



End-2-end-flexibility and dynamic grid monitoring

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List of Abbreviations and Acronyms

Acronym	Meaning
AgNes	Revision of the network tariff framework
CIM	Common Information Model
DSO	Distribution System Operator
EnWG	Energiewirtschaftsgesetz (Energy Industry Act)
EV	Electric Vehicle
FDT	Federated Digital Twin
HAN	Home Area Network
HEMS	Home Energy Management System
IGP	Intelligent Grid Platform
iMSys	Intelligent smart metering systems
MAE	Mean Absolute Error
MASE	Mean Absolute Scaled Error
MaStR	Marktstammdatenregister (Core energy market data register)
MVP	Minimum Viable Product
OEM	Original Equipment Manufacturer
OSM	OpenStreetMap
RMSE	Root Mean Squared Error
SOC	State of charge
TSO	Transmission System Operator
WFS	Web Feature Service

Executive Summary

The ongoing digital transformation of Europe's energy systems is accelerating the need for new tools and approaches to manage distributed generation, flexibility, and grid constraints. In this context, Deliverable D6.4 presents the implementation and results of the German demonstrator within the TwinEU project, which aims to enable dynamic grid monitoring and end-to-end activation of flexibility through the use of digital twin technologies.

At the heart of this deliverable are seven demonstrator use cases spanning three thematic clusters: grid monitoring and state estimation (Ge01–Ge03), end-to-end flexibility activation and preventive congestion management (Ge04–Ge06), and TSO–DSO–Aggregator data exchange (Ge07). Use Case 8, covering hosting capacity and grid connection processes, is reported separately in Deliverable D6.5. The seven use cases test new methods for grid observability, predictive congestion management, flexibility aggregation, and secure multi-actor coordination.

In the area of grid monitoring, advanced state estimation — running at a 1-minute cycle with topology-aware inputs and bad-data detection — has been deployed operationally at Westnetz. The Field Assistant, combining virtual switching, incident detection, and live measurement access, is in active use and has been quantified to reduce transformer maintenance planning time by approximately 35% and to decrease the need for on-site analyser-box installations for voltage complaints by approximately 33%.

For preventive congestion management, the envelope curve concept has been implemented end-to-end: a day-ahead feeder load forecasting model — achieving a MASE (Mean Absolute Scaled Error) of 0.57, corresponding to a 43% reduction in mean absolute error versus the naïve baseline — generates power envelopes that are distributed to Flexibility Service Providers via Apache Kafka and monitored through a dedicated Intelligent Grid Platform (hereafter referred to as “IGP”) dashboard. The approach enables Distribution System Operators (DSOs) to define safe operational limits for local flexibility in advance, reducing the need for reactive interventions.

Field tests with pilot customers demonstrated that household flexibility can be activated to comply with envelope curve constraints: in a two-week long-term test with 7 customers, 95% of EV steering actions were completed successfully. Aggregator-mediated redispatch was also simulated, with cloud-to-cloud EV control confirmed as technically functional but subject to high signal latency — identified as the primary limitation for real-time redispatch applications. Wallbox-based control is recommended for future implementations. The minimum power floor of 5 kW per household was identified as a critical design parameter requiring further regulatory and technical review.

For TSO–DSO–Aggregator coordination, the TwinEU Data Space connector was successfully deployed at three organisations — Westnetz (DSO), Amprion (TSO), and RWTH Aachen (Aggregator) — and a hypothetical day-ahead flexibility coordination simulation was executed end-to-end. Eight technical issues were identified during testing and resolved in collaboration with the connector software developer. The evaluation concluded that the connector is well-suited for non-critical planning-oriented data exchange; its reliance on public internet infrastructure currently limits direct application to operational grid control contexts.

Taken together, the results confirm strong technical progress across all three thematic clusters, with several components already at operational deployment stage. Key challenges — including regulatory clarity for Redispatch 3.0, standardized interfaces for multi-actor flexibility coordination,

and the scaling of pilot implementations across larger DSO portfolios — have been clearly identified and provide a concrete agenda for follow-up projects and regulatory engagement.

Overall, the work presented in D6.4 contributes foundational building blocks — operationally deployed real-time state estimation with topology adaptations, the end-to-end envelope-curve workflow for preventive congestion management, validated household and aggregator flexibility activation, and a deployed TwinEU Data Space connector for TSO–DSO–Aggregator coordination — for a digitalized, flexible, and more coordinated European electricity system, thereby supporting TwinEU's broader objectives of validating a pan-European reference architecture and advancing interoperable, secure cross-operator coordination.

1 Introduction

The digital transformation of power grids is driving unprecedented changes in how we manage and optimize electricity distribution. As grid operators face increasing challenges from renewable energy integration, electrification of transport, and decentralized power generation, innovative solutions are becoming essential for maintaining grid stability and efficiency.

This deliverable presents the implementation and results of the German demonstrator within the TwinEU project, covering seven use cases developed under Tasks 6.4 (End-to-end flexibility activation and monitoring) and 6.6 (Flexibility activation for redispatch and small-scale coordination). The work addresses the operational challenges arising from the rapid growth of distributed renewable generation, sector coupling, and the increasing demand for coordinated flexibility management across distribution and transmission system boundaries.

The seven use cases are organized in three thematic clusters. The first cluster — Grid Monitoring (Ge01, Ge02, Ge03) — focuses on real-time grid observability, dynamic state estimation, and congestion management. The second cluster — End-to-end Flexibility (Ge04, Ge05, Ge06) — covers the generation and distribution of power envelope curves for preventive congestion management, the integration of household flexibility via home energy management systems, and the simulation of aggregator-mediated redispatch using low-voltage assets. The third cluster — TSO/DSO/Aggregator Data Exchange (Ge07) — explores conceptual requirements for a future Redispatch 3.0 regime, evaluates the TwinEU Data Space connector for secure multi-actor data exchange, and demonstrates a day-ahead coordination simulation between TSO, DSO, and Aggregator.

The implementation of these use cases represents a significant step forward in grid modernization, offering a comprehensive approach to addressing current challenges while preparing for future developments in the energy sector. Through careful coordination and strategic deployment, these solutions will help create a more resilient, efficient, and sustainable power grid. This initiative combines technical innovation with practical implementation strategies, focusing on both immediate operational improvements and long-term grid optimization goals. By addressing critical aspects of grid management through these seven use cases, we aim to establish a robust foundation for the future of power distribution systems.

The demonstrator activities are grounded in the practical infrastructure and regulatory conditions of the German energy system — including §14a and §14c EnWG, Redispatch 2.0, and the distributed topology of over 800 DSOs and four TSOs. All use cases were developed in close collaboration with Westnetz (DSO), Amprion (TSO), envelio (IGP platform), and academic partners such as Fraunhofer FIT, RWTH Aachen, OFFIS e.V. and TU Dortmund.

1.1 Task 6.4 and 6.6

This deliverable reports on the work performed under Task 6.4 (End-to-end flexibility activation and monitoring) and Task 6.6 (Flexibility activation for redispatch and small-scale coordination). The methodology involves both system-level concept design and implementation of demonstrator-based use cases at the interface between DSOs and TSOs. These include activities around real-time grid monitoring, congestion management, and the integration of distributed flexibility into redispatch planning.

Where appropriate, simulation-based approaches and laboratory tests complement live operational testing, allowing both technical feasibility and practical constraints to be evaluated.

1.2 Objectives of the Work Reported in this Deliverable

The main objective of this deliverable is to document the implementation, results, and insights from selected German demonstrator use cases within the TwinEU project. The report focuses on:

- Improving grid visibility at low and medium voltage levels through dynamic monitoring.
- Enabling congestion management via preventive analytics and flexibility activation.
- Facilitating coordination across system boundaries (DSO–TSO) for redispatch and flexibility procurement.
- Investigating data exchange frameworks, including the potential application of federated data spaces.

The work contributes to validating key aspects of the TwinEU reference architecture and supports the broader European goal of a more integrated, responsive, and secure digital energy system.

1.3 Outline of the Deliverable

The deliverable is structured as follows:

- Chapter 2 outlines the business and technical motivation for using digital twins in the energy sector. It contextualizes the German pilot within European trends and summarizes the current state of digital twin technologies and use cases.
- Chapter 3 presents the implementation of core demonstrator activities across three thematic clusters: dynamic grid monitoring, end-to-end flexibility activation, and TSO–DSO data exchange. Each section covers use case definitions, challenges, implementation details, and results.
- Chapter 4 draws conclusions from the demonstrator activities and provides recommendations for future work, particularly regarding the scaling and standardization of digital twin and flexibility solutions.

1.4 How to Read this Document

This deliverable builds upon prior work within the TwinEU project. Readers are advised to be familiar with the following background documents for full context:

- D2.1 – for insights into stakeholder needs and digitalization challenges in the energy system.
- D2.2 – for the definition of digital twin concepts and the broader pan-European framework.
- D3.1 – which introduces the TwinEU reference architecture and interoperability strategy.
- D5.1 – for the specification of use cases relevant to the German demonstrator.

This document should be read as a final implementation and evaluation report. It is targeted at both technical experts and stakeholders involved in grid operations, regulatory development, and digitalization strategy.

1.5 Scope and regulatory context clarification

The activities in this deliverable span different maturity levels, from operationally deployed tools (e.g., real-time state estimation and the Field Assistant at Westnetz) to field tests with pilot customers and proof-of-concept simulations (e.g., aggregator-mediated Redispatch and the TSO–DSO–Aggregator coordination via the TwinEU Data Space connector).

To assess the full technical potential of Digital Twin-based coordination, some assumptions extend beyond current operational practice — in particular enhanced TSO–DSO data exchange and the availability and controllability of distributed flexibility (e.g., EVs, household energy management systems). These are research and validation assumptions and do not necessarily reflect the present regulatory framework or market arrangements; implementation at scale would require regulatory evolution, clear roles and responsibilities, contractual mechanisms for flexibility activation, and secure, privacy-compliant data sharing.

The simulation- and prototype-based results should therefore be read as a proof-of-concept demonstration of technical feasibility, not applicable to the components already in operational use, whose reported performance reflects live deployment.

2 Business/technical needs of digital twins

The transformation of the European energy system is driven by the rapid growth of renewable energy sources, sector coupling, and digitalization, which poses significant challenges to grid planning, operation, and coordination. Accelerating renewable energy sources expansion and the growing number of low- and medium-voltage grid connection requests are placing increasing pressure on DSOs and TSOs. These developments require more dynamic, data-driven tools to manage grid complexity, ensure stability, and support decarbonization. Digital twins have emerged as a promising solution to address these evolving system needs. As highlighted in Deliverable D2.1 [1] on digitalization challenges and opportunities, digital twins can enhance grid observability, facilitate predictive maintenance, and improve coordination among stakeholders, provided that interoperability, cybersecurity, and data integration are sufficiently addressed.

The current landscape of Digital Twin (DT) solutions in the European energy sector reflects growing momentum toward data-driven, interoperable systems capable of supporting a decentralized and resilient electricity grid. Deliverables D2.1 and D2.2 of the TwinEU project consolidate the state of the art, outlining the requirements of stakeholders and assessing current technological capabilities. One key concept that has emerged is that of the Federated Digital Twin (FDT). The FDT is conceived as a network of interoperable DTs across multiple domains and actors, enabling cross-organizational collaboration without centralization. This chapter, however, focuses specifically on the German pilot's business and technical motivations. For this, digital twins are enablers for addressing real-world grid management challenges at the distribution and transmission interface.

The German Demonstrator: Contributions to the Current Landscape

The German energy system faces a distinct set of operational and regulatory demands. Among the most pressing issues are:

- Missing cross-sectoral Integration: Existing models often lack integration across sectors like electricity, heating, and transport.
- Lack in scalability and modularity incl. limited adaptability to different geographic scales.
- Difficulties translating simulation outputs into actionable insights.
- The rapid increase in RES installations, particularly solar PV and wind, which continues to grow at double-digit annual rates.
- A sharp rise in DSO-level connection requests, often requiring complex evaluations of local grid capacity and topology.
- The need for stronger TSO-DSO coordination, especially in the context of flexibility activation, congestion management, and system stability.

The use cases defined in the German pilot link directly to these gaps and requirements, taking into account the specifications of the German system. Germany's grid is operated by over 800 DSOs and 4 Transmission System Operators (TSOs), leading to high data fragmentation and heterogeneity. This highlights the need for harmonized data models and interoperability standards, especially pressing and considered in the use case about state estimation at Low Voltage/Medium Voltage (LV/MV) levels as well as automated grid connection processes.

The rapid electrification of heating and transport in Germany requires cross-sectoral modelling, something many current tools lack. With Redispatch 2.0, DSOs are required to take operational

decisions under uncertainty. Advanced scenario analysis and actionable forecasts are crucial but often missing, which are analyzed in the use case about flexibility activation and simulation of grid states.

Germany has strict data protection laws and strong public awareness of digital privacy. Sharing real-time operational data across platforms requires robust privacy and sovereignty safeguards, which is taken into account in the German use case about data exchange between TSOs and DSOs.

These dynamics require more than what traditional planning and tools can offer. Instead, they call for dynamic, interoperable, and predictive capabilities, which are functions digital twins can provide. As elaborated in D3.1 [2], the reference architecture of TwinEU supports such capabilities through a federated, modular, and standards-aligned approach to DT design and implementation. Within the broader European vision of Federated Digital Twins, the German Demonstrator contributes specific technical developments that address national infrastructure and regulatory conditions. While the demonstrator does not represent a full implementation of a FDT, it builds important foundational capabilities in selected areas. The following five areas currently represent the core of its contribution to the state of the art.

- **Grid Monitoring:** Insufficient real-time and high-resolution data complicates accurate simulations and forecasting. Reliable and real-time grid monitoring forms the foundation for advanced system operation. The German Demonstrator includes developments in state estimation under dynamic topologies, the identification of congestion risks, and the integration of real-time measurement data. These capabilities are essential to support automated grid management and to enable more complex coordination mechanisms. This topic is investigated in chapter 3.1 Grid Monitoring.
- **Preventive Congestion Management:** The demonstrator explores the use of envelope curves in low-voltage grids to proactively manage congestion. These curves define safe operational boundaries, enabling local flexibility markets to act preemptively and cost-effectively. This approach also respects Germany's strict data privacy requirements by allowing decentralized processing and control without compromising user data. This topic is investigated in chapters 3.1 Grid Monitoring and 3.2 End-to-end flexibility usage.
- **Aggregation of Small-Scale Flexibility:** The technical and conceptual basis for identifying and bundling small-scale flexibilities - such as those from residential heat pumps, electric vehicles, and batteries - is under development. However, the system-wide integration of such aggregated flexibility remains limited, due to open challenges in areas such as control architecture, market design, regulatory frameworks, and standardized data exchange. Aggregation is considered critical for unlocking the full flexibility potential at the distribution level. This topic is investigated in 3.2 End-to-end flexibility usage.
- **DSO-TSO Coordination and Data Exchange:** The exchange of operational data between DSOs and TSOs is a key enabler for integrated grid operation. Currently, this exchange is limited to specific processes such as Redispatch 2.0, which mandates coordinated action in case of forecasted congestion. However, broader interoperability is needed - especially to leverage small-scale flexibility resources for TSO-level services. Concerns around data privacy and control when sharing information across platforms, the need for harmonized data formats and a modular and scalable architecture for digital twins are major concerns when dealing with these topics. In this context, the concept of Data Spaces is being explored within the German Demonstrator as a mechanism to structure secure, standardized data exchange. While this exploration is limited to selected use cases (e.g., congestion management), it provides insight into the practical constraints and opportunities of implementing Data Spaces in grid operation contexts. Outside of this context, however, Data Spaces have not yet been operationalized,

and their broader application remains subject to the individual constraints of other use cases. This topic is investigated in chapter 3.3 TSO/DSO/Aggregator exchange to enable small-flexibility usage.

- Connection request, online connection request tools and capacity maps, supporting faster, automated grid access for end-users and service providers (described in deliverable 6.5).

These use cases are in line with the pan-European frameworks and technical foundations described in D2.2 and D3.1, but are customized to reflect the regulatory, infrastructural, and market conditions in Germany. The implementation of these use cases will offer practical validation for the architectural approach proposed in D3.1, feeding back operational experience into the wider TwinEU ecosystem.

The German Demonstrator contributes to this landscape by testing and refining selected digital twin components, grounded in the practical realities of the national grid infrastructure and regulatory environment. However, comprehensive and interoperable digital twin ecosystems as envisioned at the European level are still in early stages, with significant work ahead in aligning technology, regulation, and operational practice.

The following chapter describes the concrete implementation of the use cases outlined above, addressing the business needs and technical requirements identified in Chapter 2. Each use case section covers the specific challenges encountered, the solutions developed within the German demonstrator, and the results and next steps.

3 Use Case Implementation and Results

3.1 Grid Monitoring

3.1.1 Overview use case 1-3

Introduction to Grid Monitoring

The increasing penetration of renewable energy sources (RES), the electrification of sectors like mobility and heating, and the overall decentralization of the energy system pose new challenges for distribution system operators (DSOs). Traditional operational strategies relying on static planning assumptions and manual interventions are no longer sufficient to ensure grid stability and efficiency.

Grid monitoring is a comprehensive system encompassing three essential use cases (Ge01, Ge02, Ge03) that focus on enhancing distribution network visibility and control. The system focuses on advanced monitoring and optimization of grid operations through real-time data collection and analysis. Key components include state estimation capabilities and sensor measurements for improved grid visibility. The system incorporates automated data processing and visualization tools to provide operators with actionable insights into grid conditions. It also includes specialized monitoring solutions for effective congestion management.

Ge01: Grid Transparency and Utilization Monitoring

A fundamental requirement for modern distribution networks is real-time visibility into grid conditions, particularly in low-voltage (LV) and medium-voltage (MV) networks. Unlike transmission systems, distribution grids often suffer from limited sensor coverage, leading to an operational "blind spot" for DSOs. The key objective of Ge01 is to provide DSOs with accurate information on voltages, currents, power flows, and asset utilization.

Key aspects of Ge01 include:

- High-resolution real-time monitoring of electrical parameters.
- Utilization of smart meter data to improve spatial and temporal observability.
- Detection of critical conditions such as overloads, voltage deviations, and phase imbalances.

Ge02: State estimation under changing topology

Given the sparse deployment of measurement sensors in distribution networks, direct monitoring alone is insufficient. State estimation techniques fill this gap by providing an accurate representation of grid conditions based on limited measurement inputs.

Challenges addressed by state estimation:

- **Sparse measurement data:** LV/MV grids typically have limited real-time sensor coverage. State estimation combines the grid model (topology + asset data) with the available measurements and synthetic inputs (e.g., SLP-based injections) to infer voltages and loadings for non-measured elements.
- **Handling of incomplete measurement data through probabilistic inference:** Operational measurement streams often contain gaps, delays, differing sampling rates, or device-specific reporting behavior (e.g., threshold-based sending). State estimation must remain stable and still produce a physically consistent grid state under these imperfect inputs.

- **Dynamic network topology:** Switching operations and temporary reconfigurations can change the electrically active topology. State estimation needs to reflect the actually operated switch states (e.g., from field operations) to avoid calculating on an outdated model.
- **Accuracy and robustness:** SE must be robust against non-convergence and contradictory constraints, and resilient to faulty/outlier measurements (e.g., via bad-data detection and selective exclusion). Transparency tools (e.g., Measurement Analyzer) help validate inputs vs. SE outputs and build operational trust.

State estimation is a critical component that enables predictive monitoring and supports more advanced applications such as congestion management.

Ge03: Advanced monitoring & control tools for congestion management

With the growing integration of distributed energy resources (DERs) and the rise of flexible loads, DSOs must shift from reactive to proactive congestion management. This use case leverages real-time grid monitoring to detect and mitigate grid congestions before they occur.

- **Identify congestion risks** before they lead to operational issues.
- **Recommend control actions** for mitigating congestion (e.g., shifting loads or adjusting flexible assets).
- **Congestion forecasting models** based on historical and real-time data.
- **Automated generation of control signals** for load balancing and flexibility activation.
- Integration with **market-based congestion mitigation strategies**.
- **Enable DSOs to react proactively**, reducing unplanned interventions (such as §14a EnWG in Germany) and improving grid stability.

Regulatory background - §14a and §14c EnWG [4]: §14a of the German Energy Industry Act (Energiewirtschaftsgesetz, EnWG) grants distribution system operators the right to temporarily reduce the power draw of controllable consumption facilities (e.g., heat pumps, EV wallboxes, battery storage [3]) in cases of local grid congestion, in exchange for reduced network charges. This direct access right forms the legal basis for automated congestion management of household-level assets in Germany. §14c EnWG, introduced to transpose Article 32 of EU Directive 2019/944, creates a complementary framework under which DSOs may procure flexibility services from the market in a voluntary, competition-based manner — as an alternative or supplement to the mandatory direct access under §14a. Together, §14a and §14c define the two-track approach to demand-side flexibility in German distribution grids: direct regulatory access (§14a) and market-based procurement (§14c). Both frameworks are directly relevant to Use Cases Ge03–Ge06 of this demonstrator.

3.1.2 Challenges & Complications in Grid Monitoring

Several significant challenges impact the implementation of effective grid monitoring systems. The primary challenge is the limited sensor coverage, particularly in low voltage grids, which creates blind spots in the monitoring system. Data quality issues and measurement uncertainties can affect the reliability of monitoring results. The integration process is complicated by multiple measurement providers using different interfaces, requiring complex standardization efforts. Real-time topology tracking presents its own set of challenges, particularly in dynamic grid conditions. State estimation accuracy is hampered by limited measurement points, and there's an ongoing challenge to balance comprehensive monitoring deployment with cost-effectiveness.

Beyond these technical limitations, additional challenges include:

- Scalability Issues: Monitoring systems must handle a growing number of connected devices, leading to high data volumes and processing requirements.
- Cybersecurity Risks: Increased digitization of the grid introduces vulnerabilities, requiring robust encryption and security protocols.
- Availability Risks: Increasing reliance on congestion management systems for stable grid operation makes the continuous availability of grid monitoring and control systems critical.
- Regulatory Constraints: Compliance with grid codes and data privacy regulations imposes restrictions on monitoring and control measures.

3.1.3 Solutions and Methods

The implemented solutions address these challenges through a modular approach. At the core is the integration of smart meter data and substation measurements via standardized interfaces, ensuring consistent ingestion and mapping of sensor data to the grid model for near-real-time grid status assessment.

Online Monitoring was expanded with additional operational tooling to support day-2 operations and large-scale rollouts. A clearer Grid Status configuration explicitly differentiates grids that are not monitored, or qualified as controllable for congestion management, while a Statistics view provides rollout transparency over time (for example observed vs. controllable grids, voltage-level split, and daily maxima).

For Ge02, we improved transparency and troubleshooting by introducing a dedicated time-series view for State Estimation results (plots + table, synced time selection, downsampling for large timeframes, and explicit highlighting when SE cannot produce a result). This helps distinguish genuine grid events from missing measurement coverage or non-convergence and supports validation under changing topology and data-quality conditions.

To better reflect the actually operated network, we progressed concepts and implementation steps for topology awareness by considering dynamic switching operations (for example from field operations tooling), so that Online Monitoring and State Estimation can account for temporary switch states during ongoing switching actions.

To close the loop from transparency (Ge01) and inference (Ge02) to operational action, Ge03 adds congestion-management tooling for early detection of emerging overloads/voltage violations and for recommending and/or (semi-)automatically triggering suitable countermeasures (e.g., flexibility activation or load/generation management) based on monitoring and state estimation results.

Overall, the system runs state estimation algorithms on the best-available topology and measurement set, provides centralized monitoring dashboards for operational visibility, and includes warning mechanisms for boundary violations as well as automated logic to support handling of critical grid states.

3.1.4 Methodology

Overall System Architecture

The grid monitoring system is built on the Intelligent Grid Platform (IGP), operated by envelio in collaboration with Westnetz. While the IGP comprises a broader set of functional components, three core layers are the most relevant for the use cases described in the following sections: (1) a Data

Ingestion Layer that collects and normalises measurement streams from heterogeneous sources (smart meters, substation RTUs, MQTT-based providers); (2) a Computation Layer that runs state estimation and congestion detection algorithms on the ingested data; and (3) a Visualisation and Control Layer that presents results to DSO operators and triggers control actions where applicable. The system operates on a 1-minute cycle, enabling near-real-time grid condition assessment.

State Estimation Process (Ge02)

The state estimation combines three categories of input data: (i) direct measurements – real-time voltage, current, and power readings from smart meters and substation sensors ingested via standardised interfaces; (ii) synthetic load profiles – Standard Load Profiles (SLPs) used as injection estimates for grid participants where live measurement data is unavailable, improving stability in sparsely monitored LV grids; and (iii) a topology model – the electrically active grid topology derived from the network asset model and updated to reflect dynamic switching operations performed by field crews.

The state estimation component computes a consistent grid state at each 1-minute interval based on the available measurement and model information. It includes mechanisms to increase robustness against inconsistent or low-quality inputs (e.g., identifying and excluding individual measurement inputs from the calculation where appropriate), and it accounts for topology changes so that temporary reconfigurations are correctly reflected in the model used for computation. The Measurement Analyzer tool allows operators to trace which measurements were included or excluded in a given state estimation run and to compare state estimation outputs against raw sensor values, building operational trust and supporting root cause analysis.

The state estimation produces a consistent estimated grid state at each 1-minute interval, including estimated nodal voltages and branch currents for all monitored and non-monitored elements, limit violation flags for voltage bands and line/transformer ratings, and quality indicators reflecting measurement coverage and calculation health. Results are stored and exposed via the Time Series Control Center (TSCC) for historical inspection and displayed spatially in the Online Monitoring interface for operational situational awareness.

Congestion Management Mechanism (Ge03)

Congestion detection is performed continuously on the output of the state estimator. Limit violations – for voltages, line loadings, or transformer loadings – trigger automated notifications to operators. The system distinguishes between measured violations at instrumented nodes and branches, and inferred violations at non-instrumented elements derived from SE results. A Grid Status classification is maintained for each monitored grid: grids are categorised as Not Monitored, Monitored, or Controllable, the latter indicating that automated control actions may be initiated.

For grids classified as Controllable, the congestion management workflow supports two modes of response. In the semi-automated mode, the system surfaces actionable recommendations to DSO operators, who can manually initiate and dispatch control actions based on these recommendations.

In the automated steering mode (§14a EnWG), the system can directly reduce the power draw of qualifying loads – such as EV wallboxes and heat pumps – without requiring individual operator approval, once a grid is explicitly registered/enabled for congestion management and an overload/voltage violation is detected in Online Monitoring.

A complementary Measurement Input Control mechanism allows operators to deactivate specific sensor inputs for SE purposes while continuing to observe raw values in TSCC, ensuring the congestion management chain remains stable even when individual sensors report erroneous or delayed data.

Key Performance Indicators

The following KPIs are used to evaluate the methodology in the results section. The TwinEU KPI VAL_KPI2 measures DT computational performance and latency (from data input to DT output), e.g., state estimation end-to-end latency and throughput under representative operational workloads. Additional internal KPIs tracked include SE convergence rate (percentage of 1-minute cycles producing a valid SE result) and operator response time (time from limit-violation notification to control action dispatch).

3.1.5 Results

Initial implementations have demonstrated significant progress across several areas. The system has successfully integrated various measurement sources and implemented a new streaming service that improves performance for large batches of live measurement data processing. Grid visibility has been enhanced through improved state estimation capabilities, leading to better detection and analysis of grid issues. The monitoring of renewable energy integration has shown marked improvement, and response times to critical grid states have been reduced. Notably, pilot tests of the congestion management chain have been successful.

Impact on Grid Transparency

One of the major achievements so far has been the improvement in low-voltage grid observability. Measurement integration coverage was expanded (including additional continuous integrations such as MQTT-based provider connections), increasing the addressable set of grids that can be monitored with higher data freshness.

Key results and developments:

- Improved LV grid observability: More monitored nodes and measurement points reduce estimation uncertainty and increase confidence in operational interpretation. Reference: KPI VAL_KPI8 – Data quality index for DT input data (completeness, accuracy, timeliness), see Deliverable 9.1.
- Operational transparency in spatial context: Operators can quickly assess voltage and utilization states, drill down into affected assets, and navigate between overview and detailed result views.
- Actionable asset insight: Better identification of substations/feeders where additional sensor deployment would yield the highest value.

Figure 1 shows how grids are visualized with individual colors in the grid transparency section and also when analyzing this grid in further detail, a result view opens up, in which several functionalities, statuses etc. can be checked and exported for that grid.

The Grid Transparency feature offers a comprehensive, map-based visualization of network status and current supply tasks. It uses colour coding to help users quickly distinguish network areas and interpret key status layers in the interface. It enables users to analyze their asset base by providing:

- Overview of different voltage levels and network areas
- Integration potential assessment capabilities

- Results of topological and electrical testing
- Detailed asset inspection (lines, nodes, transformers, participants)
- Targeted search functionality for addresses, stations, and asset types
- Immediate visibility of power outage areas in the grid

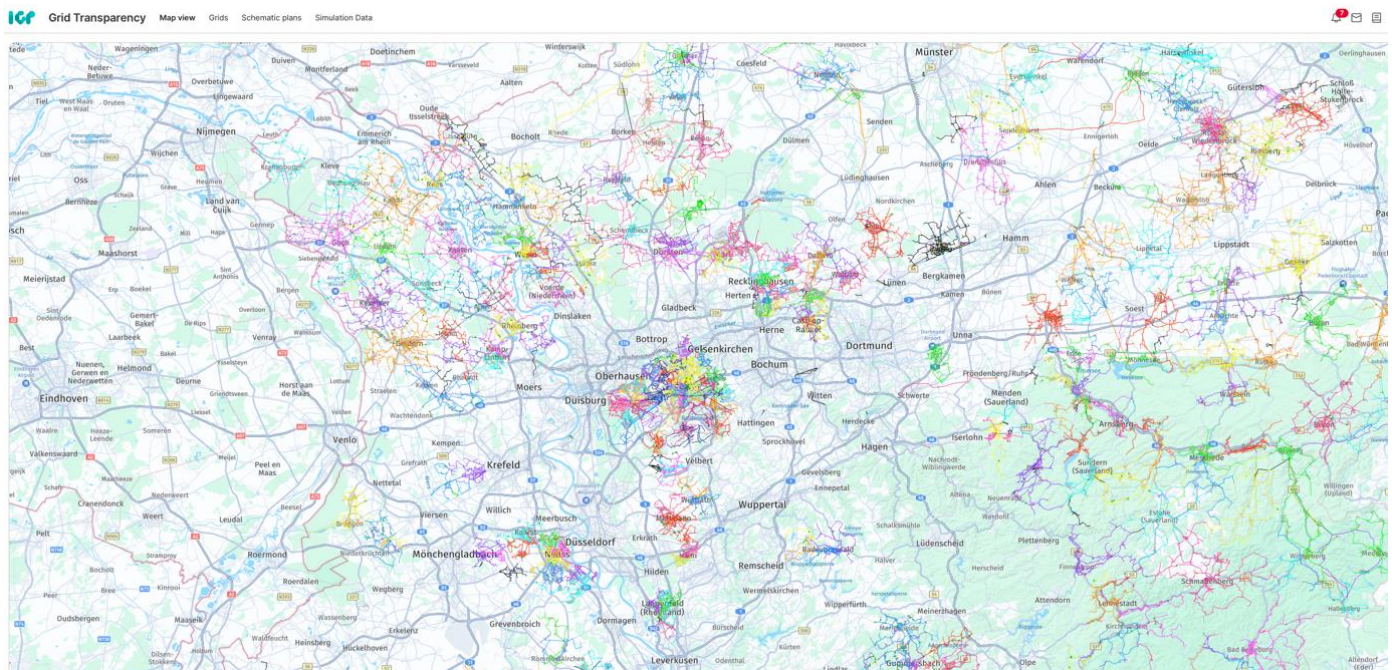


Figure 1: Grid visualization in the Intelligent Grid Platform using sample data

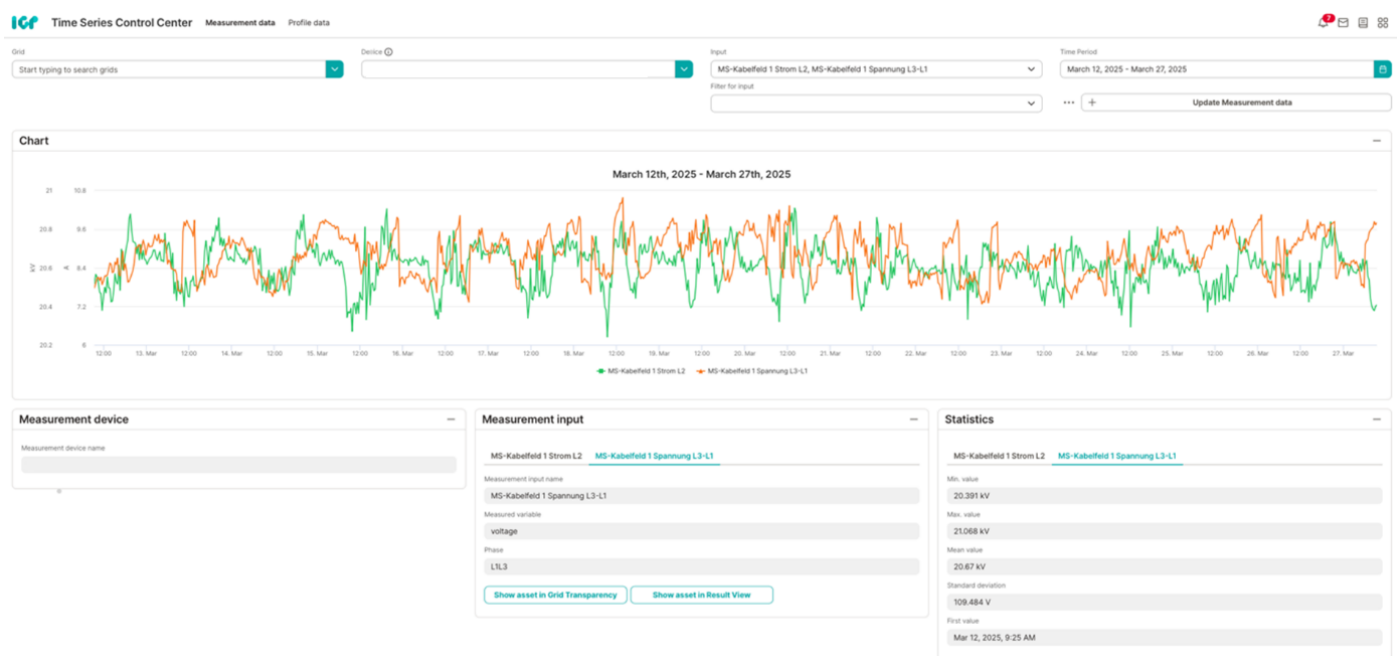


Figure 2: Time Series Control Center with sample data

The Time Series Control Center (TSCC) in Figure 2 enables users to analyze all existing measurement data within the grid area. Measurements are received live, stored, and displayed at selectable resolutions. Users can inspect both actual measurements and measurement profiles, with the ability

to switch between different measurement devices and time series. The tool also provides seamless integration with Grid Transparency, allowing users to jump back to network views for spatial context (Reference: KPI VAL_KPI2 – DT computational performance and latency, see Deliverable 9.1.).

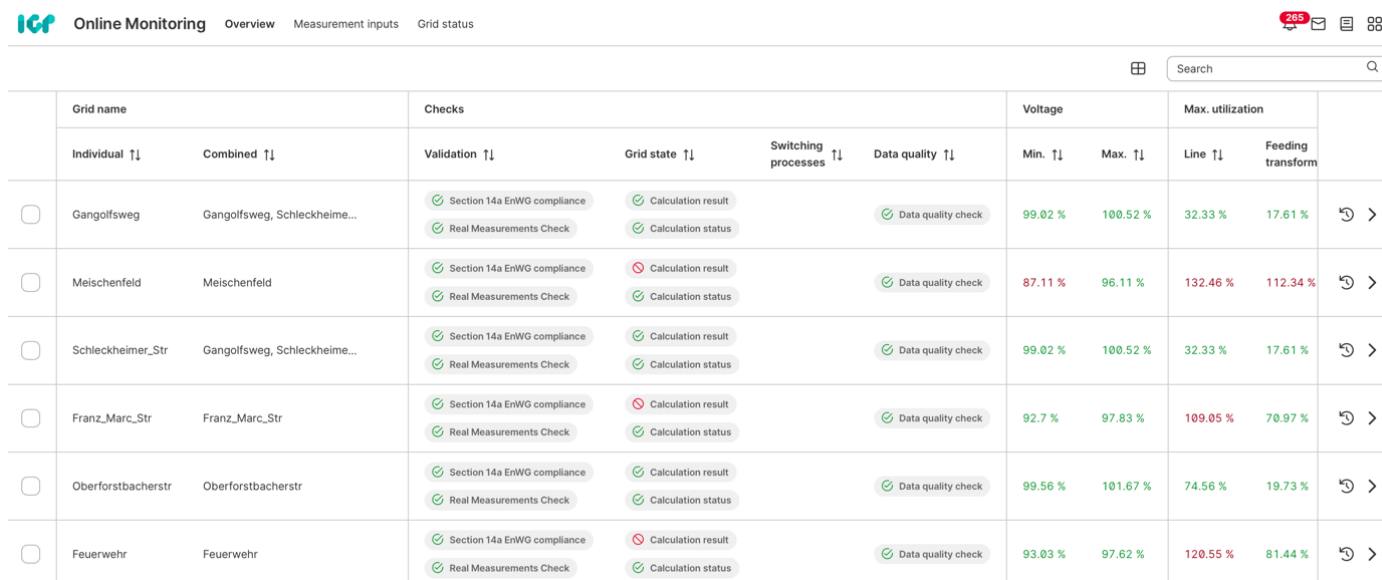
State Estimation & Online Monitoring – Performance and Operational Maturity

Over the last two years, state estimation evolved from a calculation component into an operationally usable monitoring capability.

Key improvements and outcomes include:

- Higher robustness and convergence stability: The solver and workflow were hardened against non-convergence and contradictory inputs, including selective exclusion of problematic measurements when needed.
- Faster detection of critical states: Notifications are created when limit violations are detected, allowing operators to react quickly and open the affected grid directly
- Better model coverage with sparse measurements: Standard Load Profiles (SLPs) are used for non-measured participants to improve stability and applicability of SE in sparsely measured LV grids
- Operational transparency for troubleshooting: The Measurement Analyzer enables tracing which measurements were used for a specific SE run and how much results deviate from input values, improving root cause analysis
- Faster computation times, enabling near real-time condition assessments even with sparse measurement data.

For reference see KPI GE01_KPI1 – Increase in grid observability accuracy: structural mapping coverage at Westnetz in Deliverable 9.1.



The screenshot shows the 'Online Monitoring' interface with a navigation bar (Overview, Measurement inputs, Grid status) and a search bar. The main table displays data for six grids. Each grid row includes a checkbox, grid name, combined name, a 'Checks' column with status indicators for Section 14a EnWG compliance, Real Measurements Check, Calculation result, Calculation status, and Data quality check, followed by Voltage (Min. and Max.), Max. utilization (Line and Feeding transform), and a final column with a refresh icon and a right arrow.

	Grid name		Checks					Voltage		Max. utilization		
	Individual ↑↓	Combined ↑↓	Validation ↑↓	Grid state ↑↓	Switching processes ↑↓	Data quality ↑↓		Min. ↑↓	Max. ↑↓	Line ↑↓	Feeding transform ↑↓	
☐	Gangolfsweg	Gangolfsweg, Schleckheime...	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✓ Calculation result ✓ Calculation status		✓ Data quality check		99.02 %	100.52 %	32.33 %	17.61 %	↻ >
☐	Meischenfeld	Meischenfeld	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✗ Calculation result ✓ Calculation status		✓ Data quality check		87.11 %	96.11 %	132.46 %	112.34 %	↻ >
☐	Schleckheimer_Str	Gangolfsweg, Schleckheime...	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✓ Calculation result ✓ Calculation status		✓ Data quality check		99.02 %	100.52 %	32.33 %	17.61 %	↻ >
☐	Franz_Marc_Str	Franz_Marc_Str	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✗ Calculation result ✓ Calculation status		✓ Data quality check		92.7 %	97.83 %	109.05 %	70.97 %	↻ >
☐	Oberforstbacherstr	Oberforstbacherstr	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✓ Calculation result ✓ Calculation status		✓ Data quality check		99.56 %	101.67 %	74.56 %	19.73 %	↻ >
☐	Feuerwehr	Feuerwehr	✓ Section 14a EnWG compliance ✓ Real Measurements Check	✗ Calculation result ✓ Calculation status		✓ Data quality check		93.03 %	97.62 %	120.55 %	81.44 %	↻ >

Figure 3: Online Monitoring overview (on demo cluster) for all low voltage grids

The Online Monitoring feature (see Figure 3 and Figure 4) provides dynamic visualization of grid states and measurement data with several key capabilities:

- Grid Status Configuration: Users can set different monitoring states for grids (Not Monitored, Monitored, or Controllable grid) to control how grids behave regarding monitoring and control.

- State Estimation Quality: Includes bad data detection to identify and exclude potentially faulty measurement inputs, with indicators showing excluded values
- Historical data access: Ability to inspect recent results for operational context.
- Measurement coverage analysis: Coverage metrics for active/reactive power and key measurement types.
- Limit Violation Detection: Flags voltage, line, and transformer limit violations in the computed grid state (State Estimation), with violations potentially being measured at sensor points or inferred for non-measured elements
- In the second picture (Figure 4) the state estimation for one grid per minute is shown:

265

Online Monitoring

Overview

Measurement inputs

Grid status

← Gangolfsweg

Area

TestArea

Feeding transformer

tr2w_1274_F1T118

Voltage level

Low voltage

April 4, 2025 10:49 - April 7, 2025 10:49

	Grid name	Checks	Voltage			Max. utilization			Latest state estimation		
	Combined	Validation	Grid state	Data quality	Min. ↑↓	Max. ↑↓	Line ↑↓	Feeding transformers ↑↓	Subordinate transformers ↑↓		Timestamp ↑↓
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	99.02 %	100.52 %	32.33 %	17.61 %	-	Apr 7, 2025, 10:49 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	98.96 %	100.46 %	32.5 %	17.58 %	-	Apr 7, 2025, 10:48 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	99.33 %	100.83 %	32.26 %	17.55 %	-	Apr 7, 2025, 10:47 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	99.08 %	100.59 %	32.57 %	17.55 %	-	Apr 7, 2025, 10:46 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	99.07 %	100.58 %	32.59 %	17.45 %	-	Apr 7, 2025, 10:45 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check	99.12 %	100.62 %	32.3 %	17.43 %	-	Apr 7, 2025, 10:44 AM	>
☐	Gangolfsweg, Schleckheimer_Str	✔ Section 14a EnWG compliance ✔ Real Measurements Check	✔ Calculation result ✔ Calculation status	✔ Data quality check		100.79 %				Apr 7, 2025,	

Figure 4: Online Monitoring (on demo cluster) for a specific low voltage grid

Advancements in Congestion Forecasting and Management

Congestion Management was strengthened by aligning monitoring results with controllability qualification, helping ensure controls are applied consistently and only where preconditions are met.

Key developments and results include:

- End-to-end workflow maturity: The Congestion Management beta application enables automated steering of controllable devices (SteuVE) according to §14a EnWG, based on periodic SE runs and congestion detection. Reference KPI GE03_KPI1 – Increase in response time to congestion events, see Deliverable 9.1.
- Improved handling of data quality issues: Operators can deactivate specific measurement inputs (Measurement Input Control) to stabilize SE/CM behavior while still observing incoming values in TSCC (see also Measurement Input Control concept described in project reporting).
- Faster root cause analysis: Diagnostic layers (incl. SE transparency tooling such as Measurement Analyzer) support quicker identification of missing measurement coverage vs. genuine grid events.
- Quality Indicators (measurement availability & §14a conformity): Added a quality indicator that makes measurement sufficiency for §14a transparent in OM results (informational indicator to support operational decisions)

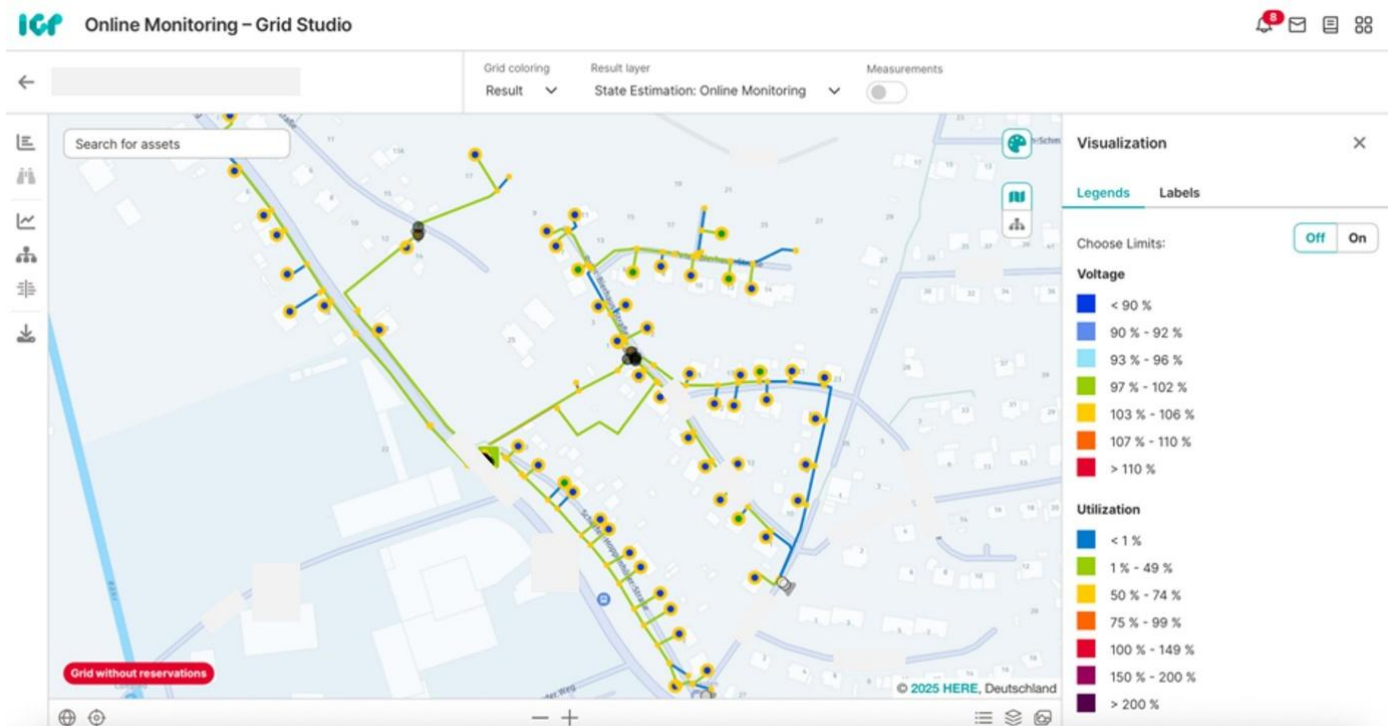


Figure 5: Online Monitoring Grid Studio (on westnetz qa cluster)

Figure 5 shows the Online Monitoring (OM) Grid Studio interface (on demo cluster) with several key functionalities and agenda items:

The interface displays a graphical representation of grid components with several key elements:

- The "Voltage" section uses a color-coding system where:
 - Green indicates voltage levels within acceptable limits
 - Yellow signifies voltage levels approaching boundaries
 - Red shows voltage limit violations
- The "Utilization" section employs similar color indicators:
 - Green shows normal utilization levels
 - Yellow indicates approaching maximum capacity
 - Red represents overutilization

The visualization provides operators with an immediate understanding of grid conditions and potential issues requiring attention. Both voltage and utilization metrics are critical for monitoring grid stability and performance.

Figure 6 shows a detailed view of measurement values in the Online Monitoring (OM) interface. Each measurement badge displays two numbers in the format (x/y), where:

- The first number (x) represents how many measurements are currently used by the state estimation
- The second number (y) shows the total number of available measurements for that grid element

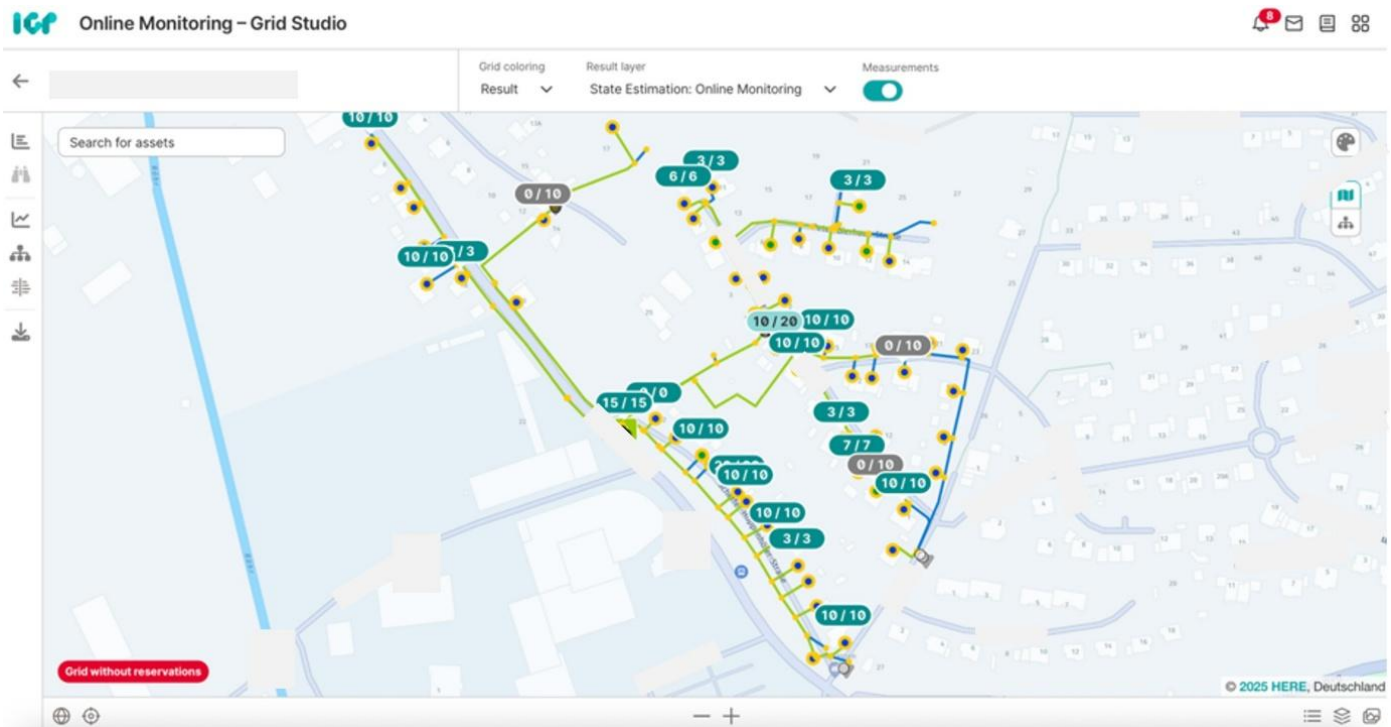


Figure 6: Measurement Values in the Online Monitoring interface (on westnetz-qa cluster)

Measurement coverage badges (used vs. available):

When the congestion map shows a badge like (10/10), this means that 10 out of 10 available measurements are currently used as inputs for the state estimation. A badge like (8/12) means that 12 measurements are available in principle, but 4 are currently excluded from the calculation.

Measurements can be excluded intentionally to keep the computed grid state physically consistent and operationally robust. Typical reasons include:

- Data quality / plausibility checks: the measurement is flagged as outlier, inconsistent, or otherwise invalid (bad-data detection).
- Stale or missing values: the measurement is not recent enough, has gaps, or is not delivered reliably in the selected time window.
- Conflicting or inconsistent signals: where multiple signals for the same quantity/asset disagree, an inconsistent input may be excluded to avoid contradictory constraints. Genuine redundancy, however, is not a reason for exclusion — consistent signals for the same quantity are aggregated (e.g. combined by mean), and as additional weighted inputs they generally improve the state estimation by filtering measurement noise.
- Operational deactivation: an operator may temporarily deactivate a problematic input (Measurement Input Control) to stabilize SE/CM behavior while still observing incoming values (e.g., in TSCC).

This is why an (8/12) badge does not necessarily indicate “missing” measurements, but often a deliberate selection to ensure stable and explainable results.

The interface also indicates measurement status (availability, quality) through color coding and provides quick access to detailed measurement information for each grid component. This helps in monitoring data quality and ensuring reliable grid state estimation.

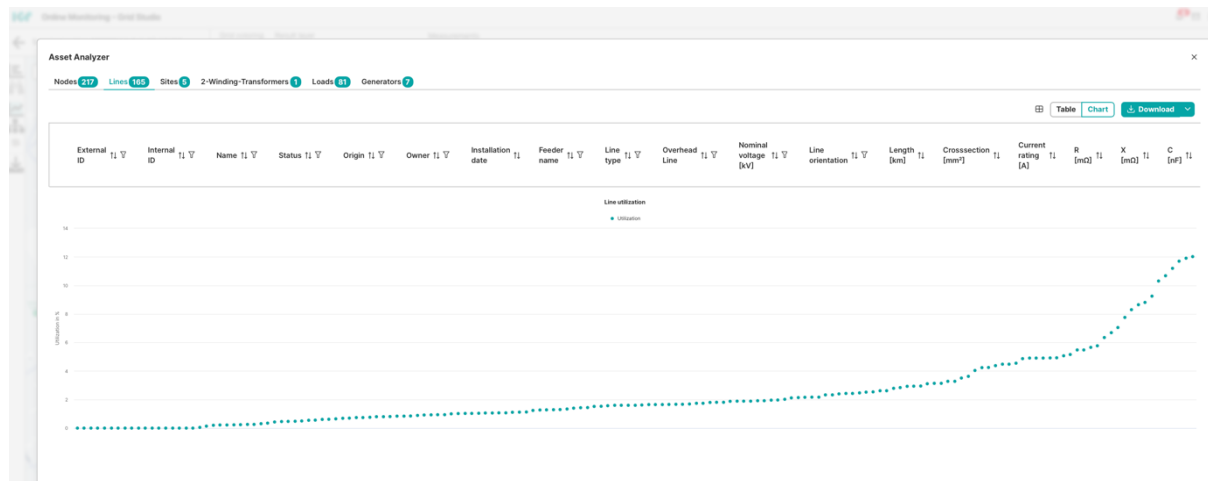


Figure 7: Asset Analyzer (on westnetz qa cluster)

The Asset Analyzer in Figure 7 is a powerful tool that provides comprehensive information about grid assets. The assets are organized into different tabs (e.g., Nodes, Lines, Sites, Transformers, Loads, Generators)

- Key Information Available:
 - Power metrics (effective, contractual, installed)
 - Asset utilization data
 - Technical specifications (e.g., length for lines, power ratings for transformers)
 - Asset identification information (IGP ID, external IDs)

The tool allows users to effectively analyze and compare grid assets, making it valuable for both operational monitoring and planning purposes.

Measurement Analyzer

Grid name

Timestamp

Measurements

May 18, 2025, 11:54 AM

Partially measured (measuring & profile)

▼ Data quality overview

Accepted input value (100%)

Asset		Calculation			
Asset type	Asset	Measured variable	Calculated value	SE input value	Deviation
Transformer	External ID: 1074	Active Power	85.32 kW	84.98 kW	0.34 kW
	Measured node: T18 node: T18	Reactive Power	-58.82 kVAr	-78.36 kVAr	0.54 kVAr
		Current	159.88 A	159.89 A	0.89 A

Figure 8: Measurement Analyzer 1

The Measurement Analyzer table in Figure 9 shows detailed information about measurements and state estimation calculations. When switching to "Measurements", the table expands to show:

- The measurement value as captured from the measurement device;
- The corresponding SE input value that was used for state estimation;
- The origin of the measurement (whether it was a real measurement or based on a profile);
- The participant information if applicable;
- The specific phase(s) that were measured;
- Whether the measurement is an aggregation (like an average or sum of multiple values).

Stellen-Messung - Grid Studio

Measurement Analyzer

Grid name: [redacted] Timestamp: Apr 7, 2025, 10:43 AM Measurements: ☒

Partially measured (measuring & profiles)

▼ Data quality overview

Accepted input value (100%)

Asset		Calculation				Measurements						
Asset type	Asset	Measured variable	Calculated value	SE input value	Deviation	Measurement value	Measurement input	Origin	Participant	Phase type	Aggregation type	
Transformer	External ID: [redacted] Measured node: [redacted]	Active Power	13.69 kW	16.20 kW	-2.51 kW	16.20 kW	MS-Trafofeld 1 Wirkleistung	Measuring	-	L1 L2 L3	Instantaneous Value	
		Reactive Power	2.59 kVAr	3.32 kVAr	-0.73 kVAr	3.32 kVAr	MS-Trafofeld 1 Blindleistung	Measuring	-	L1 L2 L3	Instantaneous Value	
		Current	0.77 A	1.17 A	-0.39 A	1.17 A	MS-Trafofeld 1 Strom L2	Measuring	-	L2	Instantaneous Value	
Transformer	External ID: [redacted]	Voltage	10.39 kV	10.43 kV	-0.04 kV	10.43 kV	MS-Trafofeld 1 Spannung L3-L1	Measuring	-	L1 L3	Instantaneous Value	
Transformer	External ID: [redacted] Measured node: [redacted]	Active Power	-13.69 kW	-7.46 kW	-6.23 kW	-7.46 kW	NS-Trafofeld Wirkleistung Mittelw.	Measuring	-	L1 L2 L3	Average	
		Reactive Power	-2.58 kVAr	-0.15 kVAr	-2.43 kVAr	-0.15 kVAr	NS-Trafofeld Blindleistung Mittelw.	Measuring	-	L1 L2 L3	Average	
		Current					16.85 A	NS-Trafofeld Strom L1 Mittelw.	Measuring	-	L1	Average
							24.49 A	NS-Trafofeld Strom L2 Mittelw.	Measuring	-	L2	Average

Figure 9: Measurement Analyzer 2 (on westnetz-qa-cluster)

The "Deviation" column shows the difference between the state estimation result and the measurement input value. This is particularly important for validating the quality of the state estimation. Not all measurement values are directly used as SE input values. For example, if voltages of all phases are measured individually, the average of these values is used for state estimation since it works with a one-phase equivalent. Similarly, for power values, the sum would be used instead of the average.

Online Monitoring

Overview

Measurement inputs

Grid status

Search

Grid name		Checks		Voltage		Max. utilization			Latest state estimation		
Individual	Combined	Validation	Grid state	Min.	Max.	Line	Feeding transformers	Subordinate transformers	Timestamp	Grid state last 24h	Grid state last 72h
		Section 14a EnWG compliance Real Measurements Check	Calculation result Calculation status	103.39 %	104.29 %	10.72 %	4.81 %	-	Mar 26, 2025, 4:19 PM	Calculation result Calculation status	Calculation result Calculation status

Figure 10: Overview online monitoring & congestion management (on westnetz qa cluster)

Grids that have real time measurements available can be monitored on a continuous level and will be shown in the "Online Monitoring" section (see Figure 10). All monitored grids are calculating their state estimation on a 1 minute basis. This algorithm builds upon several analysis of the incoming real time measurement data, topology, power flow calculation.

Figure 11 shows a topological view of the grid where controllable loads are color-coded: green for actively controlled loads under Congestion Management, yellow for uncontrolled loads, and red for loads where control transmission failed. Areas of congestion, such as transformers or line elements, are highlighted in red, and users can filter the view by individual feeders to monitor specific regulator interventions.

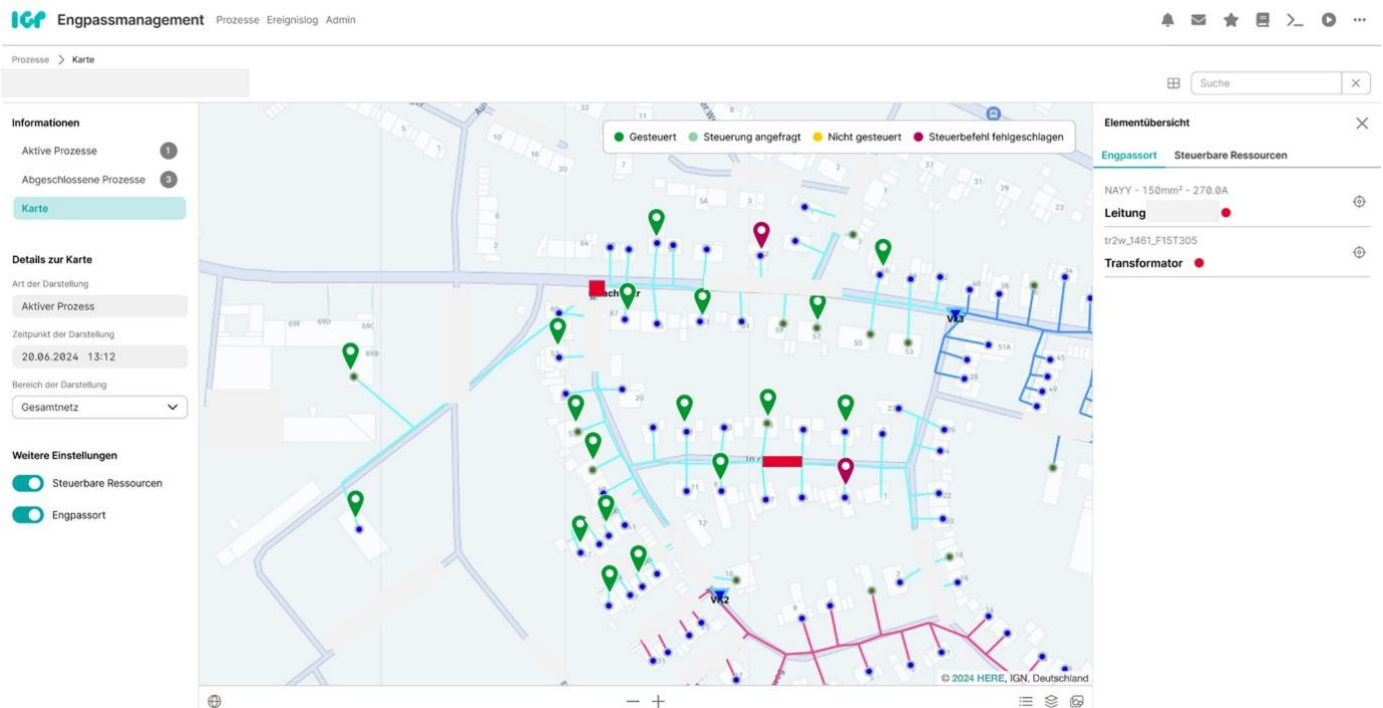


Figure 11: Overview congestion map (on westnetz qa cluster)

3.1.6 Operational Review and Practical usage of the results in real DSO processes – Field Assistant

3.1.6.1 Operational Perspective of Westnetz as DSO

In addition to the technical progress described above, Westnetz provided an operational perspective on how model-based grid transparency and Incident Detection can support day-to-day DSO workflows under real-world data availability constraints.

In operational practice, Westnetz emphasized that Incident Detection becomes particularly valuable when the model-based grid view in IGP can be complemented with (near) real-time measurements at selected connection points (e.g., via intelligent smart metering systems (iMSys)). This allows operators not only to flag deviations from operating limits, but also to validate and interpret them using recent measurement histories and trends, supporting plausibility checks and faster decision-making.

In the same context, Westnetz pointed to grid transparency workflows in IGP that allow operators to calculate and assess whether a given grid state complies with operational limits and to test the impact of adding further grid participants at specific connection points. Depending on the data situation, calculations can be based on different input sources (e.g., iMSys versus secondary substation), and results are commonly presented as an intuitive traffic-light indicator (e.g., “green” if limits are respected). Compared to a purely static feasibility check, this approach is considered more flexible because it supports iterative “what-if” assessments based on the available measurements and model assumptions.

A prominent example discussed by Westnetz is the detection and handling of voltage limit (voltage band) violations that may prevent PV systems from feeding in. Here, the upper voltage limit of 253 V (+10% of nominal voltage) is a relevant operational threshold. Westnetz described cases where

additional iMSys installations made such violations transparent across multiple measurement points and where Incident Detection supported identifying and validating the issue. Building on this, the intended direction is to link detected limit violations more closely with forecasting and proactive operational measures, which may reduce the need for immediate on-site intervention in certain cases.

3.1.6.2 Introduction Field Assistant

One exemplary use case at Westnetz combines the results of the TwinEU use cases 1–3 into a feature called “Field Assistant” within the Intelligent Grid Platform (IGP). The Field Assistant is the result of an analysis of current work processes. Its functional requirements were clustered into five main use cases which are mainly built on the previously described use cases 1-3 of the TwinEU project:

- Asset Map and Measurement Data View: Provide fast access to asset information and time series data.
- Incident Detection: Display grid incidents, e.g., voltage quality, overloads, or outages, both spatially on the map and in structured lists per asset.
- Virtual Switching: Enable digital planning of switching actions, validation of temporary grid configurations and documentation of switching plans.
- Route Map: Automatically generate cable route maps to support efficient cable fault localization.
- Data Issue Reporting: Allow simple logging of identified data inconsistencies for subsequent correction.

3.1.6.3 Process and Business Impact

Following the requirements analysis and initial prototyping of the Field Assistant, a business impact assessment was conducted. From the five identified use cases, two high-impact operational sub-processes were modelled quantitatively: safe switching of a transformer for maintenance and access to historic and live measurement data for complaint analysis. Process data were collected from multiple grid service centres and averaged. Additional qualitative business impacts were identified but not quantified due to limited data availability and modelling complexity. The business impact is expressed as working hours saved through streamlining or automation of manual processes. As the complexity of LV grid operation increases, the working hours saved can be reallocated to critical operational tasks.

Quantifiable Business Impact 1: Maintenance of Transformer (Virtual Switching)

Transformers are maintained regularly and must be disconnected from the grid during maintenance for safety reasons. To ensure uninterrupted supply, typically radial or open-ring LV grids are temporarily connected to neighbouring grids. This requires careful planning: Where are suitable connection points located? Do neighbouring grids have sufficient capacity? Are overloads likely to occur? Many of these steps currently require extensive manual work, such as identifying connection points in the GIS, or depend heavily on detailed local grid knowledge. Planning errors may lead to asset overloading or unnecessary deployment of backup systems. The Virtual Switching feature enables digital planning of switching operations by selecting which connections are to be opened and closed. Once the switching sequence is defined, a steady-state grid calculation verifies the resulting temporary grid configuration to prevent overloads and voltage violations.

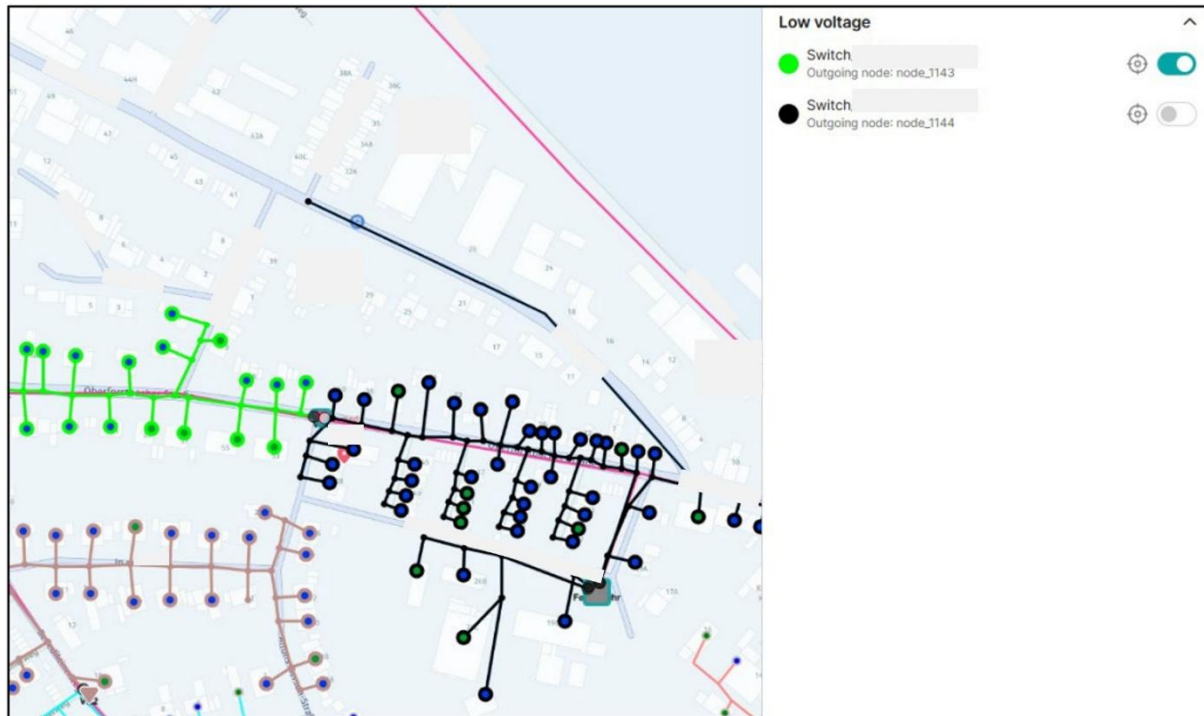


Figure 12: Connecting a disconnected grid (black) to a neighbouring grid (green) via a cabinet (cropped for clarity)

Figure 12 shows an intermediate step in the planning process. The transformer of the grid on the right has already been disconnected; consequently, this grid section is displayed in black. A cable cabinet (represented by an inverted triangle) is selected, and by activating the black switch, colour-coded to match the grid section, the two grids are connected. All switching actions are recorded to generate a structured switching plan, in which the sequence of actions can be adjusted. The plan is automatically documented and can be set to active for execution in the field.

Figure 13 presents the results of the grid calculation for the connected grids under a load-only scenario. Green and blue cables and substations indicate low loading levels. One cable in the northern section shows a loading of 65% and is therefore highlighted in yellow, which remains well within the permissible operating range. The voltage levels at the nodes (circles) are also within acceptable limits. In the eastern section, a minor voltage drop to 96% of nominal voltage is observed, indicated by blue borders.

Considering both simple and complex planning scenarios, the overall time required for planning and documentation is projected to decrease by approximately 35% compared to the projected baseline scenario in 2030.



Figure 13: Results of the grid calculation for the connected grids (cropped for clarity)

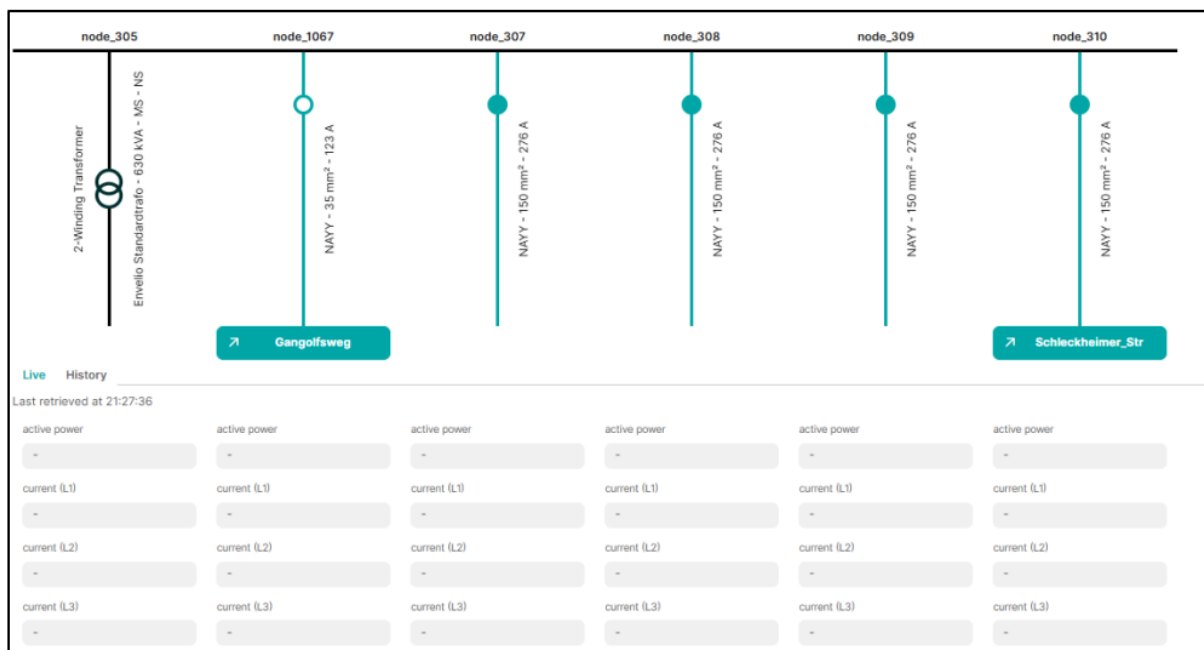


Figure 14: Live and historic measurement data at a secondary substation (no data shown, cropped for clarity).

Quantifiable Business Impact 2: Confirmation of Complaint (Measurement Data View)

If customers report voltage quality issues, e.g., inverter shutdowns, the current procedure involves installing an analyser box at the location, recording data for up to two weeks, and subsequently analysing the data manually. This process is time-consuming and depends on the issue recurring during

the recording period. Where available, access to time series data from smart assets enables immediate evaluation of voltage and load behaviour.

In the Field Assistant, smart assets are highlighted. Selecting such an asset opens the measurement tab, as shown in Figure 14, displaying current live values and historical time series data for the transformer and each feeder over the previous week. If more extensive data analysis is required, users can directly access the Time Series Control Center within the IGP to view complete historical data. The availability of time series data reduces the need for analyser box installations by approximately 33% compared to the projected baseline scenario in 2030.

3.1.6.4 Lessons Learned and Outlook

The development and deployment of the Field Assistant highlighted several key factors for successful data-driven LV grid operation:

- First, digital tools only generate sustainable value when embedded in formal operational processes. Voluntary usage increases familiarity, but process integration ensures consistency, accountability and measurable efficiency gains.
- Second, data quality is the single most critical success factor for digital twin-based applications. Even minor inconsistencies can significantly reduce user confidence. Continuous data governance and technician involvement are therefore essential.
- Third, user-centric development substantially accelerates acceptance. Early involvement of grid operators ensured that the Field Assistant was perceived as an operational support tool rather than an additional administrative burden.
- Fourth, the economic value of digitalisation increases with grid complexity. As LV grids become more dynamic due to distributed energy resources, manual planning processes scale poorly.

The Field Assistant demonstrates how a digital twin can be transformed from a planning instrument into an operational decision-support system. Its continued rollout and integration across E.ON DSOs will further validate the scalability of data-driven LV grid operation under real-world conditions.

3.1.7 Next Steps in Future Projects

Future development plans focus on several key areas for enhancement. The primary goal is to expand monitoring coverage to additional grid sections while enhancing state estimation accuracy through additional measurement points. Advanced analytics for grid operation are being developed, along with improved integration with flexibility management systems. The roadmap includes developing predictive maintenance capabilities and better integration with outage management and switching operations. A key focus is on scaling the solution across multiple grid areas to achieve broader implementation.

Planned Enhancements in Monitoring Infrastructure

- Extension of smart meter integration to cover a larger share of low-voltage feeders.
- Deployment of AI-driven analytics for anomaly detection and predictive congestion analysis.
- Enhancement of the digital twin framework, enabling DSOs to simulate different grid scenarios and optimize control strategies.

State Estimation and Flexibility Integration

- Further refinement of machine learning-based state estimation to enhance predictive accuracy.

- Integration with flexibility trading platforms, enabling DSOs to procure demand-side flexibility more efficiently.

Scalability and Market Readiness

To ensure a successful transition from pilot implementations to large-scale adoption, upcoming steps include:

- Interfacing with upcoming regulatory frameworks, ensuring compliance with evolving grid operation standards (i.e. Network Code Demand Response)
- Validation of business models for flexibility integration in real-world conditions.
- Rollout of the solution across multiple European DSOs, leveraging cross-border collaborations to accelerate deployment.
- Further development of the operational framework and the IT system architecture to ensure requirements concerning availability and mitigation of cybersecurity risks are met.

The advancements in grid monitoring, state estimation, and congestion management represent a significant step toward the digitalization and automation of distribution networks. By leveraging real-time data processing, AI-driven analytics, and market-based flexibility activation, the proposed solutions can offer a robust framework for next-generation DSO operations. Future research and development efforts will focus on scaling these solutions, integrating predictive maintenance strategies, and enhancing cybersecurity measures to ensure a resilient and adaptive power grid.

From the perspective of Westnetz GmbH, the next steps in Use Cases 1–3 focus on identifying additional analysis and monitoring scenarios based on the Intelligent Grid Platform (IGP). This includes examining how existing and newly developed IGP functionalities can be used for model-based grid state analyses.

In addition, new and enhanced analytical functions of the IGP are tested under different levels of data availability in distribution networks. The aim is to assess their applicability in grid areas with varying measurement coverage, to identify data requirements, and to document the applied analytical methods and assumptions. This provides a basis for deriving and evaluating further application scenarios beyond those considered so far.

3.2 End-to-end flexibility usage

3.2.1 Overview use cases 4-6

End-to-end flexibility represents a comprehensive approach to managing flexible resources in the distribution grid, focusing on the integration of market-based solutions and preventive congestion management. The system encompasses multiple stakeholders and aims to create a coordinated framework for flexibility activation between different grid levels. Key focus areas include the management of flexible resources, integration with market mechanisms, and development of monitoring solutions for effective congestion management.

Generic Micro-Flexibility Deployment for the Flexibilization of the Energy System

The growing penetration of renewable energy sources (RES) and the increasing electrification of demand (e.g., electric vehicles, heat pumps) require a more flexible energy system. Micro-flexibility deployment focuses on small-scale flexibility assets, such as §14a EnWG assets, PV inverters, or demand-side management programs. Section 14a of the German Energy Industry Act (§14 EnWG [4])

regulates that grid operators may temporarily reduce the power of the controllable devices namely EV chargers, heat pumps, battery and cooling devices in case of grid congestion. The goal is to leverage these decentralized assets to balance supply and demand dynamically.

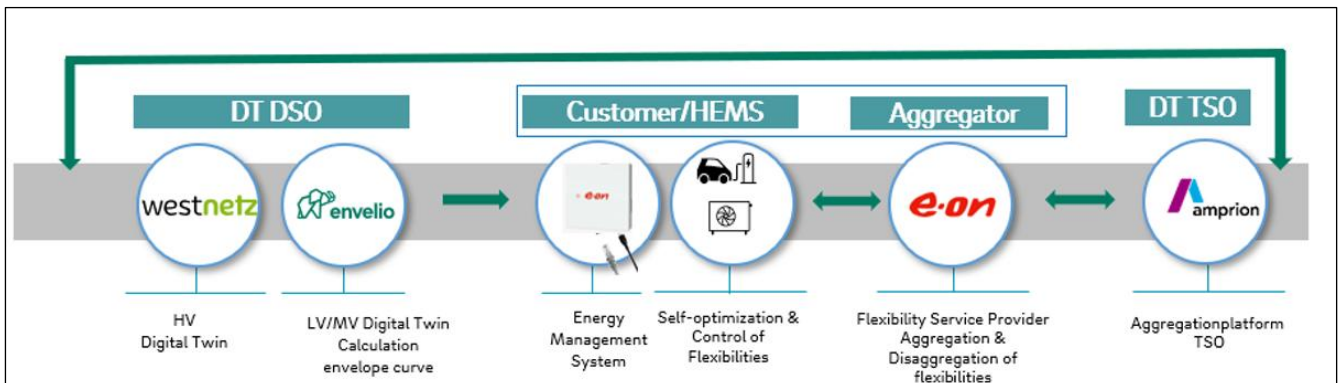


Figure 15: A flowchart illustrating the interaction between household flexibility assets, aggregators, and grid operators

Preventive Congestion Management through Envelope Curve (Ge04)

One of the key innovations in this pilot is the generation and application of envelope curves in the low voltage grid, which predict grid congestion based on forecasted load and generation patterns. These curves define the maximum allowable flexibility activation before a constraint occurs. By anticipating congestion, distribution system operators (DSOs) can take preventive measures, avoiding costly last-minute interventions. For Flexibility Service Providers (FSP) and aggregators, the envelope curves provide the framework and the available degree of freedom in which they can operate and utilize their available flexible assets.

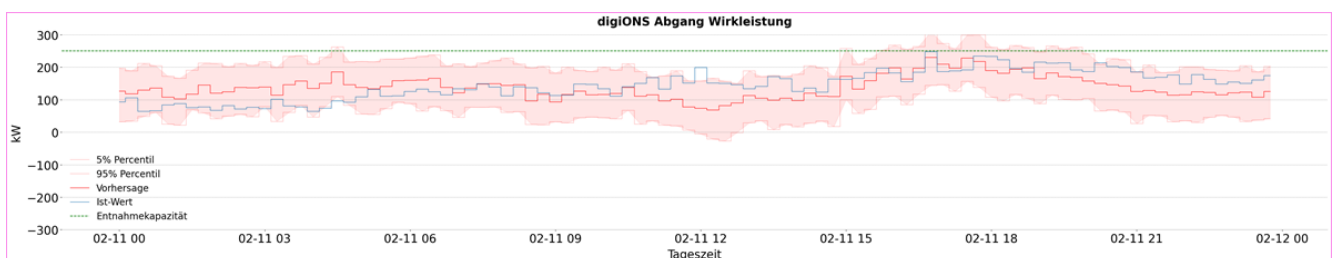


Figure 16: Example of an envelope curve

In order to implement the concept of an envelope curve at the customer level, the grid restrictions or the available capacities must be allocated to individual customers. Therefore, a distribution of the envelope curve to single customers is needed. Within the project a concept was developed to detect the base load of single customers and avoid sending envelope curves that are too restrictive to be realized. An exemplary visualization of an envelope curve, showing predicted congestion levels and available flexibility windows is shown in Figure 16.

The aim of the project is to investigate whether the envelope concept, broken down to individual customers, is an effective means of avoiding bottlenecks in the low voltage grid – without restricting households in their use – and enabling them to get the most possible capacity for their flexible consumers (e.g. for charging their vehicles).

Utilization of the Flexibility Potential within the Household (Ge05)

Households represent a significant source of flexibility, particularly with the rise of smart appliances, home energy management systems (HEMS), and dynamic tariffs. This use case investigates how household flexibility can be coordinated efficiently, ensuring that residential demand-side response contributes to grid stability while maintaining customer comfort. The objective is to examine if breaking down the envelope concept to individual customers represents an effective means to avoid bottlenecks in the low-voltage feeder. The aim is not to restrict households in their usage and enable them to achieve the highest possible performance for their flexible consumers (for charging their vehicles).

Utilization of the Flexibility Potential for Advanced Congestion Management (Ge06)

Beyond household flexibility, aggregated flexibility resources from multiple customers can be used for higher-level congestion management strategies. These include market-based mechanisms, for example for Redispatch applications. A key aspect is ensuring that such activations align with local grid constraints. For the market design context (PKME study [5], §14c framework, Redispatch 3.0 concept) underlying Ge06, see Ge07 Workstream 1.

3.2.2 Concept of Envelope Curve

Definition and Concept of Power Envelopes

Power envelopes are a grid-oriented concept designed to describe a permissible power corridor within which flexible consumption and generation can be operated without violating local grid constraints. They define the technically admissible operating range between lower and upper power limits for a given grid segment over time.

Unlike static connection capacities or purely reactive congestion management measures, power envelopes represent a time-dependent and situation-specific view of available grid capacity. They reflect the remaining operational margin before critical grid limits are reached and enable a preventive consideration of grid constraints based on forecasted system conditions.

Conceptually, power envelopes translate grid-related constraints into an operationally usable and communicable form for downstream actors such as flexibility service providers (FSPs). While traditional grid operation primarily focuses on compliance with individual asset-specific limits (e.g. transformer loading or voltage bands), power envelopes aggregate these constraints into a unified, time-resolved power corridor that can be communicated externally.

From a conceptual perspective, power envelopes define:

- an upper power boundary, indicating the maximum admissible consumption or minimum admissible feed-in under current and forecasted grid conditions,
- a lower power boundary, indicating the minimum admissible consumption or maximum admissible feed-in,
- a temporal resolution, allowing the admissible power corridor to vary over time in accordance with expected grid utilization.

By defining these boundaries, power envelopes do not prescribe specific control actions or dispatch decisions. Instead, they provide a technical constraint framework within which flexibility can be offered, aggregated, and activated in a grid-compatible manner. Decisions regarding concrete dispatch

and optimization remain with downstream actors, while the role of the distribution system operator (DSO) is limited to defining and updating grid-related constraints.

The methodological foundation follows a top-down approach, in which power envelopes are derived from feeder-level forecasts—referring to aggregated load and generation at the level of individual outgoing feeders of a transformer—rather than from individual household or asset-level forecasts.

These feeder-level forecasts represent the expected net loading at transformer or feeder level, taking into account historical measurements, calendar effects and weather forecasts. Based on the forecasted loading profiles, envelope curves are constructed to quantify the remaining admissible operating margin before grid-relevant constraints, such as thermal limits or voltage violations, are reached.

A key characteristic is the explicit consideration of forecast uncertainty. In addition to point forecasts, probabilistic forecasts in the form of quantile predictions are used to derive envelope bands with different degrees of conservatism. In particular, upper quantiles are applied to reduce the risk of underestimating peak loading situations, which are identified as the most critical failure mode for preventive congestion management in low-voltage grids.

Within the German TwinEU demonstrator, the envelope curves are derived by considering thermal limits only – specifically the maximum admissible current per feeder – and not voltage limits. These envelope curves provide the technical basis for preventive congestion management and for the integration of small-scale flexibility in low-voltage grids.

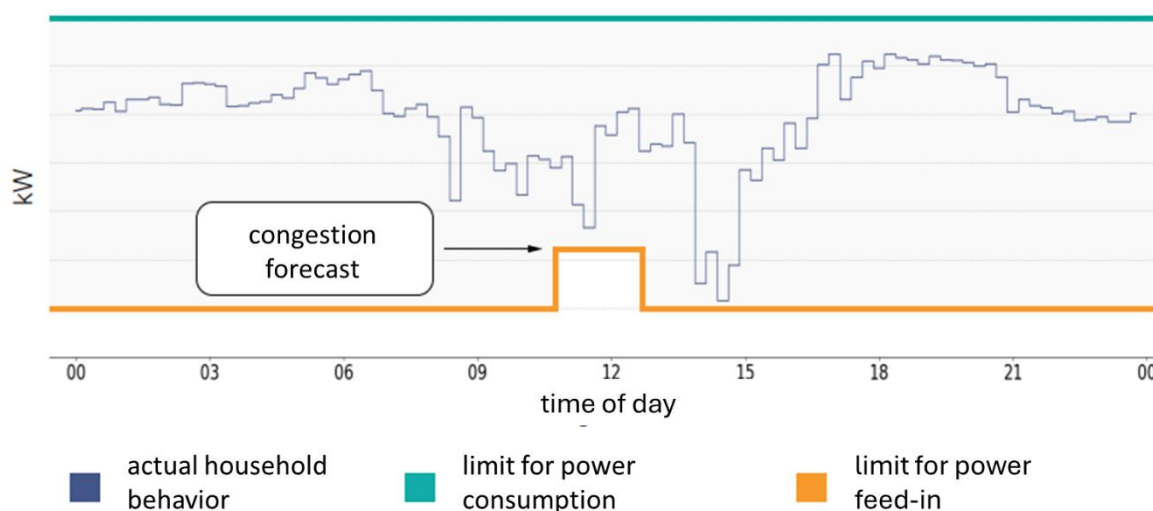


Figure 17: Illustrative envelope curve over 24 hours

3.2.3 Challenges & Complications in Flexibility Management

The implementation of end-to-end flexibility in distribution grids presents several overarching challenges, as well as specific challenges for the individual use cases (Ge04–Ge06). These challenges arise from the increasing complexity of flexibility management, the technical limitations of data exchange and forecasting, and the need to balance market mechanisms with real-time grid operation.

3.2.3.1 Generic Challenges in Micro-Flexibility Deployment

The concept of micro-flexibility deployment aims to unlock decentralized flexibility sources at the household and small-business level to support grid operation. However, scaling such an approach across a complex energy system introduces several fundamental challenges that impact all use cases (Ge04–Ge06):

Stakeholder Coordination and Market Integration

- Coordination across multiple stakeholders (DSOs, aggregators, prosumers, suppliers, and regulatory bodies) requires standardized communication mechanisms.
- Market-based flexibility activation must be synchronized with grid operation needs, which adds complexity to real-time decision-making.
- Aligning financial incentives for all parties involved is critical but difficult to achieve given existing regulatory constraints.
- Market design and incentive structures need careful consideration to ensure participant engagement.

Availability and Predictability of Flexible Assets

While forecasts for individual customers with flexible assets are highly uncertain, pools of flexible assets can be quite predictable through the portfolio effect. Therefore, when it comes to availability, it is important to distinguish which voltage level should be considered.

Especially for Forecasts on Low Voltage level, the following points need to be considered:

- Small-scale flexibility sources (EVs, heat pumps, home batteries) are not always available for grid support, and their availability depends on user behavior.
- Unlike industrial demand response, household flexibility is highly volatile and challenging to predict.
- Forecasting methods must account for non-controllable household consumption as residual load. They must ensure that user comfort (e.g., heating needs, vehicle charging, cooking) is not compromised.
- Due to the small number of customers in the feeder of low voltage networks, portfolio forecasts are not feasible, and individual forecasts have to be aggregated.

Interoperability and Standardization of Interfaces

For flexibility mechanisms to function efficiently, seamless data exchange between different systems is required. However, the lack of harmonized communication standards complicates integration. Key challenges include:

- Exchange of envelope curves: How to define and share forecasted congestion thresholds across different platforms and market actors?
- There is no universal standard for exchanging flexibility data across platforms and market actors.
- Data formats and protocols: Ensuring compatibility between flexibility platforms, SCADA systems, and third-party applications using standards such as IEC 61850 or custom APIs.
- Cybersecurity and data privacy: Protecting sensitive customer data while enabling real-time control of assets.

Customer Acceptance and Comfort Considerations

Flexibility activation must not negatively impact end users. Households expect minimal interference in their daily routines, meaning that non-controllable base consumption (e.g., lighting, refrigerators, or minimum heating requirements) must be considered. Additionally, ensuring that an EV has the required charge when needed imposes constraints on when and how flexibility can be activated. If flexibility mechanisms do not align with user preferences, customer participation may decline, reducing the available flexibility potential.

3.2.3.2 Specific Challenges for Use Cases Ge04–Ge06

Each use case (Ge04–Ge06) faces additional domain-specific challenges that must be addressed for successful implementation.

Challenges in Ge04: Preventive Congestion Management through Envelope Curve

Forecasting accuracy and adaptability: Envelope curves are created based on forecasted grid conditions, but fluctuations in renewable generation and load behavior introduce uncertainty. Additional uncertainty in the forecast is created by bad quality of grid data and missing measurement values, which is why the data onboarding process and robustness of the state estimation is especially important for introducing the envelope curve.

Using a bottom-up approach would mean aggregating large-scale industrial demand response, household and small commercial flexibility units into meaningful portfolios. However, the diversity of household energy consumption and different asset control capabilities create challenges in forecasting and dispatching flexibility, especially if you consider the small number of customers in the local network and feeder. In addition to these systematic topics, due to the low number of houses and sensors there is very little data in the low voltage. This reduces the forecasting capabilities furthermore.

Moreover, small individual flexibility contributes to overall grid stability, but their effectiveness depends on accurate control mechanisms that prevent overcompensation or underutilization. Latency in activation signals impacts the real-time control, since quick response times are necessary. Delays in flexibility activation due to communication constraints may render the flexibility ineffective in critical grid situations. Other key challenges are:

- Dynamic grid conditions: Since congestion risks evolve rapidly, envelope curves must be updated continuously, requiring substantial computational resources.
- Data granularity and sensor limitations: In low-voltage grids, limited sensor coverage makes it difficult to obtain real-time data with sufficient resolution.
- Integration with DSO operational workflows: Envelope curves must be seamlessly embedded in grid operation tools, ensuring compatibility with existing congestion mitigation strategies (e.g., redispatch, topology adjustments).
- Network restrictions in the low-voltage grid are more likely in the feeder than in the entire local network.
- Distribution/disaggregation of the envelope curve to single customers is highly inaccurate. In the current version of implementation, the disaggregation algorithm is based on a linear modulation which needs to be further investigated and improved.
- For the disaggregation level of power envelopes, a trade-off between the maximized usage of flexibility (e.g. only one power envelope for each FSP) and the minimization of grid congestions (one power envelope for each household) needed. By using the first approach, the FSP would

get the opportunity to maximize flexibility within the whole portfolio instead of having constraints for each household. In the scope of this project, the second option was used to quantify the grid behavior – see result section.

- There are discussions about whether the allocation of the envelope curve, within which power can be freely accessed, refers only to the controllable assets of a household or whether the requirement applies to the consumption of the entire household including the controllable assets. In the scope of this project, the grid connection point of each household was used to allocate the power envelope.

Challenges in Ge05: Utilization of the Flexibility Potential within the Household

- Behavioral uncertainty: Household flexibility activation depends on end-user engagement, which varies significantly and cannot be fully controlled.
- Technical challenge: Measurements are available for technical units, but there is a lack in real time measurement of the total household consumption. To receive real time measurements from the intelligent smart metering systems (iMSys), the HAN interface (Home Area Network) must be certified by (German Federal Office for Information Security).
- Comfort constraints and autonomy: Flexibility should not disrupt household activities (e.g., an EV must be ready when needed, heating must maintain comfort levels).
- Lack of financial incentive to participate in envelope curve: Taking into account network restrictions may contradict financial optimization of the household. The prices during times of high renewable energy generation are favorable with dynamic tariffs and can trigger a grid congestion. Separate incentives are needed for voluntary participation in considering the envelope curve.
- Low number of customers: There is only a small number of customers in a local network, especially at the feeder line. The number is further limited due to the voluntary participation of households.
- Compatibility of assets with HEMS (Home Energy Management System): there is no communication standard for protocols. This complicates communication after software updates or requires protocol conversions. A variety of existing assets need to be addressed through individual retrofitting.

Challenges in Ge06: Utilization of the Flexibility Potential for Advanced Congestion Management

- Cross-voltage level congestion coordination: Activation of household flexibility must be coordinated with congestion management efforts at both the local (low-voltage) and system-wide (medium- and high-voltage) levels.
- Real-time flexibility activation: The availability of flexibility assets changes dynamically. EVs may be unplugged when needed, or batteries may already be at full capacity, limiting their controllability.
- Lack of direct control: In most cases, DSOs or aggregators do not directly control household devices and must rely on intermediaries such as sub-aggregators, which introduce communication delays and inefficiencies.
- Interoperability between grid operators and flexibility providers: The real-time dispatch of flexibility assets must align with aggregator strategies and grid constraints.
- Missing definition of redispatch through flexibility: Decision on whether only the consumption by the flexible assets or the total consumption at the grid connection point is considered in the baseline is still pending.

- Complexity of automated control mechanisms: While AI-based algorithms can optimize flexibility dispatch, ensuring trust, transparency, and explainability of automated congestion management decisions is critical.
- Compatibility of assets with Aggregator: In the case that the aggregator directly controls the controllable assets, the challenges regarding communication compatibility also apply to the aggregator.

3.2.4 Solution, Implementation

3.2.4.1 Preventive Congestion Management through Envelope Curve (Ge04)

Practical application within the TwinEU project: Development of Power Envelope Curve in the E.ON Lab

At the E.ON Lab, the development of Power Envelope Curve, also referred to as “low-voltage envelopes”, has been tested in collaboration with Westnetz, Avacon, and envelio. The approach was based on a day-ahead forecast that enables early identification and assessment of flexibility requirements within the grid. The model region provides a realistic, practice-oriented environment in which the concept can be tested and further developed under real-world conditions.

Key principle: Power Envelope Curves are forecasts

Power Envelope Curves are calculated proactively. Grid operators forecast the capacities available at each grid connection for the following day based on load profiles, weather data, consumption patterns, and the local grid situation. This allows potential bottlenecks to be identified early and avoided preventively before they occur.

From the customer perspective, the concept (in combination with possible, future tariff structures) is straightforward:

- To represent a “non-flexible” part of the power consumption, in this demo use case a basic band with for each customer of 5 kW was introduced which is reasonable by looking at current capacity-based tariff discussions.
- As a future design option customers operating additional flexible loads, such as EV charging stations, can book an additional Power Envelope Curve in exchange for reduced or variable network charges.

This arrangement is governed by a Flexible Connection Agreement (FCA). The FCA specifies the conditions under which the grid connection may be used flexibly and is concluded with a Flexibility Service Provider (FSP).

Role of the Flexibility Service Provider (FSP)

The FSP acts as the central link between customers, grid operators, and the energy market. It receives Power Envelope Curve forecasts from the grid operator, forwards this information to the customer side, and automatically controls flexible assets accordingly. At the same time, the FSP aggregates numerous small-scale flexibility potentials—such as those from EV chargers or heat pumps—into a usable portfolio of overall flexibility, which it technically manages and offers to the market.

Method: AI-Driven Forecasting and Envelope Curve Generation

The solution is a first MVP (Minimum Viable Product), incorporating several key components. At its core is the assumption of comprehensive flexibility platforms that enable standardized flexibility products and coordination mechanisms. A significant innovation is the development of low voltage forecasting capabilities, including the generation of envelope curves.

The integration of AI models improves the accuracy of state estimation and congestion forecasting. These models continuously refine predictions based on real-time and historical data. Envelope curves are automatically updated, ensuring DSOs receive up-to-date flexibility constraints.

Due to the different requirements that unmeasured and measured grids place on a forecast, a top-down forecast for measured MV/LV transformers was developed in the first step. The implementation leverages AI models that incorporate weather forecasts and feeder measurements as input parameters and generates utilization forecasts for each feeder. The system includes advanced monitoring tools for grid status assessment and implements preventive congestion management algorithms. All these components must be integrated with existing grid operation systems to ensure seamless operation. A graphical interface to analyze the forecasts of all feeders in comparison to the measurements is in development. If the utilization exceeds the limit of the feeder, the overload is distributed via restrictive envelope curves for the consumers behind the feeder (in the current MVP implementation via a simple linear disaggregation approach). Smart Meter measurements can enable the DSO to understand whether the customer has complied with the restriction or not.

Additional restrictions for envelope curve

To represent a non-flexible share of power consumption, a basic band of 5 kW was introduced, which is considered reasonable in light of current discussions on capacity-based tariffs. This value is also consistent with common practice in Germany, where a customer's grid connection capacity typically corresponds to the

use rating at the grid connection point. Therefore, the 5 kW basic band was applied to all pilot customers.

Standardized Interfaces for Flexibility Communication via Apache Kafka

A crucial aspect is the development of interfaces enabling DSOs to communicate envelope curves to households. At its core is the assumption of comprehensive flexibility platforms that enable standardized flexibility products and coordination mechanisms. To enable end-to-end flexibility, standardized interfaces must be developed, ensuring seamless data exchange between DSOs, aggregators, and consumers. The solution integrates common communication protocols (e.g., for flexibility dispatching).

Within Use Case 4 of the TwinEU project a platform-based approach using Apache Kafka [6] to exchange grid congestion information and envelope curves is used, enabling every FSPs to receive the envelope curves for their end customers. Apache Kafka is a distributed event-streaming platform that is widely used as middleware to enable reliable, scalable, and decoupled data exchange between heterogeneous systems. It is primarily applied in data-intensive, distributed architectures and microservices environments.

Kafka's topic-based architecture ensures reliable, asynchronous, and scalable delivery: multiple FSPs can independently consume envelope curve updates without requiring direct point-to-point

connections to the DSO system. For a detailed technical description of the Kafka configuration and topic design used in this project, see Appendix A.

3.2.4.2 Utilization of the Flexibility Potential within the Household (Ge05)

In this use case, customers provide flexibility by connecting their EVs with wallboxes to a HEMS and allowing them to be optimized to meet the envelope curve restrictions. The goal of the use case is then to optimize the consumption to reduce the household's energy costs.

Processing of the envelope curve with HEMS

The envelope curve is taken into account when controlling flexible assets, for example by shifting the charging processes of the car. The inflexible base load of the household corresponds to the residual load without the controllable loads and is not influenced. The purpose of using the flexible asset should not be affected. We assume that there are enough time periods where demand can be shifted.

The grid restrictions are used in line with other technical restrictions of the assets. These power limitations can be compared to power limitations used in other countries or even with RLM customers.

Meter readings

The prerequisite for complying with the envelope curve is knowledge of the total household consumption. Since usually no measurement values are available during the day for optimizations, additional measuring devices have been installed to measure the total household consumption.

Optimization

The optimization in HEMS aims either at maximizing self-consumption of self-generated PV electricity or at cost optimization based on a price curve. Both variants can be combined with an envelope curve.

Basis for these optimizations is that the customer always has the possibility to configure the preferred departure time and SoC of his car to match his personal needs.

Incentive for customers to participate in the project

Since there is no financial incentive via the grid for considering the enveloping curve, participation was incentivized by sales through a one-time participation bonus.

Technical requirements

On the customer side it is necessary to meet the technical requirements for EV steering according to Figure 18. Besides an additional measuring device to measure the total household consumption for real-time EV charging control, a HEMS has to be connected to the local infrastructure and the wallbox as compatible asset via ethernet (preferred) or WiFi mostly using the Modbus protocol. The network infrastructure must also be in place so that all necessary devices are connected to each other and have an active internet connection.

Data is processed in the HEMS backend and can be shown in the corresponding App. Customers can also monitor and configure charging processes there (departure time, SoC, priority charging).

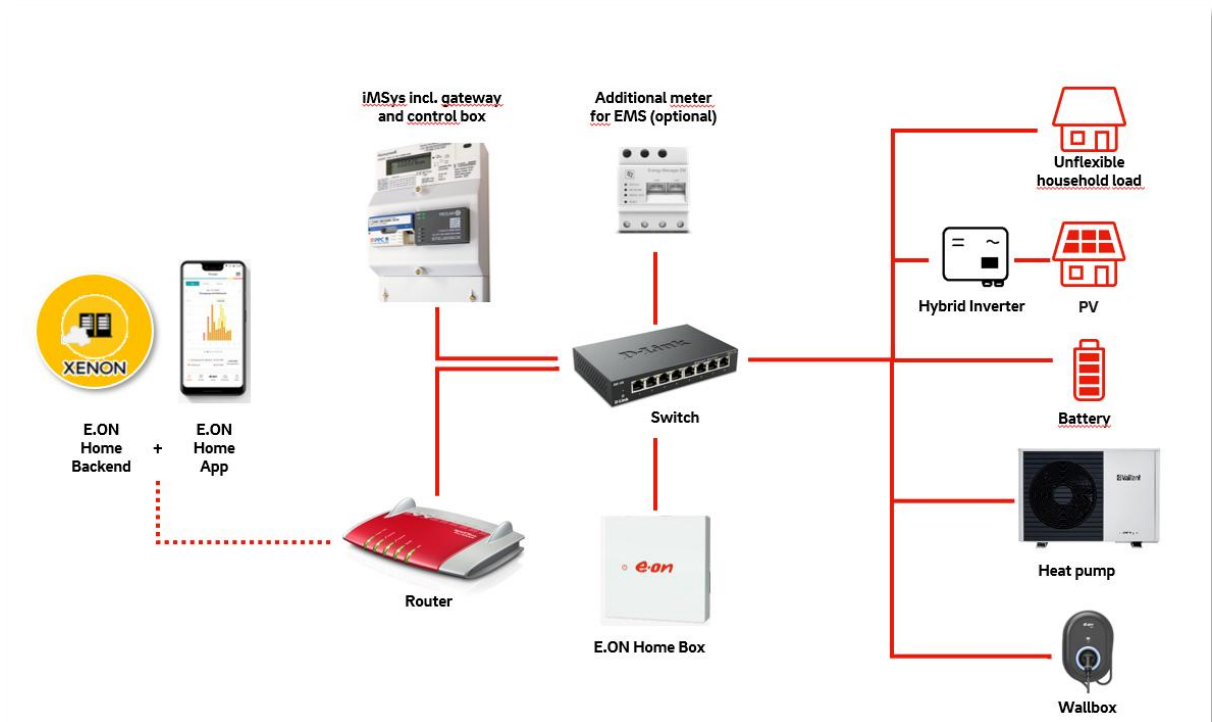


Figure 18 Technical requirements on customer side

3.2.4.3 Utilization of the Flexibility Potential for Advanced Congestion Management (Ge06)

In use case 6, flexibility from low voltage (households) is used for congestion management at higher voltage levels (medium and high voltage). In particular, the aggregation of car charging flexibilities for redispatch was implemented. Congestion on the LV level are considered by taking the envelope curve into account as a kind of technical framework. It was assumed that the assets participating in the redispatch pool will be reported to the TSO by the aggregator.

Sub-Aggregators

In households with multiple controllable assets, it is beneficial for optimizing overall consumption that the assets are not directly controlled by the aggregator but by a sub-aggregator. However, in the project setting, the sub-aggregator was omitted. Therefore, compatibility between the aggregator and the car's battery as a controllable asset must be ensured. In this use case the charging behavior of the car battery is directly controlled by the aggregator through a cloud-to-cloud connection with the OEM backend instead of using a local HEMS.

Aggregation of the flexibility of controllable assets

The flexibility forecast of charging processes is done at pool level. By having a sufficiently large number of cars in the pool, a distribution should result in the pool so that enough cars can be controlled for flexibility retrieval.

Individual daily values for SoC (state of charge), departure time, or instant charging must not be considered in the pool forecasts. There is an adjustment by a discount on the pool.

For the tests in the TwinEU project, this approach is negligible due to the small number of pilot customers.

Request for activation of redispatch

For verifying if a request for activation was successful, a baseline for behavior without activation is needed. This baseline is the planned load of the cars, referring only to controllable consumers (EVs). The flexibility request for activation of redispatch is simulated.

Disaggregation

When a call-up of flexibility occurs, it is checked which cars are suitable for control. This involves checking which cars are connected and do not have the status of "instant charging".

Then, the current state of the battery is determined, and considering customer preferences for charging (e.g., the car should be charged to a target percentage at a specific time like departure time), the flexible energy amount is calculated.

The allocation of the requested power to switchable cars is done considering network restrictions in the low voltage through the envelope curve from the low voltage congestion management.

3.2.5 Results

3.2.5.1 Preventive Congestion Management through Envelope Curve (Ge04)

Connecting grid, customers, and market

Field tests conducted in the E.ON Lab demonstrated that Power Envelope Curves seamlessly integrate three previously separate domains grid, customers and market:

1. Grid security – through forward-looking power windows

Power Envelope Curves increase predictability by defining in advance how much power households can safely consume. This enables grid operators to avoid local congestion preventively, particularly in regions with high penetration of heat pumps and EV charging infrastructure.

2. Fair incentives – instead of flat cost allocation

Capacity-based network tariffs ensure that costs are allocated where they are caused: during periods of high simultaneous load. Flexible usage is rewarded, while sustained peak demand is priced appropriately. This improves acceptance and strengthens the social fairness of the energy transition. Even if this aspect was not yet tested within the project setup, an integration of the power envelope concept in future capacity-based market designs is possible and highly recommended.

3. Automation – instead of behavioural change

For customers, flexibility is fully automated. Aggregators control smart household devices via home energy management systems in line with the Power Envelope Curves —anticipatory, intelligent, and without compromising comfort or security of supply. Flexibility thus becomes the default operating mode.

4. Market integration – with FSPs as the connecting entity

The FSP links all levels of the system: it receives Power Envelope Curve forecasts from the grid operator, controls customer devices, and aggregates their flexibility into a marketable resource. In this way, very small-scale assets become system-relevant and market-active for the first time.

The forecast management system has shown significant progress in several key areas. A major achievement has been the development of utilization forecast per feeder based on weather forecast data and feeder measurements, enabling effective preventive congestion management.

The integration of AI models has been successful, incorporating both weather forecast and measurement data as input parameters to improve prediction accuracy. The system features interfaces that allow DSOs to send envelope curves directly to FSPs for efficient load management at single households.

These developments provide a robust foundation for preventive congestion management through sophisticated envelope curve generation and household load control mechanisms. The combination of AI-driven forecasting, the distribution to single households and the visualization for grid operators creates a comprehensive system for effective grid management.

Day-Ahead Forecasting Performance

Point-Forecast Benchmark Across Modelling Strategies

Table 1 summarises the point-forecast accuracy for active power over the full test period for all evaluated model variants. The comparison includes two training strategies—static train-test split and expanding-window retraining—as well as two modelling scopes—generic pooled models and feeder-specific models.

All results are benchmarked against a two-day persistence baseline (for more details see [1]).

Table 1: Forecast accuracy across evaluated model variants

Training strategy	Model scope	RMSE (kW) Root Mean Squared Error	MAE (kW) Mean Absolute Error	MASE Mean Absolute Scaled Error
Static	Pooled	4.82	2.96	0.60
Static	Feeder-specific	4.77	2.92	0.60
Expanding-window	Pooled	4.73	2.90	0.58
Expanding-window	Feeder-specific	4.66	2.84	0.57
Baseline	Feeder-specific	8.60	4.96	1.00

The performance of the day-ahead feeder load forecasts has been systematically evaluated on a monitored benchmarking feeder set. Across all configurations, the evaluated models substantially outperform the two-day baseline, indicating that the enriched feature set provides significant additional predictive value.

Two main observations emerge from the results: First, expanding-window retraining consistently improves forecast accuracy compared to static training. This finding supports the operational assumption that low-voltage feeder behaviour evolves over time due to changing consumption and generation patterns (concept drift) and that regular model updates allow better adaptation to current operating regimes. Second, feeder-specific models achieve the best overall performance. This suggests that individual feeders exhibit sufficiently distinct characteristics that can be more effectively captured by dedicated models, provided that sufficient historical data are available. At the same time, pooled models remain competitive, which is particularly important for feeders with limited training data. From an operational perspective, this enables a pragmatic hybrid strategy: feeder-specific models are

applied when their validation error falls below a predefined threshold, while pooled models serve as a robust fallback.

The best-performing model achieves a MASE of 0.57, corresponding to an approximately 43% reduction in MAE compared to the naïve baseline. In practical terms, this reduces typical day-ahead forecast deviations by several kilowatts relative to persistence, which can be operationally significant under tight low-voltage capacity margins.

Interpretation of Error Magnitudes

While aggregate error metrics indicate that the model tracks feeder load well for the majority of time steps and across the most common load ranges, operational risk is primarily driven by the tail of the error distribution. In rare cases, measured feeder loads exceeding 30 kW are substantially underestimated, with predictions in the range of 10–20 kW, corresponding to relative errors of up to 50 %.

In a top-down workflow for deriving envelope curves, underestimation represents the critical failure mode, as it may translate into overly permissive household constraints during periods of network stress. These cases therefore warrant particular attention in operational use.

Quantile Forecast Bands: Added Value and Trade-Offs

Quantile forecasts (25–75 % and 5–95 %) provide time-varying uncertainty bands that reflect the diurnal structure of load variability. The bands are typically narrower during nighttime and widen during daytime hours, particularly during periods of photovoltaic injection and increased behavioural variability.

From an operational perspective, quantile forecasts mitigate severe underestimation by offering conservative trajectories, such as upper quantiles during anticipated load peaks. However, this comes at the cost of increased conservatism. If applied without decision-aware downstream logic, higher percentile thresholds may lead to false-positive congestion warnings and unnecessarily restrict available flexibility.

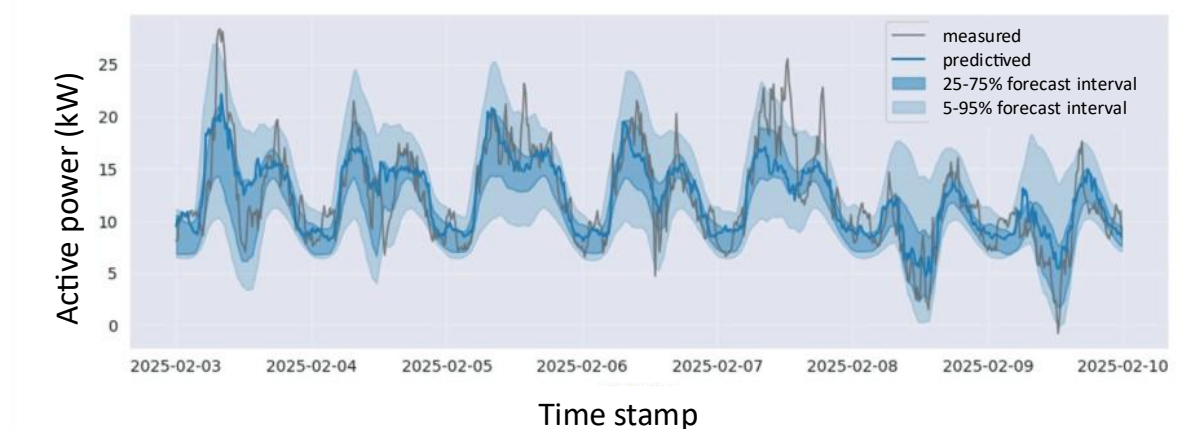


Figure 19: AI-based feeder-level forecasting model

Public Holidays as High-Error Days

The largest daily forecast errors are observed on weekday public holidays, including 18 April 2025 (Good Friday, 5.71 kW), 21 April 2025 (Easter Monday, 5.30 kW), 9 June 2025 (Whit Monday, 5.23 kW), 1 May 2025 (Labour Day, 5.19 kW), and 29 May 2025 (Ascension Day, 5.00 kW). This pattern is

consistent with the absence of explicit holiday and vacation features in the model, causing these days to be treated as regular weekdays despite their distinct consumption behaviour.

Dashboard Development

In addition to forecast generation and envelope distribution, a dedicated dashboard for power envelope monitoring has been developed and integrated into the IGP – see Figure 20 for reference. The dashboard enables transparent evaluation of grid-friendly behavior at household connection-point level by tracking compliance with communicated envelope limits.

The upper section of the dashboard summarizes key indicators, including the envelope violation rate, data availability, and envelope transmission status.

The violation rate per household allows grid operators to assess how consistently envelope constraints are respected (e.g., 86 % operation within envelope versus 14 % outside). Envelope breaches are visualized with precise magnitude and timing information, enabling rapid root-cause analysis and operational learning.

Beyond operational monitoring, this transparent evaluation provides an objective, data-driven basis for incentive models, such as grid tariff adjustments or reward and penalty schemes linked to compliance with envelope constraints.

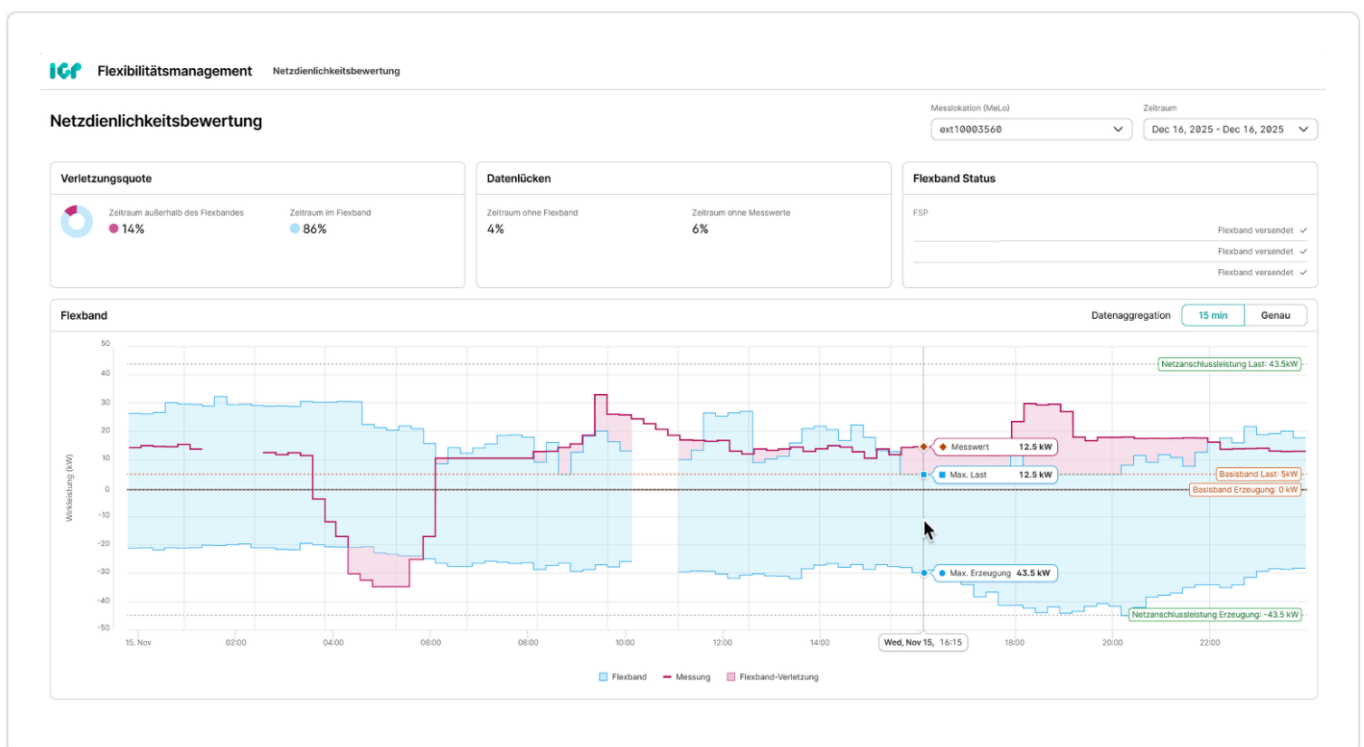


Figure 20: IGP Dashboard for Power Envelope Monitoring

The Flexibility Management app supports grid operators in monitoring and evidencing how distributed flexibility contributes to congestion avoidance under grid constraints. In the German §14c-EnWG context, the workflow starts with forecast-based planning (e.g., feeder-level day-ahead forecasts, including approaches for unmeasured feeders) to anticipate congestion risks and derive operational limits (e.g., envelope / flexibility bands). These limits are then communicated to the relevant flexibility service providers and become the basis for operational steering and retrospective evaluation.

A core part of the workflow is compliance validation: the app aggregates and visualizes whether participants stayed within the communicated flexibility bands and how the overall system performed. This includes dashboard-style monitoring that enables users to independently verify what was delivered, to whom, and when, while keeping scope deliberately focused on aggregated compliance rather than a full end-to-end transparency layer across all upstream/downstream processes.

In addition, roadmap work outlines the evolution towards more robust envelope definition methods, including the integration of probabilistic forecasts into the §14c envelope curve definition. This strengthens decision quality under uncertainty and supports the longer-term goal of turning pilot-specific implementations into reusable, product-ready building blocks for §14c readiness.

An important extension is the ability to also generate day-ahead forecasts for unmeasured grids/feeders. This addresses cases where no high-quality measurement data is available at the feeder head or connection point.

3.2.5.2 Utilization of the Flexibility Potential within the Household (Ge05)

The pilot customer test to manage household flexibility for compliance with the restrictions of envelope curve was conducted with pilot customers who made their EVs available for control via a HEMS.

3.2.5.2.1 Usability of the envelope curve

The goal is to determine if the envelope curve is being considered. This can only be achieved through tests with pilot customers. If the envelope curve with the minimum level at 5 kW cannot be met, there is a fallback level through German law (§14a EnWG). If the system fails regarding congestion management, the steerable assets will be dimmed to the level of 4.2 kW via the smart meter communication structure, and a network expansion will be included in the grid planning. This might be the case due to a significant bottleneck or because too few customers in a feeder participate in the envelope curve system.

3.2.5.2.2 Description of tests and results with the HEMS

The backend of the HEMS (Home Energy Management System) operator gridX retrieved the envelope curve information from a Kafka server and sends it to the HEMS via API. Thus, the HEMS has the envelope curve available as an intraday restriction for the entire household at the grid connection point. To remain within the limits of the envelope curve, only the assets specified in the German regulation §14a EnWG (Energy Industry Act) are to be used. Assets, not mentioned in §14a EnWG, such as washing machines or other large consumers, are therefore not included in this concept.

In the tests performed, EVs were used as flexible assets. The control of the EV charging behaviour was implemented through the control of the wallbox. Individual tests and a two-week long-term test with 7 customers were realized. The individual tests were realized with different levels of the envelope curve, start/stop of the charging process, increase and decrease of household load, and the consideration of PV generation.

In the long-term test, the user experience was evaluated. Customers were provided with an app through which they could enter their desired state of charge (SOC) and preferred departure time. Additionally, there was a “charge now” function that allowed them to initiate immediate charging regardless of the envelope curve. This enabled short-term unplanned charging.

The tests demonstrated that compliance with the envelope curve at the grid connection point through a HEMS controlling the EV essentially works.

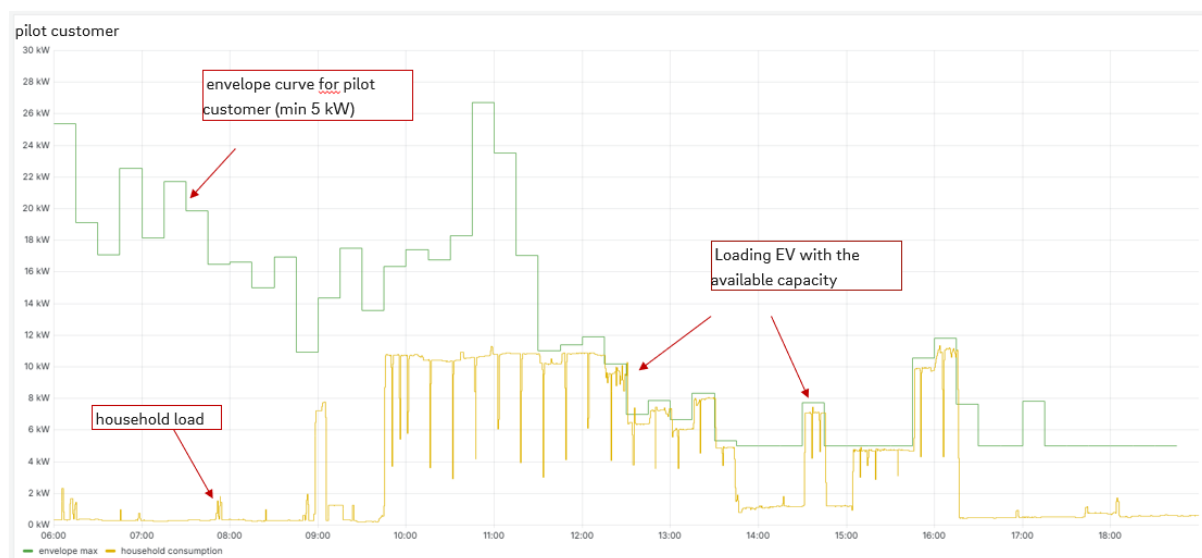


Figure 21: Dashboard view with household load, envelope curve and controlled EV charging

Triggers for changes in charging behaviour caused by the envelope curve can be both a change in the level of the envelope curve and a changing consumption in the household load due to non-controllable consumers. All in the tests used EV chargers allowed a minimum charging rate of about 4.2 kW for three-phase-charging. The maximum power allowed is restricted either by the charger or the vehicle, in most cases about 11 kW.

Large household load

The envelope curve could not be maintained in cases where the household load from non-controllable consumers exceeded the envelope curve. Due to the lower limit of the envelope curve set at 5 kW, there were situations that led to exceeding the envelope curve, for example, during cooking times.

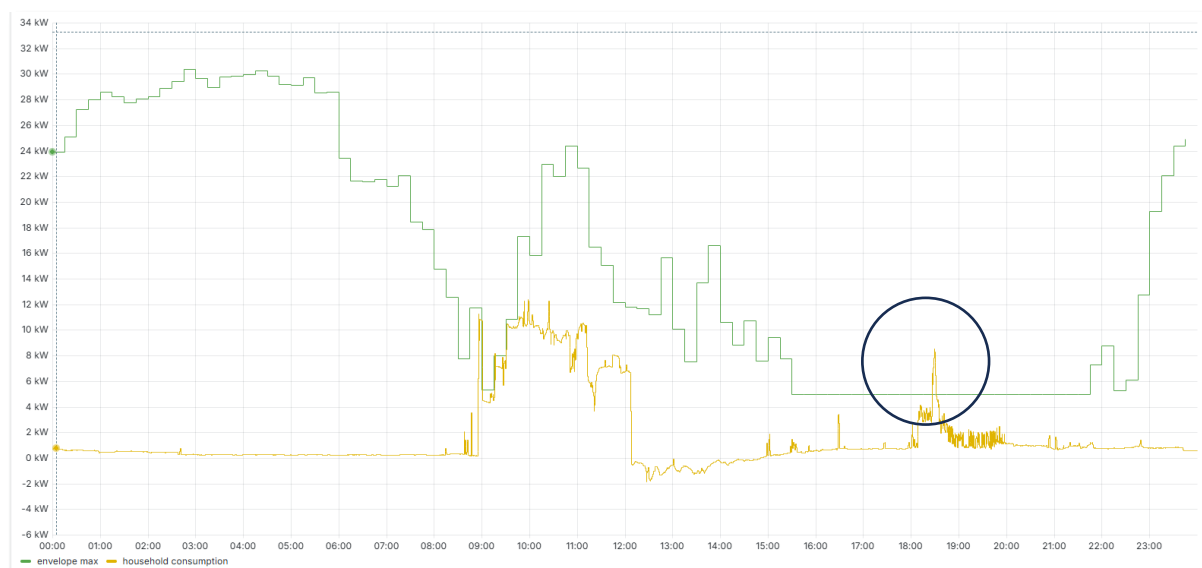


Figure 22 Dashboard view with household load exceeded the envelope curve

PV generation

The tests showed that PV generation has a positive effect on the charging power since the envelope curve for grid consumption is applied at the grid connection point (NAP): Due to power provided by the PV, the EV could charge with full power without exceeding the envelope curve restrictions.

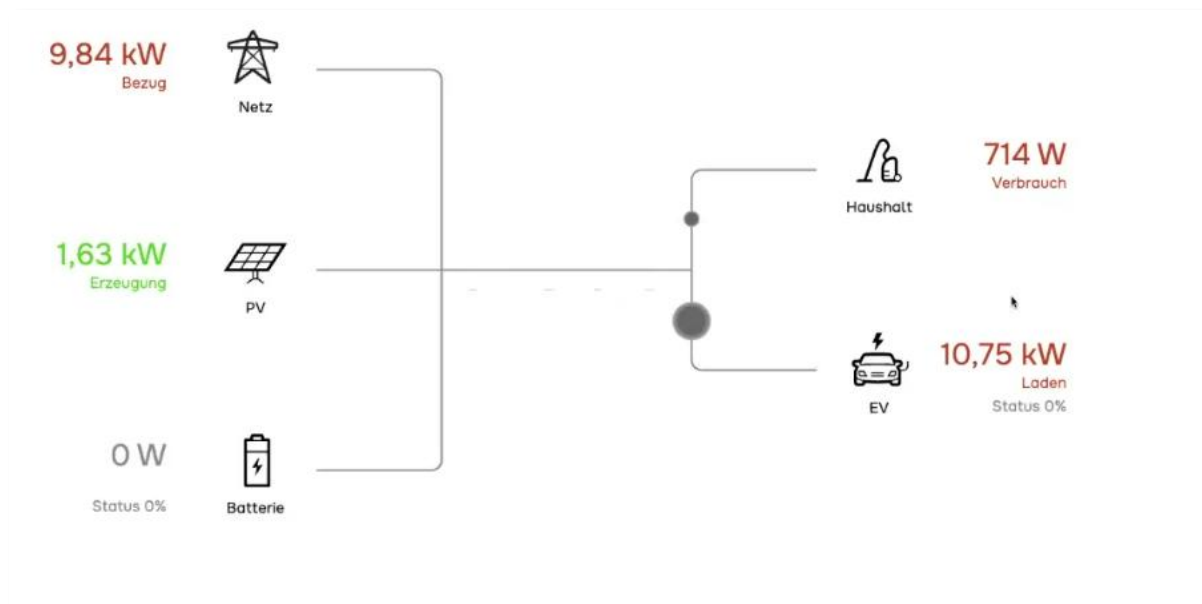


Figure 23: Cockpit showing the influence of PV generation on EV steering

3.2.5.2.3 Conclusion & limitations

The test customers are located within a limited grid area but are distributed across different local substations. The simulated bottleneck (created by artificially restricting the available power at the transformer) is therefore not distributed among multiple customers. This behaviour of several customers at one substation with bottleneck would need to be examined in further tests.

For a real bottleneck, several participating households within the local grid section will be necessary to effectively resolve the constraint. Hence, a sufficient number of participants with controllable assets must be involved. This can be encouraged either through a regulation (obligation) or attractive compensation.

Furthermore, the minimum power of 5 kW allocated to the household must be reconsidered. Further tests will also be required here to establish a limit that is acceptable to all parties.

Figure 22 shows that the envelope curve remains at the minimum of 5 kW over several hours. The resulting restrictions cannot always be resolved by shifting the load or charging process. In conclusion, exceeding the envelope curve should be allowed in exceptional cases.

Throughout the project, it became evident that focusing the tests on EVs is the most effective approach. This is primarily because EVs have the highest impact due to their high charging capacities. In contrast, heat pumps present technical challenges related to integration and compatibility. Battery usage is closely linked to PV systems, while the project itself focuses on energy consumption rather than feed-in. Additionally, cooling systems currently have a low level of market penetration, limiting their relevance within the scope of the project.

3.2.5.2.4 KPIs for envelope curve fulfilment (Ge05)

The aim of the pilot customer tests is to ensure fulfillment of the envelope curve through steering actions.

GE05_KPI1 Successful steering actions (absolute value)

An absolute value is determined for all successful steering actions that have led to fulfillment of the envelope curve.

Table 2: Data for KPI GE05_KPI1 about successful steering events

Pilot customer	Steering events [n]	Successful events [n]	Deviation measurement vs. setpoint
TK2	49	43	-3,7%
TK3	94	83	-3,8%
TK6	306	296	-4,5%
TK9	80	80	-0,3%
Sum	529	502	-3,7%

VAL_KPI3 Successful steering actions (percentage value)

A percentage value is determined for all successful steering actions that have led to fulfillment of the envelope curve in relation to all steering actions and led to 95% successful steering events.

VAL_KPI2 Latency of steering actions

Trigger point for HEMS is a change in the household load or envelope curve, which leads to a control action of the EVs. Latency is measured as the time interval between when a command is triggered and when it is fulfilled.

Table 3: Data for KPI VAL_KPI2 about latency of successful steering events

Pilot customer	Successful events [n]	Mean [sec]	Max [sec]	Min [sec]
TK2	43	2	12	0
TK3	83	4	15	0
TK6	296	7	16	1
TK9	80	3	7	0
Alle	502	5	16	0

Latency was measured until the target value was reached and remained stable. A slight deviation of the target value from the setpoint was accepted as long as it remained below the setpoint. Because measurements were taken at discrete time points, the latency represents an upper estimate.

3.2.5.3 Utilization of the Flexibility Potential for Advanced Congestion Management (Ge06)

A redispatch call for flexibility from a transmission system operator (TSO) via a virtual power plant (VPP) was simulated. In this design, the VPP participates in the redispatch market. It requests the desired power from the aggregator's system. The requested power for this call must lie within the aggregator's available offer. The aggregator's system optimizes to meet the requested power as closely

as possible. Therefore, optimization focuses on minimizing load deviation, and no upper load limit is imposed.

Since the provision of power for redispatch assumes that individual technical assets are reported separately with their IDs into the redispatch pool, only the controllable assets are considered in Ge06, unlike Ge05, where the power at the grid connection point (NAP) was considered. Although in this use case only the individual assets were controlled, the envelope curve at the NAP was taken into account as a restriction. This allows flexibility to be made available at higher voltage levels without causing restrictions in the low-voltage grid operator's network.

The control of flexible assets was technically implemented via cloud-to-cloud connections provided by a service provider. The electric vehicles (EVs) were controlled via the car manufacturers' apps, not via the wallboxes. This type of control introduced various restrictions: EVs could not be controlled continuously but only switched on or off. Moreover, there was a limited number of control actions allowed, due to the car manufacturers' app policies. The cloud-to-cloud data transmission caused signals to be transmitted and received with sometimes significant time delays.

Looking ahead, the control from Ge05 using a HEMS (Home Energy Management System) and Ge06 via an aggregator providing redispatch power would be staggered / performed sequentially. In this setup, controllable assets would only be controlled via the HEMS.

3.2.5.3.1 Description of tests and results with the HEMS (Home Energy Management System)

Tests were conducted with 7 test customers. These included simultaneous tests with 6 test customers as well as a long-term test.

Reducing the redispatch demand (setpoint) led to a stop of one car's charging process to fulfil the requested demand. As soon as a car left the pool because of unplugging, other cars of the pool started charging as expected. Additionally, the envelope curve restrictions have been considered and led to starting and stopping charging processes.

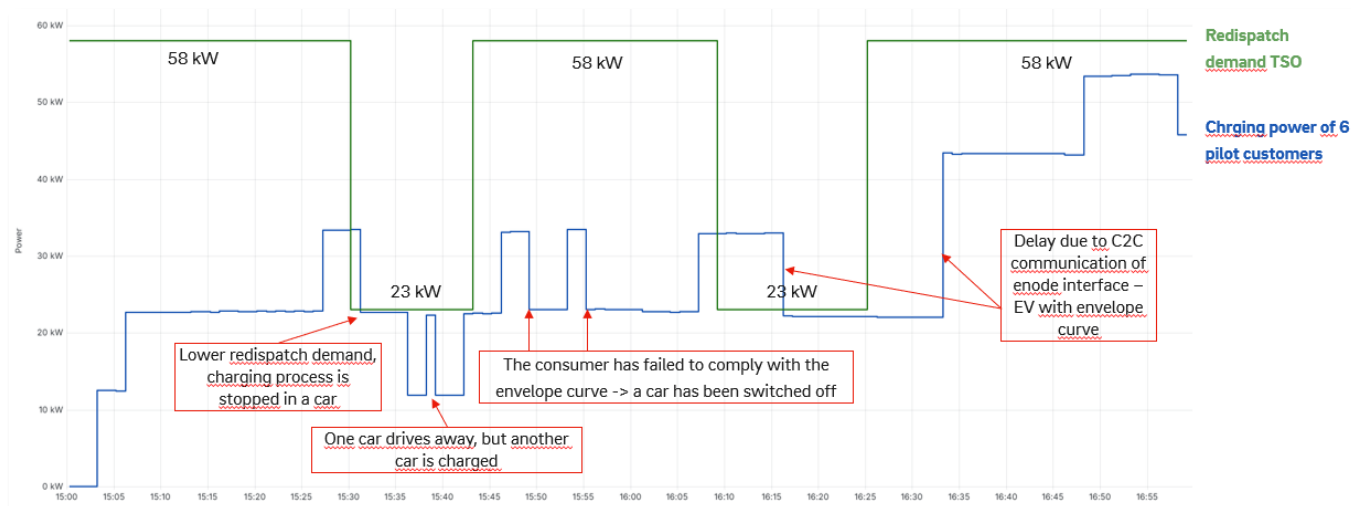


Figure 24: Charging behaviour because of changing redispatch demand

3.2.5.3.2 Conclusion & limitations

The long-term test must be conducted with significantly more customers, as the charging processes did not overlap in time.

The connection via the service provider - controlled through the service provider's app and the vehicle manufacturer's backend all the way to the vehicle - resulted in high latency, but it is a simple and cost-effective solution for integrating EVs without additional hardware (HEMS) or installation effort. If faster response times are to be achieved, from a technical standpoint, combined control via the wallbox's local connection should be implemented, taking into account information from the vehicle (such as the state of charge, SOC).

To gather quantitative and qualitative feedback, a survey was conducted among 7 customers. The survey covered the following topics: Installation & Technology, App Usability, Reliability & Trust in Everyday Use, and Perceived Added Value.

- Challenges in terms of Installation & Technology: Wallbox and system integration can be complex in some cases; recurring technical challenges with connectivity.
- The main criticisms of the app concern occasional synchronization issues.
- The solution is seen as useable in terms of reliability & trust. It is generally functional in daily use, with occasional charging interruptions and uncertainties.
- While the added value is recognized (e.g., price and consumption transparency, contribution to grid stability), a financial incentive is also necessary for a resulting product.

In summary, the pilot project has generally been well received and is considered useful, but still faces challenges regarding installation and technology. For scaling, robust technology and compatibility, as well as clear, monetarily tangible added value for the customer, are therefore crucial.

The focus of the tests was again placed on EVs in order to build a pool with strong responsiveness for market participation. This is largely due to the ability of EVs to provide high power that can be activated quickly, making them particularly suitable for such applications. Other controllable assets in line with §14a, namely heat pumps, batteries, and cooling systems, exhibit similar limitations as discussed in the previous case in Chapter 3.2.5.2.3, which further reinforces the choice to prioritize EVs within the testing approach.

3.2.6 Next Steps in Future Projects

Future development plans focus on several key areas. Advanced forecasting tools are being developed to further enhance prediction accuracy and robustness, especially data availability and system complexity continue to increase. A significant focus lies on scaling forecast models to handle large numbers of low-voltage grids and manage big data effectively. The enhancement of monitoring capabilities remains to be a priority, including the integration of additional data sources such as smart meter measurements

The concept of envelope curves is still at a very early stage and will evolve further over the coming years. As more and more data becomes available, AI-based models can be continuously improved. One important development path consists of clustering measured low-voltage grids of a DSO to analyze typical grid behavior. On this basis, future steps may include predicting the behavior of currently unmeasured grids by transferring insights from these representative clusters.

This approach supports scalability while acknowledging that there is an inherent tension between achieving an optimal, highly granular distribution of grid capacities and the need to provide simple, standardized, and market-compatible solutions. For example, a static distribution of capacity among individual households represents only a sub-optimal solution. Further development could therefore include mechanisms that allow aggregators to exchange unused flexibility, improving overall capacity allocation and system efficiency.

Beyond forecasting and monitoring, the implementation of a full end-to-end flexibility solution is planned. This includes the systematic integration of preventive congestion management features that allow grid constraints to be considered proactively rather than through curative measures alone. Comprehensive testing and validation under real grid conditions are essential to ensure reliability, effectiveness, and operational readiness of these solutions.

Reducing technical complexity

The technical complexity on customer side is quite high and should be reduced step by step to make the solution possible for mass markets:

Currently, real-time data cannot be read via CLS channel of the iMSys. To avoid additional measuring devices, a prompt approval by the relevant authority (Federal Office for Information Security) is necessary.

Also the network infrastructure is a challenge and would be easier to be handled if WiFi connection could be used instead of LAN.

Scalability and Expansion

The next phase involves scaling the forecasting and flexibility activation models across a broader network of DSOs and aggregators. Further enhancements in AI prediction and automation are key focus areas.

In this context, the Power Envelope Curve logic offers a promising opportunity to achieve grid expansion planning with the intelligent use of digital infrastructure. The Power Envelope Curve concept can initially be implemented in a simplified form and then expanded step by step to include additional mechanisms such as flexibility and quota markets. These mechanisms aim to align the interests of grid operators, connection users, and aggregators as effectively as possible.

Power Envelope Curves have the potential to evolve into a cross-voltage coordination mechanism between network levels. At interface points between grid levels - for example between medium- and low-voltage networks - a Power Envelope Curve could define maximum permissible power limits. If these constraints are respected, Power Envelope Curves serve as a forward-looking and reliable instrument for grid stabilization and can be considered in future grid planning processes, with significant potential to reduce grid expansion requirements and overall energy system costs.

Based on the challenges mentioned above, the implementation of the current MVP power envelope algorithm needs to get improved and more robust with various real world test cases. Additionally, the current implementation of the forecast and congestion detection needs to get extended to consider voltage limits, combined with a full grid state estimation, as well. Two further improvements would be the disaggregation algorithm from feeder level towards each customer and a further investigation of the combination with FCAs and capacity-based tariffs to get a clear picture of the granularity needed for each envelope and forecast accuracy (e.g. the used 5 kW basic band or 15 minutes data resolution).

Expansion to Other Assets

So far, the focus has been exclusively on electric vehicles (EVs), as they offer the greatest impact while being subject to existing technical limitations. Going forward, this approach needs to be expanded to include additional flexible assets in accordance with §14a, such as heat pumps, batteries, cooling systems, and photovoltaic (PV) installations.

Data Quality, Regulation, and System Integration

During implementation and stepwise expansion, several challenges become apparent. A core prerequisite for the effective use of Power Envelope Curves is a sufficiently high level of data availability and forecasting quality. Inaccurate forecasts may lead to unnecessary restrictions or trigger curative interventions under existing regulatory provisions (e.g. §14a EnWG). The timing of Power Envelope Curve determination therefore plays a critical role: while short-term forecasts generally offer higher accuracy, longer-term forecasts introduce greater planning uncertainty for aggregators and end users.

Furthermore, the current regulatory framework still focuses predominantly on curative grid stabilization measures. Consequently, Power Envelope Curves must be piloted and tested in real-world projects at an early stage, while regulatory foundations are developed in parallel. Another key challenge lies in establishing a reliable end-to-end communication chain—from grid control systems through intelligent metering systems and energy management systems to controllable end devices—based on manufacturer-independent standards.

Integration with Future Market Designs and Redispatch

Ongoing discussions with regulatory bodies and market stakeholders aim to align the solution with future flexibility markets, ensuring commercial viability and regulatory compliance.

In the longer term, Power Envelope Curves enable flexible household devices to be controlled in a way that not only stabilizes the local distribution grid but also provides reliably schedulable flexibility for system operation. By aggregating many small assets, the aggregator transforms these distributed resources into a genuine marketable unit: a *Flex Package* that is sufficiently large, reliable, and standardized to allow flexible small-scale devices to become effective at the supraregional system level.

This is precisely where market-based redispatch becomes relevant. Under the EU Network Code on Demand Response, such flexibility is required to be activated through market-based mechanisms. This implies that flexibility should no longer be optimized solely within grid-internal processes but must be activated transparently, fairly, and competitively via market mechanisms. Instead of redispatching large conventional power plants, system operators will increasingly be able to access these aggregated small-scale flexibilities. To this end, flexibility is standardized, offered through auctions, and activated when required.

Follow-up pilot projects such as DataFlex demonstrate how this end-to-end process can be implemented in practice—from Power Envelope Curve forecasting and technical grid constraints to market-based activation and verification. DataFlex investigates in practice how small-scale flexibilities such as EV charging stations, heat pumps, and stationary batteries can be aggregated and utilized in a grid-supportive, market-supportive, and system-supportive manner. To achieve this, the project develops an interoperable data infrastructure, a market design for *Redispatch 3.0*, and secure interfaces between grid operators, aggregators, and end devices. In the pilot setup, grid operators provide Power Envelope Curve forecasts. Flexibility Service Providers (FSPs) derive usable flexibility potentials from these forecasts for their customer portfolios and offer them in auctions. Activation and verification are handled via a central platform, ensuring transparency and auditability of all processes. This represents the first end-to-end implementation in which household-level flexibility is reliably integrated into redispatch operations.

Outlook: Path Toward Regulation by 2030

The revision of the network tariff framework (AgNes) is expected to enter into force by 2029. Insights gained from pilot projects and from the Power Envelope Curve concept play a critical role in

informing this reform. The target vision for 2030 includes:

- Market-based redispatch as the standard process for congestion management;
- Power Envelope Curve as an integral component of grid planning and market mechanisms;
- An affordable energy transition enabled by the intelligent use of flexibility.

Conclusion: Flexibility as a New Pillar of the Energy Transition

The Power Envelope Curve concept demonstrates how the growing complexity of the electricity system can be managed effectively. Even though further improvements and modifications will be necessary (such as the consideration of voltage limits), it establishes clear technical boundaries, creates fair economic incentives, and enables flexibility without requiring behavioural changes from end users. Through automation and aggregation by FSPs, numerous small devices are transformed into a reliable contribution to the overall system—locally effective, system-wide usable, and, in the future, accessible through market-based mechanisms.

As a result, flexibility evolves from a peripheral concept into a central building block: it stabilizes the grid, reduces system costs, and makes the energy transition economically viable. Together, Power Envelope Curves, market-based processes, and automated control mechanisms form the core pillars of a smart, robust, and affordable energy system.

3.3 TSO/DSO/Aggregator exchange to enable small-flexibility usage

Use Case 7 (Ge07) differs structurally from the preceding use cases (Ge01–Ge06). Rather than following the standard Challenges/Solution/Results format, Ge07 is organized into three parallel workstreams that reflect its exploratory, multi-actor character: (1) Workstream 1 focuses on the conceptual design of a future Redispatch 3.0 regime; (2) Workstream 2 evaluates the TwinEU Data Space technology for TSO–DSO–Aggregator data exchange; and (3) Workstream 3 demonstrates the data exchange workflow through a simulation. This structure was chosen because regulatory frameworks, market design, and operational rules for Redispatch 3.0 are not yet finalized, making a single end-to-end implementation infeasible at this stage.

3.3.1 Overview use case 7

The integration of new users within the distribution grids changes the distribution system characteristics. With generation units like solar or wind power plants and new flexible loads like heat pumps, electric vehicles or batteries, all connected to the medium and/or low voltage level as depicted in Figure 25, the distribution system becomes more and more active. Besides their primary use, those entities have the potential to offer flexibility to the system.

As power systems evolve towards a more decentralized structure, the role of small-scale flexible units becomes increasingly crucial. Their flexibility potential is currently not used in redispatch mechanisms, which are essential for balancing supply and demand and managing congestion in the grid, not exclusively, but also on the high and extra high voltage level.

Within the existing legal framework in Germany, system services such as Redispatch 2.0 are often limited to generation units above a certain nominal unit size and their activation is based on predefined cost rankings rather than a direct market-driven approach. Although there is more need for flexibility coming from the lower voltage levels in the distribution grid, those mechanisms exclude a vast pool of smaller flexible resources that, if aggregated and coordinated effectively, could provide significant benefits to both TSOs and DSOs.

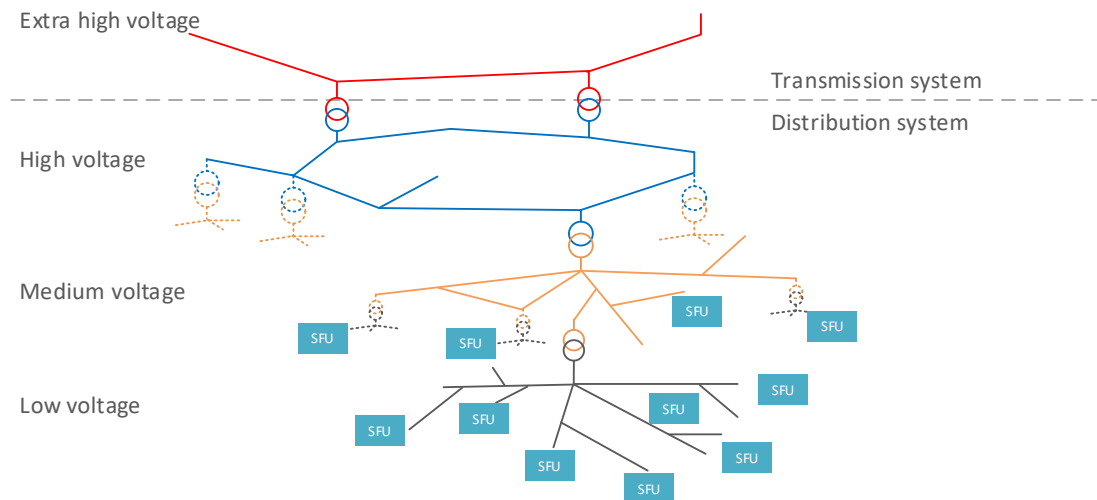


Figure 25: Location of the small flexibility units (SFU) in the system

Incorporating these small-scale units into future redispatch markets requires a new market design that enables efficient TSO-DSO coordination, standardized data exchange formats, and robust IT infrastructures. Additionally, the activation of distributed flexibility should complement existing wholesale and balancing markets, ensuring that redispatch actions remain economically and technically efficient. With these objectives, use case 7 plays a role in shaping the future redispatch market, allowing small-scale flexible assets to contribute effectively to grid stability and congestion management. By addressing key challenges related to data exchange, market design, and system interoperability, this use case supports a more decentralized and market-driven redispatch approach. The results will provide valuable insights for industry stakeholders, regulators, and policymakers, helping to define the future integration of distributed flexibility into European transmission system operations.

Use Case 7 (Ge07) addresses the coordination and data exchange between DSOs, TSOs, and Aggregators to enable the use of small-scale flexibilities for congestion management at transmission system level.

The use case is positioned as a conceptual and simulation-based exploration, motivated by the fact that regulatory frameworks, market design, and operational rules for Redispatch 3.0 and beyond are not yet finalized. Ge07 therefore focuses on analyzing roles, responsibilities, information flows, and technical requirements as well as testing the TwinEU connector for data exchange, rather than implementing operational or market-ready solutions.

A central design principle of Ge07 is the use of day-ahead coordination, allowing the consortium to study DSO/TSO-interaction under simplified and controllable conditions without interfering with real grid operation. A fundamental aspect of the use case is examining efficient and standardized communication channels between TSOs, DSOs and aggregators. However, unlocking redispatch potential from small flexibility units in the distribution grid means, as a first step, determination of the availability of data. Up to now, most distribution grids are not observed nor are measurements available. Hence, we will derive fundamental assumptions on the distribution of small flexibility units in the distribution grid and their allocation to the HV and EHV nodes. Besides the available data, we also take a closer look at the software and tools within the TwinEU Data space. We evaluate the key components and how they fit the use case. Therefore, the key objectives are:

- Identifying available datasets (e.g., grid measurements, publicly available data, forecast models).
- Comparing different concepts of coordination between all actors and necessary requirements for future Redispatch mechanisms
- Assessing the data exchange via the TwinEU Data Spaces between actors in the energy system, including TSOs, DSOs and aggregators.
- Evaluating the suitability of Data Spaces for a TSO/DSO/FSP coordination with regards to the usage of SFUs for higher voltage levels

3.3.2 Motivation for use case 7: Problems in small-scale flexibility utilization

The integration of small-scale flexibility into the energy system offers promising benefits, but several challenges must be addressed to fully realize its potential.

One significant obstacle is data availability and transparency. Effective redispatch relies on real-time or near-real-time information about the grid state, yet this data often lacks visibility at the distribution level. This limitation makes it difficult for TSOs to accurately assess the impact of aggregated flexibility on transmission constraints.

Another challenge lies in interoperability and standardization. The IT systems, protocols, and interfaces used by various TSOs and DSOs are often non-harmonized, complicating data exchange between stakeholders. To streamline this process, common standards such as the Common Information Model (CIM), the Common Grid Model Exchange Standard (CGMES), and Data Spaces require evaluation and adaptation.

The absence of finalized Redispatch-3.0 processes limits the possibility of defining binding operational workflows. Market roles, timelines, and liabilities are still under discussion, making it necessary to rely on abstract and simplified coordination concepts.

Market design and economic feasibility present additional hurdles. Unlike traditional redispatch, which is centrally controlled with predefined cost structures, future redispatch regimes should incorporate market-based mechanisms. This approach would allow FSPs to bid their aggregated flexibility into redispatch markets, fostering a more dynamic and competitive environment.

Finally, scalable and robust communication and IT infrastructure that ensure system reliability are vital for effective coordination between TSOs and DSOs. The aggregation of thousands of small-scale flexibilities leads to high communication volumes and strict requirements regarding availability and robustness of the underlying IT infrastructure. This infrastructure must be secure and scalable, capable of handling large volumes of flexibility activation requests in real-time. The role of platforms such as Connect+ [7] and Equigy [8] must be assessed to determine their effectiveness in facilitating this communication.

Addressing these challenges is essential to harness the full potential of small-scale flexibility in redispatch, paving the way for a more efficient and resilient energy system.

3.3.3 Solution, Implementation challenges and Results

Ge07 addresses the identified challenges through a structured, multi-workstream approach combining conceptual analysis, technical exploration, and simulation.

The overall solution is based on:

- a clear separation of roles between DSO, Aggregator, and TSO,
- the use of power envelope curves to communicate grid constraints,
- an explorative data space-oriented architecture, and
- a day-ahead simulation scenario enabling end-to-end validation.

Use case 7 is structured in three workstreams as depicted in Figure 26. Workstream 1 analyses current studies for a conceptual design of a future redispatch regime. In workstream 2 the evaluation of the suitability of the data space concept, especially the TwinEU technology was done. Additionally, based on open data, an approach for estimating SFUs in a geographic area was developed. Based on the results of the workstreams 1 and 2, we developed an exemplary simulation of a redispatch negotiation between TSO, DSO and aggregator in workstream 3.

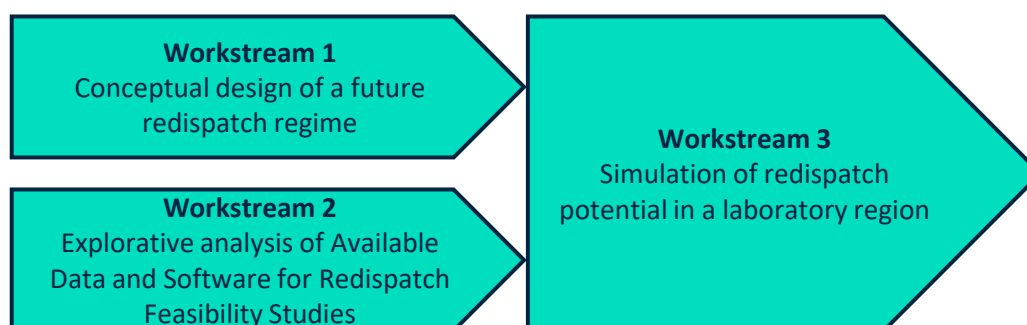


Figure 26: Workstream structure in Use Case 7 of the German demonstrator

3.3.3.1 Workstream 1 - Conceptual Design of a Future Redispatch Regime

Historically, avoiding bottlenecks in the power grid has so far been the sole responsibility of transmission system operators (TSOs). With increasing decentralization of generation and the increasing integration of volatile energy producers, the regulatory framework and the previous procedure for grid operation were adjusted within the regulation. The so-called redispatch actions aim to prevent grid bottlenecks across all grid levels and thus enhance the efficiency, cost-effectiveness and resilience of the power grid.

With the concept *Redispatch 2.0*, the previously separately regulated feed-in management was transitioned into a comprehensively optimized, plan-based mechanism. In addition to around one hundred large power plants for grid stabilization, several hundred thousand plants nationwide were integrated, each with nominal power exceeding 100 kW or controllable by the grid operator. *Redispatch 2.0* aims to decentralize the necessary planning and regulatory processes for avoiding grid bottlenecks across all grid levels, thereby making the power grid more efficient, economical, and resilient.

Distribution system operators (DSOs), whose voltage levels connect the majority of generation plants, play a key role as an operational interface to decentralized energy systems. This includes taking over the operational schedules of plants within their own grid, detecting grid bottlenecks, determining redispatch requirements, and reporting forecast schedules and the associated redispatch potential to the TSO and other affected DSOs. However, the potential of prosumers in the low-voltage level cannot yet be harnessed.

A future redispatch regime (often referred to as “Redispatch 3.0”) aims to integrate small-scale flexibility at the low-voltage level and to improve cooperation and information exchange between

TSOs, DSOs, and Aggregators/Flexibility Service Providers (FSPs). As regulatory frameworks and market designs for Redispatch 3.0 are still under development, Workstream 1 focused on defining a theoretical and technology-oriented scenario to explore improved DSO–TSO coordination without making assumptions on binding regulatory or market arrangements.

The workstream therefore deliberately applies simplified and theoretical scenarios, enabling the testing of technically demanding components—such as data-space architectures, standardized connectors, and digital twin concepts—under controlled conditions. While the design of detailed operational processes, remuneration mechanisms, and regulatory specifications lies outside the scope of this use case, the approach allows transferable insights for future real-world implementations. Particular attention is given to scalability, performance of data exchange processes, and the unique identification of small-scale flexible assets, for which digital twins are identified as a promising solution.

Based on this high-level design, several key requirements for integrating small-scale flexibility into future redispatch mechanisms were identified:

- **Defining data exchange requirements between TSOs, DSOs, and FSPs.**
Integrating flexibility potential into the redispatch regime requires precise and efficient data exchange between Transmission System Operators, Distribution System Operators, and FSPs. Clear requirements must be defined regarding which data should be exchanged, at what times, and in what format. It is crucial that these requirements ensure the transparency and reliability of the information to facilitate smooth coordination and optimal utilization of available flexibilities. The data to be defined include real-time performance values, forecast schedules, flexibility potentials, and constraints. A precise definition of the data exchange processes is essential to avoid inefficiencies and misunderstandings and to ensure high system stability.
- **Evaluating potential IT platforms (e.g., Connect+, Equigy, and Data Spaces) for information exchange.**
The selection of suitable IT platforms is essential for efficient information exchange and coordination within the redispatch regime. Platforms such as Connect+, Equigy, and Data Spaces offer various functions and benefits that need to be carefully evaluated. Factors such as scalability, security, interoperability, and user-friendliness must be considered. The evaluation of these platforms includes a detailed analysis of their technical specifications, their ability to integrate into existing systems, and their support for the defined data exchange requirements. Through evaluation, it can be ensured that the chosen platform provides the best possible support for the implementation of Redispatch 3.0 and enhances the efficiency and reliability of power grid operations.
- **Assessing standardization needs, including data formats and communication protocols.**
Smooth and efficient data exchange requires the standardization of data formats and communication protocols. These standards must be consistent and widely adopted to ensure seamless interoperability between different systems and actors. Assessing standardization needs involves identifying currently used formats and protocols and analyzing their suitability for the future requirements of Redispatch 3.0. Additionally, international standards and best practices must be considered to enable harmonized integration at the European level. Developing and implementing uniform standards will help improve the efficiency of communication processes and simplify operational workflows.
- **Involving external TSOs, DSOs and other Stakeholders beyond the scope of the project to ensure broad applicability.**
Ensuring the broad applicability and acceptance of Redispatch 3.0 requires the involvement of external TSOs, DSOs, and other stakeholders. These actors provide valuable perspectives,

experiences, and requirements that should be considered during development and implementation. Collaboration with external stakeholders allows potential obstacles to be identified early and solutions to be developed based on broad consensus. Workshops, consultations, and pilot projects are suitable methods to promote this involvement. Through dialogue and joint work with external partners, it can be ensured that the redispatch regime is not only technically feasible but also practically implementable and aligned with the needs of all parties involved.

These pre-defined requirements are crucial for enhancing operational coordination, transparency, real-time decision making, regulatory compliance, data validation, and future scalability.

Standardized data exchange ensures seamless coordination among TSOs, DSOs, and small-flexibility providers by facilitating swift and accurate information sharing related to flexibility forecasts, redispatch region definitions, and market offers. This efficiency reduces misunderstandings and delays, optimizing redispatch operations and ensuring grid stability.

Timely and accurate data exchange supports real-time decision making, allowing DSOs and TSOs to respond quickly and effectively to grid congestion and enhance stability. Regulatory compliance is upheld as standardized protocols enable monitoring and verification of exchanged data, ensuring adherence to legal and technical standards. To ensure a reliable and standardized integration of SFP's within the energy management system, a robust and clear definition of data exchange demands is required. The following framework conditions must be observed when designing the data exchanges:

- Requirements-driven enhancement of the existing data exchange, in particular from Redispatch 2.0 and market communication. This includes following existing use cases, data formats, interfaces and technical requirements.
- Enabling mass data exchange processes, considering the enormous volume of systems and process participants - in addition to data economy, this also includes the provision of interfaces that are as standardized and uniform as possible.

From a regulatory perspective, Workstream 1 considered ongoing developments such as § 14c EnWG, which creates a framework for market-based procurement of flexibility by DSOs while remaining compatible with cost-minimisation principles of redispatch. Insights from complementary studies, underline the relevance of envelope curves, aggregator-based pooling approaches, and market-based activation mechanisms as promising building blocks for future grid congestion management.

The new § 14c distinguishes itself from direct access to flexibility resources, as regulated in § 14a for controllable consumption facilities in the low voltage and currently to be adapted. Likewise, the instrument established here for market-based congestion management should not be confused with consumption control through direct price incentives, such as time-variable and network situation-dependent network charges. Instead, the new market elements concern the target-value-based congestion management process, as is to be implemented anyway by the distribution system operators as part of Redispatch 2.0. Therefore, § 14c provides distribution system operators with the additional possibility to procure flexibility in a market-based manner in addition to the target-value-based Redispatch 2.0. In addition to the option of procuring flexibility services in the distribution network in the future through market-based means, the draft of § 14c of the EnWG also includes the requirement for distribution system operators to develop the specifications of the process and to obtain approval from the federal agency. The specifications must guarantee that distribution networks are operated more efficiently, and that congestion management is carried out at the lowest possible

overall system cost. Voluntary flexibility should only be remunerated if it leads to a reduction in congestion management costs. There are also important points of contact in the design of Redispatch 2.0.

All grid operators are obliged within the framework of Redispatch to make the selection decision of the available measures under the premise of cost minimization. The network technical effectiveness of the flexibility service on congestion in cost calculations must be considered. By comparing the actual costs, a cost-optimal selection of flexibility options can be made, ensuring maximum efficiency.

The specifications of market-based flexibility procurement must be seamlessly integrated into the current market design. E.ON initiated several workforces to cover all dimensions of the topic including a feasibility study and analysis together with Amprion, Tennet and TransnetBW executed in partnership with E-Bridge Consulting GmbH, titled “Vorbereitung der Pilotierung des komplementären marktbasierten Engpassmanagements (PKME)” [5]. The study examines the integration of low-voltage flexibilities into a hybrid redispatch regime in order to address grid congestion at high and extra-high voltage levels. The PKME-study came to the following conclusions. They are reproduced here as the primary analytical foundation of Workstream 1.

- **1 - Complementary market-based redispatch:** This mechanism supplements the existing cost-based redispatch 2.0 and enables the voluntary participation of low-voltage flexibilities in order to address congestion at the high-voltage and extra-high-voltage level. It offers incentives to integrate these flexibilities into congestion management. Low-voltage flexibilities can only be made usable with a market-based approach for congestion management, as cost-based compensation cannot be adequately determined and is too complex in terms of processes at individual system level
- **2 - Envelope curve concept:** Serves the pragmatic consideration of low-voltage grid restrictions through preventive information to marketers. It forecasts the remaining grid capacity and allocates it to low-voltage flexibilities in a non-discriminatory manner.
- **3 - Piloting and challenges:** Piloting the process is complex and requires several years. There is an acute need for action to harness the potential in good time and verify the benefits. Market-distorting behavior represents a high risk for low-voltage flexibility in practice and is reduced to a minimum by decoupling the call-off decision from marketing (D-2).
- **4 - Market and product design:** To prevent market-distorting behavior, a tender is proposed two days in advance. The flexibility potential is marketed in pools and the selection is made via a joint redispatch merit order list. Aggregator and aggregation concepts enable the inclusion of many distributed flexibilities on a voluntary basis. The aggregator contracts these as the party responsible for deployment and combines them into pools for each grid region in order to market the flexibility for congestion management at higher voltage levels.
- **5 - Technical requirements:** To participate, systems must be controllable and able to record quarter-hourly measured values for balancing. A high degree of digitization is required. The technical requirements that are currently being created and will be created in the coming years with regard to control technology, metering (via §14a EnWG) and communication infrastructure (via Redispatch 2.0) are sufficient and can be used extensively after completion.

The proposed concept in this study is a promising building block in future congestion management and recommends an early trial to validate its benefits and feasibility. There are several workstreams inside different E.ON DSO's that intend to demonstrate technical feasibility based on the concept proposed in the PKME study. First approach is to carry out an initial redispatch test activation of locally

aggregated pilot customers with micro-flexibilities in a selected distribution grid region, to gain insights into technical/process-related and market design elements and to derive corresponding recommendations for the further market ramp-up. Therefore, the results from these field tests in combination with the use cases in TwinEU promise worthy insights for future redispatch mechanisms design.

Concepts for splitting and distributing the envelope curve and for designing products for a market-based redispatch are to be described and then initial test activations are to be carried out by a small number of customers. Recommendations will also be derived as to how relevant specifications of the Network Code Demand Response can be applied to existing solutions and integrated into existing market designs (e.g. Redispatch 2.0). In addition, any need for adjustments to the network operator coordination concept (incl. data exchange formats) that arise during the pilot will be addressed.

The main recommendation out of this workstream was to take the concept of data spaces and digital twins with standardized connectors and data models as solid foundation for designing national or pan-EU wide requesting mechanisms for small scale flexibilities.

3.3.3.2 Workstream 2

In workstream 2, we evaluated the usability of the provided TwinEU data space technology and components in the context of our use case. For a general introduction to the Data Space concept we refer to [9].

Testing the TwinEU Dataspace for our use case

Within the second workstream, we established a data space environment between Westnetz, Amprion, and RWTH based on the TwinEU Connector and exchanged test files to perform a handshake between the parties. This environment was then used to implement the simulation in workstream 3. Regarding the technical development in the project, OFFIS supported the configuration of a data space prototype to be developed in the consortium for the demonstration among the German partners.

The TwinEU Connector is based on the TRUE Connector, which aims to enable a European Data Space (IDSA 2024). The connector integrates IDS principles with the benefits of the FIWARE ecosystem, enabling seamless as well as secure data exchange through a fully end-to-end decentralized approach (IDSA2024). The TwinEU Connector is the connector used in the overall TwinEU consortium. To ensure conformity at European level, this connector is also used in the German pilot.

The proposed data space in TwinEU already provides different components conforming to IDSA. In terms of interoperability, a uniform interface for all the stakeholders to connect to their platform is already part of the benefits of being part of a Data Space. The interfaces consist of a Graphical User Interface (GUI) where manual data exchange can be made, and a uniform REST API, which can be used to provide data exchange automation, and in this case, a connection to it should be made via a script.

Another IDS-based component is the Vocabulary Hub, which should contain structured information specific to the domain to provide semantic interoperability and ensure that different systems interpret the data in the same way. The OneNet connector, in terms of a common vocabulary, provides a catalogue of standardised services called cross-platform services that define the scope of the data and allow others to discover interesting data more easily. This catalogue is expected to be extended or validated during the project, and the data definitions used inside this pilot can contribute to this.

Besides this catalogue, an interface is provided through the GUI called semantic definition, and the Data Providers use it to give a scheme to which their data conforms, an example of the data and a

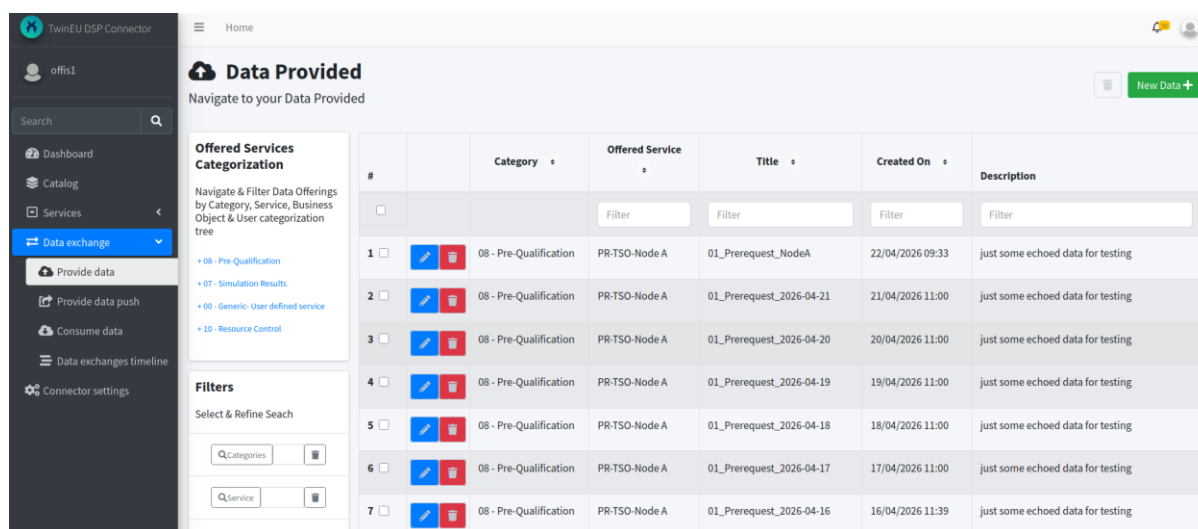
description for others to understand the meaning of the attributes. This means that currently, the semantic definition still needs to be done manually. The data exchange gaps identified in Deliverable 2.1 talk about different systems using varying data schemas and data formats, and consequently, the need for mapping and harmonising ontologies across platforms to enable meaningful data exchange.

A common problem is to have different solutions with data conforming to the Business Cases of different institutions. For a DSO-TSO data exchange, as well as for a DER or customer integration, this mapping process is normally time-consuming. A service that provides some level of automation can enhance semantic interoperability and help data consumers and data providers in understanding or explaining the data, respectively. Ge07 integrates TSO, DSO and Aggregator (fulfilled jointly by Fraunhofer FIT and RWTH Aachen University within this project), providing insights about this process when mapping the digital twins' generated data to the Catalogue provided by the TwinEU connector. Furthermore, it explores the use of tools to automate the use of the TwinEU Connector's API to exchange data from the digital twins on a specified schedule without human intervention.

Evaluation of Usability of the TwinEU Data Space

To exchange data via the TwinEU Data Space, the TwinEU connectors have been set up at the three participants in this demonstration use case: the TSO, the DSO, and the aggregator. The TSO connector was operated by OFFIS, the DSO connector by Westnetz, and the aggregator connector by RWTH Aachen. Within the German Demonstrator, the connector-software setup was tested together with the TwinEU-partner/company “Engineering”, the provider of the software.

Insights and errors collected during this process were iteratively reported to Engineering, which used this feedback to improve the setup procedure. In total, eight issues were identified, falling into three categories: (i) deployment and configuration complexity (Issues 1, 4, 5), (ii) security and access control (Issues 2, 3, 6), and (iii) UI/API functionality (Issues 7, 8). These issues were resolved through new software releases, updated deployment files and documentation; the full list is provided in Annex D. The most relevant finding for grid operators concerns security: automated IT security scans in the grid operators' environments repeatedly detected known vulnerabilities, forcing temporary shutdowns of the connector until patched releases were available. Operating such software within critical infrastructure therefore requires continuous vulnerability scanning and a structured release and patch process.



#	Category	Offered Service	Title	Created On	Description
1	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_NodeA	22/04/2026 09:33	just some echoed data for testing
2	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-21	21/04/2026 11:00	just some echoed data for testing
3	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-20	20/04/2026 11:00	just some echoed data for testing
4	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-19	19/04/2026 11:00	just some echoed data for testing
5	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-18	18/04/2026 11:00	just some echoed data for testing
6	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-17	17/04/2026 11:00	just some echoed data for testing
7	08 - Pre-Qualification	PR-TSO-Node A	01_Prerequisite_2026-04-16	16/04/2026 11:39	just some echoed data for testing

Figure 27: Screenshot of the TwinEU Dataspace Connector Interface, where exemplary flexibility pre requests are added to a data exchange channel between TSO and DSO.

Conclusion for Utilizing the TwinEU Data Space

In addition to the explorative and methodological focus of Workstream 2, further aspects become relevant when assessing the practical applicability and scalability of the analyzed approaches from an operational perspective. The analysis shows that the effort required to set up, operate, maintain and update data exchange infrastructures and software components is currently high and largely manual. Changes to configurations, interfaces or data models require substantial coordination efforts and cannot be assumed to function reliably without dedicated operational involvement. For a potential continuation or scaling of the demonstrated approaches, increased automation of update and maintenance processes would therefore be essential to reduce operational workload and associated uncertainties.

Furthermore, the automation of recurring process steps along the entire data exchange and simulation workflow represents a key prerequisite for sustainable operation. This includes not only data preparation and transfer, but also mechanisms for validation, monitoring and error detection and handling. From an operational point of view, the robustness of the overall workflow is strongly dependent on the quality, consistency and timeliness of the exchanged data. In particular, unclear data responsibilities, heterogeneous update cycles or insufficient validation mechanisms may lead to inconsistencies that directly affect simulation results and operational decision making. Consequently, clearly defined data quality requirements, explicit responsibilities for data maintenance and agreed update frequencies would be required to support reliable day-to-day operation and to reduce manual intervention along the workflow.

Beyond technical aspects, the results also highlight the importance of clearly defined organisational responsibilities for sustainable operation. In the demonstrated setups, many operational tasks rely on project specific roles and informal coordination structures. For long-term application beyond a pilot or research context, explicit definitions of operational ownership would therefore be necessary, including responsibilities for system operation, data provision, quality assurance and incident management across the involved stakeholders. Establishing such organisational structures represents a key prerequisite to ensure reliability, transparency and continuity when transitioning from explorative implementations to regular operational use.

In addition, security aspects need to be explicitly considered when assessing the operational applicability of the demonstrated approaches. Data exchange and system integration in distribution grid operation are subject to high requirements regarding IT and OT security, system availability and protection against unauthorised access or manipulation. The integration of additional data sources, interfaces and automated processes increases overall system complexity and expands the potential attack surface. Consequently, robust security concepts — including authentication and authorisation mechanisms, secure communication, monitoring and incident response processes — are essential prerequisites for operational deployment. These requirements may further increase implementation effort and therefore need to be considered when evaluating the feasibility and scalability of redispatch analyses based on distributed flexibility in real world distribution grid environments.

The analysis further indicates that the approaches demonstrated are currently well suited for project-based analyses but cannot be transferred directly into regular operation without additional adaptations. Project specific configurations, manual coordination efforts and a limited degree of automation constitute significant barriers to scalability. For broader application, the transition from prototype or pilot setups to operational systems would need to be explicitly addressed, including the standardisation of interfaces, operational processes and responsibilities, as well as integration into existing operational environments.

Finally, operational robustness would also require explicit consideration of resilience aspects and failure scenarios. This includes the ability to detect partial system failures, handle temporarily unavailable data sources and operate under degraded conditions. Defining fallback strategies and transparent error handling mechanisms would be essential to maintain trust in the results and to support operational decision-making under nonideal conditions.

Overall, these aspects highlight that, beyond data availability and methodological feasibility, operational robustness, governance structures, security requirements and automation capabilities play a decisive role in enabling data space technology for redispatch use cases.

Even though the TwinEU Connector / provided TwinEU Data Space technology has worked for the Ge07 simulation (see workstream 3), its architectural design decisions restrict its applicability to non-critical grid operation use cases. Due to its reliance on the public internet infrastructure, the solution is vulnerable to blackout scenarios as well as other disruptions of public internet services, which are outside the control of electrical system operators.

Regarding software development, it's well known that all software requires maintenance to extend and adapt its functionalities; therefore, new versions are expected. For this reason, for each new version, it's recommended to follow best practices that explain compatibility with past versions of the connector, so users understand whether their version is still stable and usable with other versions and with the middleware. Furthermore, it should pass a rigorous security test to identify any vulnerabilities in the libraries used.

3.3.3.3 Workstream 3

To address the challenges described in section 3.3.2 regarding the utilization of small-scale flexibilities for congestion management at transmission system level, use case 7 examines a conceptual day-ahead coordination scenario between the TSO, the DSO, and an Aggregator. Within the scope of the project, the roles involved in the process are deliberately simplified; in reality, the role of the DSO often comprises two, and in some cases even three, distinct DSOs.

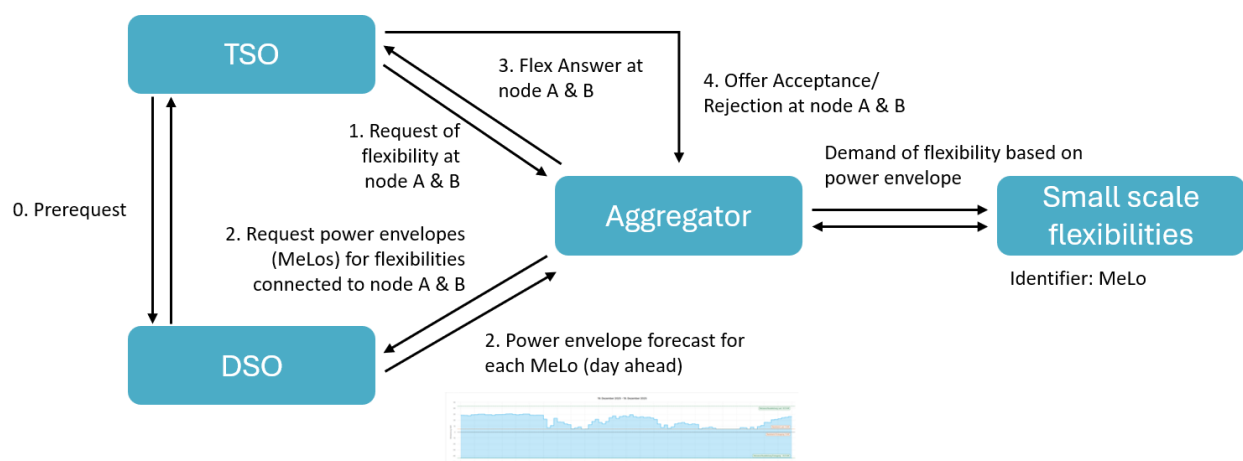


Figure 28: Visual description of the simulation of a flexibility request procedure

The scenario is therefore deliberately designed as a simplified and simulated setup to analyze roles, information flows, and data requirements without relying on real-time operation, detailed grid models, or an established market design. While this simplification is appropriate for the demonstrator, it should be noted that real-world implementations are inherently more complex. In particular, the

value of data space concepts becomes even more pronounced in such multi-actor environments, where coordinated data exchange across numerous stakeholders is required.

The process considered in use Case 7 is schematically illustrated in Figure 28 and forms the basis for the day-ahead coordination flow between the actors involved.

To keep the scenario focused on the day-ahead coordination logic and the data-exchange workflow, the simulation deliberately abstracts from several technical, operational, and market aspects. In particular, the following elements were considered out of scope for this first, illustrative setup:

- Load-flow data / grid topology data
- Realistic power envelope data (only simulated)
- Realistic power generation (e.g., PV)
- Measurements / live data (only day-ahead)
- Impact assessment and next steps for TSO & DSO strictly limited to the evaluation of the TwinEU Connector and Data Space
- Specific and fully designed market design or market roles
- DSO need for flexibilities (the scenario focuses on TSO grid needs only)
- Medium-voltage production/demand and congestions; the simulation focuses on small-scale flexibilities in low voltage only
- Complexity of coordination between different grid operators (TSO, low-voltage DSO, medium-voltage DSO and high-voltage DSO)
- Complexity of coordination between different aggregators

Initially, the focus was on using real-world open data of the energy system (see Appendix: Open data for German grid infrastructure), but then a decision to use artificial data due to simplicity was made.

As visible in Figure 28, the process starts with a day-ahead pre-request from the TSO to the responsible DSO, indicating that a flexibility demand is expected for the following day at a specific transmission grid node (Node A). This prerequest (step 0) serves purely for early information and does not yet trigger an assessment or provision of flexibility. Nevertheless, the DSO is challenging this request already in advance with its predicted grid constraints in the low voltage level (connected to the TSO Node A) without taking the possible flexibility offer by the Aggregator into account. If the TSO requests are already causing congestion in the low-voltage network, the DSO will provide an answer without causing congestions accordingly. The following steps in the process are:

1. In the subsequent step, the TSO issues a formal day-ahead flexibility request to the Aggregator (taking the DSO answer based on the prerequest into account). The request specifies the required positive and/or negative flexibility in a 15-minute time resolution for the following day and refers to the same transmission grid node A.
2. Following receipt of the TSO request, the Aggregator requests power envelope information from the DSO for the low-voltage grid areas that are electrically associated with the requested transmission grid node. The power envelopes define forecast-based operational boundaries for active power consumption or generation in the low-voltage grid and ensure that any potential flexibility provision remains within local grid constraints.
3. The DSO subsequently provides the Aggregator with day-ahead power envelope forecasts in 15-minute resolution. These envelopes are based on synthetic and simplified assumptions and are used solely to simulate the information exchange and aggregation logic within the use case. They do not originate from detailed load-flow calculations or realistic grid topology models. Only

one DSO (Westnetz) is considered in the scenario, and constellations involving multiple aggregators are excluded.

4. Based on the received power envelopes, the Aggregator performs an internal clearing and assessment step to determine which aggregated flexibility potential from small-scale units could technically be made available within the specified limits. Communication with individual assets or end customers, as well as their technical control, is explicitly outside the scope of this scenario.

Finally, the Aggregator communicates the aggregated information on the available flexibility potential back to the TSO. In parallel, the same information may be shared with the DSO to ensure transparency and consistency across system levels. No market clearing, activation, remuneration, or actual redispatch execution is performed as part of this use case.

Table 4 provides an overview of the process steps within the simulation including a short description of the event that takes place in the step, as well as detailed information on when the data is sent from the data producer to the data receiver.

Table 4: Process steps of use case 7 simulation

Step ID	Name of Step	Event	Data-Producer	Data-Receiver	Time-frame	Time
0.1	Prerequest TSO Node A	TSO sends day-ahead request for two grid nodes	TSO	DSO	Daily	11:00
0.2	Prerequest TSO Node B	TSO sends day-ahead request for two grid nodes	TSO	DSO	Daily	11:00
0.3	Prerequest DSO Node A	DSO sends day-ahead infos about network constraints	DSO	TSO	Daily	11:05
0.4	Prerequest DSO Node B	DSO sends day-ahead infos about network constraints	DSO	TSO	Daily	11:05
1.1	Flex-Request TSO Node A	TSO sends day-ahead request for flexibility	TSO	Aggregator	Daily	11:15
1.2	Flex-Request TSO Node B	TSO sends day-ahead request for flexibility	TSO	Aggregator	Daily	11:15
2.1	Envelope-Request Aggregator Node A	Aggregator sends request for power envelopes to the DSO	Aggregator	DSO	Daily	12:00
2.2	Envelope-Request Aggregator Node B	Aggregator sends request for power envelopes to the DSO	Aggregator	DSO	Daily	12:00

2.3	Envelope-DSO-Node A	DSO provides power envelopes for each customer on low voltage level as requested by the aggregator	DSO	Aggregator	Daily	12:05
2.4	Envelope-DSO-Node B	DSO provides power envelopes for each customer on low voltage level as requested by the aggregator	DSO	Aggregator	Daily	12:05
3.1	Flex-Answer Aggregator Node A	Aggregator sends aggregated power to TSO	Aggregator	TSO	Daily	12:15
3.2	Flex-Answer Aggregator Node B	Aggregator sends aggregated power to TSO	Aggregator	TSO	Daily	12:15
4.1	TSO Offer Acceptance/Rejection Node A	TSO informs Aggregator if the offer is accepted and thus binding	TSO	Aggregator	Daily	12:30
4.2	TSO Offer Acceptance/Rejection Node B	TSO informs Aggregator if the offer is accepted and thus binding	TSO	Aggregator	Daily	12:30

The entire scenario is based on synthetic data structured identically to the data that would be required in a real operational process, without using live measurements, realistic generation profiles, or actual grid calculations. The scope is limited to day-ahead processes and small-scale flexibilities in the low-voltage grid. Medium- and high-voltage generation, intraday or real-time operation, DSO-internal flexibility needs, and detailed market roles are explicitly excluded.

With this conceptual setup, Use Case 7 illustrates how power envelopes can serve as an interface between DSOs and Aggregators, enabling TSOs to assess the availability of flexibility from the low-voltage level without requiring access to detailed distribution grid data. The scenario thus provides a structured foundation for evaluating TSO–DSO data exchange concepts and aggregation logic and supports further discussion on future redispatch frameworks.

Technically the simulation was set up on the data space environment between Westnetz, Amprion, and the Aggregator partners (Fraunhofer FIT and RWTH Aachen) based on the TwinEU Connector that was established in workstream 2. In line with this approach, the primary objective is to validate and test the information flows through the connector, rather than to replicate a fully realistic representation of market design or real-world measurement data.

3.3.3.3.1 Description of the used data

TSO

The TSO opens the day-ahead exchange by posting the prerequisite to the DSO (step 0.1/0.2) at 11:00 h, as described in the “Prerequisite” section of the report. The DSO’s constraint reply (step 0.3/0.4, 11:05 h) feeds directly into the TSO’s formal flexibility request to the Aggregator (step 1.1/1.2, 11:15 h), which is documented under “Flex-Request”. After the Aggregator returns its

aggregated offer (step 3.1/3.2, 12:15 h), the TSO evaluates the proposal against the envelope limits and sends the acceptance or rejection (step 4.1/4.2, 12:30 h), as outlined in the “Offer Acceptance/Rejection” part of the report.

DSO

Within this simulation, Westnetz GmbH as DSO has provided synthetic datasets in two elementary process steps. The data is purely fictitious and serves exclusively to test aggregation logic, feasibility assessment, and data exchange mechanisms via the TwinEU connector, without representing real customers, grid states, or operational decisions. Especially when considering the information flows through the connector as the key aspect and goal of the simulation, key challenges related to the use of real-world data can be effectively mitigated such as:

- issues of data governance and data security
- data completeness and plausibility validation
- limited smart meter penetration and associated data gaps
- complexities in IT/OT system integration, particularly regarding the separation of live operational data and planning data.

Prerequisite:

Within the process step 0 “prerequisite” Westnetz has provided an answer in the form of day-ahead information about network constraints to the prerequisite by the TSO. The synthetic dataset contains 96 15-minute steps for one representative day and includes flexibility requests from the TSO and corresponding non-binding DSO responses for two low-voltage aggregation areas (Node A – Arpe and Node B – Nehden). For each node, the dataset distinguishes between requested and feasible flexibility (positive and negative active power in MW) and provides underlying aggregated DSO load and generation values that explain the envelope-based response.

Power Envelope Request:

Furthermore, within the process step 2 “power envelope request” Westnetz has provided power envelopes for each customer on low voltage level for the two respective grid nodes Arpe (1.000 households) and Nehden (1.500 households) as requested by the aggregator. Both datasets are structured as 15-minute time series covering a full day (96 intervals), containing individual customer values for electrical load and local generation as well as aggregated DSO-level totals. In addition, power envelope curves are derived to represent upper and lower bounds of consumption and generation across customers, enabling boundary-based flexibility assessment. The data are organized per customer and time step and are suitable for simulation, aggregation, and scenario analysis.

Aggregator

Within this simulation, the Aggregator role is fulfilled jointly by Fraunhofer FIT and RWTH Aachen University, with a deliberate division of responsibilities. Fraunhofer FIT implements the aggregation logic, processing the received DSO envelopes, running the multi-stage computation described below, and generating the Aggregator output files. RWTH Aachen handles the data exchange with the TwinEU Connector, publishing and consuming files through the connector interface on the Aggregator's behalf. All Aggregator data is synthetic and serves exclusively to test the aggregation logic and the data-exchange workflow through the TwinEU Connector, not to represent real customers or market participation.

Envelope-Request (Steps 2.1 / 2.2, 12:00 h)

Upon receipt of the formal flexibility request from the TSO (steps 1.1 / 1.2 at 11:15 h), the Aggregator initiates the envelope-request handshake with the DSO. Each file contains the list of low-voltage customer IDs that fall within the Aggregator's portfolio under the relevant TSO grid node: 1,000 IDs for Node A, Arpe (identifiers Kunde A 1 through Kunde A 1000) and 1,500 IDs for Node B, Nehden (Kunde N 1 through Kunde N 1500). For the purposes of this simulation, the customer-to-node mapping is pre-provisioned by mutual agreement between Fraunhofer FIT and Westnetz, avoiding a separate identity-resolution step. In a productive setting, such mappings would be derived from contractual relationships between the Aggregator and the connected end-customers, using standardized identifiers such as MeLo codes.

Internal aggregation logic

Once the per-customer envelopes are received from the DSO (steps 2.3 / 2.4 at 12:05 h), a six-stage internal computation is run to translate the envelope data and the TSO flexibility request into a single aggregated offer per grid node. The algorithm was developed in close coordination with Westnetz through an iterative email exchange and refined across multiple simulation rounds.

1. Stage A - Customer asset assignment: Each synthetic customer is assigned to one of six asset-mix categories: pure consumer (CONS, 45%), PV-only (PV, 20%), PV with battery (PVB, 15%), PV with battery and wallbox (PVBW, 10%), wallbox-only (W, 7%), and PV with wallbox without battery (PVW, 3%), reflecting a plausible suburban-rural distribution for the region. Per-customer peak capacities are drawn from uniform distributions: household peak load 3-8 kW, PV 5-12 kWp, battery peak power 3-6 kW, and wallbox 7-11 kW. All random draws use a fixed seed (numpy seed 42) to ensure full reproducibility.
2. Stage B - Reference profile construction: Four normalised 96-slot day profiles are constructed analytically: a P25-style household load curve (flat night baseline combined with Gaussian peaks at 07:30, 12:30, and 19:00, normalised to a peak of 1), a cosine-shaped PV generation bell (active 05:30-19:30, peaking at 12:30), an evening wallbox-charging profile (Gaussian centred at 20:00, active 17:00-23:30), and an S25-style battery contribution shape (midday charge combined with evening discharge Gaussians, amplitude scaled by 0.35). The P25 and S25 shapes were reconstructed from reference charts shared by Westnetz, as the underlying numerical time series were not available at the time of the simulation.
3. Stage C - Per-customer baseline: Each customer's expected day-ahead net power draw is computed by scaling the four reference profiles by that customer's peak capacities according to the formula: $\text{baseline} = \text{peak_load} \times \text{P25} - \text{pv_kWp} \times \text{PV_gen} + \text{wallbox} \times \text{WB} - \text{battery} \times \text{BATT}$, in consumer convention (positive = net consumption from the grid).
4. Stage D - DSO envelope clipping: The per-customer baseline is clipped slot-by-slot into the feasible corridor defined by that customer's individual load and generation envelopes received from Westnetz (steps 2.3 / 2.4). In practice, the per-customer envelopes provided for this simulation (ranging from approximately ± 5 to ± 43 kW per customer) are substantially wider than the customers' synthetic baseline swings (typically within ± 10 kW), so the envelope rarely constitutes the binding constraint at the individual customer level. This is consistent with Westnetz's operational observation that local grid congestion affects fewer than 1% of customer slots under typical conditions.
5. Stage E - Efficiency factor: Per-customer flex-up and flex-down deltas are computed as the headroom between the clipped baseline and the corridor boundaries, then scaled by a customer-specific efficiency factor. Customers with a battery or wallbox receive a factor of

85%, as these assets offer genuine dispatch flexibility. Customers without either receive 50%, reflecting the irreducible baseload of pure consumers and the limited controllability of PV without storage. This differentiated factor was specified by Westnetz to address the simulation's initial tendency to produce unrealistically high portfolio coverage. Across the full customer portfolio, the average efficiency factor is approximately 62% at both nodes, reflecting that roughly 35% of customers own a battery or wallbox and the remaining 65% do not.

6. Stage F - Portfolio aggregation and offer matching: The efficiency-adjusted flex deltas are summed across all customers and converted from kW to MW, yielding the portfolio-level flex-up and flex-down capacity per time slot. For each slot, the Aggregator's offer is set to the TSO's request capped by the available portfolio capacity in the requested direction. The TSO flexibility request received by the Aggregator has already been constrained by the TSO-DSO pre-request exchange (steps 0.1-0.4) and is therefore not re-clipped against the DSO envelope sum.

The aggregation pipeline was implemented in Python. The full standalone script is provided in Annex C. All configurable parameters, including random seed, asset-type distribution, peak capacity ranges, reference profile shapes, and efficiency factors, are documented within the script and in the Assumptions tab of each output file, to allow the simulation to be re-run with updated inputs without modifying the algorithm logic.

Flex-Answer (Steps 3.1 / 3.2, 12:15 h)

The resulting Flex-Answer file contains 96 rows per node, each holding the TSO's original flexibility request, the portfolio flex-up and flex-down capacity, the aggregated offer in MW, and a constraint-source label indicating whether the slot was unconstrained, fully met, or limited by portfolio capacity in the flex-up or flex-down direction. Each file is identified by a date-stamped Offer ID in the format AGG-FLEX-<NODE>-<YYYYMMDD>-<NNN> (e.g. AGG-FLEX-ARPE-20260501-001), as confirmed by Amprion. The date stamp makes the identifier idempotent under daily automation: a repeated publication of the same file carries the same ID and is identifiable as a duplicate, while a new operating day produces a distinct identifier.

3.3.3.2 Data exchange mapping

The three subsections above (TSO, DSO, Aggregator) describe the content and logic of the data files exchanged by each actor: what the data represents, how it was produced, and what it means. The following subsections address a separate but complementary question: how these files are transmitted in practice. This covers two aspects. First, the mapping of each process step to a specific channel in the TwinEU Connector catalogue, which determines where each file is published and which party subscribes to it. Second, the automation layer developed by RWTH Aachen connects the locally generated files from each actor's pipeline to those connector channels without manual intervention. Together, the channel mapping and the automation layer constitute the practical data-exchange infrastructure through which the Workstream 3 simulation was executed.

The TwinEU connector is composed of a catalogue of defined Cross-Platform Services that can be selected to create the specific channels needed for the data exchange interactions (publish/subscribe). The data mapping for each Digital Twin was carried out by identifying the most suitable service from the catalogue, based on the data that the Digital Twin's operation aims to provide. This mapping was made on the steps defined in Table 4 and can be seen in Table 5, which, in addition, shows the description of the data and the explanation of the values.

Table 5: Steps of the Use Case 7 simulation with focus on Data and TwinEU Connector

Step ID	Description of data	Explanation of values	TwinEU Connector Channel Name
0.1	Adaption of active power at two grid nodes (excel file "time series flexibility")	Positive value means increasing active power, negative value means decreasing active power	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
0.2	Adaption of active power at two grid nodes (excel file "time series flexibility")	Positive value means increasing active power, negative value means decreasing active power	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
0.3	sum of all power envelopes for low voltage level	96 values (á 15 minutes) in MW for the relevant two nodes	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
0.4	sum of all power envelopes for low voltage level	96 values (á 15 minutes) in MW for the relevant two nodes	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
1.1	Adaption of active power at two grid nodes (excel file "time series flexibility") considering 1b = constraints from Prerequisite to DSO	Positive value means increasing active power, negative value means decreasing active power	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
1.2	Adaption of active power at two grid nodes (excel file "time series flexibility") considering 1b = constraints from Prerequisite to DSO	Positive value means increasing active power, negative value means decreasing active power	08-Pre-Qualification/Grid qualification results (for new resource group registration)/ (Flexibility) Resources
2.1	File with all needed (and allowed) customer IDs (e.g. MeLo or other mapping ID) referring to TSO node A	List with customer mapping IDs	07 - Simulation Results/Grid Constraints Assessment -> Node A - Customer ID list for envelope request
2.2	File with all needed (and allowed) customer IDs (e.g. MeLo or other mapping ID) referring to TSO node B	List with customer mapping IDs	07 - Simulation Results/Grid Constraints Assessment -> Node B - Customer ID list for envelope request

2.3	See Excel file "TWIN EU_UC7_Hüllkurven DSO". Household/customer could include several assets such as PV, wallbox, battery	2x96 values (max. demand and max. production) á 15 minutes in kW for every costumer as requested from the aggregator (1 file per aggregator)	07 - Simulation Results/Grid Constraints Assessment
2.4	See Excel file "TWIN EU_UC7_Hüllkurven DSO". Household/customer could include several assets such as PV, wallbox, battery	2x96 values (max. demand and max. production) á 15 minutes in kW for every costumer as requested from the aggregator (1 file per aggregator)	07 - Simulation Results/Grid Constraints Assessment
3.1	File with aggregated power as an offer incl. OfferID	96 values for additional power to be consumed (> 0) or generated (<0) by the aggregator, relative to originally planned consumption/generation	02-Measurements and Monitoring/Resource information/Flexibility needs (i.e., balancing, congestion) -> AP-AGG-Node A - Flex-Answer Aggregated Power Node A
3.2	File with aggregated power as an offer incl. OfferID	96 values for additional power to be consumed (> 0) or generated (<0) by the aggregator, relative to originally planned consumption/generation	02-Measurements and Monitoring/Resource information/Flexibility needs (i.e., balancing, congestion) -> AP-AGG-Node A - Flex-Answer Aggregated Power Node B
4.1	File with ID of Offer and 1 (for acceptance) or 0 (for rejection)		
4.2	File with ID of Offer and 1 (for acceptance) or 0 (for rejection)		

3.3.3.3.3 Automation of data exchange

Automation is required in this dataspace interactions between digital twins because operational coordination processes involve continuous and time-sensitive exchange of information between distributed actors. In the congestion management scenarios, flexibility requests, network constraints, forecasts, and operational responses must be exchanged reliably and within defined response windows. Manual interaction with dataspace services would not scale efficiently and could introduce delays and operational inconsistencies.

By automating publication and consumption processes, digital twins can exchange information directly through machine-to-machine workflows while preserving dataspace characteristics such as decentralization, interoperability, and policy-controlled access. An automation service is needed to reduce integration complexity by abstracting the connectors' API calls and authentication mechanisms from existing operational applications.

TwinEU Connector CLI wrapper

The Connector CLI wrapper provides a lightweight command-line interface for interacting directly with the TwinEU dataspace connector. It exposes a small set of core operations that enable users and automated processes to publish, retrieve, and remove data assets through the connector's API. Designed for simplicity and scriptability, the CLI allows these interactions to be executed from standard shell environments such as Bash, making it suitable for integration into existing workflows, cron jobs, and automation pipelines.

At its core, the CLI supports three primary commands: providing data to the dataspace, consuming data from it, and deleting previously published assets. The *provide* operation uploads local files to the connector and registers them under a specific service or dataset context. The *consume* operation retrieves available data assets from the connector service on which the consumer had subscribed previously and stores them locally, while the *delete* operation removes data that has been published earlier. Together, these commands form a minimal but complete interface for managing data exchange with the connector.

The CLI communicates with the connector through its REST-based API and handles authentication transparently. It manages access tokens, attaches them to outgoing requests, and ensures that each operation is executed within a valid authenticated session. This encapsulation of authentication and request handling allows users to focus on data operations without needing to interact directly with low-level API details.

Because the CLI is stateless and command-driven, each invocation represents a single, explicit action. This design makes it predictable and easy to integrate, but it also means that higher-level concerns—such as continuous monitoring, scheduling, or coordination between multiple data sources—are not handled within the CLI itself. Instead, these aspects can be implemented externally by orchestration layers or automation mechanisms built on top of the CLI.

In this sense, the Connector CLI serves as a foundational building block: it provides the essential primitives for interacting with the TwinEU connector, while leaving more advanced behaviors—such as automated file detection, transfer scheduling, and state management—to complementary components.

CLI extended functionality: Watchers

The watcher's functionality is a complementary component designed on top of the TwinEU Connector CLI, that implements a lightweight, client-side runtime that connects local file-based workflows with the external TwinEU dataspace connector. Its purpose is to automate the exchange of data between local producer and consumer folders and the remote connector interface. In this way, the system acts as a bridge between filesystem operations and authenticated dataspace transactions.

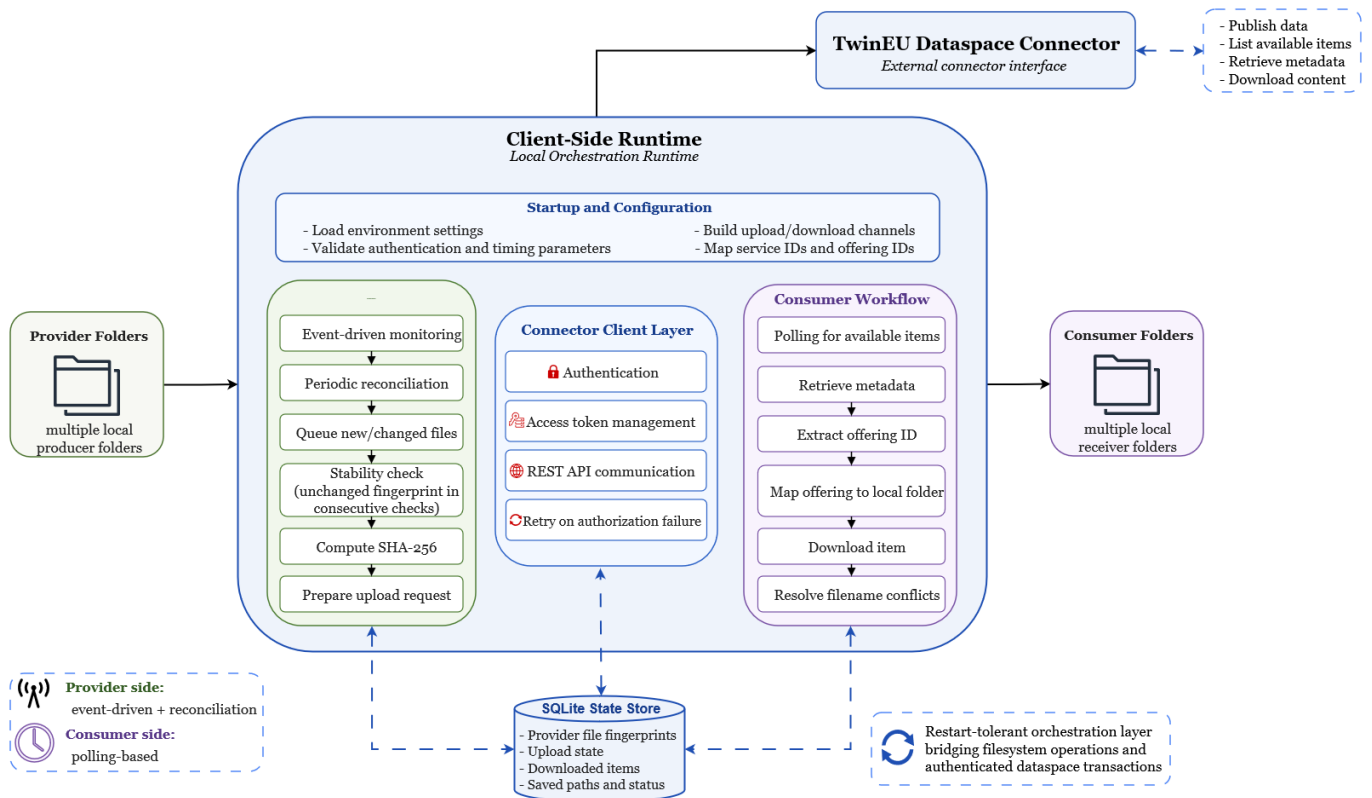


Figure 29: System architecture of the proposed TwinEU-connected runtime

Figure 29 illustrates the overall architecture of the system, including the provider workflow, connector client layer, consumer workflow, and the SQLite-based persistent state store. At startup, the runtime loads its configuration, validates authentication and timing parameters, and constructs multiple upload and download channels from predefined environment settings. This design allows one running instance to manage several provider folders and several consumer folders at the same time. Each provider folder is associated with a specific service identifier for upload, while each consumer folder is associated with a specific offering identifier for download. As a result, the runtime can route files automatically to the correct remote service through the TwinEU connector and store received files in the correct local destination.

Communication with the external connector is handled through a dedicated client layer that encapsulates authentication and REST-based data exchange. The client authenticates with the TwinEU connector, stores an access token, and retries requests when authorization errors occur. After authentication, it performs the operations required for both upload and download workflows, including publishing local files, listing available remote items, retrieving metadata, and downloading content. This separation of concerns improves modularity because connector communication remains isolated from folder monitoring and state management logic.

On the provider side, the runtime monitors configured local folders for newly created or modified files. The design combines event-driven monitoring with periodic reconciliation. Event-driven monitoring allows the system to react quickly to local filesystem changes, while reconciliation scans reduce the chance that missed events lead to permanent data loss. This hybrid strategy is especially useful in long-running deployments where filesystem notifications alone may not always be reliable.

When a new or modified file is detected, the runtime does not transfer it immediately. Instead, it first places the file in a processing queue and checks whether the file remains stable across repeated

observations. Only when the file fingerprint is unchanged in consecutive checks is the file treated as complete and ready for transmission. This mechanism reduces the risk of uploading partially written files, which is particularly important for large datasets that may take time to finish copying into the watched folder.

Before triggering an upload, the runtime computes a SHA-256 checksum of the local file and stores it as part of its persistent state, providing a local record of the uploaded content. The actual transfer is then delegated to the client module, which reads the complete file into memory, base64-encodes it, and embeds it in a JSON request sent to the connector API. This design is simple and easy to integrate, but it is not ideal for large files, because the upload path requires whole-file buffering and incurs additional base64 overhead. Consequently, the current implementation is functional and straightforward, but less suitable for very large files or memory-constrained environments.

A further design decision concerns startup behavior. Files that already exist in provider folders when the runtime starts are not automatically uploaded. Instead, they are recorded as already known. This prevents the system from replaying old data after a restart and helps ensure that the upload process reflects newly produced content rather than historical folder contents.

On the consumer side, the runtime follows a polling-based design. Because remote connector changes cannot directly trigger local filesystem events, the system periodically queries the TwinEU connector for available items. For each previously unseen item, it retrieves metadata, extracts the offering identifier, maps that identifier to a configured local download folder, and then stores the received file in that location. If a filename conflict occurs, the runtime modifies the local name by appending a short identifier so that existing files are not overwritten. This provides a simple but effective safeguard against accidental data loss.

The asymmetry between provider and consumer behavior is an intentional architectural choice. The provider side can rely on local event notifications because file creation occurs within the local environment. The consumer side, by contrast, must rely on polling because the TwinEU connector does not directly signal changes to the local machine. The system therefore combines two different interaction models to reflect the practical differences between local and remote data observation.

To support reliability across restarts, the runtime stores persistent state in a local SQLite database. The database maintains information about provider-side files, including fingerprints, upload state, deletion status, and the most recently uploaded content hash. It also stores consumer-side information, including which remote items have already been downloaded, where they were saved locally, and whether the transfer completed successfully. This persistent state gives the system restart tolerance and provides a basic audit trail of completed and pending transfers. In simple terms, the runtime can remember what it has already processed, even after it is stopped and started again.

Overall, the proposed system constitutes a lightweight, restart-tolerant orchestration layer that transforms local file production and consumption workflows into authenticated dataspace transactions through the TwinEU connector. Its primary contribution is the integration of folder monitoring, transfer routing, authentication, and persistent state management within a unified operational runtime.

The timing results in Table 6 are in seconds and were measured using small congestion-management files of less than 5 kB. For the scalability check, the transferred dataset size was increased to around 10 MB. Within this tested range, the end-to-end exchange time remained stable and predictable. However, the current upload path reads the complete file into memory, base64-encodes

it, and sends it inside a JSON request. Therefore, the prototype is suitable for the evaluated data-size range, but it can be optimized for very large files or memory-constrained environments.

Table 6: Timing Measurements of Automated Dataspace Interactions

Workflow Stage	Minimum	Average	Maximum
File placement into monitored folder	0.000261	0.000525	0.001164
Detection by automation service	0.000946	0.002196	0.003855
Publication through dataspace connector	0.920825	1.199988	1.811187
Consumer-side polling	0.144982	0.160646	0.165072
Data retrieval and storage	3.458975	4.817165	13.187035
Complete exchange workflow	4.525989	6.180520	15.168313

Technical Recommendations for the TwinEU Data

- A bidirectional channel/service can be useful for real operations. In this setup, a service could be created on one side, then that same created service could be used to push data from both the provider and the consumer sides.
- Fine time granularity: Persisting and showing precise time units about the data exchange (data provided) in the connector UI/API is important to show and measure the real-time capabilities. At the moment, the datetime is shown only until the minute; but showing seconds and milliseconds would be a better approach.
- In the UI, when the connector settings are configured with the requested endpoints, messages will appear showing successful connections to the connector and API, but this doesn't guarantee that the data exchange will work. A better way to show if the connector is working as intended could be to provide a testing button that runs a predefined data provision workflow, and when clicked, it can have well-defined error codes that show the users and developers where exactly the error is occurring or if the data provision is really working during the configuration process. A similar workflow can be used to test the consumption functionality.
- A feature for the user to get notifications about the subscription status and requests, and also to show the new versions of the software and the expected changes.
- Make the software open source to provide more transparency for developers to check what is happening during the handling process of their data. That will also facilitate the creation of a community of developers/testers that can help to enhance or extend the capabilities of the connector.

3.3.4 Next Steps in Future Projects

The implementation and testing activities conducted within the TwinEU project – in particular the validation of the TwinEU Connector for TSO–DSO data exchange – demonstrated the fundamental feasibility of a decentralized, peer-to-peer communication approach based on data space principles.

At the same time, the demonstrator's activities clearly showed that the technical testing of the Connector marks only an initial milestone, while several strategic, technical and regulatory questions

remain open. These open points need to be addressed in follow-up projects in order to ensure that future solutions are scalable, secure, and fit for long-term operational deployment.

Key Insights

One key insight concerns the potential conflict between existing proprietary or established platforms (e.g. operator-specific or market-driven solutions such as Connect+) and emerging concepts such as data spaces or blockchain-based platforms. This conflict of interest must be explicitly considered in future projects. It is essential to ensure that competition between platform approaches do not unintentionally slow down the development of a future-proof and system-optimal solution, particularly in the context of European interoperability and harmonization goals.

Furthermore, the TwinEU project highlighted that data security, and trust frameworks are strongly dependent on the chosen identity provider and the underlying data space middleware. While the conceptual architecture addresses secure and sovereign data exchange, further validation is required to assess security robustness under operational conditions and across multiple organizations.

In addition, the functional capabilities of data spaces beyond the mere exchange of data could only be tested to a limited extent within the scope of this use case. These aspects remain an important open point for future investigation.

Recommendations for Action (Regulation, Follow-up Projects, etc.)

Based on these insights, several concrete recommendations for future action can be derived:

- **Assessment of peer-to-peer suitability for OT data exchange:**
Future projects should systematically evaluate whether a peer-to-peer approach is suitable not only for planning and coordination data, but also for operational technology (OT) data exchanges of grid operators. This must include a clear definition of IT and OT security requirements, latency constraints, availability expectations and certification needs.
- **Redispatch evolution beyond TwinEU:**
Additional, in-depth analysis is required to address the transition from Redispatch 2.0 to Redispatch 3.0, extending beyond data space concepts and beyond the scope of TwinEU. This includes process redesign, role allocation, regulatory alignment and the interaction between grid operation and market-based flexibility.
- **Alignment of platform strategies:**
Regulatory and programmatic frameworks should encourage coexistence and interoperability between legacy platforms and emerging data space solutions, rather than reinforcing fragmentation. Clear guidance at European level would help to reduce uncertainty and investment risk for system operators and market actors alike.

Overall Outlook

In summary, TwinEU successfully demonstrated the technical potential of the TwinEU Connector and data space-based communication for future TSO–DSO cooperation. However, it also made clear that significant strategic, regulatory and operational questions remain open. Addressing these questions requires dedicated follow-up projects that go beyond feasibility testing and focus on operational integration, security, governance and regulatory evolution.

By building on the lessons learned in TwinEU, future initiatives can ensure that data space-based solutions evolve from promising prototypes into robust, scalable and future-proof infrastructures for the European energy system.

4 Conclusions

The work carried out within the German demonstrator has provided comprehensive insights into the applicability of digital twin technologies for enhancing flexibility activation, grid monitoring, and system coordination. It has delivered concrete implementations across all seven use cases, producing operational tools, validated technical concepts, and quantified performance indicators. The results span real-time grid monitoring and automated congestion management at Westnetz, day-ahead feeder forecasting with demonstrated accuracy improvements, household flexibility tests with pilot customers, aggregator-mediated redispatch simulations, and a data space-based coordination simulation involving TSO, DSO, and Aggregator partners. Taken together, these activities establish a solid technical foundation for the broader integration of digital twin technology into European grid operations.

The demonstrated solutions range from operationally deployed tools — such as the Field Assistant at Westnetz and the §14a-based automated congestion management — to validated prototypes that require further scaling and regulatory embedding before broader rollout. In all cases, the gap between demonstrator-level implementation and production-scale deployment has been made explicit in the use case findings, and concrete next steps have been identified.

The purpose of this chapter is twofold: first, to summarize the conclusions drawn from the demonstrator use cases; and second, to outline practical recommendations for follow-up activities building up on the experience and lessons learned.

4.1 Conclusion from the use cases

The implementation and testing of selected use cases have yielded concrete insights into both the potential and limitations of digital twin-based approaches in the current energy system environment. The following key conclusions can be drawn:

- Significant progress was achieved in integrating heterogeneous data sources, improving real-time grid monitoring, and validating technical concepts such as state estimation, envelope curves, and data space-based communication. This resulted in measurably improved transparency in low-voltage grids and more informed operational decision-making.
- However, most solutions remain at a pilot or prototype stage. Their transition to operational use requires further development regarding scalability, robustness, and integration into existing systems and regulatory frameworks.
- A central conclusion is that end-to-end flexibility activation depends on coordinated interaction between DSOs, TSOs, and market actors, supported by standardized interfaces and reliable data exchange mechanisms.
- Grid monitoring is an essential enabler: The use cases have shown that deploying real-time, topology-aware monitoring at low and medium voltage levels significantly enhances network observability. This is not only beneficial for direct operational purposes but also forms the basis for flexibility activation, congestion prevention, and future automation.
- Preventive congestion management is technically feasible: The application of methods such as the envelope curve concept appears to be an effective way to anticipate and manage local grid constraints. This proactive approach helps reduce the need for costly grid reinforcements or late-stage curtailment of renewable generation.
- Small-scale flexibility activation is possible but complex: While the demonstrator has successfully shown that individual flexible resources (e.g. in households or local aggregators)

can be integrated, the implementation at scale remains challenging. Barriers include data availability, real-time control capabilities, market integration, and regulatory clarity.

- TSO–DSO coordination requires further standardization: Data exchange and coordination between system operators have been initiated, but practical implementation reveals a need for common data models, interfaces, and governance structures. These are essential to fully exploit flexibility across voltage levels and organizational boundaries.

Ge07 — Data Space and Redispatch 3.0 Coordination: The TwinEU Connector was successfully set up at three organisations (Westnetz, Amprion, RWTH Aachen) and a fictive day-ahead coordination simulation between TSO, DSO, and Aggregator was completed. Eight technical issues were identified and resolved in collaboration with the software developer. The connector is suitable for non-critical, planning-oriented data exchange; its reliance on public internet infrastructure currently limits applicability to operational grid control contexts.

Ge05/Ge06 — Household and Aggregator Flexibility: Field tests with 7 pilot customers demonstrated that EV charging can be steered to comply with envelope curve constraints, with 95% of steering actions completed successfully. The minimum power floor of 5 kW allocated to each household was identified as a critical design parameter requiring further review. Aggregator-mediated redispatch via cloud-to-cloud EV control was demonstrated, but high signal latency, inherent to car-manufacturer app interfaces, was confirmed as the primary technical limitation. Wallbox-based control is recommended for future implementations.

Ge04 — Preventive Congestion Management via Envelope Curve: A day-ahead feeder load forecasting model was developed and validated on a benchmarking feeder set. The best-performing model achieves a MASE of 0.57, corresponding to a 43% reduction in mean absolute error versus the naïve persistence baseline. Expanding-window retraining and feeder-specific models were identified as the most effective configuration. Envelope curves are generated, distributed to FSPs via Apache Kafka, and monitored through a dedicated IGP dashboard tracking household-level compliance.

Ge01–Ge03 — Grid Monitoring and Field Assistant: State estimation evolved from a calculation component into an operationally deployed monitoring capability, running at a 1-minute cycle with topology-aware inputs, bad-data detection, and automated §14a EnWG congestion steering. The Field Assistant — integrating virtual switching, incident detection, and live measurement access — was deployed at Westnetz and quantified to reduce transformer maintenance planning time by approximately 35% and to decrease analyser-box installations for voltage complaints by approximately 33%.

Overall, the demonstrator has validated the core technical concepts of the TwinEU architecture across all three thematic clusters, producing quantifiable results in key areas. It has equally exposed critical dependencies — regarding data availability, standardization, regulatory clarity, and customer-side infrastructure — that must be addressed to achieve full integration at scale.

4.2 Recommendations

Based on the experiences of the implementation and the insights gathered from the use cases, several recommendations can be derived that go beyond the scope of the TwinEU project:

1. **Deepen cross-operator coordination mechanisms (TSOs and DSOs):** To operationalize end-to-end flexibility and congestion management, TSOs and DSOs must further align their processes, responsibilities, and digital interfaces. They should jointly prioritize standardized

communication and joint planning, while taking into account existing IT/OT infrastructure and ensuring compatibility with legacy systems.

2. **Scale and generalize flexibility use cases (DSOs and aggregators):** The implementations have delivered strong proof-of-concept results. DSOs, together with aggregators, should now drive scalability and replicability across grid areas and operators, including the deployment of automated decision logic and aggregation mechanisms that function under varying regulatory and technical conditions.
3. **Strengthen data infrastructure and interoperability (DSOs, TSOs, and platform/connector providers):** Reliable real-time and historical data have proven essential for digital twin operations. DSOs and TSOs, together with platform and connector providers, should continue investing in data platforms that support secure exchange, semantic interoperability, and privacy-preserving computation, particularly for use cases involving small-scale actors.
4. **Enhance regulatory clarity and framework conditions (regulators and policy makers):** The project has confirmed that key barriers are often regulatory or procedural rather than technical. National regulators and EU-level policy makers should provide regulatory clarity - particularly regarding Redispatch 3.0 and the participation of small-scale flexibility – and develop incentive mechanisms that ensure economically viable participation of all relevant actors. Ongoing engagement between project partners, regulators, and policy makers will be necessary to align emerging digital solutions with the evolving legal framework and market design.
5. **Maintain flexibility for national specificities within a harmonized framework (standardization bodies, EU-level institutions, and national regulators):** While progressing towards a pan-European reference model, standardization bodies and EU-level institutions — in coordination with national regulators — should keep solutions adaptable to local grid conditions, regulatory environments, and stakeholder structures. This balance is critical to enable broad adoption while supporting European interoperability goals.

These recommendations are addressed to European TSOs, DSOs, and aggregators on the technical and operational side, and to national regulators, EU-level institutions, and standardization bodies on the regulatory side. They aim to ensure that the momentum and technical progress achieved during the project is sustained and translated into scalable, interoperable solutions that support Europe's digital energy transition.

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Annex A Apache Kafka - Technical Architecture Details

This appendix provides the technical background on Apache Kafka as used in Use Case 4 (Ge04) for distributing power envelope curves from the DSO system to flexibility service providers (FSPs).

Basic Principle:

Kafka acts as a central hub for data streams. Producers send events or messages to Kafka without having knowledge of the receiving systems. The data are stored in so-called topics. Consumers subscribe to relevant topics and read the data asynchronously and at their own processing pace.

Role as Middleware:

As middleware, Kafka decouples senders and receivers in terms of time, technology, and organizational responsibilities. Systems do not need to communicate directly with each other, which significantly improves the maintainability and extensibility of the overall architecture. Multiple consumers can process the same data streams in parallel, for example for monitoring, analytics, or downstream processing purposes.

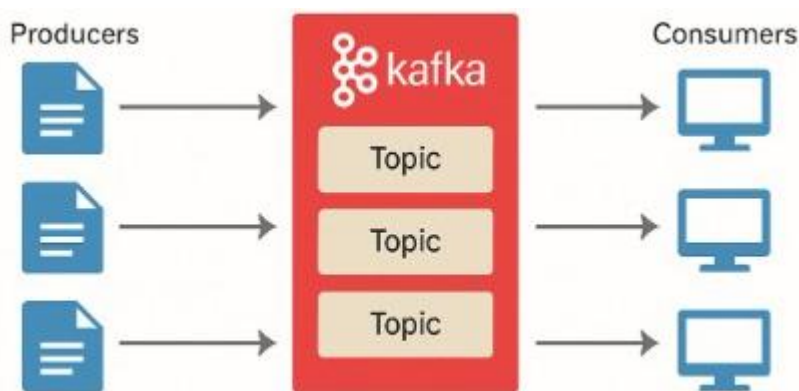


Figure 30: Illustrative Architecture of a Kafka-Centric Data Processing Pipeline

Figure 30 illustrates, in a simplified manner, how multiple producers send data to Kafka, how these data are organized into topics, and how they are subsequently processed by various consumer applications.

Kafka – Definition of functionalities & mechanism

Basic Concept of a Topic

A topic can be understood as a category or data stream (e.g., order-created, sensor-data, logs).

- Producers write messages to a topic.
- Consumers read messages from one or more topics.
- Kafka itself does not interpret the content of the messages; it merely stores and distributes the data.

Messages and Log Structure

Internally, a topic is implemented as an append-only log:

- Messages are always appended to the end of the topic.

- Each message is assigned a monotonically increasing offset (position identifier).
- Once written, data are not overwritten but retained for a configurable period of time (retention policy).

This design enables data to be reread, for example for replay scenarios or newly added applications.

Partitions: Scalability and Parallelism

A topic consists of one or more partitions:

- Each partition is an independent, ordered log.
- Message order is strictly guaranteed within a single partition.
- Multiple partitions enable:
 - Load distribution (parallel producers and consumers)
 - Horizontal scalability

Optionally, messages can be assigned to the same partition using a key (e.g., customer ID), ensuring that the order of messages is preserved for that specific key.

Consumption of Topics

Consumers read data from topics in an offset-based manner:

- Each consumer independently tracks the offset up to which messages have been processed.
- Multiple consumers can consume the same topic independently of each other.

Consumer Groups

- Consumers can be organized into consumer groups.
- Within a group, each partition of a topic is assigned to exactly one consumer.
- This enables parallel processing while maintaining fault tolerance.

Persistence and Retention

Topics are persistently stored:

- Messages are retained based on configurable time or size limits.
- Consumers do not need to be online at the time a message is produced.

Kafka is therefore not a transient message broker, but rather a streaming platform with durable storage.

Annex B Open data for German grid infrastructure

In this appended section, we elaborated on the availability and usability of open data that represents the German electricity infrastructure. This data then can be used to simulate the information transfer for flexibility management within the Data Space. We take a look at two datasets, the German Marktstammdatenregister (MaStR) [10] as well as OpenStreetMap (OSM), and also at two standardized data models, the Common Information Model (CIM) from IEC TC57 as well as the Web Feature Service (WFS) for geospatial data as defined by the Open Geospatial Consortium (OGC).

Open Data and the Common Information Model

Since January 31, 2019, the German Federal Network Agency (Bundesnetzagentur, BNetzA) has operated the **Marktstammdatenregister** (short: MaStR) as a central online database for the German energy system. Operators of electricity or gas generating units must report their master data, and large electricity-consuming units connected to high-voltage grids must also be registered. The MaStR collects only master data, such as installed capacity and location, not operational data like production volumes or storage levels. Most unit data is openly available under the Data Licence Germany – Attribution – Version 2.0 (DL-DE-BY-2.0), with some location details (e.g., street address, coordinates) withheld for units under 30 kW net capacity. The most detailed location data publicly accessible is postal code or municipality. The access to the dataset is streamlined with existing software such as the open-mastr Python package [11], which facilitates automated data access and processing.

In our project we took a first step toward representing the German Marktstammdatenregister (MaStR) in the Common Information Model (CIM) from IEC TC57. MaStR is the official German register for energy generation units, holding records for roughly 40,000 wind turbines and many other producers, but in a format that doesn't easily interface with international power system software. Converting this data to CIM makes it usable for cross-border data exchange, grid analysis tools, and any system that follows the CIM standard. The prototype covers wind turbines specifically, capturing their locations via latitude / longitude coordinates alongside attributes like MaStR ID, rated power, manufacturer, turbine type, and operational status, all structured through the CIM class hierarchy (WindGeneratingUnit under GeneratingUnit, Equipment, PowerSystemResource, and IdentifiedObject).

Instead of writing custom transformation code, the project leans on the two open-source python tools LinkML and linkml-map. The source code is available on GitHub (<https://github.com/FlorianK13/mastr-cim>). LinkML lets you describe data schemas in YAML files that are easier to read and maintain than code. The setup consists of three schema files: `schema/mastr.yml` describes the MaStR source structure (originally auto-generated from the SQLite database and then refined), `schema/map.yml` defines how each MaStR field becomes a CIM attribute, handling things like unit conversions from kW to W, building combined name strings from multiple fields, and deriving status flags from operational codes, and `schema/im\_tc57cim.yml` holds the full IEC CIM class hierarchy. A shell script (`generate-metadata.sh`) generates a focused CIM profile from this hierarchy, and linkml-map runs through the mapping automatically. The end result is a CSV file (`WindGeneratingUnits.csv`) with 39,738 wind units and their coordinates, plus a JSON-LD context file (`metadata.json`) for linked data compatibility. Because everything is driven by YAML definitions, extending this to solar, biomass, or additional attributes mainly means updating the schema and mapping files. The data for wind turbines in Germany is then provided via Zenodo.

Open Data and the WFS format

To dynamically call relevant data from the MaStR dataset, APIs can be used. This API can be standardized in the form of an Open Geospatial Consortium (OGC) API as a Web Feature Service (WFS). For testing purposes, we set up a prototypical first version of the API as a **WFS**. It contains five layers: biomass, combustion, solar, wind_extended, and aggregate. The first four provide locations and technical details of power plants from the corresponding technologies. The layer “aggregate” provides aggregated information on municipality level, i.e. the aggregated power of wind turbines, PV systems, biomass plants, and batteries in the given municipality. An exemplary visualization of the dataset is depicted in Figure 31.

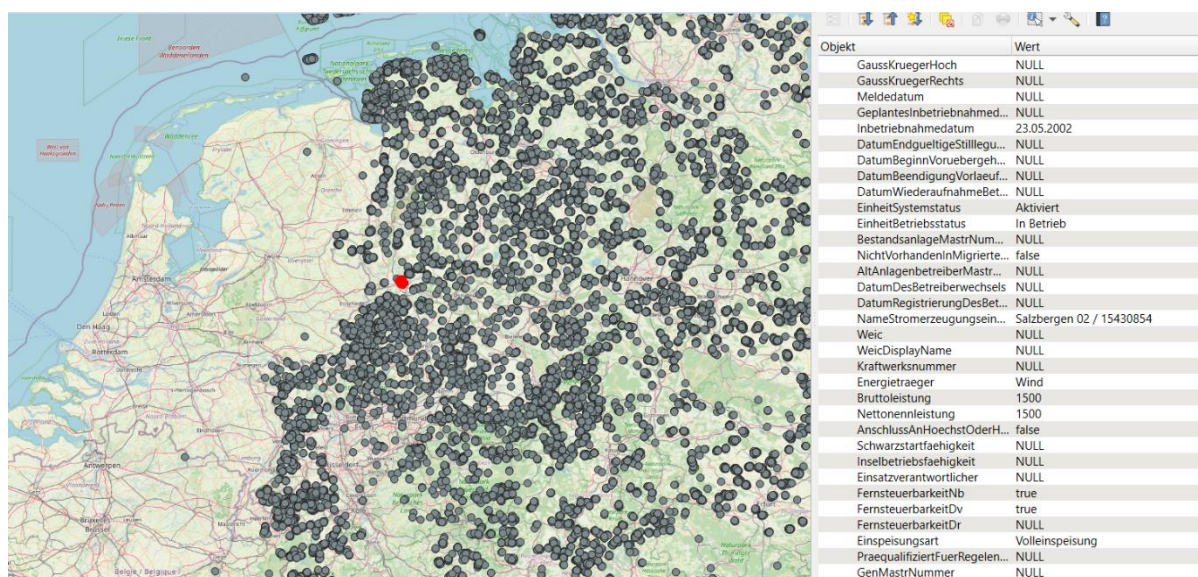


Figure 31: Screenshot from a QGIS layer of the OGC API of the Marktstammdatenregister

Another open dataset that offers great value for this use case is **OpenStreetMap (OSM)**. OSM is a collaborative project that creates an open, editable map of the world. It is built by a community of volunteers who contribute and maintain data about roads, trails, cafés, railway stations, and much more, all over the globe. The data is openly available, allowing anyone to use it for various purposes such as research, navigation, and app development. OSM also contains a lot of information about the electricity grid.

As shown in Figure 31, the open datasets of MaStR and OSM can form a baseline for simulating data exchange for various use cases and thereby testing the data space. However, both datasets are prone to errors. For detailed calculations, they can be replaced with closed data from the DSO. If all data sources adhere to the same data model (like CIM), exchanging the source data will require reduced effort.

We conclude that there is information on grid topology and small flexibilities available as open data. Since the precise topology and location of these flexibilities, as well as state information, is not available, open data can serve as a starting point to evaluate the usability of the data space for flexibility management, where precise information does not matter yet.

We also reviewed the availability and quality of open datasets of energy infrastructure in Europe, which we will summarize in an upcoming paper.

Annex C Aggregator Script

```
#!/usr/bin/env python3
```

```
"""
```

TwinEU UC7 - Aggregator day-ahead flexibility pipeline (Annex reproducer).

Reads the TSO flexibility request, the pre-provisioned per-node customer-ID lists

(agreed in advance), and the DSO per-customer power envelopes (separate load and generation files per node).

Writes one Flex-Answer CSV per node.

Six stages: (1) random asset assignment, (2) daily reference profiles,

(3) per-customer baseline, (4) envelope clipping, (5) flex deltas with an

efficiency factor, (6) portfolio aggregation and matching against the TSO request.

Dependencies: numpy, pandas.

```
"""
```

```
import os
```

```
import numpy as np
```

```
import pandas as pd
```

```
# =====
```

```
# CONFIGURATION
```

```
# =====
```

```
INPUT_DIR = os.environ.get("UC7_INPUT_DIR", ".")
```

```
OUTPUT_DIR = os.environ.get("UC7_OUTPUT_DIR", ".")
```

```
DELIMITER = ","
```

```
# Input files
```

```
F_FLEXREQUEST = "1_1_1_2_TWIN_EU_UC7_Flex-Request_TSO_Node_A_B.csv"
```

```
F_IDS_ARPE = "2_1_TWIN_EU_UC7_Envelope-Request_Aggregator_Node_Arpe.csv"
```

```
F_IDS_NEHDEN = "2_2_TWIN_EU_UC7_Envelope-Request_Aggregator_Node_Nehden.csv"
```

```
F_ENV_ARPE_LOAD = "2_3_TWIN_EU_UC7_Envelope_DSO_Node_Arpe_load.csv"
```

```
F_ENV_ARPE_GEN = "2_3_TWIN_EU_UC7_Envelope_DSO_Node_Arpe_generation.csv"
F_ENV_NEHDEN_LOAD = "2_4_TWIN_EU_UC7_Envelope_DSO_Node_Nehden_load.csv"
F_ENV_NEHDEN_GEN = "2_4_TWIN_EU_UC7_Envelope_DSO_Node_Nehden_generation.csv"

# Output files, one per node.
O_ANSWER_ARPE = "3_1_TWIN_EU_UC7_Flex-Answer_Aggregator_Node_Arpe.csv"
O_ANSWER_NEHDEN = "3_2_TWIN_EU_UC7_Flex-Answer_Aggregator_Node_Nehden.csv"

# Column headers of the two node columns in the TSO Flex-Request file.
COL_ARPE = "Arpe"
COL_NEHDEN = "Nehden"

N_SLOTS = 96
SLOT_MINUTES = 15

# Fixed random seed, makes the run reproducible.
SEED = 42

N_ARPE, N_NEHDEN = 1000, 1500
PREFIX_ARPE, PREFIX_NEHDEN = "Kunde A", "Kunde N"

# Asset-mix categories and their shares (CONS, PV, PV+battery, PV+battery+wallbox,
# wallbox-only, PV+wallbox). Plausible suburban/rural LV mix
TYPE_LABELS = ("CONS", "PV", "PVB", "PVBW", "W", "PVW")
TYPE_PROBS = (0.45, 0.20, 0.15, 0.10, 0.07, 0.03)

# Per-customer peak capacity ranges (uniform draws), kW / kWp
PEAK_LOAD_KW = (3.0, 8.0)
PV_KWP = (5.0, 12.0)
WALLBOX_KW = (7.0, 11.0)
BATTERY_KW = (3.0, 6.0)

# Reference-profile shape parameters. Gaussian bumps are (centre_h, sigma_h, amp)
P25_NIGHT_BASE = 0.18
```

```
P25_MORNING = (7.5, 1.3, 0.55)
```

```
P25_MIDDAY = (12.5, 1.8, 0.28)
```

```
P25_EVENING = (19.0, 1.7, 1.00)
```

```
PV_CENTRE, PV_HALFSPAN, PV_START, PV_END = 12.5, 11.5, 5.5, 19.5
```

```
WB_CENTRE, WB_SIGMA, WB_START, WB_END = 20.0, 1.6, 17.0, 23.5
```

```
BATT_CHARGE, BATT_DISCHARGE, BATT_SCALE = (12.5, 1.4, -1.0), (19.5, 1.4, 1.0), 0.35
```

```
# Efficiency factor: customers are not 100% flexible. A pure consumer keeps an
```

```
# irreducible baseload and PV without storage cannot be throttled to zero, so only
```

```
# part of the theoretical headroom is deliverable. Customers with a battery or
```

```
# wallbox dispatch more reliably and receive the higher factor.
```

```
EFF_HIGH = 0.85 # has battery or wallbox
```

```
EFF_LOW = 0.50 # has neither
```

```
OFFER_TOL_MW = 1e-9
```

```
MW_DECIMALS = 3
```

```
# Offer IDs, date-stamped for idempotency under daily automation.
```

```
DELIVERY_DATE, OFFER_SEQ = "20260501", "001"
```

```
OFFER_ID_ARPE = "AGG-FLEX-ARPE-%s-%s" % (DELIVERY_DATE, OFFER_SEQ)
```

```
OFFER_ID_NEHDEN = "AGG-FLEX-NEHD-%s-%s" % (DELIVERY_DATE, OFFER_SEQ)
```

```
# =====
```

```
# INPUT
```

```
# =====
```

```
def _path(name):
```

```
    p = os.path.join(INPUT_DIR, name)
```

```
    if not os.path.isfile(p):
```

```
        raise FileNotFoundError("input file not found: %s" % p)
```

```
    return p
```

```
def read_flexrequest():
```

```
    df = pd.read_csv(_path(F_FLEXREQUEST), sep=DELIMITER)
```

```
    if len(df) != N_SLOTS:
```

```

    raise ValueError("%s: expected %d rows, found %d" % (F_FLEXREQUEST, N_SLOTS, len(df)))
    return df[COL_ARPE].to_numpy(float), df[COL_NEHDEN].to_numpy(float)

def read_id_list(name, n_expected, prefix):
    ids = pd.read_csv(_path(name), sep=DELIMITER).iloc[:, 0].astype(str).str.strip().tolist()
    if len(ids) != n_expected:
        raise ValueError("%s: expected %d IDs, found %d" % (name, n_expected, len(ids)))
    if not all(i.startswith(prefix) for i in ids):
        raise ValueError("%s: not all IDs start with %r (wrong file for node?)" % (name, prefix))
    return ids

def read_envelope(name, n_expected):
    m = pd.read_csv(_path(name), sep=DELIMITER).to_numpy(float)
    if m.shape != (n_expected, N_SLOTS):
        raise ValueError("%s: expected shape (%d, %d), found %s" % (name, n_expected, N_SLOTS,
m.shape))
    return m

# =====
# STAGE 2 - reference profiles
# =====

def _gauss(h, centre, sigma, amp):
    return amp * np.exp(-((h - centre) ** 2) / (2.0 * sigma ** 2))

def reference_profiles():
    h = np.arange(N_SLOTS) * (SLOT_MINUTES / 60.0)
    p25 = P25_NIGHT_BASE + _gauss(h, *P25_MORNING) + _gauss(h, *P25_MIDDAY) + _gauss(h,
    *P25_EVENING)
    p25 = p25 / p25.max()
    pv = np.maximum(0.0, np.cos((h - PV_CENTRE) * np.pi / PV_HALFSPAN))
    pv = np.where((h < PV_START) | (h > PV_END), 0.0, pv)
    pv = pv / pv.max()
    wb = _gauss(h, WB_CENTRE, WB_SIGMA, 1.0)
    wb = np.where((h < WB_START) | (h > WB_END), 0.0, wb)

```

```

wb = wb / wb.max()

batt = (_gauss(h, *BATT_CHARGE) + _gauss(h, *BATT_DISCHARGE)) * BATT_SCALE
batt = batt / np.abs(batt).max()

return p25, pv, wb, batt

# =====
# STAGE 1 + 3 - customer attributes and baseline
# =====

def customer_attributes(n, rng):
    # Draw order (type, peak_load, pv, wallbox, battery) is fixed
    types = rng.choice(TYPE_LABELS, size=n, p=TYPE_PROBS)
    peak_load = rng.uniform(PEAK_LOAD_KW[0], PEAK_LOAD_KW[1], n)
    pv = rng.uniform(PV_KWP[0], PV_KWP[1], n)
    wallbox = rng.uniform(WALLBOX_KW[0], WALLBOX_KW[1], n)
    battery = rng.uniform(BATTERY_KW[0], BATTERY_KW[1], n)
    has_pv = np.isin(types, ("PV", "PVB", "PVBW", "PVW"))
    has_battery = np.isin(types, ("PVB", "PVBW"))
    has_wallbox = np.isin(types, ("PVBW", "W", "PVW"))
    return {
        "peak_load": peak_load,
        "pv": np.where(has_pv, pv, 0.0),
        "battery": np.where(has_battery, battery, 0.0),
        "wallbox": np.where(has_wallbox, wallbox, 0.0),
    }

def baseline(attrs, profiles):
    p25, pv, wb, batt = profiles
    # Consumer convention: positive = consumption from grid, negative = export.
    # The battery shape is negative at midday (charging draws power) and positive
    # in the evening (discharging supplies the house)
    return (attrs["peak_load"][:, None] * p25
            - attrs["pv"][:, None] * pv
            + attrs["wallbox"][:, None] * wb
            - attrs["battery"][:, None] * batt)

```

```
# =====
# STAGE 4 + 5 + 6a - clip, efficiency factor, aggregate
# =====

def portfolio_flex(load_env, gen_env, base, attrs):
    # Envelope convention: load values <= 0, generation values >= 0.
    # Consumer corridor: p_max = -load_env (max consumption), p_min = -gen_env.
    p_max = -load_env
    p_min = -gen_env
    if np.any(p_min > p_max + 1e-9):
        raise ValueError("inverted envelope corridor (require load_env <= 0 and gen_env >= 0)")
    clipped = np.clip(base, p_min, p_max)
    eff = np.where((attrs["battery"] > 0) | (attrs["wallbox"] > 0), EFF_HIGH, EFF_LOW)[: , None]
    flex_up = (p_max - clipped) * eff
    flex_down = (clipped - p_min) * eff
    return flex_up.sum(axis=0) / 1000.0, flex_down.sum(axis=0) / 1000.0

# =====
# STAGE 6b - match the TSO request against portfolio capacity
# =====

def match_offer(request, flex_up, flex_down):
    # The request is already DSO-clipped upstream (steps 0.1-0.4), so it is not
    # re-clipped against the envelope sum here; only the portfolio capacity binds.
    # Positive request -> capped by flex-up; negative request -> capped by flex-down.
    offer = np.zeros_like(request)
    source = np.full(request.shape, "no_request", dtype=object)
    up = request > OFFER_TOL_MW
    dn = request < -OFFER_TOL_MW
    up_cap = up & (flex_up + OFFER_TOL_MW < request)
    dn_cap = dn & (-flex_down > request + OFFER_TOL_MW)
    offer[up & ~up_cap] = request[up & ~up_cap]
    offer[up_cap] = flex_up[up_cap]
    offer[dn & ~dn_cap] = request[dn & ~dn_cap]
    offer[dn_cap] = -flex_down[dn_cap]
```

```

source[up & ~up_cap] = "tso_request_met"
source[up_cap] = "portfolio_flex_up_limit"
source[dn & ~dn_cap] = "tso_request_met"
source[dn_cap] = "portfolio_flex_down_limit"
return offer, source

# =====

# OUTPUT

# =====

def write_answer(name, offer_id, request, flex_up, flex_down, offer, source):
    minute = np.arange(N_SLOTS) * SLOT_MINUTES
    df = pd.DataFrame({
        "slot_id": np.arange(1, N_SLOTS + 1),
        "time_UTC": ["%02d:%02d" % (m // 60, m % 60) for m in minute],
        "tso_flexrequest_MW": request,
        "portfolio_flex_up_MW": flex_up,
        "portfolio_flex_down_MW": flex_down,
        "aggregator_offer_MW": offer,
        "constraint_source": source,
        "offer_id": offer_id,
    })
    df.to_csv(os.path.join(OUTPUT_DIR, name), index=False, float_format="%.%df" %
MW_DECIMALS)

def verify(request, flex_up, flex_down, offer):
    tol = 1e-6
    assert (flex_up >= -tol).all() and (flex_down >= -tol).all()
    assert (np.abs(offer) <= np.abs(request) + tol).all()
    nz = np.abs(request) > OFFER_TOL_MW
    assert (np.sign(offer[nz]) * np.sign(request[nz]) >= 0).all()
    assert (offer[request > 0] <= flex_up[request > 0] + tol).all()
    assert ((-offer[request < 0]) <= flex_down[request < 0] + tol).all()

# =====

```

```

# MAIN

# =====

def main():
    if not os.path.isdir(OUTPUT_DIR):
        os.makedirs(OUTPUT_DIR)

    req_a, req_n = read_flexrequest()
    ids_a = read_id_list(F_IDS_ARPE, N_ARPE, PREFIX_ARPE)
    ids_n = read_id_list(F_IDS_NEHDEN, N_NEHDEN, PREFIX_NEHDEN)
    load_a = read_envelope(F_ENV_ARPE_LOAD, N_ARPE)
    gen_a = read_envelope(F_ENV_ARPE_GEN, N_ARPE)
    load_n = read_envelope(F_ENV_NEHDEN_LOAD, N_NEHDEN)
    gen_n = read_envelope(F_ENV_NEHDEN_GEN, N_NEHDEN)
    # Envelope rows are aligned to the pre-provisioned ID lists by row order.
    assert len(ids_a) == load_a.shape[0] == gen_a.shape[0]
    assert len(ids_n) == load_n.shape[0] == gen_n.shape[0]

    profiles = reference_profiles()
    # One generator, Arpe drawn before Nehden
    rng = np.random.default_rng(SEED)
    attrs_a = customer_attributes(N_ARPE, rng)
    attrs_n = customer_attributes(N_NEHDEN, rng)

    fu_a, fd_a = portfolio_flex(load_a, gen_a, baseline(attrs_a, profiles), attrs_a)
    fu_n, fd_n = portfolio_flex(load_n, gen_n, baseline(attrs_n, profiles), attrs_n)
    off_a, src_a = match_offer(req_a, fu_a, fd_a)
    off_n, src_n = match_offer(req_n, fu_n, fd_n)

    verify(req_a, fu_a, fd_a, off_a)
    verify(req_n, fu_n, fd_n, off_n)

    write_answer(O_ANSWER_ARPE, OFFER_ID_ARPE, req_a, fu_a, fd_a, off_a, src_a)
    write_answer(O_ANSWER_NEHDEN, OFFER_ID_NEHDEN, req_n, fu_n, fd_n, off_n, src_n)

```

```
for node, src in (("Arpe", src_a), ("Nehden", src_n)):
    met = int((src == "tso_request_met").sum())
    up = int((src == "portfolio_flex_up_limit").sum())
    dn = int((src == "portfolio_flex_down_limit").sum())
    print("%-7s met=%d flex_up_limited=%d flex_down_limited=%d" % (node, met, up, dn))
print("OK - Flex-Answer written for both nodes, all checks passed.")

if __name__ == "__main__":
    main()
```

Annex D TwinEU Connector – Deployment Issues and Resolutions

The following issues were identified during the deployment and testing of the TwinEU Connector at the TSO, DSO and Aggregator within Ge07 (see Chapter 3.3.3, Workstream 2) and reported to the software provider.

- **Issue 1 – Need for a simplified Deployment Process:** The users needed a clear, step-by-step workflow that separates development (no HTTPS) from production (HTTPS + Let's Encrypt) and eliminates manual compose edits. This led to the creation of a traefik setup for https encrypted services, in the process of moving all secrets to .env, exposing only Traefik-managed ports, optional removal of debug services (Dozzle).
- **Issue 2 – Unintended Service-Disable Capability:** A regular user (offis1) could edit another participant's service (rwth1) and toggle its "disable offered service" flag from the UI, effectively disabling a remote offering. This was identified as bug and solved.
- **Issue 3 – Open Docker Ports Exposed to the Internet:** The provided docker-compose.yml opens multiple host ports (e.g., 8080, 8447, 8448). Users deploying on a server without an external firewall inadvertently expose these endpoints to the public internet; even ufw rules are bypassed because Docker creates its own NAT rules. This issue was worked on by adding a prominent "Warning" block to the README, advising users to secure the host (firewall, VPN, or host-network isolation) before running the compose file.
- **Issue 4 – Request for Let's Encrypt Integration (Traefik):** The default setup ships with self-signed certificates, causing browsers to warn users and complicating production-grade deployments. This was solved with the creation of a Traefik-Let's Encrypt example compose file that uses Let's Encrypt certificates instead of self signed certificates.
- **Issue 5 – UI Inaccessible Due to Network Mis-configuration:** When using the Traefik port-setup guide, the TwinEU UI returned a Gateway Timeout, while other services (Dozzle, Traefik dashboard) worked. The reason was that the UI container was not attached to the custom Docker network (network-a) used by Traefik, causing routing failures. This was solved by updating the compose files to include the UI service in network-a, the sub network of the docker compose setup.
- **Issue 6 – Security Scans detected vulnerabilities:** Using IT infrastructure of grid operators imposes special security requirements. When testing the Connector software, automated IT security scans detected known vulnerabilities, both in the built software and the deployment services. Since the IT infrastructure of grid operators is critical, grid operators were forced to shut down the connector several times to wait for fixes from the software developer partners. These vulnerabilities were communicated with the software developer team. For now this was solved with new releases with updated components. On the longer run this will happen frequently, and automated security scans of the Connector software needs to be established.
- **Issue 7 – Providing data via API:** It is possible to upload a file via API without specifying the fileSize attribute. If you after doing that, check the "Timeline" view in the connector UI under "Data exchange>Data exchanges timeline" is only showing a white page. Uploading the same file in the same way but including the fileSize prevents this error.
- **Issue 8 – Filtering when searching:** The filters need to be tested, the one in the page "Services/My subscriptions/New data Subscriptions/Select offering" is not working at the time of testing it to find specific users.