIST [18]

The market design, and who operates it, determine the communication flows and operational and information exchange processes that will take place between the participants, especially the SOs, for the acquisition and activation of energy and system services. In the literature, the different market, operational, and information exchange designs are known as coordination schemes [8]. Since the literature about TSO-DSO coordination schemes is extensive, the main schemes proposed are briefly introduced in Section III because of their relationship with the ICT architectures.

III. Coordination Schemes

Coordination schemes refer to the alternative possibilities to define the roles and responsibilities between TSO and DSOs when acquiring and activating system services provided by service providers which can be connected to either TSO or DSOs networks.

Coordination schemes can be defined from a market or ICT perspectives. The Active System Management (ASM) report [20] defined the coordination schemes focusing on TSO– DSO communication in general and mainly on balancing and congestion management services. In SmartNet and CoordiNet different market models are considered. The CoordiNet project, in general, considers separate markets for balancing and congestion management, while SmartNet considered a joint market for balancing and congestion management. The INTERRFACE provides integration of different markets (e.g., congestion and wholesale, or congestion and balancing) and the different options of TSO-DSO coordination [21]. TABLE I shows the equivalent coordination schemes considered in ASM report [20] and H2020 projects: SmartNet, CoordiNet, and INTERRFACE. For the latter, the schemes were identified with short alphanumeric names.

The five main TSO-DSO coordination schemes for system services defined in SmartNet project are considered as reference, not only from a conceptual market perspective [7], [22], [4], but from an ICT point of view [23], [24]:

1) *Centralised market model*: the TSO operates a unique central market (CM), where units located in both transmission and distribution are dispatched. TSO and DSO do not communicate in real-time.
2) *Local market model*: one local market (LM) operated by each DSO to dispatch the units located at the

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distribution level and one central market operated by the TSO to dispatch the remaining flexibility available at distribution level together with the flexibility at transmission level, decoupled and no real-time synchronised.

3) *Shared balancing responsibility model*: similar to the *local market model* but, in this case, the markets do not communicate between them and each SO can only use the flexibility resources connected to their system. Only network constraints are exchanged between TSO and DSO [23].
4) *Common TSO-DSO market model*: both TSO and DSO jointly manage the market. Two variants:
   a) *Centralised*: A unique market platform is jointly operated by the TSO and DSO, so data sharing between operators is crucial.
   b) *Decentralised*: The CM and the LM are integrated dynamically, whether on the same platform (two processes) or different platforms. In this case, real-time market synchronisation is crucial.
5) *Integrated flexibility market model*: the market is operated by an independent operator and flexibility is procured by TSOs, DSOs and other market agents (e.g. Balancing Services Providers, BSPs). Network constraints can be checked upfront or after the market clearing. In this last case, several iterations may be needed for a non-optimal solution.

TABLE I

COORDINATION SCHEMES COMPARISON AMONG H2020 PROJECTS AND [20]. SOURCE: OWN ELABORATION BASED ON [23] AND [25].

ASM [20]	SmartNet	CoordiNet market models	INTERRFACE
Option 1	-Local ancillary services market model -Shared balancing responsibility model	-Multi-level -Fragmented -Central -Local	-1A -1B -1C
Option 2	-Common TSO-DSO ancillary services market model	-Common -Integrated	-2A -2B
Option 3	-Centralized ancillary services market model -Local ancillary services market model	-Local -Distributed -Central	-3A -3B -3C -3D
Out of scope	-Local ancillary services market model -Integrated flexibility market model	-Multi-level -Fragmented -Central -Local	

These coordination schemes can be summarised in terms of communications/data exchange requirements between TSO, DSO and a market operator (scheme (5)), as shown in Fig. 2.

Among these schemes, the *centralised market model* constitutes currently the main scheme implemented [8]. However, a transition to any of the other schemes could allow the provision of local services to DSOs and, in the case of schemes (4) and (5), improve the cost-efficiency by having a more liquid market and economies of scale [7]. These benefits, in comparison to the ones provided by the *centralised market model*, could be high enough to neglect the ICT costs required for the transition. Therefore, ICT costs may not be a barrier to choosing one scheme or the other [26].

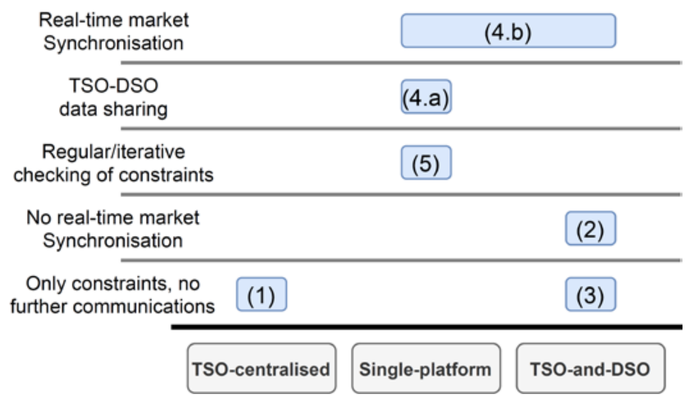

Fig. 2. Classification and communications/data exchange requirements summary of TSO-DSO coordination schemes.

IV. DATA CLASSIFICATION AND REQUIREMENTS

A. Data classification

There are different ways of classifying the data involved in the functioning of the power system: based on timeframe [27], based on who manages the data, the type of source, etc. Among the different alternatives, Eurelectric [28] categorises the data into three main classes: meter data, grid data, and market data.

Meter data are those usually collected at the customer's metering point and are mainly related to the consumption or generation of electric power. These data are collected for every customer, regardless of their voltage level and the energy market they participate in [29]. There are up to four roles related to meter data: Collector, Responsible, Aggregator, and Administrator [30]. The role in charge of storing and distributing meter data to the relevant stakeholders is the Metered Data Administrator (MDA). In some EU countries, these roles are traditionally carried out by the DSO. However, there is a trend in moving towards a centralised data hub managed by a MDA which can be either the TSO, DSO, a third party, or a mix of them [28].

Grid data are the data needed to monitor, manage, and plan the network. They include the technical data (e.g., active and reactive power, power quality, etc.) collected from different field devices (e.g., sensors, low voltage advanced supervisors, smart meters, etc.) and the data related to the topology and structure of the grid [31].

Finally, market data includes exogenous data (e.g., bids, market results, information about installations at customer premises, etc.) that are necessary to provide different services [29].

B. Data requirements

Smart grids architectures focus on optimizing the generation, consumption, and management of energy, combining ICT and Internet of Things (IoT) of several systems, creating a complex network of hardware and software applications.

As data exchange is at the base of the integration of these architectures, it is essential to define a data management and assessment process where data requirements must be defined.

In particular, the quality of the data exchanged in the power system can directly affect the output of data services, and the security, quality, reliability, and availability of supply [32].

Regarding meter data, some fundamental principles that should be adopted at the EU level as suggested by Eurelectric are [28]: security and privacy, neutrality, non-discrimination, transparency, cost-efficiency, and high quality.

These principles, including EU Data Protection and GDPR guidelines [33], should be extended to all data types (including grid data and market data), as they are essential to ensure reliable operations and data processing within the system.

In general, it is possible to define three main characteristics for data exchange in power systems [34]:

Data availability: it concerns the knowledge of the origin of the data and how this data is made available.

Data accessibility: it concerns the possibility to access the data and on which day. In case the access is limited, how to provide transparent alternatives, such as aggregating or anonymizing data.

Data usability: it concerns the format, durability, and frequency of the data. The data usability metric delineates the proper mechanism to access the data in the most usable way.

It is complex to define a unique list of data requirements that are suitable for any smart energy architecture at the European level, so the approach is to share standardization (e.g. Common Information Model, CIM [35]) and interoperability mechanisms for data exchange as much as possible, thus facilitating the integration between multiple systems.

The scope of this paper is not to enumerate data requirements but to facilitate their definition. It is therefore suggested, starting from the basic characteristics listed above, to apply a general framework where, for each dataset, it is clearly stated:

- the data source.
- the data user.
- the purpose of the data exchange.
- the principles and/or characteristics to be applied (e.g., privacy, availability or similar requirements, formats, etc.)
- the KPIs (e.g., frequency and accuracy, latencies…), to verify compliance with requirements.

TABLE II shows the matrix representing a dataset (columns), and, in the rows, information (e.g., the data source, the consumer, etc.) and specific requirements for each dataset (format, availability, etc.). This can be applied several times to each dataset; a type of data could have different characteristics and KPIs based on the purpose or the actors involved. The final matrix would include all the data requirements to be assessed.

TABLE II
DATA REQUIREMENTS MATRIX EXAMPLE

	Consumption Data	**Weather Data**
Source	Consumer	External
User	DSO	DSO
Purpose	Grid Monitoring	Simulation
Privacy	Yes	No
Non-Discrimination	Yes	No
Format	CIM	
Availability	Real Time	Historical
KPIs	Frequency: 15min	

This framework could be adapted to any architecture; it can be extended, modified or improved, based on the characteristics and needs of the architecture and the data exchanged.

V. ICT ARCHITECTURES FOR TSO-DSO DATA EXCHANGE

In this section, the ICT architectures implemented in the demonstrations deployed in different European research projects are overviewed, focusing on the information and communication layers of the SGAM [19], and highlighting the coordination scheme used.

A. SmartNet Project

The aim of the Horizon 2020 funded project SmartNet (2016-2019) was to provide architectures for TSO-DSO coordination for system services. Of the three demos carried out in this project, only the Danish and Spanish demos had congestion management as one of their use cases.

The ICT architectures presented in [23] mainly propose a set of data models and standards that could be used for each communication link, but do not specify the communication protocol or technology for each specific demonstrator, due to the lack of information regarding ICT requirements for the use cases. Nonetheless, [23] does assess which links may require wired or wireless technologies based on latency and security requirements. The architectures for the Danish and Spanish pilots are briefly described below for the congestion management use case and summarized jointly in Fig. 3:

1) Danish pilot [36]*:* In this pilot, congestion management is done through aggregated consumption shifting and load curtailment mechanisms of 30 summer houses. In this pilot, the common TSO-DSO market coordination scheme is applied.

Two different ICT systems are employed: *system A*, which includes the IoT hardware deployed in the houses that mostly use non-standard protocols and which is out of the scope of this paper; and *system B*, which is related to the LV grid and uses International Electrotechnical Commission (IEC) standards.

Within *system B*, the standards proposed for market-related communications (requirements, bids, and market results) are CIM standards (IEC 62325, IEC 61968, and IEC 61970). For the communications between the Commercial Market Parties' (CMP) management system and the DER aggregator's management system, as they are related to network operation (activation signals), the standards proposed include IEC 61850, IEC 60870-5-101/104, IEC 60870-6/TASE.2 (Inter-control Centre Communications Protocol, ICCP), OpenADR, IEC 62056 (DLMS/COSEM) as well as a Representational State Transfer (REST) architecture. Excluding REST, these standards are also proposed for the technical communications between DER units and aggregators. Regarding physical connections, only the link between the market management system and the CMP's trading system would require a wired connection [23].

2) Spanish pilot [37]*:* This pilot tested the *Shared balancing responsibility model* with the provision of local flexibility services to solve local congestion. Although the DSO manages the local market, it must meet the set-points established by the TSO. Despite implementing a different coordination scheme, the ICT architecture proposed is similar to the Danish pilot.

For congestion management, the direct communication between TSO and DSO would be done using CIM-based

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standards such as IEC 61968 and IEC 61970. For market-related communications, CIM (IEC 62325) is also proposed. Finally, communications with the DER aggregator and units consider IEC 61850, IEC 60870-5-101/104, ICCP/TASE.2, OpenADR and DLMS/COSEM as in the Danish pilot. In terms of physical connections, only the communications between the CMP's trading system and the aggregator would require a wired connection [23].

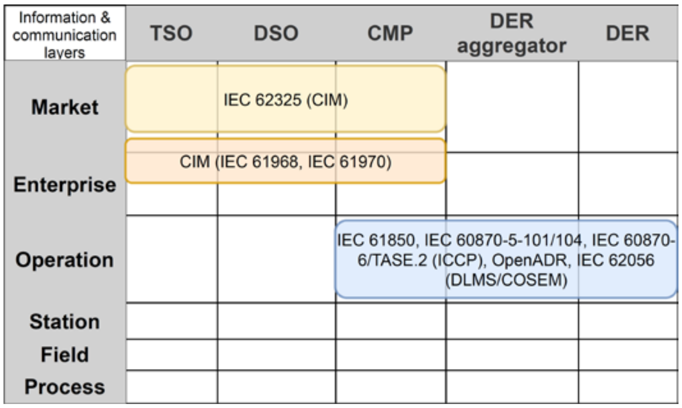

Fig. 3. SGAM Information/Communication layer of the SmartNet ICT architectures. CMP refers to Commercial Market Parties.

B. CoordiNet Project

The CoordiNet project (2019-2022) aims to demonstrate how TSO and DSO can coordinate to use the same grid resources for different services. For this, three demos are implemented: Spain, Greece and Sweden. These pilots consider different use cases, which include congestion management by the acquisition of flexibility services. In CoordiNet, data models and common interfaces will be built on ENTSO-E CIM profiles and will follow the Common Grid Model Exchange Specification (CGMES) [38].

1) Spanish pilot: The CoordiNet platform is made up of two main elements: the central or common platform, and the local platform. The pilot tests the common TSO-DSO market model.

The CoordiNet common platform is on TSO's premises and is based on two already-existing TSO systems: GEMAS, which clears and operates the market, including the execution of the congestion management market considering the DSO HV and MV networks; and eSIOS, which publishes and receives market information, acting as an interface between market agents, CoordiNet common platform, and GEMAS system.

On the other hand, the CoordiNet local platform is on DSO's premises and is only one out of the five modules that compose the DSO platform. The other modules are day-ahead operation, intraday operation, observability, and communications.

In this pilot, short-term congestion management has three parts: aggregation of congestion preconditions, activation of flexibility resources, and supervision of resource activation [38].

For the aggregation of congestion preconditions, the protocol proposed for communications between systems is the IEC 62325-504 (web services -WS -, using CIM).

The activation of flexible resources includes the congestion market clearing and the communication of results to the stakeholders. For this, the protocols used depend on the link:

- Flexibility bids are sent by DER to the CoordiNet platform using IEC 62325-504.
- Results of the congestion market are sent to the DSO platform using the Message Queuing Telemetry Transport protocol (MQTT), and to the TSO through GEMAS/ eSIOS.
- Once the definitive results are obtained, the CoordiNet common platform sends the activation signals to the Flexibility Service Providers (FSPs) (IEC 62325-504, ICCP) and notifies the SOs to supervise the activation.

Finally, during the supervision of resource activation, the TSO and the DSO will send resources' monitoring data to the CoordiNet common platform, which processes them and passes settlement processes to the relevant FSPs using IEC 62325-504. The aggregator of FSPs would use MQTT to monitor the state of the unit every five minutes.

The communication between aggregators and the local market is done through XML files, using ad hoc REST services.

Fig. 4 presents, at a high level, the ICT architecture proposed in this pilot through its mapping into the SGAM's Information/Communication layer.

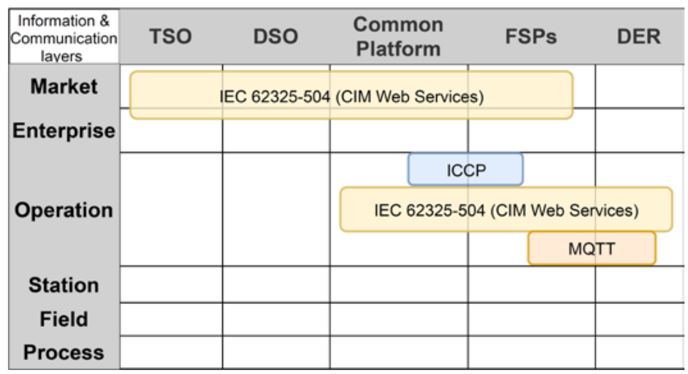

Fig. 4. Summarised SGAM Information/Communication layer of the ICT architecture for the Spanish pilot in CoordiNet.

2) Greek pilot: The CoordiNet platform consists of two platforms: the TSO-DSO collaboration platform, for the exchanges between the SOs; and the market platform, for the communications between the different market participants. Both systems use an Enterprise Service Bus (ESB) as a communication middleware, but they are independent of each other since TSO-DSO information exchange goes beyond market-related communications and different security measures might be required. The market model implemented in this demo would correspond to the local market scheme (Table I).

In the TSO-DSO collaboration platform, two protocols connect the TSO and DSO's systems with the ESB:

- ICCP (IEC 60870-6/TASE.2), using Internet Protocol security (IPsec) through a Virtual Private Network (VPN). This would be the case of the TSO's SCADA and Energy Management System (EMS).
- Secure SHell File Transfer Protocol (SFTP). Used by different DSO's systems (e.g., metering, SCADA, etc.) and the TSO's Geographical Information System (GIS).

As for the communications between the ESB of the collaboration platform and other systems (e.g., market platform, DSO support tools, metering and control microservices, etc.)

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would be done using MQTT or a REST API, implementing Transport Layer Security (TLS).

Regarding the market platform, the communications between market participants (market operator, forecast provider, TSO-DSO collaboration platform and FSPs/aggregators) would rely on MQTT/REST API.

Fig. 5 shows the summarized ICT architecture proposed in this pilot mapped into the SGAM's communication layer.

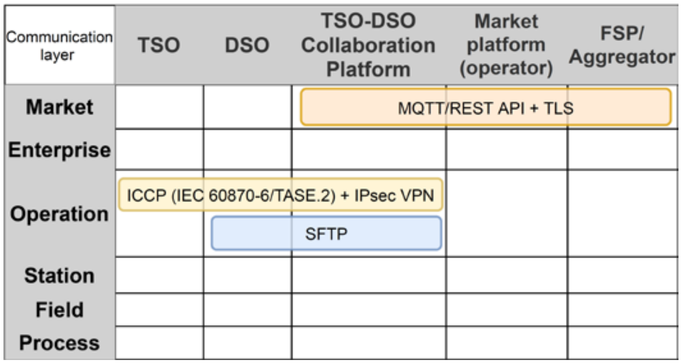

Fig. 5. Summarised SGAM Communication layer of the ICT architecture for the Greek pilot in CoordiNet.

C. TDX-Assist Project

The Horizon 2020 funded project TDX-Assist (2017-2020) aimed to develop an ICT architecture for data exchange coordination between TSO and DSO for the integration of renewable energy sources in the European marketplace using various demos in EU member states [39].

The new balancing challenges faced by SOs are typically caused by the increasing amount of distributed generation. This requires enabling an active role at the DSO level so that TSOs can coordinate with DSOs for the necessary balancing mechanisms. In the Slovenian demo of TDX-Assist, the use of DERs for balancing in a market environment was proposed and evaluated in the project using a novel business use case (BUC) methodology [39] based on the IEC 62913-1 blueprint use case method approach endorsed by the IEC SyC Smart Energy WG 6. To address different balancing market situations in the project, various scenarios were considered. The first one represented the much-needed data exchange between the TSO, the DSO, and the BSP. In the second alternative scenario, data is exchanged directly between the TSO and the DSO, where the DSO also acts as the BSP. This BUC was implemented in Slovenia to validate the required CIM-based data modelling and exchange mechanisms between DSOs and TSOs.

The ICT architecture implemented in the Slovenian demo [31] for the communication between the TSO, which hosts the market platform, and the DSO (also acting as the BSP), was based on the ICCP link and the ENTSO-E Communication and Connectivity Service Platform (ECCo SP), as depicted in Fig. 6 It could be considered that it follows the so-called *centralised market model*, although the DSO and TSO (through the market platform) exchange data as real-time information. In this case, ICCP, being a SCADA-to-SCADA protocol, is used for real-time data exchanges between the DSO's SCADA and the TSO. The rest of the data is exchanged through ECCo SP using two alternative technological ways: the Advanced Message Queuing Protocol (AMQP) and File System Shared Folders (FSSF) for large file exchanges (e.g., topology data).

To collect real-time measurements at the DSO level and send the activation signals needed for the tested balancing mechanism, MQTT is used by the DSO, making sure the CIM data model is implemented as a customized payload profile for the semantic layer. Through the MQTT broker, this data is also made available to other applications at the control centre level, such as the power quality monitoring system. For its exchange through ECCo SP, an MQTT/AMQP adapter was implemented by the respective DSO in the TDX-Assist demo.

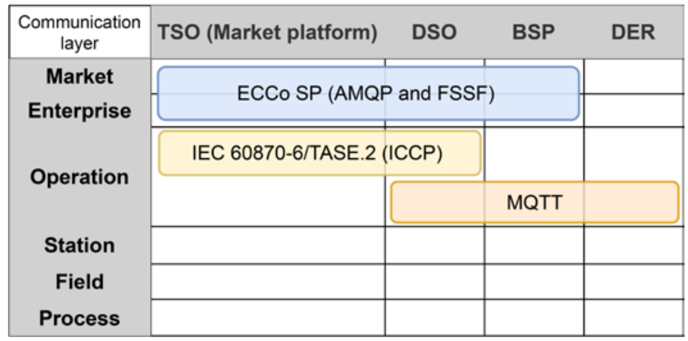

Fig. 6. Summarised SGAM Communication layer of the ICT architecture for the Slovenian demo in TDX-Assist.

D. INTERRFACE Project

INTERRFACE project (2019-2022) aims at "TSO-DSO-Consumer INTERFACE aRchitecture to provide innovative grid services for an efficient power system". It focuses on TSO-DSO coordination processes for procuring balancing, other ancillary services, and congestion management. Such services should be acquired by SOs at both transmission and distribution levels, enabling more efficient use of the power network, stronger presence of demand response, and increased hosting level of renewable generation.

With this aim in mind, INTERRFACE supports digitalization as the key driver for resource optimization from the SOs' perspective and active market participation from the flexibility providers' perspective. Interoperable pan-European Grid Services Architecture (IEGSA) is the digital tool specifically designed and developed for this as shown in Fig. 7. It acts as the interface between the SOs and the customers.

INTERRFACE has several demonstration areas and theoretical TSO-DSO coordination schemes ("options") for balancing and congestion management markets shown in TABLE I. The focus here is the 'Single Flexibility Platform' demonstrator – this is part of option 3 in [40], which corresponds to the centralized common TSO-DSO market model (TABLE I). This demonstrator involves three countries (Estonia, Finland, Latvia), and TSOs and DSOs from each of these. Its purpose is to exchange flexibility across country borders, to combine existing balancing products with congestion management products, and to enlarge the market by including distributed flexibility with locational bid information. It introduces two novel actors which are part of IEGSA framework – 'Flexibility Register' and 'TSO-DSO Coordination Platform'.

Both actors are system components that, together with SOs and flexibility providers, are involved in processes like

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managing flexibility resource and bid location information, networks' topological information, handling resource and grid qualification, product prequalification, selecting bids, etc.

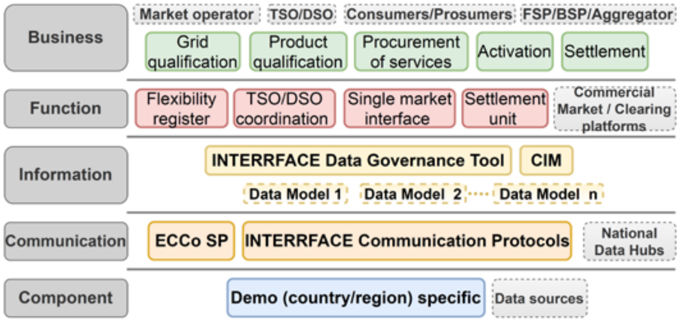

Fig. 7. Interoperable pan-European Grid Services Architecture (IEGSA). Source: own elaboration based on [16].

E. EU-SysFlex Project

EU-SysFlex project (2017-2021) stands for "Pan-European system with an efficient coordinated use of flexibilities for the integration of a large share of RES". For power systems to host more than 50% of renewable energy, which is increasingly variable and distributed, a right mix of market-based flexibility services, regulatory arrangements and operational tools is required. The project delivers proposals in the fields of market design, system operation and data management, partly validated in several demonstrators.

The demonstrators apply different TSO-DSO coordination schemes. For example, the German demo can be classified as a decentralised common TSO-DSO market model, whereby TSO/DSO data exchange is designed and tested for congestion management and voltage control for processes like resources informing SOs about availability of flexibilities; selection of needed flexibilities to solve congestions in its grid by each SO; calculate the maximum flexibility potential for the upstream SO; flexibility activation by the SO for its own need and following the request from the upstream SO [41].

Another example is "Flexibility Platform" demonstrator, which in essence corresponds to an integrated flexibility market model. Even though if such a platform could be operated by the TSO, DSO or jointly by them, it has been designed in the way that also a third party could be operating this (Market Operator role). Such an integrated approach should not imply that there is only one platform per country or larger region. Rather opposite, several platforms could compete with each other in attracting customers. The latter, of course, means that extra interoperability is required for cross-platform communication.

But even within one flexibility platform, the mix of all the functionalities and external integrations is quite complex. Up to 31 flexibility market-related functional processes were identified, which can be implemented in the Flexibility Platform. These processes include registering flexibility needs and potentials, prequalification of flexibility providers, ranking flexibility bids, managing requests for flexibility activation, baseline calculation, verifying delivered flexibilities, etc.

One objective of the project is to ensure that all stakeholders have easy access to the marketplace. This is about harmonized market rules and seamless data exchange. The Flexibility Platform is accessible for any flexibility provider and any SO, and is capable to handle any flexibility product, including 'joint products' (single product which can be used for different needs and by different SOs). This requires high attention on data management, including the secure exchange of private data.

Elering's Estfeed data exchange platform is used in the demonstrator for all data exchanges (Fig. 8). The Estfeed protocol [42] is based on SOAP and REST. Data users and data sources communicate with Estfeed adapters using HTTPS protocol. Estfeed messages are encoded using MIME multipart format. The header of the message must contain metadata in XML format, while the payload can be in any format.

The Flexibility Platform does not require explicit TSO-DSO coordination; the platform takes care of all the interactions. All SOs use it to exchange relevant data. This way, joint procurement of flexibilities creating synergies can be enabled through coordinated grid impact assessment, socio-economic bid optimization, and value stacking.

"Flexibility Platform" demonstrates a list of system use cases (SUCs) elaborated specifically for (energy) data exchange. While "Flexibility Platform" implements SUCs related to flexibility data exchange (flexibility prediction, prequalification, bidding, activation, baseline calculation, and verification of activated flexibilities), other data management demonstrators executed several 'process-agnostic' SUCs like data users' authentication, consent and data log management, etc. IEC 62559-2 standard template was used to describe the use cases [43] and, additionally, these were modelled using the SGAM framework. Standards' gap analysis was conducted for each SUC and two use cases were modelled in CIM (EU-SysFlex labelled this "CIMification" process [44]).

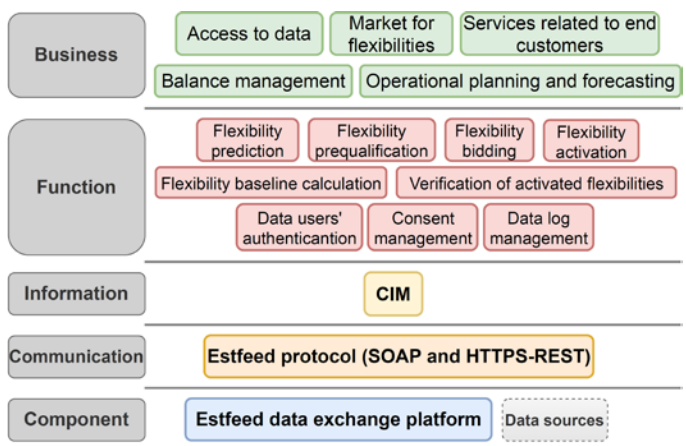

Fig. 8. High-level summary of the SGAM layers of the "Flexibility Platform" demonstrated in EU-SysFlex.

VI. COMPARISON OF ICT PROTOCOLS AND STANDARDS

The review carried out in Section V shows the wide range of ICT options and schemes to implement similar use cases. TABLE III summarises the ICT architectures of the projects reviewed.

All the projects have in common the use of CIM as information model. CIM aims to ease the exchange of grid and market data between organizations, as well as the exchange of data between systems within an organization [45].

Despite the great improvement in interoperability that CIM provides, some practical issues may arise when developing a system. These issues can be related to CIM extensions, the harmonization with other standards when connecting multiple

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systems or applications, and the validation of the model instances [46]. The gap analysis carried out within EU-SysFlex [44] concluded that CIM coverage may need to be improved when dealing with data hubs, data portability, sub-meter data, data aggregation and anonymisation, consent management, for exchanging data logs and authentication information, for the exchange of data between DERs and SOs (e.g., by harmonising CIM and IEC 61850 [47]), and when implementing other flexibility services besides balancing. On the other hand, CIM profiling proved that no CIM extensions are needed for congestion management if the manual frequency restoration reserve (mFRR) type product is used to provide this service.

Two main ICT approaches can be distinguished when applying a coordination scheme: one involves the development of new platforms (i.e., ad hoc) that may integrate with existing SO's systems (e.g., CoordiNet); and the other one involves the use of an external data exchange platform (DEP) such as ECCo SP or Estfeed (e.g., INTERRFACE, EU-SysFlex).

Regarding data exchange requirements of coordination schemes, centralised schemes such as the *centralised common TSO-DSO market model*, the *integrated flexibility market model*, the *centralised market model*, or the *local market model*, present no major data exchange challenges, since there is only one market platform interacting with the different stakeholders. However, data exchange can be challenging when the scheme requires real-time synchronisation of multiple market platforms or processes, like in the *decentralised common TSO-DSO market model*. This scheme can be considered the most challenging coordination scheme, since it would require seamless communications between markets. Regardless of the coordination scheme and approach followed, the communication protocols implemented correspond to two paradigms: Client-Server (C-S) (i.e., request-response) and Publish-Subscribe (P-S). The advantages and disadvantages of both paradigms are numerous [48] and, depending on the data exchanged and the systems connected, one or the other may be more convenient. TABLE IV provides a summary of the main advantages and disadvantages of both paradigms.

In the C-S paradigm, the client periodically polls the server to fetch its state through well-defined interfaces. In terms of efficiency this means that, unless updates are frequent or the communications are synchronized, memory, computational, and power resources are misused during some periods. In terms of reliability, the server's response acknowledges that the client's request was correctly received and processed.

Typically, most market data exchanges will occur at determined times, such as when a market process is going to be initiated or cleared. As the number of agents related to the market process can be high (Fig. 1), a WS architecture such as HTTP-based REST would guarantee a high interoperability level, synchronous communication, and the establishment of

TABLE III
SUMMARY OF ICT ARCHITECTURES IN EU-FUNDED PROJECTS

Scheme	Demo	Protocol/Platform	Type	Communication link	Information exchanged
Common TSO-DSO market	SmartNet Denmark	IEC 62325	C-S	TSO-DSO-MMS MMS ↔ CMP	Reserve needs, market bids, and activation
		IEC 61968, IEC 61970	/	TSO-DSO- Market Management System	Network constraints
		COSEM, ICCP, IEC 61850 (MMS)	C-S	CMP ↔ DER aggregator DER aggregator ↔ DER units	Asset activation. DER characteristics
		OpenADR, IEC 61850 (GOOSE, SV)	P-S		
	CoordiNet Spain	IEC 62325-504 (CIM WS)	C-S	DER generation ↔ Common Platform Common platform ↔ FSPs Common platform ↔ DSO platform	Flexibility bids. Activation signals and settlement processes DSO needs and constraints
		ICCP	C-S	Common Platform ↔ FSPs (Market)	Activation signals
		MQTT	P-S	FSPs ↔ DER units	Congestion market results. Unit monitorization.
	INTERRFACE "Single Flexibility Platform"	ECCo SP	P-S C-S	Flexibility register function TSO-DSO Coordination function Single market interface function Settlement unit function	
		INTERRFACE Communication Protocols			
Shared balancing responsibility	SmartNet Spain	IEC 62325	C-S	DSO ↔ Market Management System Market Management System ↔ CMP Trading System DSO ↔ Market Management System Market Management System ↔ CMP Trading System	Market clearing, bids, prequalification, and reserve needs
		COSEM, ICCP, IEC 61850 (MMS)	C-S	CMP Trading System ↔ DER Aggregator	Asset activation and confirmation
		OpenADR, IEC 61850 (GOOSE, SV)	P-S		
Local market	CoordiNet Greece	ICCP	C-S	TSO-DSO platform ↔ SCADA and EMS	TSO-DSO coordination
		SFTP	C-S	TSO-DSO platform ↔ DSO's systems and TSO's GIS	
		MQTT	P-S	TSO-DSO platform ↔ Market platform, other systems Market platform ↔ Market operator, forecast provider, FSPs/aggregators	Market-related communications
		HTTPS (REST API)	C-S		
Integrated flexibility market	EU-SysFlex "Flexibility platform"	Estfeed Platform	P-S C-S	All interactions	/
Centralised market	TDX-Assist Slovenia	ICCP	C-S	DSO ↔ TSO (market platform)	Real-time data
		ECCo SP (AMQP and FSSF)	P-S C-S	DSO ↔ TSO (market platform)	Meter and grid data (i.e., field measurements)
		MQTT	P-S	DER, smart meters ↔ DSO	Real-time measurements and activation signals.

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well-defined procedures through APIs. This is specifically observed in SmartNet and the Spanish demo of CoordiNet, where the market requests bids to the CMPs/DERs through WS. On the other hand, in P-S, messages are received by the topic's subscribers as they are published in that topic, using a broker as an intermediary.

This is useful when the same message has to be sent to multiple entities without setting the time or frequency in advance. However, publishers cannot know directly if the message was correctly received by all the subscribers, as the broker decouples them from the publisher.

Some market data subclasses (e.g., generation and appliance data) and meter data require immediate communication as they are generated, or to be sent by/to multiple entities simultaneously. In these cases, a P-S protocol such as MQTT may be more convenient. MQTT [49] is very used in constrained-communication IoT devices because of its low message overhead, latency, and its quality of service mechanisms, which allows the broker to ensure that the message reaches all the subscribers even avoiding duplicates.

In the Spanish demo of CoordiNet, MQTT is used by FSPs to monitor the activation of DERs (many-to-one communications). However, for market-related data exchanges between a reduced number of platforms/systems (i.e., not field devices), where communications are not expected to be heavily constrained, AMQP may be a better option than MQTT. AMQP [50] is based on queues (similar to topics) and provides further security and control over messages. To increase scalability and reliability at an enterprise level, the recommendation is to implement AMQP and limit the use of MQTT to edge connections [51] (e.g., meter data from DERs, activation signals, etc.). This approach was the one followed by the Slovenian demo of TDX-Assist, to use ECCo SP between the DSO and the market platform in the TSO.

TABLE IV
SUMMARY OF ADVANTAGES/DISADVANTAGES OF CLIENT-SERVER AND PUBLISH-SUBSCRIBE COMMUNICATIONS

Communication paradigm	**Type of information exchanges**	**Advantages / Disadvantages**
C-S	Synchronous	- Well-defined interfaces (API REST) - Waste of communication resources if information updates are not frequent or not synchronized
P-S	Asynchronous	- Lightweight protocols. Communication is more effective since transactions only occur when updates are available.

As for grid data exchanges, two main non-exclusive options are identified: ICCP and DEPs. The ICCP standard [52] defines a C-S service model for the direct exchange of time-critical data between control centres through wide and local area networks, including time-series data, control operations, scheduling information, etc. Despite ICCP is traditionally chosen for the exchange of grid data between TSO and DSO [10], its standard version is considered a legacy protocol that lacks of enough protection and that offers a large attack surface [53], [54]. Therefore, the use of DEPs as an alternative is increasing for centralised schemes, so that the system to access meter, grid, and market data can be the same and new agents can easily connect without a heavy investment in an ICCP connection. Some of these DEPs, such as Estfeed, have their own protocol [42] that defines a "Publish" protocol and a "Request-Response" protocol to fulfil the requirements of the different agents and data types, also providing adapters for data hubs and applications; others, like ECCo SP, are compatible with different protocols, such as AMQP, Web Services, and FSSF [55], which may already be in use by SOs. An overview of the DEPs used in EU projects was carried out by the BRIDGE initiative [56].

VII. Challenges and Future Developments

Regarding TSO-DSO cooperation, the Regulation and Data Management Working Groups of the BRIDGE initiative have identified the main challenges and proposed recommendations both from a regulatory and data management perspective [56].

Among the main recommendations, BRIDGE proposes to develop a conceptual European data exchange model that involves elements of the platforms developed/used like functionalities, standardization needs, etc. In addition, the use of different types of platforms in EU projects makes necessary to define the "interoperability of platforms" and identify those platforms with replicability and scalability potential at a European level, while ensuring GDPR compliance and data owner's control over their data. In addition, these platforms should also comply with EU regulation addressing data exchange, such as Regulation 2017/2195, Regulation 2017/1485, and Regulation 2016/1388. The interoperability of platforms, together with data handling (data ownership, access, quality, and harmonization) are considered the main challenges to address. To ease the addressing of these challenges, BRIDGE recommends cooperating in the development of use cases, through an accessible use case repository [57], and harmonizing the approach for defining roles to be included in the Harmonised Electricity Market Role Model [30]. Lastly, the use of CIM as the main information model and the promotion of cooperative CIM extensions are also recommendations of BRIDGE.

The goals of the OneNet project are aligned with the recommendations and challenges previously mentioned. From the IT perspective, the OneNet Framework (Fig. 9) [58] aims to facilitate the integration and cooperation of the platform as well as to provide a data interoperability mechanism to platforms to support data exchange for facilitating market and network operations and the cooperation between SOs.

The integration and homogenization mechanisms will be applied at both data and service levels. They will leverage on the most used and promising Data and Smart Energy open architectures (FIWARE Smart Energy grid Reference Architecture [59], IDS Reference Architecture Model [60]) and standardized components for platforms integration (e.g., Next Generation Service Interface Standard Context broker and REST APIs). The OneNet Framework (Fig. 9) will focus on:

- the seamless integration of platforms by the adoption of open standards and interfaces.
- data privacy control and data access according to regulations for each stakeholder.
- defining and applying standard models and protocols.
- provisioning data management features: harmonization, quality assessment, and semantic annotation.

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- dataflow monitoring and logging.
- ensuring a secure and GDPR compliant data exchange and platforms integration by applying identification, authentication, and authorization mechanisms.

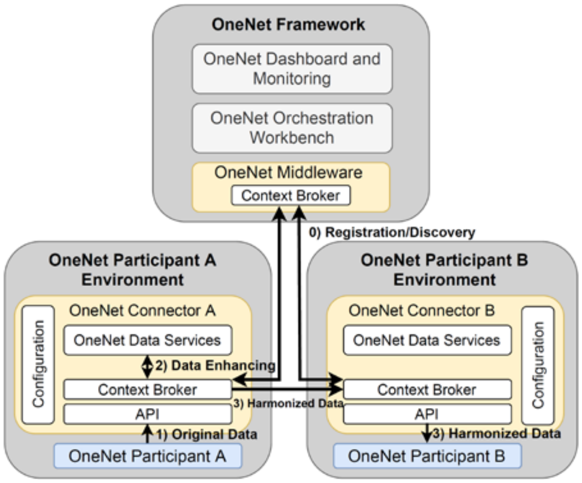

Fig. 9. OneNet Decentralised Solution. Source: own elaboration based on [58].

Fig. 9 shows how the OneNet Framework leverages on the Decentralised Middleware and Connectors. These two components enable an end-to-end fully decentralised ecosystem (the OneNet Network of Platforms) in which two or more systems (OneNet participants) can interact directly with each other, exploiting all the functionalities provided by the OneNet Framework.

VIII. Conclusion

The increasing penetration of DERs enables the implementation of new system services for SOs that will require better coordination between TSOs, DSOs, and service providers.

Seven ICT architectures implemented in five EU-funded projects have been reviewed, identifying common protocols and standards based on the type of data exchanged and the communication link. Among the different coordination schemes, *the decentralised common TSO-DSO market model* is considered to be the most challenging from the ICT point of view, requiring seamless real-time synchronization of different market platforms or processes. The analysed demos apply CIM in the information layer, combining the use of P-S and C-S communication protocols.

The use of C-S mechanisms was found appropriate for the communication of synchronous market processes (WS or https-REST) and grid data (ICCP, DEPs). However, in this last case, the standard ICCP should be replaced by more modern and secure protocols or, directly, by using DEPs.

For real-time market and meter data exchanges, P-S protocols were, in general, conveniently implemented by all the demos. However, it is suggested to keep MQTT for communications with field/remote devices, and AMQP for the communications between larger systems/platforms.

Existing DEPs such as Estfeed and ECCo SP could provide faster and more cost-effective use case implementations than ad hoc platforms or point-to-point connections because of their interoperability potential. However, they should guarantee low communication latencies for those data exchanges requiring real-time capabilities; otherwise, a mixed approach may be more convenient (e.g., TDX-Assist project).

The expected contributions of the EU-funded OneNet project were also analyzed. The OneNet framework will address the interoperability and data handling challenges by providing an end-to-end decentralized ecosystem in which two or more systems (e.g., the ones used in the projects reviewed) will be able to interact between them for different purposes.

Future research needs to analyse the coordination schemes in terms of data-intensiveness, to compare the general data requirements for each scheme. The analysis of the SGAM component layer of the ICT architectures would also be of great interest so that the component costs could be estimated and used in a cost-benefit comparison of coordination schemes together with the potential benefits that such schemes provide to the power system.

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