T 4.4 Technical Evaluation for the developed architecture based on the results of the field test

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Executive Summary

Deliverable T4.4 investigates the technical feasibility and performance of the system architecture developed in the DigIPlat project to optimize flexibility platforms in the European energy system. The aim of the evaluation is to assess the interoperability, scalability and marketability of the architecture based on field tests. A central focus is on the integration of "Bid Congestion Management" (BCM), which optimizes flexibility offers to benefit the grid. The analysis shows that the architecture is fundamentally scalable and enables efficient optimization of bids. Nevertheless, challenges remain, particularly in the interoperability between market platforms, technical standardization, and the consideration of cross-network optimization potential. Security aspects such as data minimization, access controls and comprehensive vulnerability management also require improvements. The results underscore that the architecture offers a promising basis for future market integration, but that further developments are needed in the areas of cybersecurity, interface standardization and grid integration. The insights gained from the field tests provide valuable impetus for further development and enable an optimized use of flexibilities in the energy market.

Kurzfassung

Dieses Deliverable zu T4.4 untersucht die technische Machbarkeit und Leistungsfähigkeit der im DigIPlat-Projekt entwickelten Systemarchitektur zur Optimierung von Flexibilitätsplattformen im europäischen Energiesystem. Ziel der Evaluierung ist es, die Interoperabilität, Skalierbarkeit und Marktfähigkeit der Architektur anhand von Feldtests zu bewerten. Ein zentraler Fokus liegt auf der Integration des „Bid Congestion Management" (BCM), das Flexibilitätsangebote netzdienlich optimiert. Die Analyse zeigt, dass die Architektur grundsätzlich skalierbar ist und eine effiziente Optimierung der Gebote ermöglicht. Dennoch bestehen Herausforderungen, insbesondere in der Interoperabilität zwischen Marktplattformen, der technischen Standardisierung sowie der Berücksichtigung netzübergreifender Optimierungspotenziale. Auch Sicherheitsaspekte wie Datenminimierung, Zugriffskontrollen und ein umfassendes Schwachstellenmanagement erfordern Verbesserungen. Die Ergebnisse unterstreichen, dass die Architektur eine vielversprechende Grundlage für eine zukünftige Marktintegration bietet, jedoch weitere Entwicklungen in den Bereichen Cybersecurity, Schnittstellenstandardisierung und Netzintegration erforderlich sind. Die gewonnenen Erkenntnisse aus den Feldtests liefern wertvolle Impulse für die Weiterentwicklung und ermöglichen eine optimierte Nutzung von Flexibilitäten im Energiemarkt.

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1 Introduction

1.1 Context

This deliverable examines the architecture developed in the DigIPlat project and assesses how well it can be integrated into existing energy markets. The focus is on three central aspects: interoperability, scalability and regulatory requirements. Field tests are used to check whether architecture is technically feasible and to identify challenges for market integration.

Flexibility platforms have emerged as a solution for coordinating and optimizing energy trading, distribution, and system services between transmission system operators (TSOs), distribution system operators (DSOs), and flexibility service providers (FSPs). However, the potential of these systems is limited by a lack of interoperability between existing platforms and different technical standards. Deliverable 4.4 specifically addresses these limitations by testing the developed architecture to enable seamless integration, efficient operation and compliance with regulatory requirements.

Through its evaluation, Deliverable 4.4 aims to bridge the gap between innovative technical solutions and their practical implementation in real energy systems, thus promoting a more resilient and efficient energy transition.

1.2 Scope and Objectives

The scope of deliverable 4.4 focuses on the assessment and validation of the technical architecture developed under the DigIPlat project, particularly its application in field testing. The document is embedded in the existing deliverables, which should be consulted for a more comprehensive picture. The deliverable addresses key aspects, including the implementation of Use Case 1, which combines optimization of balancing energy with grid restrictions and ensures the scalability and adaptability of the proposed solutions across different grid levels, from transmission to distribution. This scope also includes a comprehensive evaluation of the system architecture to determine whether it meets technical and operational requirements and to identify and address challenges related to reliability, interoperability, and scalability.

The evaluation process includes both macro- and micro-level analysis. At the macro level, the outcome examines the overall design, processes, and alignment of the architecture with the market and regulatory framework. At the micro level, it focuses on technical aspects such as reliability, cyber security, data security and the seamless integration of the architecture into existing platforms. Performance metrics and predefined test criteria, including network stability, system cost reduction and flexibility integration, are central to the scope and ensure compliance with regulatory standards and interoperability requirements.

The demonstrator, as the developed solution for the field test, was implemented to achieve two main goals within the DigIPlat project:

1. Evaluation of Integration Scenarios with real-world systems and parties
2. Demonstration of one defined use-case using an user-interface to interact with

The first goal was done as the “Bid Congestion Management” (BCM) described in delivery 4.1/4.2. The second goal was implemented as demonstration user interface. Evaluation here focuses mainly on the Bid Congestion Management, as this is intended to achieve the technical implementation of Use-Case 1.

1.3 Overview of Use Case I

Use Case 1"Utilization of Balancing Energy Considering Network Restrictions," addresses the impact of balancing energy (BE) deployment on grid utilization and the prevention of potential grid congestion. The focus lies on avoiding overloads in both the transmission and distribution networks. BE deployment alters grid load flows compared to the baseline, potentially leading to congestion in specific grid elements. To mitigate these challenges, the use case proposes an optimization framework that integrates grid constraints into the balancing energy allocation process.

The methodology involves three key steps: First, balancing energy bids are disaggregated into "per-technical-unit" components, which are grouped based on their respective network locations. Second, an optimization algorithm determines the most cost-effective combination of these unit-level bids while accounting for network restrictions, such as capacity limits and load flows. Finally, the optimized unit-level bids are reaggregated into complete balancing energy bids, resulting in a grid-aware merit order list.

This optimization approach relies on detailed data inputs, including grid capacity limits, simulated power flows, energy provider locations, and bid specifications such as activation schedules. By leveraging this data, the model minimizes balancing energy costs while maintaining grid stability.

A key aspect of this use case is the emphasis on interoperability and standardization across flexibility platforms. To achieve this, flexibility service providers must submit detailed data on their technical units and operational schedules. This transparency allows the optimization algorithm to exclude bids that could worsen grid congestion. In cases where no congestion-free solution is available, the algorithm selects the bid combination with the least negative impact on the grid while still meeting energy demand.

By serving as the foundation for Deliverable 4.4, this use case provides a structured approach for evaluating the technical feasibility and real-world implementation of the proposed solution. It ensures compliance with regulatory requirements while addressing key technical challenges. Ultimately, this approach enhances grid stability, reduces overall system costs, and supports the transition to a more flexible and resilient European energy system.

2 Macro-Analysis: Overall Architecture Evaluation

The macro-analysis of the developed architecture looks at the overall system from a higher-level perspective and evaluates key aspects such as market integration, scalability and interoperability. The aim of this chapter is to examine the architecture in terms of its suitability for real operation and to identify possible challenges and optimization potential.

A central element of this analysis is the evaluation of the developed IT process, particularly regarding the integration of Bid Congestion Management (BCM) into existing market structures. The extent to which the architecture is market-compatible and which adjustments are necessary to enable smooth interaction between different market players such as transmission system operators (TSOs), distribution system operators (DSOs) and flexibility service providers (FSPs) is examined.

In addition, the chapter is dedicated to identifying technical barriers that could impede the widespread introduction of the developed solution. These include regulatory requirements, differences in technical standards and challenges with integration into existing energy market mechanisms. The different versions of the ENTSO-E market documents and the heterogeneous interfaces and communication protocols of the various market platforms are a particular focus here.

Another important aspect of the macro analysis is the scalability of the architecture, specifically its ability to interact with an increasing number of market platforms and network operators. The analysis shows which measures are required to ensure smooth scaling and how the optimization processes can be adapted to larger use cases.

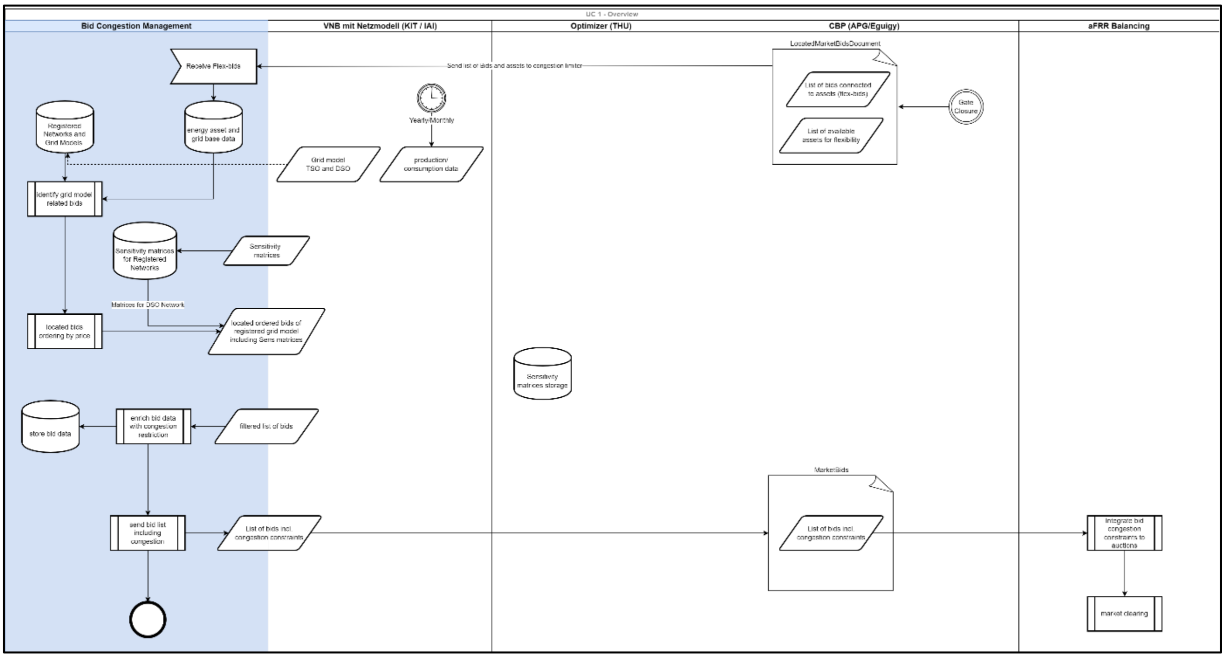
Finally, the interoperability of the developed solution is examined. A high level of interoperability is crucial in order to enable broad use of the platform across different network operators, regions and markets. The existing technical standards and interfaces will be evaluated and their adaptability to future developments in the energy market will be examined.

2.1 Evaluation of the designed IT-process

In this section, the developed IT process is analyzed on the design of its structure, functionality and market integration. One focus is on evaluating the data flows between the stakeholders involved, including distribution system operators (DSOs), transmission system operators (TSOs) and flexibility providers. It also examines how the process takes existing grid restrictions into account and whether the implementation meets the expected performance and security requirements. The aim of this analysis is to identify possible optimization potential and to assess whether the IT process is suitable for broad market application.

Description of the process flow

The process begins with the submission of a reduced grid model by the distribution system operator (DSO) via a standardized interface to Bid Congestion Management (BCM). Instead of a complete grid model, the DSO transmits an abstracted representation that records the utilization of critical grid components and their sensitivity to flexibility activations. This enables targeted consideration of grid-relevant aspects without disclosing confidential grid structures. To improve the assessment, DSOs can submit several grid models, each reflecting different operating points. This allows grid utilization to be assessed dynamically and precisely. In parallel, the transmission system operators (TSOs) take over the assignment between the connection nodes of the flexibilities and the asset identifiers on the market platforms. This ensures that the grid-side integration of flexibility resources remains consistent across markets. Flexibility providers and aggregators submit their bids via established market platforms. Before the final allocation, the bids are automatically checked by the BCM. This review ensures that the activation of flexibility is not only optimized on the market side but also serves the grid and no additional bottlenecks arise. The optimization takes place for each time slice.



Graphic 1: Overview of UC1 process. For a detailed analysis of each element consolidate Deliverable 4.1/4.2.

2.2 Market integration of the BCM: challenges and participant perspectives

As part of the BCM, it is necessary for the DSO to create simplified models by calculating piecewise linear approximated distribution grids using the Power Transfer Distribution Factors (PTDFs). Depending on the available capacity, expertise or specific requirements, the DSO can create one, a few or many operating points. The models can be displayed in different topological resolutions, allowing a targeted focus on selected components, especially critical grid components.

The methodological approach also considers the data protection concerns of the DSO in relation to the TSO, as no conclusions can be drawn about the actual grid model from the approximated model. Another advantage of these simplified models is that they are easy to update new operating scenarios can be stored without any problems, which is particularly important in view of the strong influence of topological changes on the PTDFs.

However, a critical aspect of this approach is that the calculation of PTDFs requires a complete digital network model that is as detailed as possible. In practice, however, the DSO does not always have a complete network model, which makes the implementation of this methodology considerably more difficult. Furthermore, the acceptance of the BCM poses an additional challenge, as its operation would primarily have to be carried out by the TSO and acceptance on the DSO side is questionable in this context. A neutral body could tend to be placed between the DSO and TSO in order to improve coordination and mutual trust. However, it remains questionable whether an additional body in the process chain makes sense or whether it unnecessarily complicates the market. Also, this method significantly increases the bureaucratic effort involved in recording and managing all small systems, and market participants have to adapt their own systems for integration. This is accompanied by costs that could prove challenging.

Market integration of the methodology into national balancing energy markets is possible in principle. Aggregated bids are still possible as long as the aggregator provides schedule information from the technical systems. Furthermore, it is generally possible to maintain minimum bid sizes with this methodology, even if the demonstrator implemented here according to Use Case 1 does not take this into account. The data basis for Germany with the market master data register is to be assessed positively, for Austria and Switzerland the development of a similar system is necessary. For the integration of the methodology into international markets, the BCM can generally be used to set up a verified merit order that can be forwarded to processes such as PICASSO. The integration into other markets with continuous trading instead of auction times still needs to be researched.

2.2.1 Evaluation of the optimization process

- **Non-binding nature of flexibility awards**
  The current optimization approach makes it possible to calculate a cost-optimal combination of flexibility activations that are intended to resolve or prevent grid restrictions. However, this optimization result assumes that all flexibilities provided for in the model are actually activated. In practice, however, deviations can occur, for example if aggregators make short-term portfolio adjustments or technical restrictions prevent implementation. In such cases, the expected grid-stabilizing effect does not materialize, which means that congestion can persist or even worsen.
- **Potential for discrimination**
  The current status quo of flexibility allocation on the market shows only limited potential for discrimination. One potential hurdle is the minimum bid size, which can exclude smaller market participants. Apart from this, allocation is usually based on the merit order, which ensures non-discriminatory allocation. However, the optimization approach envisaged in Use Case 1 (UC1) changes some framework conditions that could open up new opportunities for discrimination. While the minimum bid size no longer plays a role after UC1, certain suppliers may still be excluded. On the one hand, market participants can be excluded if their bid would lead to grid congestion and is therefore not compatible with the grid restrictions. On the other hand, discrimination may arise if an aggregator serving several grid areas reacts more flexibly to optimization results and can therefore submit more favourable bids than individual local market participants. Discrimination could also occur if the DSO does not properly submit its grid model to the BCM - in this case, a market participant operating on the DSO's associated grid could be disadvantaged.

2.2.2 Evaluation of network linearization

The LTDF and VTDF matrices are sensitivity matrices that are derived on the basis of a first-order Taylor expansion. The VTDF matrix corresponds to the part contained in the Jacobian matrix that describes changes in voltage magnitude due to changes in active power feed-ins, so that a separate terminology appears to be unnecessary. In contrast, the LTDF matrix reveals a methodological problem: the absolute value formation of the load flows introduces a non-linearity that proves to be problematic in the optimization process. It is therefore recommended to focus on pure PTDF matrices. In addition, the choice of operating conditions for linearization, currently represented by arbitrarily selected values of the total flexibility activation (0 %, 50 %, 100 %), requires a more sound methodological approach.

2.3 Identification of technical barriers

The current architecture provides for the optimization process to be outsourced from BCM. This potentially enables external companies to offer this process as a service. However, this has considerable disadvantages for the efficiency and fairness of the system. On the one hand, outsourcing leads to increased calculation time, as additional communication and synchronization steps are required. In addition, competing optimizations can occur if different external providers pursue different objectives, which makes consistent and transparent decision-making more difficult. Furthermore, the optimization process should not be subject to commercial interests, as this could lead to distortions and a potential preference for certain market participants. A centrally integrated optimization process in BCM, on the other hand, ensures a fair and transparent calculation that provides a level playing field for all participants. The direct embedding of the optimization process in the BCM ensures that the process remains efficient, comprehensible and independent of commercial influence. The degree of centrality is an undetermined question that needs to be considered when realising the project (For instance, one system per control area or decentralised systems within local regions).

The field test of the BCM implementation showed that different versions of the ENTSO-E market documents exist and it is to be expected that the market platforms are also implemented in different versions. This increases the effort and risks for a comprehensive market introduction.

The technical communication capabilities of the market platforms to be connected may also differ in their interfaces. It will therefore almost certainly be necessary to implement individual interfaces for participating market platforms. For example, the interfaces may differ in the forms of connection (push vs. pull), the communication paradigm (synchronous vs. asynchronous), authorization and authentication, data serialization formats (XML, JSON, other) and others.

2.4 Scalability and interoperability

The implementation of Bid Congestion Management (BCM) brings with it several technical challenges that can make a broad market launch difficult. This section identifies the key technical barriers that affect the efficiency, scalability and interoperability of the developed architecture.

Particular attention is paid to incompatible interfaces, different data standards and integration into existing network and market platforms. In addition, potential bottlenecks in the optimization calculation, challenges in processing large amounts of data and possible security risks are analyzed.

Once fully implemented and rolled out on the European market, the BCM should be able to analyze and optimize the balancing bids of all distribution grids. This requires the system to be highly scalable. Scalability refers to the ability of the BCM to maintain its performance as the rollout increases, while interoperability describes the seamless integration and standardized data exchange between the various systems.

2.4.1 Scalability the BCM architecture

The scalability of BCM for the various dimensions of connections, network load, computing capacity, storage requirements and number of distribution grids and distribution grid operators is largely possible, as listed in the deliverable for 4.1/4.2. This is achieved using serverless functions, upstream API management, the possibility of load balancing the BCM implementation through virtualization and scalable cloud resources.

2.4.2 Scalability of the integration of market platforms

The scalability of the integration of multiple market platforms is currently not ensured. At present, the process is designed so that the optimization starts immediately after bids from a market platform are received. This leads to sequential processing and prevents a holistic optimization across all market platforms. Introducing a specific gate closure time (e.g., GC+1 minute) for market platforms could resolve this issue by first collecting all bid constellations and then optimizing them collectively.

2.4.3 Scalability of integration of distribution system operators

Fundamentally, the scalability for the integration of multiple DSOs is ensured. The designed BCM can handle a growing number of distribution system operators without causing significant delays or system bottlenecks. In the implementation of the demonstrator in TP 4.2, the integration of additional DSOs was not performed.

2.4.4 Mathematical optimization

The current mathematical optimization model is formulated specifically for a single distribution network and therefore does not allow for cross-network optimization. Instead of a holistic optimization of the entire system, calculations are performed at the level of individual DSOs. This can lead to inefficient solutions, as system-wide synergy effects are not utilized. A potential improvement would be the introduction of a hierarchical optimization approach, where local optimizations are first performed, and the results are then integrated into a higher-level optimization layer. This would enhance the consideration of supraregional flexibilities and enable a more efficient allocation of resources.

2.4.5 Interoperability of flexibility platforms

The architectural design of the BCM as a cloud-based and service-providing system establishes the foundation for high interoperability. The following table presents the components used in the BCM and their impact on interoperability:

Component	Impact on Interoperability
API Management	Enables the provisioning of standardized interface endpoints for all common interface technologies and protocols (SOAP, REST, HTTP/S, WebSockets, GraphQL, etc.). Supports versatile authentication and authorization technologies such as OAuth, OpenID Connect, JWT, client certificates, and API keys.

App Service, Logic App	Enables the provisioning of custom implementations for integrating interface endpoints to connect and process third-party systems for which no standardized interfaces are available.
On Premises Data Gateway	Enables integration with data and systems through interfaces that are also located within a protected corporate network.

2.5 Conclusion Macro-Analysis

The macro-analysis has shown that the developed BCM architecture is fundamentally scalable and marketable; however, key challenges still need to be addressed for successful integration. In particular, technical market connectivity, the scaling of the architecture, and interoperability between various stakeholders prove to be critical factors for smooth operation.

The evaluation of the IT process has confirmed that the fundamental data processing and optimization have been sensibly designed, but adjustments to existing market platforms and network operator structures are still required. The market integration of BCM is complicated by varying regulatory requirements, proprietary interfaces, and heterogeneous data models, making uniform standardization necessary.

Additionally, technical barriers have been identified, particularly concerning different versions of ENTSO-E market documents, the synchronization of market platforms, and the performance of optimization algorithms. These challenges must be addressed to enable broad application across different grid areas and markets.

Overall, the BCM architecture provides a solid foundation for efficient grid and market platform integration but requires further adjustments, particularly in process harmonization, technical standardization, and interface optimization. Through targeted further development and strategic implementation measures, the system can contribute in the long term to stabilizing energy grids and improving the efficient utilization of flexibility options.

3 Micro-Analysis: Technical Evaluation

The micro-analysis focuses on the detailed technical evaluation of the architecture developed within the DigIPlat project and assesses its practical performance. While the macro-analysis examines the overall system from a higher-level perspective, the micro-analysis delves into specific technical aspects that are crucial for the system's reliability, security, and efficiency.

A key focus is on the reliability of the architecture, particularly in terms of availability and fault tolerance. This involves analyzing how robust the system is against failures of individual components and which mechanisms are in place for redundancy and disaster recovery.

Another important area is data and cybersecurity. Since the system handles sensitive energy-related data, data protection and defense against cyberattacks are of high importance. In this context, the security measures implemented—such as data encryption, access controls, and vulnerability management—are evaluated. Additionally, it is assessed whether the architecture complies with the requirements of critical infrastructure (KRITIS) and the applicable regulatory security standards.

Furthermore, performance metrics are examined to quantify the system's efficiency. This includes analyzing whether the optimization processes can be completed within the given time frames and whether the architecture remains capable of handling an increasing number of network operators and flexibility offerings.

3.1 Reliability

The reliability of the developed architecture is a crucial factor for its successful deployment in the energy market. This chapter examines the extent to which the system can be operated stably and fail-safe. Key aspects such as redundancy, availability, fault tolerance, recovery time, and load resistance are in focus. A reliable system must be capable of maintaining stable operation even under high load or technical disruptions. Therefore, an analysis is conducted on the measures implemented to safeguard against failures and whether further optimizations are needed for productive deployment. It is assessed whether the chosen cloud-based infrastructure components meet the requirements for seamless operation and what adjustments are necessary to enhance resilience.

Redundancy:

- As a service-oriented and stateless implementation, the BCM system is designed to be made highly redundant through infrastructure setup. For this purpose, clustering methods such as Kubernetes could be used.
- The developed demonstrator is not designed with redundancy in any system element. The failure of a system component directly impacts operations.
- The system environment used for operational management is already designed with infrastructure redundancy by the operator to ensure protection against hardware failures. This redundancy also determines the availabilities presented below.

Availability:

The BCM and the demonstrator are operated on virtual machines in the Microsoft Cloud. Availability is presented by Microsoft as follows [1], [2]:

- App Service: 99,95%
- Azure Database for PostgreSQL: 99,99%
- Logic Apps: 99,9%
- Storage Account: 99,9%
- API Management: 99,95%
- Virtual Network: 99,9%

These base figures of availability represent the least possible options using the Cloud providers Infrastructure. For productive workloads it is advised to extent the system using options that ensure even higher availability using automatic fail-over, hot-standby, clustering and scaling.

Fault tolerance:

Fault tolerance regarding infrastructure failures in the demonstrator is set to the most cost-effective standards of the utilized system environment. In principle, the same system environment in the Microsoft Cloud can be expanded to achieve increased fault tolerance with premium plans [1]. This includes, for example, availability sets for virtual machines, which distribute them across different physical servers and network components. App Services and Azure Functions can be distributed across multiple instances and automatically redirected in case of failures.

Recovery Time:

Specific optimizations for recovery scenarios have not been implemented in the operation of the demonstrator and Bid Congestion Management. The standard availability and disaster recovery commitments offered by the infrastructure provider apply. In the selected Basic execution plan, these must be manually ensured by the operator. Backups that can be used for recovery are automatically created once daily for the database. The recovery time depends on the size of the data in the database. In the research project, this size is less than 50 MB.

For a more securely protected productive operation, the chosen architecture can be based on incremental backups and redundant zone distribution (data centers), allowing the recovery time for all components of the entire architecture to be close to zero, as the redundantly operated systems can take over immediately in the event of a failure [3].

Load resistance:

The cost-effective options chosen for the demonstrator are sufficient for demonstration purposes but have characteristics (e.g., automatic standby, use of a physical machine shared among multiple customer environments with divided CPU, memory, and network bandwidth) that make them unsuitable for productive operation.

While maintaining the architecture, the utilized resources (see list under availability) can be adjusted to the expected load by selecting offered production environments at higher monthly costs. This can be achieved through both better and dedicated machines as well as clustering.

Conclusion on Reliability:

The analysis shows that the developed architecture fundamentally offers high availability, as it is based on a scalable cloud infrastructure. However, the demonstrator currently lacks redundant system components, which means that individual failures can impact operations. While the deployed cloud services provide a solid foundation for stability and fault tolerance, targeted improvements, such as the implementation of redundancy mechanisms and automated recovery strategies, could further enhance operational security.

For productive deployment, additional measures are required to optimize load resistance and fault tolerance. These include enhanced failure protection, optimized recovery times, and continuous monitoring of system stability.

3.2 Data Security

The security and integrity of the processed data are crucial factors for the reliable operation of the developed architecture. This chapter examines the measures implemented for data minimization, secure storage, encryption, and access control to ensure the protection of sensitive energy industry information.

Focus is placed on compliance with regulatory requirements, securing data transmission channels, and the separation and management of data from different market participants. The analysis assesses the extent to which the current security concept meets these requirements and identifies potential optimizations for enhanced data security.

Minimization of data

All data flows into and out of the BCM, as well as data storage within the BCM system, are considered. The reduction to only the data necessary for the relevant process is examined.

Interfaces

Data domain / Interface	Transmitted data	Result
SSTM01 **- CheckBids**	ReserveBidDocument with list of assets	ReserveBidDocument partially carries data that is not relevant for the use case.
SSTM02 **- CheckBidsResult**	ReserveBidDocument with ListofConstraintPoints	ReserveBidDocument is not necessary. The unique identification of the bids is sufficient, not the entire documents.
SSO01 **- OptimizeBidWithScenarios**	List of technical bits, VerteilnetzId, Daytype	Only process-essential data is retained.
SSO02 **- OptimizeBidResults**	Optimal costs, list of services of the technical bids, used reference point	Only process-essential data is retained.

SSO03 - PutScenarios	Transfer of computable grid models	Only process-essential data is retained.
SSN01 - PutNetworkModel	Registration / Transfer of distribution grids	Only process-essential data is retained.
SSN02 - AssetData	Asset data for enrichment of existing grid connection points as needed by DSO.	The standardized BDEW format carries more data than the process requires. Identification and grid connection point are sufficient for the use case.

Data storage

The data stored by the BCM is all maintained in its own local database. There is no separation by tenants (e.g., different DSOs or market platforms). The following table lists the storage areas and assessment regarding data minimization:

Area	Stored data	Assessment
Market bids	Complete bid data as provided by the marketplace standard interface. Structure is based on ENTSO-E standards.	The ENTSO-E standard document also contains information on individual bids that are not used within the use case but are included as part of the standard.
Distribution networks	Geographic data and location information for registered distribution grids	Geographic data is not required for the use case. Assigning location information to the DSO responsibility area is necessary.
Computable grid models	Reduced matrices for grid load calculation with base states of the grid nodes.	Only data necessary for the use case is retained here.
Asset information	Basic and additional information on asset data that can be used for flexibility bids, if needed by DSO.	Certain information (minimum and maximum power) is not necessary for the use case. Location information, asset types, and assignment to the distribution grid should be sufficient.

Data security

Data security must be maintained, particularly during the transmission of data and, if necessary, also at the data storage level according to the security requirements for the data. In the research project, no personal data as defined by the General Data Protection Regulation (GDPR) were processed.

According to the regulation for determining critical infrastructures, trading within the energy sector also falls under the German KRITIS regulations [4]. In this context, data from energy infrastructure (distribution grids) and data from energy trading (balancing energy market) are processed in WP 4. The obligations under German BSIG §8a [5] apply to ensuring the confidentiality and integrity of the information processed here, as long as this ensures the functionality of critical infrastructure. We assume that this applies to market bids, the distribution grid, and information about plants in the distribution grid within the BCM system.

Ways of transmission:

Data domain / Interface	Protection measures	Assessment
Market platform / BCM	Data encryption at the transport layer (TLS)	Sufficient. Improvement: Ensure data integrity.
BCM / optimizer	Data encryption at the transport layer (TLS)	Additional protective measures can only be omitted if the optimizer is integrated into the BCM system.
DSO / BCM	-	In the research project, this interface has not been implemented.
BCM Data storage	Access restriction via firewall / application gateway. Encryption of database storage.	Sufficient protection for the selected scope. Measures to ensure data integrity and monitoring should still be integrated.
Demonstrator Web app	None	Not critical. Synthetic data is not used in the research project. Recommendation: Restrict access to the demonstrator web application to known user groups, e.g., through registration.

Data storage:

Data backup and data recovery are carried out using the strategies provided by the cloud provider for the BCM database “PostgreSQL”.

The following can be configured for the backup strategies:

- Frequency of full backups, differential backups
- Retention period of backups, automatic deletion of backups
- Secure storage of backup data

Other data-related security aspects:

Aspect	Assessment
Anonymization/Pseudonymization	It’s not implemented through the current implementation. This aspect can be omitted if the reduction is made to only the necessary data for bids and plants.
Data lifecycle management	Is not foreseen within the implementation.
Monitoring and surveillance	As part of logging and the deployed infrastructure, access and data flows can be configured through API management.

The analysis shows that basic security measures, such as data transmission encryption (TLS) and access restrictions, have been implemented. However, there is potential for improvement in data minimization, as some interfaces transmit more information than required for the respective process. Additionally, there is a lack of strict tenant separation, which would require clearer segmentation of data from different market participants.

For enhanced security, additional measures such as improved access control, data integrity monitoring, and optimized management of stored data should be introduced. Particularly with regard to regulatory requirements and the protection of critical infrastructures (KRITIS), further adjustments are advisable.

3.3 Cybersecurity

The cybersecurity of the developed architecture is essential to ensure protection against unauthorized access, data manipulation, and potential cyberattacks. This chapter examines which security mechanisms have been implemented to minimize vulnerabilities and secure the integrity of the system.

Key aspects such as access controls, vulnerability management, threat detection, and encryption are the focus. The aim of the analysis is to assess the existing security measures and identify potential improvements to strengthen the resilience of the architecture against cyber threats.

The following aspects of the IT security requirements for the application have been evaluated:

Aspect	Result
Access Control	The implementation of access control mechanisms was not required for the demonstrator and has not been implemented. The selected runtime environment of the cloud service provider allows access control through authentication and authorization at the interface level.
Vulnerability Management	Vulnerability management in the implementation is performed at the source code level in the demonstrator when integrating third-party libraries and through static vulnerability analysis in source code management. Vulnerability management within the runtime environment has not been set up.
Threat Detection and Management	Not implemented in the research project.
Encryption	Standard encryption methods for communication (TLS) are used.
Third-Party Risks	Monitoring of third-party libraries during the development process. Dynamic updating of libraries in the runtime environment is not planned.

Conclusion on Cybersecurity

The analysis shows that basic security measures, such as transport encryption (TLS) and authentication at the interface level, are in place. However, more advanced mechanisms for access control, threat detection, and vulnerability monitoring, which are necessary for protecting critical infrastructure, are lacking.

In particular, ongoing security review and updating of third-party libraries, as well as comprehensive vulnerability management, should be enhanced. To elevate cybersecurity to a higher level, additional measures such as a monitoring system for detecting attacks and stricter access control are necessary.

3.4 Performance Metrics

In order for Use Case 1 to function in real operation, it must be able to complete the bid optimization within the time window between Gate Closure and Clearing. This 10-minute time window is shared with other market processes that run after Gate Closure. We assume that a maximum of 5 minutes will be available for the bid optimizer.

According to T 4.2, the current implementation requires less than 1 second for optimization on the sample distribution grid (with 241 nodes) and scenarios (with 241 bids), with a total runtime of less than 20 seconds. With optimizations, the total runtime can be reduced to less than 5 seconds. A linear scaling would thus allow the optimization to work within a 5-minute time window for up to approximately 110 distribution grids of comparable complexity.

Since the optimization has already been performed with the maximum number of technical bids, the chosen architecture scales very well depending on the market bids, as these are broken down into technical bids (disaggregation), preventing the maximum number of technical bids from increasing further. The computation time for the disaggregation and aggregation of the bids is also well below one second.

3.5 Conclusion Micro Analysis

The micro-analytical assessment of the BCM architecture has confirmed that the system is technically feasible, but it requires targeted optimizations in the areas of reliability, data security, cybersecurity, and performance.

Regarding reliability, it is evident that the architecture is fundamentally scalable, but currently, no redundant mechanisms have been implemented to ensure continuous operational security. Improved fault tolerance and recovery strategies are necessary to avoid the failure of critical components.

Data security provides a solid foundation, such as encrypted transmission paths; however, there is room for improvement in data minimization and tenant separation, particularly in the storage of market and grid data. Additionally, measures for data integrity checks are needed to further increase security against tampering.

In the area of cybersecurity, basic security mechanisms like TLS encryption have been implemented, but there is a lack of comprehensive vulnerability management and active monitoring for threat detection. Furthermore, access controls should be more strictly regulated, and automated security updates for third-party components should be introduced.

The performance analysis has shown that the architecture is fundamentally capable of performing optimizations within the required timeframes. However, the scaling to a large number of network operators and market participants has not yet been fully tested. By improving the parallelization of processes and utilizing resources more efficiently, performance can be further optimized.

Overall, the micro-analysis confirms that the developed architecture provides a solid technical foundation, but targeted improvements in operational security, data protection, cybersecurity, and load stability are necessary to enable broad market deployment and productive use.

4 Key Learnings and Recommendations

The evaluation of the developed architecture has provided valuable insights into its strengths, weaknesses, and optimization potential. This chapter summarizes the key findings from the field tests and derives concrete recommendations for future improvements.

The focus is on technical, operational, and security-related aspects that are critical for the successful implementation and scaling of the system. The insights gained serve as a foundation for further development and enable targeted optimization of the architecture for practical use in the energy market.

4.1 Lessons from Field Testing

The evaluation of the BCM/Demonstrator implementation has yielded several key insights that highlight both the technical potential and the challenges of the system. The choice of the runtime environment proved promising, as it offers high scalability and is suitable for use in a production environment. At the same time, it became clear that comprehensive documentation, as well as interviews with the involved partners, are essential to ensure transparent traceability of the system development.

The practical implementation of a previously theoretical use case has also revealed new aspects and shortcomings that not only require adjustments to the current development stage but also necessitate further research work. Despite the challenges, it appears that the chosen architectural approach allows the scaling of the field test implementation towards productive operation, even though only a smaller expansion stage was initially realized in the research project.

In addition to these general insights, other technical aspects are particularly important in the implementation of the demonstrator according to Use Case 1. For example, the non-availability of individual components, such as the optimizer, must be considered early on to avoid unnecessary delays in market processes. A fixed timeout interval of five minutes is not practical in this context and should be adjusted flexibly to meet the system requirements.

It also became evident that interoperability between different market participants and infrastructures is as significant a challenge as interface integration within a single stakeholder. The combination of both factors makes technical implementation significantly more difficult, requiring close coordination and standardization among the involved parties.

Regarding the procurement of real test data we found that this can be a challenge too. Since access to real-time market data is not possible in a research project of this type, alternative solutions must be found. Future evaluations will therefore require the synthetic creation of test data that adheres to available standards and reflects realistic scenarios.

These insights provide important clues for the further development of the system and highlight the challenges that need to be addressed when scaling and launching it in the market.

4.2 Best Practices and Roadmap for Improvement

The successful implementation of the developed architecture requires targeted improvements and proven approaches to further optimize its performance and security. Based on the insights from the evaluation, key measures have been identified that enable sustainable further development.

A crucial aspect is the integration of the optimization process directly into the runtime environment of the BCM system to reduce calculation times and ensure higher efficiency. Furthermore, for a production operation, the inclusion of additional distribution grid areas is necessary.

For a stable and secure system architecture, automated tests for validating and load-testing the BCM implementation are required. This will allow potential bottlenecks to be identified early and improve system stability. Additionally, the area of cybersecurity should be further strengthened, particularly through the implementation of comprehensive vulnerability and threat management.

Another central area of action is the procurement of real test data from market platforms, for example, by using historical bidding data from the balancing energy market. This would significantly improve the validity of the evaluation and enable more realistic optimization processes. Moreover, the introduction of a DSO gate closure point could help optimize market integration and synchronization with existing processes.

Additionally, it is recommended to expand the optimization model to include grid-related aspects to ensure better control of flexibilities in the energy system. To further simplify the technical integration, interfaces should be standardized, and the optimization process should be parallelized.

Finally, access control to the demonstrator should be improved, thus further enhancing security and data protection. The implementation of these measures ensures that the architecture will remain market-ready in the long term and enable seamless integration into existing energy markets. Questions relating to liability remain open.

5 Conclusion

In this evaluation of the demonstrator, further insights have been gained regarding both the chosen solution approach and the integration tasks in market processes and existing market systems. The integration into national balancing energy markets is considered feasible, while international integration and use in other markets require further research. A key factor is the improved DSO/TSO interaction, as well as the creation of digital distribution network models, which are essential for the presented method. The data protection concerns of DSOs are addressed by transmitting the PTDFs, which do not allow conclusions to be drawn about the complete network model.

The analysis shows that the non-availability of individual components, such as the optimizer, must be accounted for in the market process to avoid delays. It also becomes clear that interoperability between different stakeholders in the energy market and infrastructure is as complex as the interaction within the same. This places particularly high demands on technical implementation.

The potential of the chosen runtime environment was demonstrated, which has proven to be scalable and suitable for use in production environments. In the implementation of theoretically described use cases, new aspects, shortcomings, and follow-up questions were identified, which necessitate further research.

In the area of cybersecurity, essential security requirements were evaluated, including access control, vulnerability management, threat detection, and encryption measures. The implementation of access control mechanisms at the interface level through the cloud service provider's runtime environment and static vulnerability analysis when integrating third-party libraries were positively assessed. However, comprehensive vulnerability management within the runtime environment and dynamic updating of the libraries used are missing.

In conclusion, the developed architecture offers promising approaches to improving the integration of flexibility platforms. However, further research and development work is required to ensure smooth scaling and market integration. Improving interoperability, further developing optimization methods, and strengthening cybersecurity are key aspects for future implementation. The insights gained from the field test provide a valuable foundation for the further development and potential productive use of the system.

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