



Final demonstration results for testing propagation of threat detection on market activities with DT

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List of Abbreviations and Acronyms

Acronym	Meaning
ADMS	Advanced Distribution Management System
API	Application Programming Interface
DER	Distributed Energy Resource
DG	Distribution Grid
DSO	Distribution System Operator
DT	Digital Twin
EMS	Energy Management System
FIRMe	Flexibilidade Integrada em Regime de Mercado (Integrated Flexibility in a Market Regime)
FSP	Flexibility Service Provider
GUI	Graphical User Interface
KPI	Key Performance Indicator
LFM	Local Flexibility Market
LFMO	Local Flexibility Market Operator
LTS	Local Trading System/Solution
mFRR	Manually Activated Frequency Restoration Reserve
MO	Market Operator
P	Active power
Q	Reactive power
RT	Real Time
SCADA	Supervisory Control and Data Acquisition
SIOM	Market Operator Information System
SQL	Structured Query Language
TSO	Transmission System Operator
UC	Use Case
V	Voltage

Executive Summary

This deliverable presents the final validation and demonstration results of two complementary Iberian Pilot use cases investigating how Digital Twins can improve electricity-market cybersecurity, grid-market coordination, and the integration of distributed flexibility. In the case of the Spanish side of the Iberian electricity systems, UC Ib04 works to provide a set resilience measures to identify abnormal market participation behaviours prior to the entry into force of local flexibility markets. In the case of Portugal, the analysis is focused on how local flexibility markets at distribution level can provide flexibility services to the Transmission System Operator (TSO) increasing the overall system resilience.

UC Ib04 addresses abnormal market participation and the activation of coordinated mitigation procedures in Local Flexibility Markets. The work analysed the Local Flexibility Market value chain and identified three priority cybersecurity scenarios: S1 fake offers (selected for validation and demonstration activities), S2 unexpected or inadequate delivery of contracted flexibility, and S3 compromised database integrity. For each scenario, a protocol was characterised covering the actors and systems involved, exchanged information, identified risks, mitigation mechanisms, requirements, success criteria, and validation methods.

The demonstration confirmed that a secure and independent information channel can act as a redundancy and validation mechanism, preventing a compromised offer from propagating into market clearing and grid operation. It also showed that the TwinEU Data Space connectors could be integrated into the participating Digital Twins through APIs without major changes to their internal architectures. To enable deployment at scale, the validation procedure should be automated and supported by formal rules for bid quarantine, incident escalation, root-cause investigation, participant suspension, penalties, market re-clearing, and activation of replacement flexibility.

UC Ib12 examined whether flexibility procured at distribution level through FIRMe [1], Portugal's first local market for electricity flexibility services in the distribution level, could be technically validated, forwarded, and included alongside native mFRR resources in the TSO balancing process. The demonstration used 2025 operational and market data at 15-minute resolution and combined market eligibility checks, aggregation where necessary, DSO technical validation, and merit-order clearing.

Across 4,502 analysed intervals, FIRMe resources were selected in 160 intervals and supplied a cumulative 7,138.85 MW, corresponding to approximately 1.60% of total cleared volume. Native mFRR supplied 439,192.06 MW. The selected FIRMe flexibility generated estimated FSP revenues of €548,453.76 and estimated system savings of €63,563.11. Although local flexibility remained a supplementary resource, the results demonstrate that it can be economically valuable during periods in which competitively priced distribution-connected resources replace more expensive balancing resources.

Together, the results show that Digital Twins can provide a shared technical basis for secure market operation and TSO-DSO coordination. They enable market information to be linked with the physical state of the grid, support the validation of flexibility before activation, and provide a controlled environment in which cybersecurity and coordination procedures can be tested. Future work should focus on automated cross-validation, common data models, improved metering and observability, coordinated incident response, backup flexibility, broader FSP participation, and the integration of demonstrated procedures into regulatory and operational frameworks.

1 Introduction

The electricity sector is becoming increasingly decentralised, digitalised, and interconnected. The growth of distributed renewable generation, energy storage, demand response, electric vehicles, and active consumers is increasing the number of resources capable of providing grid services. At the same time, it creates a need for improved coordination among Transmission System Operators (TSOs), Distribution System Operators (DSOs), market operators, and Flexibility Service Providers (FSPs).

Digital Twins (DTs) can support this coordination by providing dynamic digital representations of physical networks, market processes, or interconnected energy systems. By combining system models with operational and market data, DTs allow stakeholders to reproduce system conditions, assess expected behaviour, test alternative scenarios, and evaluate the consequences of operational or market decisions without directly affecting the physical system.

In electricity-market activities, DTs can represent and support processes such as bid submission, eligibility verification, aggregation, market clearing, flexibility activation, delivery validation, and settlement. When grid and market DTs are interconnected, commercially available flexibility can be assessed against the technical state of the network before it is procured or activated. This is particularly relevant for Local Flexibility Markets and for the participation of distribution-connected resources in transmission-level balancing services.

T5.4 shows how Digital Twins can strengthen the cybersecurity and operational resilience of electricity markets. The increasing number of participants, automated processes, and digital interfaces creates additional points at which credentials, offers, measurements, databases, or control signals could be compromised. DTs, combined with secure data-exchange mechanisms, can help identify abnormal behaviour, cross-validate sensitive information, evaluate its possible propagation through market and grid processes, and support coordinated mitigation measures.

Against this background, the Iberian Pilot activities reported in this deliverable address two complementary applications. UC Ib04 investigates the detection of abnormal participation in Local Flexibility Markets and the activation of protocols to mitigate potential cyberthreats. UC Ib12 assesses whether distribution-level flexibility can be technically validated and integrated into the TSO mFRR process. Together, these use cases demonstrate how interconnected grid and market Digital Twins can support more secure, coordinated, and efficient electricity-market activities.

1.1 Task 5.4

As the aim of WP5 is to develop and demonstrate digital twinning to assess and increase the cyber-physical power system resiliency, the Iberian Pilot focuses its participation, under the framework of T5.4, on (1) increasing the grid operational resilience at TSO and DSO levels, and (2) developing a dedicated procedure for abnormal market participation detection and protocol activation in a context with a large number of Distributed Energy Resources (DERs) acting as Flexibility Services Providers (FSPs) in Local Flexibility Markets (LFMs).

1.2 Objectives of the Work Reported in this Deliverable

This deliverable aims at reporting the final results of the work developed by the Iberian Pilot partners in the framework of the cybersecurity work package. The document presents the methodology that was followed, the consolidation of the concepts and the developments performed to undertake the validation activities.

1.3 Outline of the Deliverable

Chapter 2 describes the methodology and the consolidation of the grid and market services involved in the pilot activities, as well as the development work that was carried out to validate and demonstrate the Use Cases.

Chapters 3 and 4 report the validation and demonstration activities performed for UCs Ib04 and Ib12. These chapters include a first part that presents the experiments and a second part that reports both quantitatively and qualitatively the results obtained.

Chapter 5 analyses the common applicability of the protocols developed in UC Ib04 to the specific market architecture of UC Ib12.

Chapter 6 provides the document conclusions.

1.4 How to Read this Document

This document summarises the work done from M15 (when D5.3 [2] was delivered) until the end of the task. D5.4 is the final report delivered under T5.4 and it showcases the development activities and the methodology followed as well as the results of the validation activities, finalising with a set of conclusions derived from these results.

2 Methodology, consolidation and development of grid and market services and value chain links subject of study

2.1 (UC Ib04) Local Flexibility Markets (LFM) value chain and protocol applicability

D5.4 takes the baton of the first phase of the task (reported in D5.3 [2]) that was aimed at identifying the most relevant market services of applicability for the abnormal market participation studies. In D5.3, it is exposed how Local Flexibility Markets seemed the most appropriate case of study as it had the potential to create a safe-by-design implementation in a context where these markets are not yet operational in the Iberian electricity system. One of the main reasons for this safe-by-design implementation was that the entry into operation of these markets genuinely implies the active interaction of a much higher number of actors in the electricity system (markets).

A first identification of steps over the value chain of local flexibility markets was performed (see Figure 2.1). The work identified long and short-term activities from registry and validation of the market participant to negotiation of market positions. The time span includes the D Day (assets activation) up to after-delivery operations.

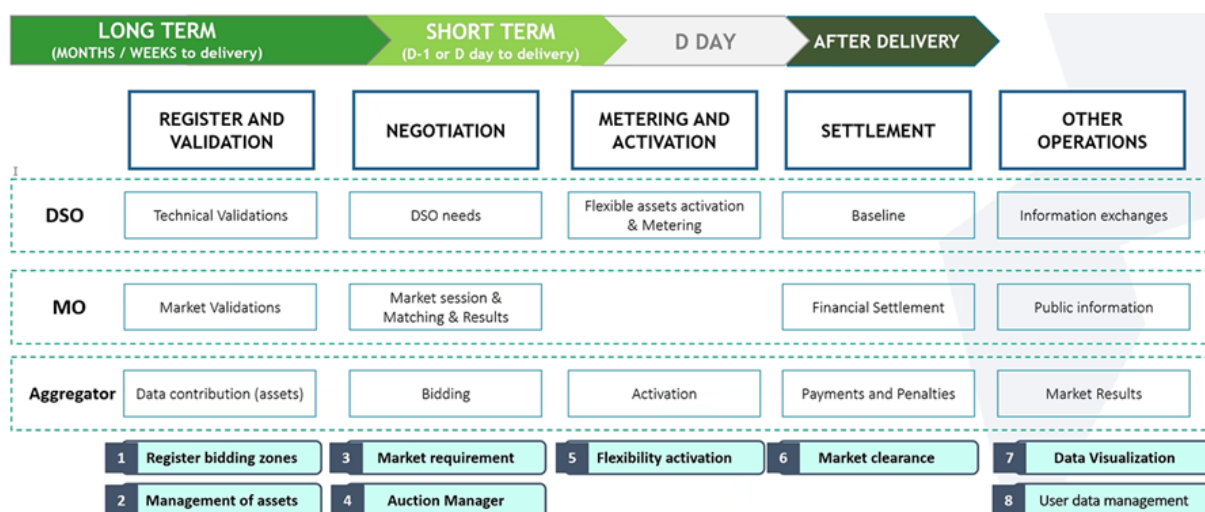


Figure 2.1. LFM value chain assessment, market services mapping and activities identification

T5.4 studied each one of the links in the chain with the view of identifying which could be more prone to detect abnormal market participation behaviours in the grids. In order to do so, different specific activities were pointed out as key steps towards the identification of these issues (see Figure 2.2). First, in the negotiation phase (2) fake offers were identified as potential markers of abnormal market participation behaviours in the negotiation phase. In the activation and metering phase, both (3) forced operation strategies over flexible assets and a (4) corrupt metering infrastructure were identifiable triggers. Moving on to settlements the clearest activity to be detected is an (5) unexpected delivery validation, where a resource does not behave as expected according to market results. Last but not least, and outside of the consequent steps, other operation could trigger abnormal market participation behaviours through (1 and 6) corrupt certificates or information exchange.

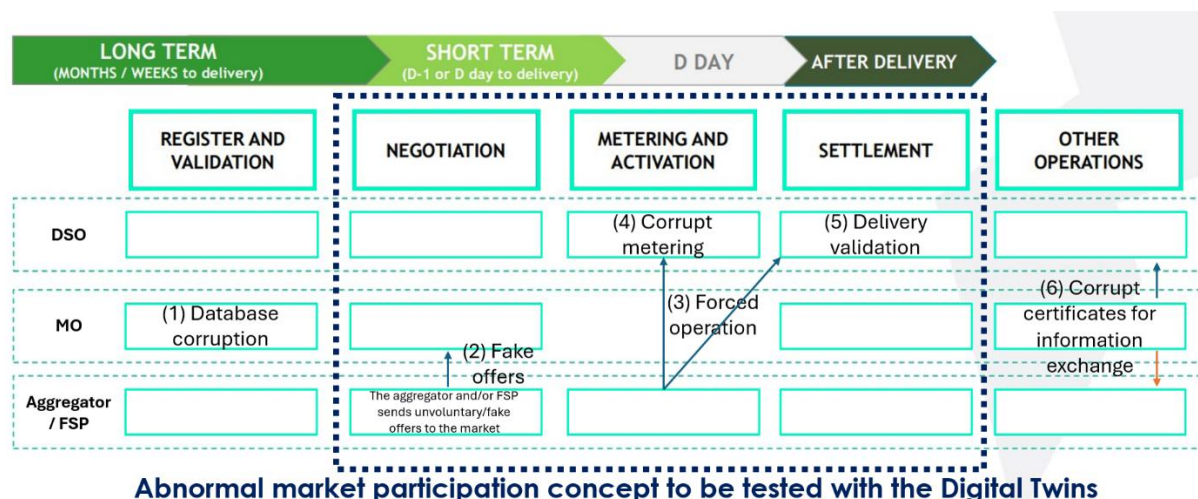


Figure 2.2. Value chain links identification as potential trigger for cyberthreats detection

Out all the activities identified, T5.4 partners grouped them into scenarios where these triggers could be given. These scenarios are:

- S1 on Fake Offers, focused on the negotiation phase
- S2 on Delivery Validation, focused on the metering and activation and settlement phases.
- S3 on Databases Integrity, focused on register and validation and other operations.

2.1.1 Scenarios definition (based on how to detect abnormal market participation behaviours in the market)

2.1.1.1 Fake offers

Local systems in the premises of FSP may be subject to cyberthreats resulting in sending fake offers to the LFM via their EMS without the assets operator realises.

How to detect it? The offers are visible for the DSO only when matched. Partners needed tools that would help mitigate the risk by offering secure communications. A platform for the exchange of certain sensitive-marked data could be implemented.

Under these conditions, UC Ib04 partners proposed the use of TwinEU's Data Space as a secure and parallel communication channel to the Local Trading System implemented for UC Ib14.

2.1.1.2 Delivery validation

(Eventually due to a cybersecurity breach) The asset, resource or system of the FSP performs an actuation different to the one committed in the LFM settlement. This is especially critical when there was a certain committed position (power to be delivered) and it is not fulfilled. It could also occur that a corrupt metering system was in place. In that case, the FSP would be delivering the committed position (power) but a disruption in the metering infrastructure provides wrong information to the DSO.

How to detect it? In both cases, a surveillance system at the DSO's RT operation services of the DT must be in place. When an anomaly is detected

How to detect it? Can this be part of the verification in the previous protocol or it should be a different one? An asset validated to participate in LFM must have independent submetering infrastructure?

2.1.1.3 Database corruption and corrupt certificates for information exchange

Once a market player is registered, its data is stored in a dedicated database. If the database has been corrupted, the contained data could be jeopardised.

How to detect it? In this case, the scenario is more complex, as it implies many entry gates for the attacks. To detect a cyberattack affecting database integrity across the market process, the protocol should continuously monitor for unauthorized access, data manipulation, and abnormal system behaviour at every stage: registration, bid submission, market clearing, results publication, settlement, data storage, and stakeholder integration. Key detection measures include strong authentication monitoring to identify credential theft, digital signatures and hash verification to detect altered bids or results, database activity monitoring to uncover unauthorized queries or modifications, integrity checks on algorithms and financial records, audit trails and immutable logging to track all actions, anomaly detection on APIs and network communications, and Data Loss Prevention controls to identify data exfiltration attempts. Any mismatch between submitted, processed, published, and settled data, unexpected privilege changes, unusual access patterns, failed integrity checks, or discrepancies between internal and external records should trigger alerts and incident response procedures, ensuring that compromised data or systems are quickly identified and contained. Based on Sheet S3, these controls are essential to detect attacks such as credential theft, bid tampering, database injection, result manipulation, financial record fraud, data exfiltration, and exploitation of external integrations.

2.1.2 Cybersecurity coordination plan consolidation

The protocols included in the cybersecurity coordination plan are a set of cross-agent coordination action plans aimed at evaluating a specific situation and establishing the most appropriate communication channels and flow to mitigate the risk and consequences of an eventual cyberthreat.

The cybersecurity coordination plan requires a significant improvement in the identification and management of incidents as well as on their cross-actor notification and communication. The DSO's DT will implement a surveillance service monitoring the identified market-related parameters in RT to flag unexpected behaviours potentially caused by a cybersecurity breach.

2.1.2.1 Scenario description for PROTOCOL to mitigate the risk and consequences of FAKE OFFERS sent to the market

The first elemental steps for the protocol to mitigate the risk and consequences of fake offers having been sent to the market were identified:

1. A flexibility request is sent by the DSO to the LFM and a LFM session is opened by the LFMO.
2. FSPs send their bids to participate in the flexibility service provision.
 - A fake offer could have been sent due to a cybersecurity breach in the premises of an FSP.
3. The LFMO validates that all offers comply with the minimum requirements to participate in the market.

- The fake offer complies with all formal requirements to participate in the market and it is not detected by the LFMO.
- 4. The LFMO clears the markets and send the preliminary market results to the DSO.
 - The fake offer is matched.
- 5. The LFMO double-checks with all FSP that have matched offers their validity.
 - The validation process can highlight the issue, but it must be secured. A certificate-based communication exchange via the data space could make it.
- 6. The DSO runs the selected scenario in its DT (ÉTER), validating at a technical level the proposed solution or imposing the necessary technical restrictions.

2.1.2.2 Scenario description for PROTOCOL to mitigate the risk and consequences of unforeseen DELIVERY VALIDATION

The first elemental steps for the protocol to mitigate the risk and consequences of unforeseen delivery validation were identified. This scenario could either be a continuation of the scenario 1, considering that the fake offer wasn't detected or a direct attack on the service delivery process.

- 7. The technical restrictions have been implemented and the final LFM results have been defied.
- 8. On D-day for the specific session, the RT monitoring capabilities of the DSO's DT (ÉTER) detects that one FSP does not respond as expected.
 - This point would require a mandatory submetering for FSPs flexible assets that disaggregates the flexibility provision from the rest of its consumption.
- 9. The scenario can be recalculated considering the new FSP position.
- 10. If it created congestions or an unstable state of the grid
- 11. Offline verification of root causes for the market disruption. Can be a forced operation, an uncommunicated failure in the FSP's systems or an issue on the metering devices.

2.1.2.3 Protocol 3 for detecting a cyberattack affecting databases integrity

The first elemental steps for the protocol to mitigate the risk and consequences of compromised databases integrity were identified.

- 1. Participant Registration: A market participant registers on the market platform. Authentication, identity, financial guarantees, and asset data are submitted. The system verifies identities and records all registration activities. Cyberattack detection: monitor failed logins, unusual access locations, unauthorized account creation, or unexpected changes to participant data.
- 2. Bid Submission: The participant submits buy/sell bids through the market system. Bids are encrypted, timestamped, and acknowledged by the platform. Integrity checks verify that submitted and stored bids are identical. Cyberattack detection: identify bid modifications, missing acknowledgements, abnormal bid patterns, or suspicious communication activity.
- 3. Market Clearing Execution: The market operator runs the clearing algorithm using all valid bids. Results are calculated and stored in the market database. Algorithm code, configurations, and input datasets are validated. Cyberattack detection: detect unauthorized

database changes, SQL injection attempts, abnormal administrator activity, or discrepancies between expected and actual results.

4. **Market Results Publication:** Market results are published internally and externally. Public information is anonymized while private information remains restricted. Digital signatures protect published results. Cyberattack detection: identify altered results, defaced web pages, failed signature checks, or unauthorized publication actions.
5. **Settlement Processing:** Settlement calculations are generated from the final market results. Financial records are stored and distributed to participants. Access controls limit modifications to authorized services. Cyberattack detection: monitor for unauthorized changes in financial records, unexpected fund movements, or inconsistencies between settlement data and market outcomes.
6. **Data Storage and Historical Records:** Market, bidding, and settlement information is stored for future access and auditing. Continuous integrity monitoring is applied to databases. Cyberattack detection: identify unusual data exports, excessive queries, unauthorized access to sensitive information, or signs of data exfiltration.
7. **Stakeholder Integration:** Information is exchanged between the Market Operator (MO), DSO, and other stakeholders through APIs and secure interfaces. Communications are authenticated and logged. Cyberattack detection: detect abnormal API traffic, failed authentication attempts, unauthorized connections, or lateral movement between systems.
8. **Incident Detection and Response:** Logs, database events, API activity, and integrity checks are continuously monitored. Any anomaly triggers an alert. Affected records are cross-checked against original submissions, acknowledgements, and calculations. If a compromise is confirmed, access is isolated, forensic analysis begins, and affected market processes can be reviewed or re-executed.

Outcome: A cyberattack is detected when any unauthorized modification, integrity mismatch, abnormal access pattern, suspicious communication, or unexplained discrepancy is identified between the original data, processed data, published results, and settlement records. This ensures end-to-end protection of database integrity throughout the market lifecycle.

2.1.3 Consolidation of protocols and scenarios

Based on the previous initial consideration, the three protocols were defined based on the following information:

1. Number of the step and step description.
2. Actors, systems and DTs involved.
3. Applicability to demo activities (only applicable for Scenario 1 on fake offers).
4. Vulnerabilities and potential attacks (only applicable for Scenario 3 on compromised databases integrity).
5. Data or information exchanged.
6. Identified risks and mitigation mechanisms (only applicable for Scenario 1 on fake offers and for Scenario 2 on delivery validation).
7. Requirements, assumption and/or specifications.
8. Success criteria for the step.

9. Validation mechanisms.

10. Any further comments.

With all that information the scenarios and protocols are fully characterised and UC Ib04 partners could proceed to develop and implement the services needed to undertake the validation activities of the UC (focused, due to regulatory capacity of the national framework on LFM, on the validation of scenario 1 on fake offers via the DT simulation module in ÉTER and its integration with the LFM).

The three scenarios fully characterised are presented below with Table 2.1 for the scenario 1, Table 2.2 for the scenario 2 and Table 2.3 for scenario 3.

Table 2.1. Scenario for protocol to mitigate the risk and consequences of fake offers

Scenario for PROTOCOL to mitigate the risk and consequences of FAKE OFFERS sent to the market										
Step	Step description	Actors / systems / DTs involved	Applicability to demo activities	Data or information exchanged	Identified risks	Mitigation mechanism	Requirements, assumptions and/or specifications	Success criteria	Validation	Comments
P1.1	A flexibility request is sent by the DSO to the LFM and a LFM session is opened by the LFMO.	DSO LFMO	Validation of UC Ib04	Flexibility request (timeframe and quantity)	n.a.	n.a.	For the DSO: API SOAP for authentication and AMQP for data	(unitary test-like) Request sent and received via OMIE LTS	LFM session opened by the LFMO	
P1.2	FSPs send their bids to participate in the flexibility service provision.	FSP LFMO	Validation of UC Ib04	Flexibility provision bids (timeframe and quantity)	A fake offer can be sent due to a cybersecurity breach in the premises of an FSP.	P1.5	For the FSP: API REST for authentication and AMQP for data	(unitary test-like) Bids sent and received via OMIE LTS	Bids are stored and ordered	
P1.3	(The offer were legit) The LFMO validates that all offers comply with the minimum requirements to participate in the market.	LFMO	Validation of UC Ib04	-	A fake offer complies with all formal requirements to participate in the market and it is not detected by the LFMO.	P1.5	Orders must include: - agentID - message - zone - area - unit - sessionID - contractID - type - price - quantity	Bids are compliant with the set of form-and-content requirements defined by OMIE.	Bids go forward to clearing process	
P1.4	The LFMO clears the markets and sends the preliminary market results to the DSO.	LFMO DSO	Validation of UC Ib04	Preliminary market results	The fake offer can be matched.	P1.5	Units matched, power to be delivered, timeframe and marginal price	LFM is cleared	The DSO receives the LFM results	
P1.5	The LFMO double-checks with all FSP that have matched offers their validity.	LFMO FSP	Validation of UC Ib04	As described in the protocol (tbc)	The entire system at the FSP premises (including the connection to the dataspace) can be compromised.	S2. Delivery validation	A different channel should be used to recude the risk of compromised communications.	A predefined data exchanged process (via the dataspace) is executed	Cross-validation mechanism to be developed for the protocol.	The validation process can highlight the issue, but it must be secured. A certificate-based communication exchange via the data space could make it.
P1.6a	(The offers were legit) The DSO runs the selected scenario in its DT (ÉTER), validating at a technical level the proposed solution or imposing the necessary technical restrictions.	DSO LFMO Eventually FSPs	Validation of UC Ib04							
P1.6b	(A fake offer was spotted) The DSO inform the LFMO for the market to be cleared again without considering that offer.	DSO LFMO FSPs	Validation of UC Ib04							Measures must be put in place towards the participation of that FSP in future markets until the issue is solved.

Table 2.2. Scenario for protocol to mitigate the risk and consequences of delivery validation

Scenario for PROTOCOL to mitigate the risk and consequences of unforeseen DELIVERY VALIDATION										
Step	Step description	Actors / systems / DTs involved	Applicability to demo activities	Data or information exchanged	Identified risks	Mitigation mechanism	Requirements, assumptions and/or specifications	Success criteria	Validation	Comments
P2.1	After the successful validation of the LFM results (P1.6a), the DSO imposes technical restrictions/viability to achieve the final position of all market participants.	DSO LFMO FSP	n.a.	Viability of the scenario	n.a.	n.a.	The DSO's DG DT validates the suitability of the scenario	GO	GO / NO-GO decision	Technical restrictions are something related to transport and curtailment, maybe it is not the most accurate term in that scenario. Maybe technical conditions would suit better
P2.2	On D-day for the specific session, the RT monitoring capabilities of the DSO's DT (ÉTER) detects that one FSP does not respond as expected.	DSO FSP	n.a.	RT submetering data	Conventional baseline power curves for FSPs are complex to obtain and could fail to provide a fair starting point	The most practical solution would be a neutral, accredited sub-metering system that all parties could access.	Neutral, accredited sub-metering system available	Submetering systems reveals failure in delivery spotted by the surveillance module	The DSO's DG DT receives the data in RT and an alert pops up	Would this require mandatory submetering for FSPs flexible assets? How is that disaggregated from the rest of its consumption?
P2.3a	The scenario is recalculated in RT considering the new FSP position and the congestion has anyways been solved.	DSO FSP	n.a.	n.a.	Internal risk to the scenario - the market solution obtained was suboptimal or forecasts were not accurate enough	(External to the scenario) improve algorithms	Monitoring needed for the specific session	n.a.	n.a.	Not the desirable scenario as the market solution would not have been optimal. Considered anyways.
P2.3b	The scenario is recalculated in RT considering the new FSP position and the congestion arises or the grid is under unstable conditions.	DSO FSP	n.a.	n.a.	The situation would be severe in a scenario of increasing consumption to compensate for an excess of generation, since in that case, if activation does not occur, the system would be at risk.	FSPs "on standby" to be activated immediately? Perhaps a mechanism could be put in place whereby, when the auction closes, 10% of the flexible power is left as a "reserve" that can be activated. This would involve an economic availability reward, similar to the one we previously discussed for the SRAD, but it might be an interesting consideration. To do so, a margin will be implemented on top of the required flexibility (e.g., if the DSO needs 1MW in flexibility, the offer to be sent to the LFM may be for 1,6MW, having a set of FSP matched and only activated if necessary)	LFM must consider the figure of reserve FSP to be immediately activated upon need - paid per capacity (always) and per service delivered (when required).	The reserve unit delivers the power and the congestion is solved	The DSO's DG DT validates the scenario viability considering the new FSPs' positions	what should then be done? Could the market be interrupted? What does that imply?
P2.4	Offline verification of root causes for the market disruption. Can be a forced operation, an uncommunicated failure in the FSP's systems or an issue on the metering devices.	DSO LFMO FSP	n.a.	On-demand data required by the DSO	n.a.	n.a.	A framework for penalties upon non-compliance must be in place	n.a.	n.a.	

Table 2.3. Scenario for protocol to mitigate the risk and consequences of compromised databases integrity

Scenario for PROTOCOL to mitigate the risk and consequences of compromised DATABASES INTEGRITY									
Step	Step description	Actors / systems / DTs involved	Systems/ DTs involved	Vulnerabilities	Potential Attack	Data exchanged	Requirements, assumptions and/or specifications	Success criteria	Validation
3.1	Market participant registration	MO + Market player	Market System and if the connection is automatic, the platform developed by the market participant (to exchange information)	Authentication mechanisms + Insecure storage of credentials and personal data.	Credential theft or impersonation to gain unauthorized access.	The data required for market participation includes identification information, a declaration of guarantees to be able to bid in the market, and other relevant information. Asset data consists of technical parameters; for each installation, it is necessary to declare the power output and other technical data required by the DSO.	Participant must provide verified identification, legal and financial guarantees, and asset technical data. Secure authentication and encrypted communication are required. Integration with MO systems must follow approved protocols.	Registration completes without errors; data is verified and securely stored; only authorized users access the platform; asset data accepted by DSO	Check of submitted data; validate identity and asset information with DSO; test authentication security; verify communication protocol; ensure participant can access the market system.
3.2	Bid Submission	Market Player	Market System and if the connection is automatic, the platform developed by the market participant (to exchange information)	Unencrypted data transmission + Lack of bid integrity verification.	Attack to intercept or alter bids, affecting market prices.	In the offers it is necessary to identify whether it is a buy or sell offer and the amount of power for each time period that the market participant is willing to offer.	Bids must follow MO-defined formats (buy/sell, volumes, periods, price). Transmission must be encrypted and respect gate closure times. Automated interfaces must comply with MO APIs and integrity controls.	Bids are received and acknowledged before deadlines; all bid parameters are stored correctly; no data alteration occurs; participants can verify their submitted bids.	Validate bid structure and schema; check integrity; ensure timestamps meet deadlines; confirm asset capability limits; review logs and acknowledgments.
3.3	Market Clearing Algorithm Execution	MO	Only the market system and the application dedicated to settlement	Algorithm manipulation via database injection + Insider threats or compromised admin accounts.	Fake result injection or defacement of public data to mislead participants.	Economic data on a market participant's gains or losses after market participation. The final profit situation for each market participant.	Algorithm runs within a secure MO environment, with integrity controls.	Algorithm executes without errors; results match expected models; results stored securely and delivered to settlement; logs show no anomalies; process completes within regulatory deadlines.	Validate input dataset; verify algorithm code/configuration integrity; confirm consistency between internal and published outputs.
3.4	Market results	MO	Market System (the section of results) and the public website	Web server vulnerabilities + Lack of digital signature on published data.		There is public data (anonymized offers such as the marginal price, the total volume of energy sold...) and private data (energy offer and price matched by each market participant...)	Public and private results must be segregated. Public data must be anonymized. Web servers must be hardened. Results must have digital integrity protection. Private data only accessible via authenticated/secure channels.	Results published on time; public data accurate and anonymized; private data securely accessible; integrity checks pass; no defacement or unauthorized modification; logs show no suspicious activity.	Verify public results match internal calculations; validate anonymization; check signatures; perform vulnerability scans; review access logs
3.5	Settlement	MO	Market System (the section of settlement)	Insecure database access.	Manipulation of financial records or unauthorized fund transfers.	Market settlement data is broken down by each market participant based on their final program (the status of their buy and sell order units at the end of market trading).	Settlement engine operates with strict access control. Inputs (market results, programs) must be validated. Only service accounts write settlement data.	Settlement completes accurately and on time; no unauthorized database changes; financial results consistent with final programs; secure distribution to participants;	Validate inputs vs official results; perform integrity checks; audit user/service account activity; cross-check calculations with verification tools; publication of reports
3.6	Data storage and access	MO			Data exfiltration for competitive advantage or sabotage.				
3.7	Integration with stakeholders (DSO as a main stakeholder and others)	MO + Stake holders		API vulnerabilities + Insecure interconnection protocols	Lateral movement across systems or cross-border disruption.				

2.1.4 Development and integration of associated grid and market services

The use case implementation, especially for the validation and demonstration activities of Scenario 1, is based on the established collaboration between the DSO's DG DT and the LFM DT. The collaboration was both established as a direct integration and through the reference collaboration framework designed in WPs 3 and 4.

ANELL's Distribution Grid DT is based on ETRA's Advanced Distribution Management System (ADMS) – ÉTER –. ÉTER targets Distribution System Operators (DSOs), aiming at facilitating the monitoring, control and planning activities of modern distribution grids efficiently. The tool is equipped with a Digital Twin module provided with the Advanced Simulation Profiling capabilities. Apart from the DT service, ÉTER offers the main service that will trigger the demonstration activity, which is the Congestion Management layer. Figure 2.3 represents the entire ADMS architecture.

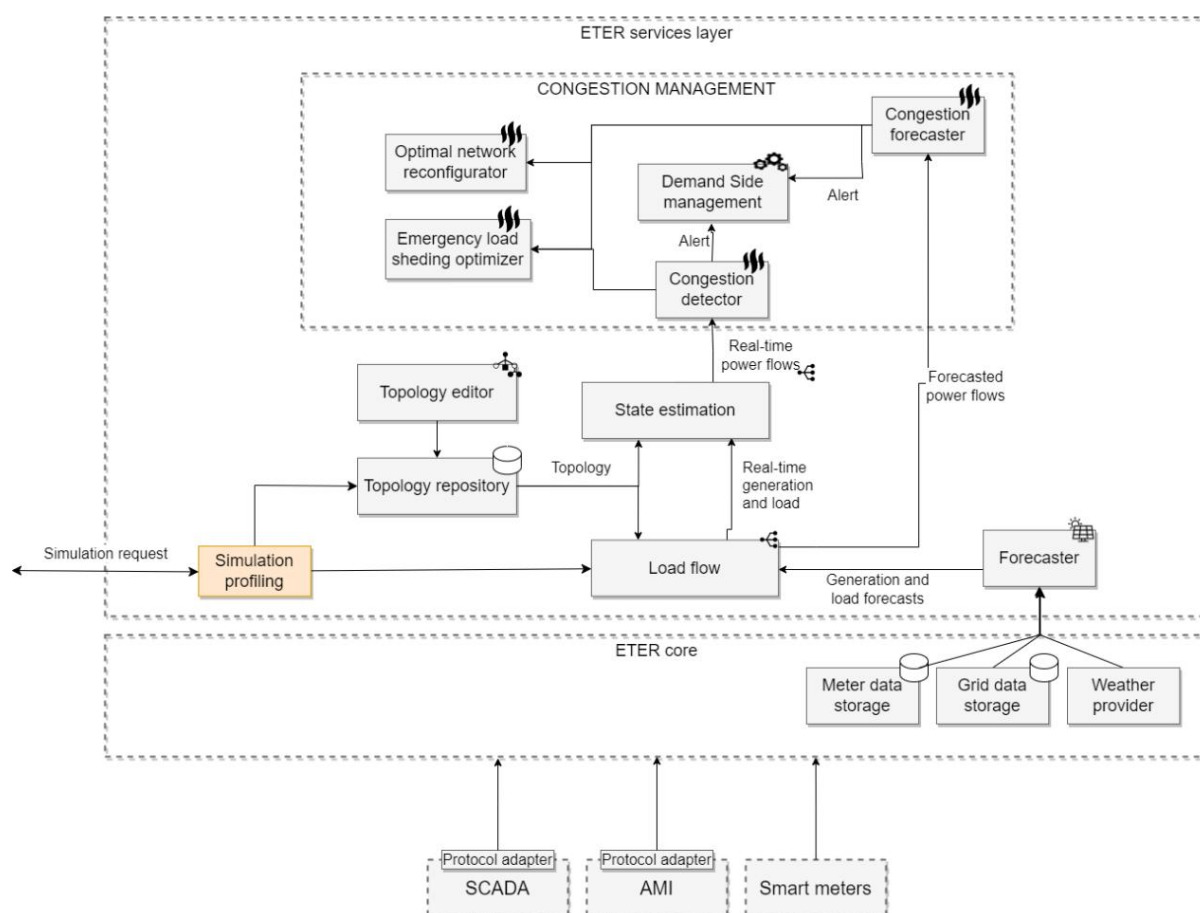


Figure 2.3. ÉTER Architecture.

OMIE's LFM DT involves the modelling of two market platforms for procuring local flexibility markets. One for local short-term negotiations (with the same technology as the LTS system to provide grouping functionalities in the same market tool) and a second one for long-term flexibility negotiations. UC Ib04 makes use of the short-term flexibility trading platform to request flexibility to FSPs to solve congestion issues in the grid.

This market platform and its DT is based on a web application where users, both flexibility-providing market participants and DSOs, can register themselves using a username and password. Once registered, users will be able to participate in long-term flexibility auctions through the GUI to integrate their energy flexibility into the markets. Figure 2.4 represents OMIE's DTs, including the

forementioned DTs – applicable to LFM – as well as the DT of the wholesale electricity markets in the Iberian system.

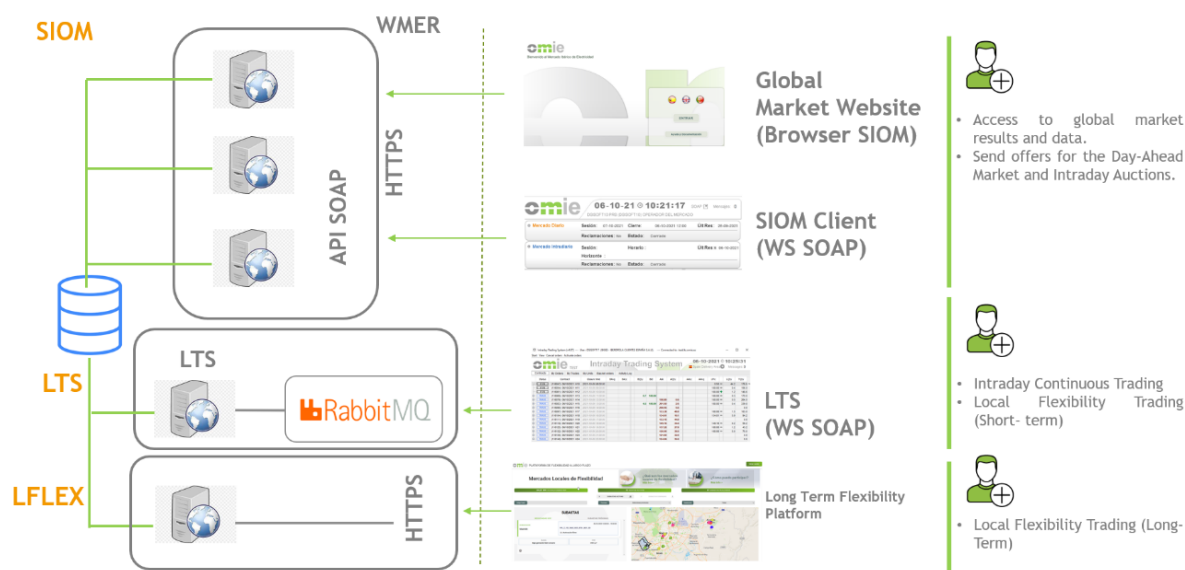


Figure 2.4. OMIE's Market Operator Information System (SIOM) Architecture

To enable the data exchange between the DSO and LFM Digital Twins, the deployment files for the TwinEU Dataspace connector [3] were provided and used. The connector is based on the OneNet Connector and was deployed in each DT premises. This deployment exposed an API that could be integrated into the existing Digital Twins without requiring major changes to their internal architecture.

The API was integrated into ETER DT and LFM DTs to support the exchange of the information required for congestion management and flexibility procurement. This includes grid-related data, such as detected congestion situations, affected grid areas, time periods, and the flexibility requirements needed to mitigate the congestion. It also includes market-related data, such as flexibility requests and offers submitted by flexibility service providers, including the offered volume, availability period and other relevant conditions.

The TwinEU Dataspace connector implements the Dataspace protocol and supports the complete controlled data sharing process through the API. This process includes the creation of a data offer, the subscription of a consumer to that offer, the negotiation and generation of a contract, and the subsequent upload or download of data. As a result, relevant information has been exchanged between the DSO and LFM DTs through the TwinEU Dataspace in a secure and structured way.

2.2 (UC Ib12) Integration of TSO-DSO-MO-Prosumer coordination schemes as well as market coordination

UC Ib12 addresses the coordination between distribution-level flexibility procured through FIRME and the TSO mFRR balancing service. The methodology developed for the use case combines market-side processing with grid-side technical assessment in order to determine whether flexibility available at distribution level can also be used to support transmission-system balancing needs.

The approach establishes a coordinated value chain between the Flexibility Service Provider (FSP), FIRME, the Distribution Grid Digital Twin (DT), the DSO and the TSO. This allows flexibility to be assessed from both a market and a network perspective before being considered for mFRR activation.

2.2.1 FIRME flexibility market services

FIRME [1] is used as the main market interface for identifying and managing flexibility resources connected to the distribution network. Through FIRME, FSPs provide flexibility offers containing information such as available volume, bid price, activation direction, location, availability period and response characteristics.

Within UC Ib12, this information is used as the starting point for assessing whether distribution-connected flexibility can also participate in a TSO balancing service.

Before being forwarded, the available FIRME offers are processed through a set of eligibility checks. These checks include:

- Availability of flexibility resources during the relevant delivery period;
- Compatibility between the required and offered activation direction;
- Compliance with response and activation requirements;
- Qualification status of the resource;
- Compatibility with the applicable market period;
- Compliance with minimum bid-volume requirements.

Where an individual flexibility offer does not satisfy the minimum volume requirement, compatible resources can be grouped through an aggregation process. The resulting aggregated offer can then be considered as a single flexibility resource for subsequent assessment.

2.2.2 Grid-side technical assessment and Digital Twin services

A key component of the methodology is the connection between the FIRME market information and the physical condition of the distribution network.

This connection is provided by the Distribution Grid Digital Twin and the grid services associated with it. The DT provides a digital representation of the relevant distribution-network topology, electrical assets and operating conditions and can therefore support the assessment of the impact of flexibility activation on the grid.

The relevant grid-side information and services include, where available:

- Network topology and connectivity;
- Electrical location of the flexibility resource;

- Network operating state;
- Voltage conditions;
- Line and transformer loading;
- Congestion and operational constraints;
- Power-flow assessment;
- Determination of the maximum technically admissible flexibility volume.

The role of the DT is therefore not to perform market clearing, but to provide the technical information required by the DSO to assess whether the flexibility identified through FIRME can be safely activated.

This distinction is important because the flexibility commercially offered by an FSP is not necessarily equal to the flexibility that can be physically delivered without affecting distribution-grid security.

2.2.3 Integration of market and grid-side services

The interface between FIRME and DT links the market representation of the flexibility resource with its physical location and operating conditions in the distribution grid.

For each candidate resource, FIRME provides the information required to identify the requested activation, including its location, direction, available volume and delivery period. This information can then be used by the DT and associated grid services to evaluate the expected network impact.

The grid-side assessment returns the information required for technical validation, which may include:

- technical validation status;
- maximum admissible activation volume; and
- identification of the limiting network constraint, where applicable.

Based on this information, a FIRME resource can be:

1. fully validated and forwarded with its original volume;
2. partially validated and forwarded with a reduced volume; or
3. rejected when its activation would violate distribution-network operating limits.

The process therefore separates two different types of decision. FIRME and the market-processing services determine whether the resource is commercially eligible, while the DT and DSO determine whether the resource is technically feasible.

2.2.4 Forwarding and integration with the TSO mFRR service

After the market and grid validation stages, the eligible FIRME resources are prepared for participation in the TSO mFRR process.

The relevant information is transferred to the balancing-market layer, including the validated flexibility volume, price, activation direction and delivery period. Where required, the resources are aggregated before being forwarded.

The validated FIRME resources can then be considered together with native mFRR resources as part of the available flexibility pool for each balancing interval.

The purpose of this integration is to enable distribution-connected flexibility to contribute to a transmission-level balancing requirement, provided that the resource satisfies both the market and technical conditions applicable to the service.

2.2.5 Market clearing and activation

For each balancing interval, the TSO balancing requirement is compared with the available eligible resources.

The FIRME and native mFRR resources are ranked according to the applicable economic selection criteria. In the methodology developed for UC Ib12, the resources are ordered according to their bid price and selected until the required balancing volume is covered.

This means that the final selection of a FIRME resource is subject to two distinct stages:

1. **Technical decision:** the DSO and DT/grid services determine whether and how much flexibility can be safely activated.
2. **Economic decision:** the TSO market-clearing process determines whether the validated flexibility is competitive and required to cover the balancing need.

Following clearing, the selected resources can proceed to activation and the corresponding settlement process.

3 UC Ib04 validation and demonstration activities

3.1 Validation and demonstration activities description

3.1.1 General information on the demonstration activities

UC Ib04 deals with Abnormal market participation detection and protocol activation for mitigating the risk and consequences of eventual cyberthreats in LFM. A defined methodology guided project partners to come up with a set of scenarios that could be derived from the implementation of this new market mechanism in the Iberian electricity system and define proposal for dedicated protocols to mitigate the risk and consequences of cyberthreats in the operating systems.

This process spanned for the whole duration of the project until the execution of the demonstration activities that comprised one out of the three proposed scenarios. The scenario on Fake Offers sent to the LFM was demonstrated between July and August 2026, M34 and M35.

The main target of this demonstration was to validate the use of the central architecture of TwinEU (in this case the TwinEU data space) as a redundancy buffer to identify eventual cyberthreats in the communications between the EMS of the Flexibility Service Provider and the Local Trading Systems from the LFM.

In the case of Local Flexibility Markets, a large number of participants whose main business is not energy trading are expected to jump into the system. The nature of these new market players often is SMEs with energy assets that can valorise them and get extra revenue by offering automated services to the DSO. The increased number of participants plus the fact that non-expert industries with lower cybersecurity capacities are now part of the equation, increases the risk of the system being disrupted with a large number of new possible entry gates for attackers.

3.1.2 Actors, assets and systems involved

There are three main actors involved in the execution of the use case: the Flexibility Service Providers (FSPs), the DSO and the LFMO.

In this case, the FSPs have been simulated based on real industrial users connected to the grid of ANELL that can provide the service of balancing the grid thanks to their flexible assets and processes.

The DSO, ANELL, used the software tool ÉTER developed by ETRA that embeds the DT of their grid and includes real time information from the SCADA (P, Q, V, I) for the grid nodes as well as data from Smart metering infrastructure (exported and imported power).

Last but not least, the LFMO, OMIE, makes available their Local Trading System (LTS) as LFM platform for solving congestion issues.

ÉTER and the LFM platform are integrated both through direct integration via the LTS and through the TwinEU's central architecture, and more specifically through the data space with two connectors deployed, one at each end.

3.1.3 Triggering event description and pre-conditions

The triggering event that activates the UC is a request for flexibility by the DSO through the short-term local flexibility market. Once that happens, FSP are required to send their bids via the LTS GUI or

their own EMS connected to the LTS as well as via the TwinEU dataspace, following the simplified data model proposed.

3.1.4 Experiment description and post-conditions

Once the offers have been sent to the market, the LFMO executes a validation process for matching the offers received via the LTS and the offer received via the data space. If they match, the offer goes forward to the clearing phase and, if they don't, the offer is discarded, the DSO is notified and the offline process to clarify the root causes of the mismatch is started.

The post-condition comes with the fake offers erased as valid participant into that specific market session.

3.1.5 Datasets required for the experiment and field data to be gathered

The essential dataset needed are forecasted power flow values (P, Q, V, I) to open the session for flexibility request upon the identification of a congestion. Once that is available, the UC generates all further data, which essentially is market results. First with the amount of flexibility required by the grid and the price at which the DSO is willing to pay for it, and second the final results based on the offers that the FSP send to the market and thus, are matched.

3.1.6 Related KPIs

The defined KPI that is associated with UC Ib04 is described below in Table 3.1.

Table 3.1. KPI Ib04-1 description

KPI ID	Ib04-KPI1
KPI Name	Number of new methodologies/protocols defined for mitigating the risk and consequences of an eventual cyberthreat in LFMs
Related Use Case	UC Ib04
KPI Description	Within the concept of mitigating the risk and consequences of eventual cyberthreats in LFMs there are several fields of actuation. This KPI aims at identifying the scenarios that were case of study in the TwinEU project.
Unit of measurement	n.a.
Baseline	0 (not yet considered in the current definitions of LFMs in the Iberian electricity system)

3.2 Validation and demonstration activities results

3.2.1 Results of the demonstration activities

While no congestions (with their associated flexibility needs) were observed during the demonstration period, this should not be construed as evidence that flexibility is unnecessary. The absence of flexibility requirements during the monitored timeframe simply indicates that the specific operating conditions did not give rise to network constraints. Under different load, generation, or

network conditions, flexibility may still play a crucial role in maintaining secure and efficient grid operation. Therefore, the demonstration results should be interpreted as reflecting the conditions encountered during the trial rather than the long-term absence of flexibility needs.

Thus, the execution of the test case starts with the simulation of a congestion with the DT (ÉTER). This was done by artificially rising the consumption in a specific node, generating a scenario where a line is expected to withhold a 246.79% of its rated power.

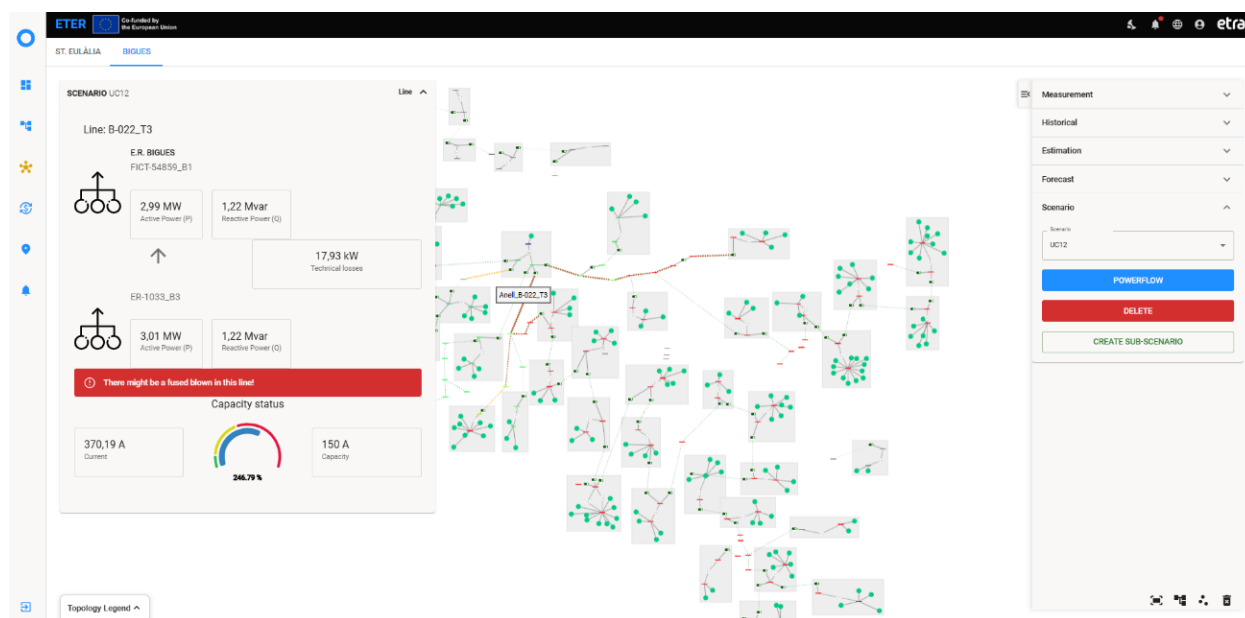


Figure 3.1. ÉTER DT simulation module generating a virtual congestion in the grid

When this happens, ÉTER offers the DSO the possibility of generating a flexibility request to launch/open a session in OMIE's Local Flexibility Market (LFM). In this case, the congestion was simulated for the hour H16 with the need for 0.05 MWh at a maximum price of 93.05 €/MWh.

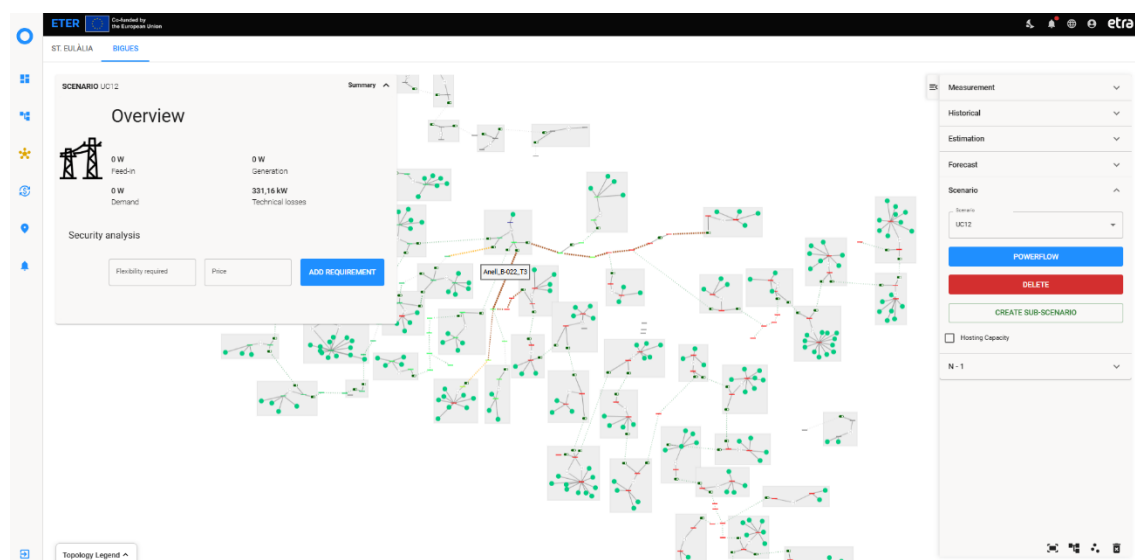


Figure 3.2. ÉTER DT direct integrated interface with the LTS for the DSO to request flexibility

For session H16 on August 6th, two offers were sent to the market, simulating a valid and a fake offer:

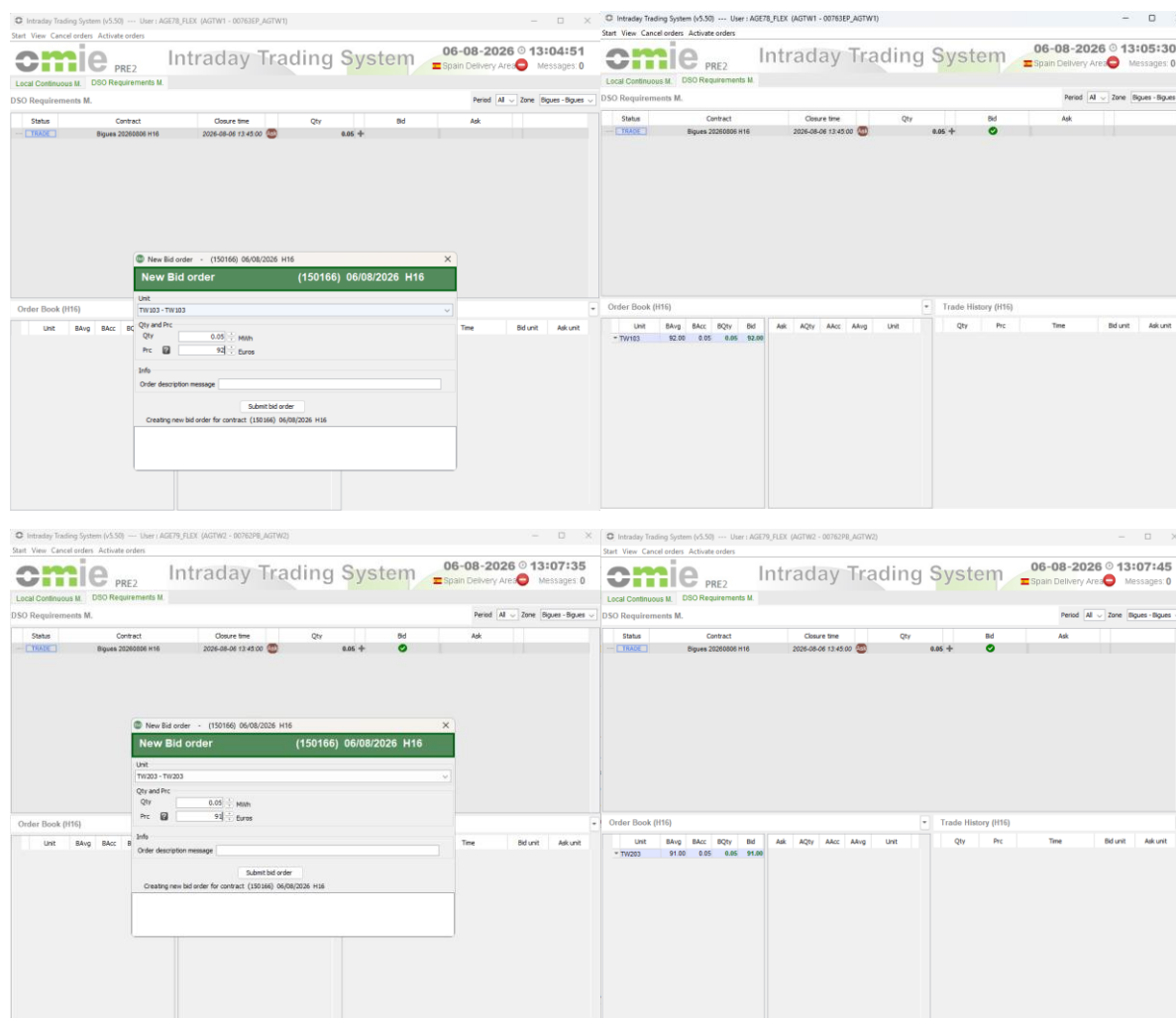


Figure 3.3. LTS GUI for submitting offers in the short-term flexibility market

The second offer was conceived to replicate a fake offer and thus, was not sent through the dataspace as the parallel validation method. Following the agreed simplified data model, the offer would be sent in a csv file containing the following information:

- Code of the session
- Zone of applicability
- Date and hour of the session
- Quantity of the offer
- Price of the offer
- Code of the bidding unit

That data format makes the offer files sent via the data space like:

- 149764;Bigues;06/08/2026 H16;0.05;92.00;TW103 (AGE78 – increase consumption)
- 149764;Bigues;06/08/2026 H16;0.05;91.00;TW203 (AGE79 – decrease generation)

	A	B	C	D	E	F
1	149764	Bigues	06/08/2026 H16	0.05	92	TW103
2						
3						

Figure 3.4. Content of the cross-validation file shared via the TwinEU dataspace

When performing the validation process, the LFMO accessed the data space to consume the data (see Figure 3.5).

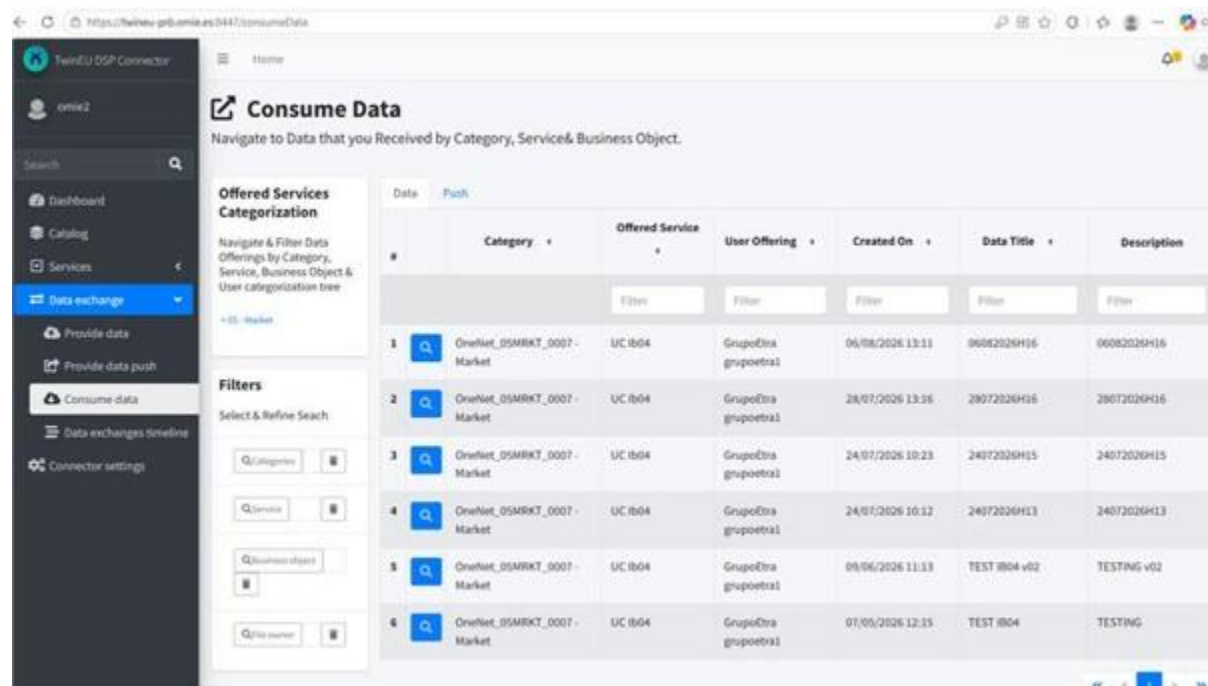


Figure 3.5. TwinEU's dataspace GUI for accessing the services to consume data

Having accessible for download only one file:

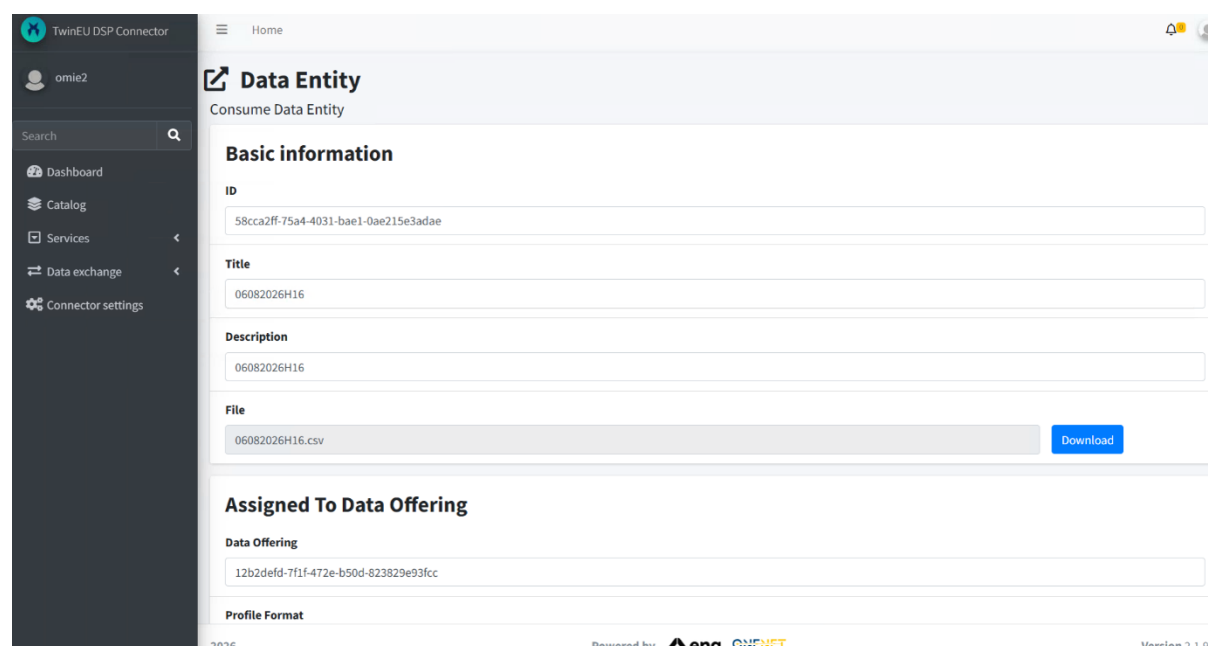


Figure 3.6. TwinEU's dataspace GUI of a dedicated data entity that allows data consumption

Following the protocol's procedures, the fake offer, is cancelled, moving the service provision to the following cheaper offer (the other offer sent in the experiment).

Consultas OMIE - Histórico de resultados (AGE78_FLEX) - Google Chrome

mercadoslocales.omie.es/jsiom/app/web/configuracionConsulta?codConsulta=6551#

Histórico de resultados

Zona: Bigues - Bigues

Fecha de entrega: 06/08/2026

Días anteriores: Treinta días

Consultar

	Zona	Cód. transacción	Fecha transacción	Código contrato	Fecha entrega	Periodo	Agente	Unidad	Tipo transacción	Cantidad	Precio	Cód Oferta
1	Bigues	2944	06/08/2026 13:45:30	150166	2026-08-08 00:00:00.0	16	AGTW1	TW103	Bid	0.05	92.00	5520

Filas: 1/1

Figure 3.7. LTS historical accepted bids consultation

3.2.2 Qualitative assessment of the results

The proposed scenarios and associated protocols cover most of the value chain of the current implementation proposal for local flexibility markets in Spain. Although other solution could be studied for the operational implementation of the scenario, the TwinEU central architecture has proved to be a valid redundancy mechanism to mitigate the risk and consequences of abnormal market participation behaviours in LFM.

The results provided by the UC Ib04 demonstrations offer a solid basis for the inclusion of such mechanisms by design when LFM are implemented as regulated figures in the Spanish regulatory framework.

In that scenario, UC Ib04 partners have already identified processes that should be automatised and/or modified to include the outcomes of TwinEU results into the conceptual model. The offline verification performed by the LFMO should be automatised on the MO premises to ensure that the system is scalable. The model for flexibility services provision through LFMs should not only include the match of the most suitable offer but it should also consider an additional capacity reserve in case that the delivery is unsuccessful. This last modification proposal touched both S2 (as of the unexpected delivery validation) and S1 when offers are sent to the market and the optimal market solution is calculated. This case also implies that an incentives framework for DSO should consider the backup capacity as a running cost for the LFM.

DSOs and LFMO should closely collaborate to identify the root causes of the fake offer (and the unforeseen delivery validation in the case of S2) and apply penalties in a similar way as how it is done in wholesale electricity markets when a market player incurs into deviations from the declared/matched market position. In the validation and demonstration activities executed the offer 149764;Bigues;06/08/2026 H16;0.05;91.00;TW203 was the cheapest offer to deliver the service but the redundancy offer was never received though the TwinEU Dataspace. In this case, the fake offer was simulated to validate the process but for an effective implementation of the protocol in an operative LFM, additional offline investigation would be required in parallel to the calculation of the penalties associated to the fake offer. These penalties could vary from suspension of the capacity to participate in the market until at least when the root cause is identified, to economic penalties associated to the activation of the subsequently received offer, to undoing the technical and financial

prequalification process that all resources must undergo to participate in the LFM pending to an amendment of the available resources to avoid propagating a cyberthreat in the market.

3.2.3 Associated KPIs calculation

The results of the KPI presented in Chapter 3.1.6 is depicted below in Table 3.2.

Table 3.2. KPI Ib04-1 results

KPI ID	Ib04-KPI1
KPI Name	Number of new methodologies/protocols defined for mitigating the risk and consequences of an eventual cyberthreat in LFMs
Related Use Case	UC Ib04
KPI Description	Within the concept of mitigating the risk and consequences of an eventual cyberthreat in LFMs there are several fields of actuation. This KPI aims at identifying the scenarios that were case of study in the TwinEU project.
KPI Formula	<i>n. a.</i>
KPI Value	3 (Fake offers protocol, unforeseen delivery validation protocol and compromised data bases protocol).
Comments	n.a

4 UC Ib12 Integration of TSO-DSO-MO-Prosumer coordination schemes as well as market coordination

4.1 Validation and demonstration activities description

4.1.1 General information on the demonstration activities

The demonstration activities concern UC Ib12 – Integration of TSO-DSO-MO-Prosumer market coordination. The use case investigates how flexibility resources procured at distribution-system level can potentially support transmission-system balancing needs, namely due to the resolution of technical constraints after the clearing of the intraday markets, strengthening coordination between the DSO, TSO and flexibility service providers (FSPs). R&D Nester developed Digital Twins of the bid forwarding and market clearing processes to support the execution of this use-case.

The demonstration is based on 2025 operational and market data, with simulations performed over the full year at 15-minute resolution, consistent with the temporal granularity of the mFRR market data used in the analysis. Historical mFRR activation volumes and prices are combined with FIRMe [1] bid information in order to reproduce different market-clearing situations and evaluate the possible participation of local flexibility in the balancing market through bid forwarding.

The main target of the demonstration is to assess whether technically eligible FIRME bids can be validated, forwarded and integrated into the TSO mFRR clearing process while respecting the relevant market and technical requirements. Particular attention is given to bid eligibility, minimum bid size, response time, aggregation of smaller flexibility offers, merit-order selection and the interaction between FIRME bids and native mFRR resources.

The demonstration also evaluates the potential impact of this coordination on key performance indicators such as FIRMe cleared volume, native mFRR volume, share of local flexibility in the total clearing requirement, clearing prices and estimated system costs or savings. Overall, the activity aims to provide evidence on the feasibility and potential value of using DSO-procured flexibility as an additional resource for TSO balancing, while identifying the operational and market interfaces required for effective TSO–DSO coordination.

4.1.2 Actors, assets and systems involved

The demonstration involves several actors across the transmission and distribution system, reflecting the coordination required between local flexibility procurement and balancing services.

The main actors are the Transmission System Operator (TSO), the Distribution System Operator (DSO) and the Flexibility Service Providers (FSPs). The DSO is responsible for procuring and technically validating flexibility through the FIRMe local flexibility market, while the TSO is responsible for system balancing and the activation of mFRR resources. FSPs provide the flexible resources and submit bids indicating the available capacity, price, location and relevant technical characteristics. Aggregation may also be used when individual flexibility resources do not meet the minimum volume required for participation in the balancing market.

The assets involved are the distributed flexible resources participating in FIRMe , including controllable generation, demand-response resources, storage systems and other assets capable of

modifying their power injection or consumption. These resources are connected at distribution-system level and are associated with specific FIRMe service areas. On the transmission-system side, the demonstration also considers the existing native mFRR balancing resources, which compete with eligible FIRMe flexibility in the simulated market-clearing process.

The main systems involved include the FIRMe local flexibility market environment, through which flexibility offers are procured and managed by the DSO, and the TSO balancing market environment, where mFRR bids are evaluated and activated according to balancing requirements. A simulation framework is used to represent the interface between these systems, including bid validation, aggregation, forwarding and merit-order clearing.

4.1.3 Triggering event description and pre-conditions

The triggering event for UC Ib12 is the identification of a need at TSO level requiring alleviating a technical grid constraint after the clearing of the intraday market. When such a need occurs, the TSO must procure sufficient upward or downward flexibility to restore the balance between generation and consumption. Within the demonstration, this event is represented using historical mFRR activation requirements from 2025.

Once the balancing need is identified, eligible flexibility previously procured through the FIRMe local flexibility market may be considered as an additional source of flexibility. Instead of relying exclusively on native mFRR resources, the use case evaluates whether suitable FIRMe bids can be forwarded by the DSO and included in the balancing market clearing process.

Before a FIRMe bid can be forwarded and considered for clearing, several pre-conditions must be fulfilled. The flexibility resource must be available for the relevant delivery period and direction, the bid must comply with the applicable minimum volume and response-time requirements, and the resource must have successfully completed the required prequalification and DSO technical validation. Where individual bids are below the minimum participation threshold, aggregation may be applied when technically and operationally feasible.

4.1.4 Experiment description and post-conditions

The experiment evaluates the integration of DSO-procured FIRMe flexibility into the TSO mFRR market clearing process. Using historical 2025 mFRR activation requirements and FIRMe bid data, each 15-minute interval is assessed to determine whether eligible FIRMe bids could contribute to satisfying the balancing need.

For each interval, FIRMe bids are first checked against the defined eligibility conditions, including availability, direction, response time, minimum bid size, prequalification and DSO technical validation. Where necessary, smaller bids may be aggregated to meet the minimum participation threshold. The eligible FIRMe bids are then combined with native mFRR resources and ordered according to their bid price. Resources are selected following the merit order until the required balancing volume is covered.

The experiment records the resulting market outcome for each interval, including the FIRMe volume cleared, native mFRR volume cleared, marginal clearing price, share of FIRMe participation and estimated clearing cost. These results are compared with the corresponding historical mFRR values in order to assess the potential technical and economic impact of incorporating local flexibility into the balancing process.

The main post-condition is that the required balancing need is either fully covered by the combination of FIRMe and native mFRR resources or any remaining unmet requirement is identified.

The experiment also produces a clear record of which FIRMe bids were selected, their contribution to the balancing requirement and their effect on market prices and costs.

4.1.5 Datasets required for the experiment and field data to be gathered

The experiment requires datasets describing both the historical mFRR balancing activity and the FIRMe flexibility offers available at distribution-system level. These datasets are combined to evaluate whether eligible FIRMe bids could have participated in the TSO balancing process during the selected demonstration period.

The main historical dataset contains 2025 mFRR market and activation data at 15-minute resolution. The relevant information includes the delivery period, activated upward and downward balancing energy, associated valuation and historical mFRR prices. These data are used to define the balancing requirement and provide the reference market outcome against which the coordinated FIRMe–mFRR clearing results are compared.

The second main dataset contains the FIRMe bids submitted by Flexibility Service Providers. Relevant fields include the FSP identifier, service area or location, offered flexibility volume, bid price, direction, availability period, response time, product type and bid acceptance status. Additional information is required to determine whether each bid satisfies the conditions for forwarding to the TSO, including prequalification status, DSO technical validation and reusability after previous activation, where applicable.

4.1.6 Related KPIs

The defined KPIs that are associated with UC Ib12 are described below in Table 4.1, Table 4.2 and Table 4.3.

Table 4.1. KPI Ib12-1 description

KPI ID	Ib12-KPI1
KPI Name	Number of qualified Local FSPs
Related Use Case	UC Ib12
KPI Description	This KPI measures the number of pre-qualified FSPs that provide reserves to the DSO and are also qualified to provide grid support in real-time to the transmission grid. The target is greater than zero.
Unit of measurement	n.a.
Baseline	0

Table 4.2. KPI Ib12-2 description

KPI ID	Ib12-KPI2
KPI Name	FSP Revenues
Related Use Case	UC Ib12
KPI Description	This KPI measures the revenues of FSPs, particularly local FSPs, obtained by providing grid support to solve technical constraints in real-time. The target is greater than zero.
Unit of measurement	Euros
Baseline	0€

Table 4.3. KPI Ib12-3 description

KPI ID	Ib12-KPI3
KPI Name	Service cost difference
Related Use Case	UC Ib12
KPI Description	This KPI assesses the cost reductions in real-time technical constraint management. The target is greater than zero.
Unit of measurement	Euros
Baseline	0€

4.2 Validation and demonstration activities results

4.2.1 Results of the demonstration activities

As shown in Figure 4.1, native mFRR provided the majority of the balancing requirement throughout the year, while FIRMe represented a smaller contribution. Across the full-year analysis, FIRMe cleared a cumulative 7,138.85 MW across the analysed 15-minute intervals, compared with 439,192.06 MW supplied by native mFRR. This corresponds to an overall FIRMe share of approximately 1.60% of the total cleared volume. FIRMe resources were selected in 160 out of 4,502 analysed intervals, indicating that local flexibility was economically competitive only during a limited number of periods. Within the FIRMe bid pool, the flexibility selected in the clearing process originated from Valença 3, these bids were selected because their offer price, approximately €242.77/MWh, was lower than that of the other eligible FIRMe bids and was therefore positioned earlier in the merit order. In intervals where the historical mFRR price exceeded this level, the Valença 3 bids became economically competitive and were cleared before the more expensive mFRR resource, while the higher-priced FIRMe offers were generally not reached before the balancing requirement was satisfied.

As a result of these activations, the FSP Revenues reached approximately the value of €548,454 over the full year demonstration. This value demonstrates that the participation in the coordinated FIRMe–mFRR mechanism can create an additional revenue opportunity for FSPs when their flexibility bids are sufficiently competitive to be cleared.

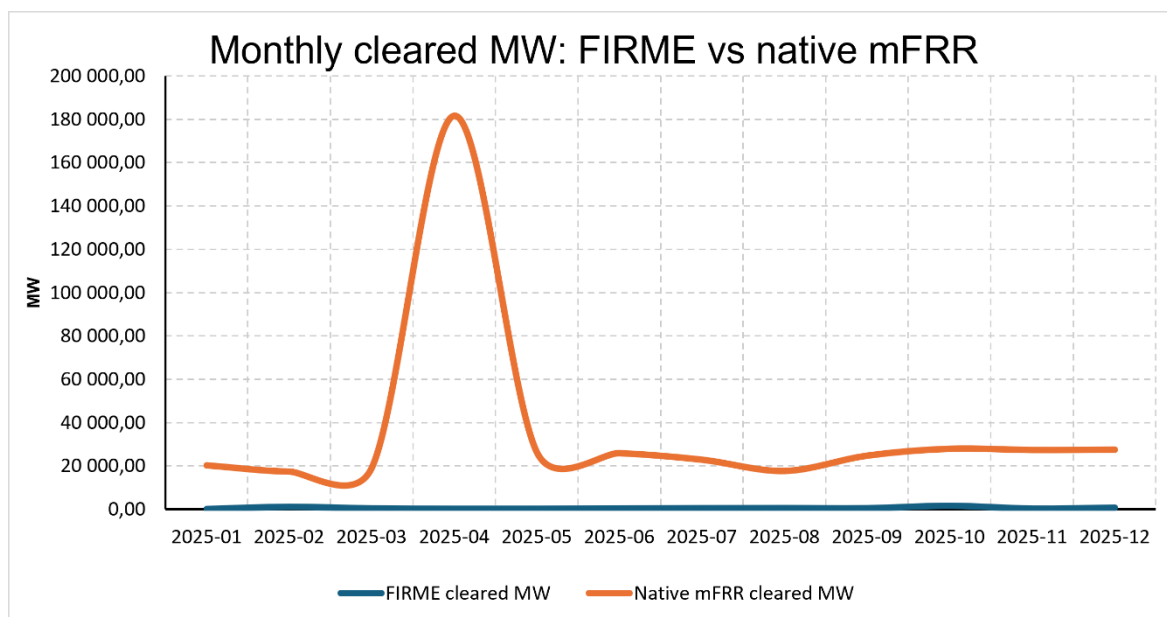


Figure 4.1. Monthly cleared flexibility from FIRMe and native mFRR resources.

Figure 4.2 presents the estimated monthly cost savings obtained when FIRMe bids are included in the clearing process. The results indicate that the economic benefit varies considerably throughout the year, depending on the amount of FIRMe flexibility selected and the historical mFRR price in each period. Over the complete demonstration period, the estimated total saving was approximately €63,563, with the largest monthly savings occurring during periods in which FIRMe bids were able to replace more expensive mFRR resources. In months with limited FIRMe participation, the resulting savings were correspondingly small.

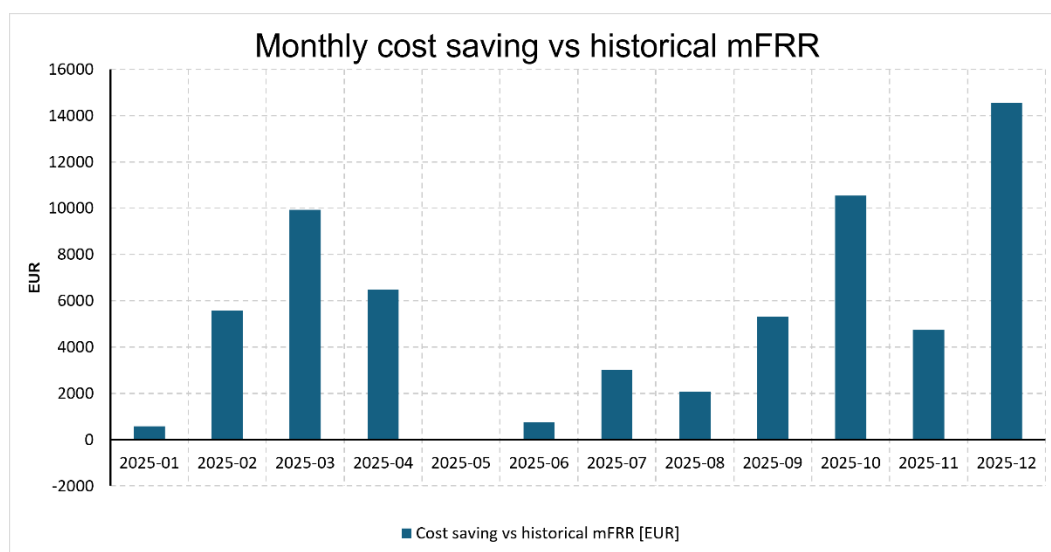


Figure 4.2. Monthly estimated cost savings resulting from the integration of FIRMe bids compared with historical mFRR costs.

The participation FIRMe on clearing prices is illustrated in Figure 4.3, which compares historical mFRR prices with the simulated clearing prices for the intervals in which FIRMe was selected. In several intervals, both prices remain equal because FIRMe resources were selected but native mFRR was still required to fully satisfy the balancing need and therefore continued to set the marginal price. In other intervals, the simulated clearing price was lower than the historical mFRR price, demonstrating that FIRMe can reduce the market clearing price when sufficient competitively priced flexibility is available.

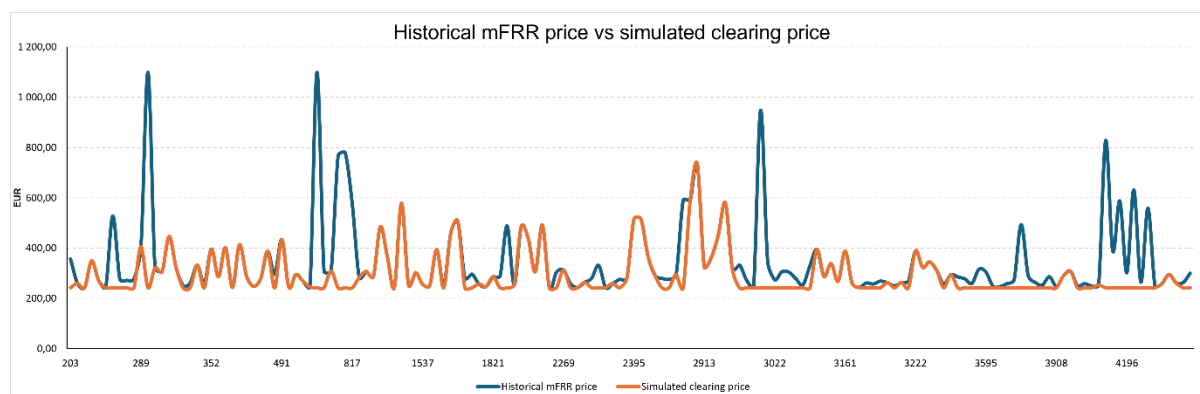


Figure 4.3. Comparison between historical mFRR prices and simulated clearing prices in intervals where FIRMe bids were selected.

4.2.2 Qualitative assessment of the results

The demonstration results provide a positive indication of the feasibility of integrating DSO-procured FIRMe flexibility into the mFRR balancing process, including the resolution of technical constraints after the clearing of the intraday markets. The simulated market-clearing outcomes show that technically eligible local flexibility can be considered together with native mFRR resources and selected according to the same economic merit-order principle.

From an operational perspective, the results confirm the importance of effective coordination between the FSP, DSO and TSO. Before local flexibility can contribute to balancing, the bids must satisfy the required technical and market conditions, including availability, response time, minimum bid size, prequalification and DSO technical validation. The demonstration therefore highlights that successful market integration depends not only on price competitiveness, but also on reliable information exchange and clear validation procedures between the involved actors.

From a market perspective, FIRMe participation was concentrated in a relatively small number of intervals, indicating that the competitiveness of local flexibility is a key limiting factor. In many periods, native mFRR remained more economically attractive. However, during higher price mFRR periods, competitively priced FIRMe resources were able to enter the merit order and contribute to the balancing requirement. This demonstrates that local flexibility can provide additional value particularly during periods of system stress or elevated balancing prices.

From the FSP perspective, the results indicate that this coordination mechanism can create an additional market opportunity for local flexibility providers. The obtained revenue shows that economically competitive flexibility can generate meaningful value when it is successfully cleared. This suggests that participation in balancing services may strengthen the financial incentive of participation for FSPs, which could lead to the potential development of more competitive and responsive local flexibility offers.

The results also show that FIRMe participation does not necessarily lead to a reduction in the clearing price in every interval. Where native mFRR is still required to fully satisfy the balancing need, it can remain the marginal resource and continue to determine the clearing price. The strongest economic impact occurs when sufficient FIRMe flexibility is available to reduce or replace the need for the more expensive marginal mFRR resource.

4.2.3 Associated KPIs calculation

The results of the KPIs presented in Chapter 4.1.6 are depicted below in Table 2.1Table 4.4, Table 4.5 and Table 4.6.

Table 4.4. KPI Ib12-1 results

KPI ID	Ib12-KPI1
KPI Name	Number of qualified Local FSPs
Related Use Case	UC Ib12
KPI Description	This KPI measures the number of pre-qualified FSPs that provide reserves to the DSO and are also qualified to provide grid support in real-time to the transmission grid.
KPI Formula	<i>n. a.</i>
KPI Value	1 (FSP from Valença 3).
Comments	n.a

Table 4.5. KPI Ib12-2 results

KPI ID	Ib12-KPI2
KPI Name	FSP Revenues
Related Use Case	UC Ib12
KPI Description	This KPI measures the revenues of FSPs, particularly local FSPs, obtained by providing grid support to solve technical constraints in real-time.
KPI Formula	$\sum_t (Cleared\ FIRME\ MW_t \times 0.25h \times Simulated\ Clearing\ Price_t)$
KPI Value	€548,453.76
Comments	n.a

Table 4.6. KPI Ib12-3 results

KPI ID	Ib12-KPI3
KPI Name	Service cost difference
Related Use Case	UC Ib12
KPI Description	This KPI assesses the cost reductions in real-time technical constraint management.
KPI Formula	$\text{Service Cost difference (€)} \\ = \text{Historical mFRR Cost} - \text{Simulated FIRME} \\ + \text{mFRR Cost}$
KPI Value	€63,563.11
Comments	n.a

5 Recommendation on testing propagation of threat detection on market activities with DTs for the implementation of Local Flexibility Markets in the Iberian electricity system

Iberian Pilot TwinEU partners assessed the suitability of replicating the cybersecurity scenarios developed for the Spanish local flexibility market within the Portuguese use case upon the analysis of the difference between the two market architectures. In the Spanish case, flexibility procurement is event-driven: the DSO requests flexibility whenever a congestion is detected or forecast, and flexibility service providers submit offers that are subsequently cleared by the market. In contrast, the Portuguese approach relies on long-term availability tenders, typically conducted on an annual basis, where flexibility providers commit capacity in advance and may later be activated if required. These structural differences were considered crucial when evaluating the applicability of the proposed scenarios.

Regarding Scenario S1 (Fake Offers), the underlying cybersecurity concept remains relevant and transferable to the Portuguese context. The scenario addresses the possibility that an attacker compromises a flexibility service provider and submits a fake offer that appears technically valid but cannot actually be delivered. The proposed mitigation consists of using the TwinEU Data Space as an independent validation channel, allowing the market operator to verify that the offer received through the market platform matches the information originating directly from the flexibility service provider. Conceptually, the same principle could be applied to the Portuguese market, since a malicious actor could similarly submit an illegitimate offer during the tendering process. The TwinEU Data Space could therefore serve as a redundant verification mechanism to strengthen bid authenticity and detect compromised credentials or manipulated submissions.

Scenario S2 (Delivery Validation) assumes that a fraudulent offer successfully passes market validation, is selected during market clearing, and is later found to be incapable of delivering the contracted flexibility during operation. In the Spanish model, this can be addressed through real-time monitoring and the activation of reserve flexibility providers to preserve network security. However, this logic does not translate to the Portuguese use case. The Portuguese mechanism is based on long-term availability contracts rather than the assignment of specific short-term delivery positions. Therefore, there is no equivalent operational situation in which an FSP is expected to deliver a predefined flexibility profile at a scheduled time and can subsequently be monitored against that commitment.

Overall, the Fake Offers scenario (S1) represents a meaningful cybersecurity concept that can be referenced as a cross-use-case synergy between the Spanish and Portuguese demonstrations, albeit without practical validation at this stage due to the fact that LFM in Portugal are managed by a private actor that does not participate in the project [1]. By contrast, the Delivery Validation scenario (S2) was deemed non-applicable due to the fundamental differences in market structure, contractual arrangements, and activation processes between the two use cases. As a result, S1 should be retained as a conceptually transferable scenario, whereas S2 should be reported as not suitable for replication in the Portuguese context.

In the case of S3, the applicability was not possible to be studied, as internal databases and related operation from the LFMO in Portugal are unknown to the project.

6 Conclusions

The activities reported in this deliverable, the final results of T5.4, demonstrate that Digital Twins can support not only the modelling and technical operation of electricity networks, but also the secure operation and coordination of increasingly interconnected electricity-market processes. The results from UC Ib04 and UC Ib12 show two complementary applications. The first uses Digital Twins and secure data exchange to improve the detection and containment of abnormal participation in Local Flexibility Markets. The second connects market and grid representations to assess how distribution-connected flexibility could contribute to transmission-system balancing and technical constraint management. Together, the two use cases illustrate how Digital Twins can enhance the operational, analytical, and coordination capacities of DSOs, TSOs, market operators, and flexibility service providers. In essence:

- UC Ib04 identified and characterised three cybersecurity scenarios covering key stages of the Local Flexibility Market value chain: fake offers, unexpected or inadequate delivery, and compromised database integrity. The successful demonstration of the fake-offer scenario showed that an independent and secure communication channel can be used to cross-validate offers received through the market platform. In the experiment, the offer submitted only through the Local Trading System, and not reproduced through the TwinEU Data Space, was detected as inconsistent and removed before clearing. The service was then transferred to the next valid offer. This provides evidence that redundancy and cross-validation can prevent a compromised submission from propagating from an individual flexibility service provider into market clearing and, ultimately, into grid operation.
- UC Ib12 demonstrated that distribution-level flexibility can be combined with native mFRR resources when it satisfies both market and technical requirements. In the year-long simulation using 2025 data at 15-minute resolution, FIRMe resources supplied 7,138.85 MW across the analysed intervals, compared with 439,192.06 MW from native mFRR. FIRMe was selected in 160 of 4,502 intervals and represented approximately 1.60% of the total cleared volume. Although this contribution was limited, it generated estimated revenues of €548,453.76 for the participating FSP and estimated system savings of €63,563.11. These results show that local flexibility can provide economic value, particularly during periods of elevated balancing prices, even when it remains a supplementary resource rather than the principal source of balancing capacity.

The comparison between the Spanish and Portuguese flexibility-market arrangements confirms that cybersecurity protocols cannot be transferred without considering market design. The concept underlying the fake-offer scenario remains relevant to both short-term markets and long-term availability tenders because both require bid authenticity and protection against compromised submissions. In contrast, the delivery-validation protocol developed for short-term scheduled activation is not directly transferable to a system based mainly on long-term availability commitments. Digital Twin services and cybersecurity procedures should therefore be modular and adaptable to the contractual, temporal, and operational characteristics of each market.

Overall, the demonstrations provide a sound basis for the further development of secure and coordinated electricity-market services supported by Digital Twins. UC Ib04 proved the value of independent data exchange and cross-validation for preventing abnormal offers from propagating through a Local Flexibility Market. UC Ib12 showed that technically validated distribution-level flexibility can contribute to transmission-level balancing and generate benefits for both FSPs and the wider system.

7 References

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- [2] TwinEU Deliverable D5.3, *Testing propagation of threat detection on market activities with DT*, March 2025, Available: https://twineu.net/wp-content/uploads/2025/05/20250331_ETRA_TwinEU_D5.3_pu_v1.pdf
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