Begonia

D3.1: Technology Landscape and Technical Requirements

Date of deliverable:

31/12/2024

Responsible partner:

Center Denmark (CDK)

This project has received funding from the European Commission under grant agreement N°101133306.

Technical References

EU Initiative | Call	CEF-DIG-2022-TA | CEF Project Grants
Granting Authority	European Health and Digital Executive Agency
Grant Agreement Nr.	101133306
Project Acronym	22-EU-DIG-BEGONIA
Project Name	Enabling the Internet of Energy and Optimized Transport through Cross-Border Digital Platforms
Project Coordinator	DANMARKS TEKNISKE UNIVERSITET
Project Duration	27 months

Deliverable No.	3.1	
Dissemination level [1]	*PU*	
Work Package	3	
Task	1	
Lead beneficiary	CDK	
Responsible Authors	Peter Mombartz-Brændgaard	
Other authors/contributors	*DTU*	*Mohsen Banaei*
	BLP	*Elena Boskov-Kovacs*
	DTU	*Xiufeng Liu*
Contributing beneficiary(ies)	*DTU, BLP*	
Due date of deliverable	*2024-12-31*	
Actual submission date	*2024-12-31*	

Review

Reviewers	**Alex Gluhak**
Reviewing period	**2024-11-28 – 2024-12-12**
Approved by reviewers	**Alex Gluhak, Razgar Ebrahimy**

Summary

Begonia Project

Europe is embarking on a transformative endeavour to modernise digital information usage, with a focus on enhancing the efficiency, sustainability, and connectivity of our energy and transportation sectors. At the core of this initiative lies the development of advanced Operational Digital Platforms (ODPs) that transcend national boundaries, leveraging state-of-the-art technologies such as data sharing, cloud computing, and network connectivity.

The BEGONIA Project is an EU-funded Coordination and Support Action that aims to expedite this digital transformation in the energy and transport sectors, analysing the most promising solutions and providing information to the European Commission to set up and fund future works project(s).

BEGONIA has the goal of identifying, studying and preparing the development of Operational Digital Platforms (ODPs) across different EU countries, starting from the identification of 10 cross-border and possibly cross-sector (energy and transport) use cases, meticulously shortlisting three based on predefined criteria, and evaluating their impacts through proof-of-concept implementation of their ODPs.

Summary of the Deliverable

This deliverable provides a detailed examination of the technical requirements essential for the successful realization of the six shortlisted use cases. By analyzing these requirements, a range of potential technologies has been identified, each capable of addressing specific functional and operational needs.

These technologies are systematically organized within the overarching layered architecture framework, which was previously developed as part of this project to ensure scalability, interoperability, and modularity across diverse applications.

In addition, the deliverable highlights critical cybersecurity considerations that are universally applicable across all six use cases, emphasizing the importance of safeguarding systems, data, and operations in increasingly interconnected digital environments. This structured approach ensures a holistic understanding of the technological landscape while laying the groundwork for secure and efficient implementation.

Disclaimer

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Table of Acronyms

Acronyms	Description
AI	Artificial Intelligence
api	Application Programming Interface
BLE	Bluetooth Low Energy
CF	Carbon Footprint
DDS	Data Distribution Service
DER	Distributed Energy Resources
DSO	Distribution System Operator
EMS	Energy Management System
ET	Electric Truck
ETL	Extract Transform Load
EV	Electric Vehicle
GPS	Global Positioning System
HVAC	Heating, Ventilation, and Air Conditioning
IoT	Internet of Things
LIDAR	Light Detection and Ranging
LoRaWAN	Long Range Wide Area Network
LPWAN	Low Poer Wide Area Network
LSTM	Long Short-term Memory
OBD	Onboard Diagnostic
OBU	Onboard Units
ODP	Operational Digital Platform
OSM	OpenStreetMap
PoE	Power over Ethernet
res	Renewable Energy Sources
TSO	Transmission System Operator

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Introduction

This technical analysis examines the implementation requirements and technological considerations necessary for a series of advanced operational digital platforms (ODPs) across diverse use cases introduced in the Begonia project. Each use case represents distinct requirements from one or more sectors, ranging from energy storage optimization to cross-border logistics, digital permit management, and smart infrastructure operations, unified by a common need for sophisticated, integrated digital solutions. In order for such an ODP to be able to satisfy these requirements, they need to rely on a range of different technologies.

In this analysis, we explore the range of technologies essential to support each use case. Depending on the use case, these technologies include AI-driven predictive systems, blockchain for secure data management, Internet of Things (IoT) frameworks, advanced data analytics, and cloud infrastructure. For instance, AI techniques and blockchain-based permits are vital for managing data integrity in drone inspections and ensuring real-time operational insights in smart port management. Furthermore, data centers and logistics systems rely heavily on digital twins and real-time data analytics for energy efficiency and carbon footprint tracking. Each use case presents unique technical requirements tailored to its domain, highlighting examples of applicable technologies and their interoperability layers within the operational framework.

This document provides a comprehensive analysis, detailing the requisite technologies and specific implementations critical to achieving the objectives outlined for each use case, fostering a digital landscape that aligns with modern environmental, economic, and operational standards.

The analysis will be used to guide the future work of BEGONIA. Specifically, the solution architectures for the use cases will need to consider how these technologies could work within them to be best meet the needs of the use case. The technologies will also have to be considered when the feasibility study for each use case is to be conducted, as the feasibility of each use case will depend on which technologies will be used.

Before we go through the proposed approach and detailed discussion, a short summary of the use cases is presented in the section to provide a better understanding of the use cases and their scope and objectives.

Summary of the use cases

In the first phase of the project, 14 use cases in energy and mobility and cross-sector mobility/energy fields were collected from stakeholders. In the second phase, following an approach and considering the feedback received from reviewers, these use cases were shortlisted into six use cases. The final six use cases are either the original collected use cases or the result of merging some of the collected use cases. The table below provides an overview of these six shortlisted use cases, outlining their objectives, geographical scope, and main functionalities.

Table 1: Overview of use cases

Use Case	Objective	Geographical Scope	Main Functionalities
I: Digitalization of Energy Storage and Reuse in Data Centers	Optimize energy efficiency in data centers by leveraging storage, renewable energy, and waste heat reuse.	Cross-border data centers	Real-time energy monitoring, flexibility services, and energy optimization.
II: AI-Driven ODP for Integration of EVs, ETs, RES, and Grid	Enhance energy efficiency and grid stability through the integration of EVs, ETs, and renewable energy sources.	Austria and Hungary	Real-time forecasting, dynamic charging management, and demand-response optimization.
III: Electricity Customers Centric ODP	Empower electricity customers with cross-border energy supplier switching and virtual energy communities.	Cross-border EU regions	Automated supplier switching, demand-side flexibility services, and RES integration.
IV: Digital Permits for Drone-Based Inspections	Streamline cross-border drone permit management for linear infrastructure inspections.	Cross-border linear infrastructure regions	Automated permit approval, regulatory compliance, and operational insights.
V: Smart Port Operations	Improve efficiency, security, and sustainability in port operations.	Ports in Spain and other EU regions	AI-driven monitoring, drone-based inspections, and IoT-enabled environmental sensors.
VI: Carbon Footprint in Logistic Operations	Establish a transparent carbon tracking system for cross-border logistics.	Cross-border logistics networks	IoT-enabled emissions monitoring, blockchain-based data validation, and analytics.

Approach

This technical analysis provides a structured methodology for identifying the software and hardware technologies needed to implement the ODP across various use cases. To present the work in a structured way, the generic reference architecture proposed for use cases is used as the baseline and the required technologies for each use case are investigated at each layer of this reference architecture. This approach ensures that selected technologies support scalability, security, interoperability, and regulatory compliance, tailored to the specific needs of each use case.

The generic reference architecture of use cases is presented in Figure 1 followed by below explanations:

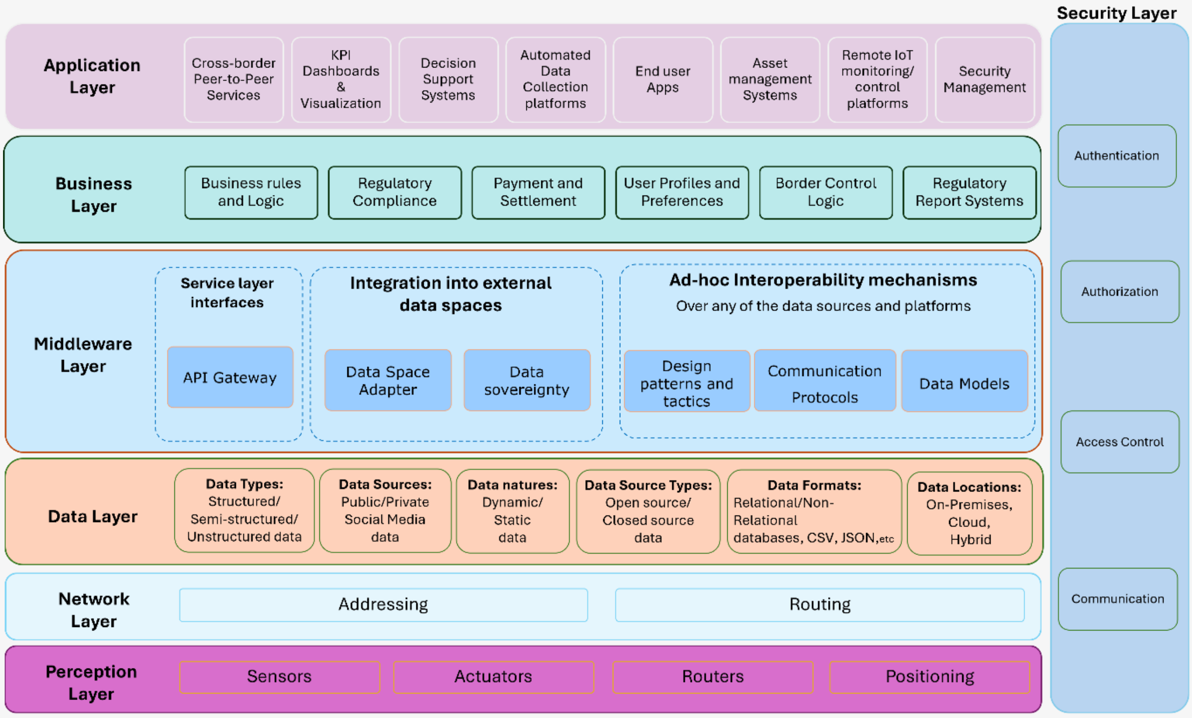


Figure 1: Generic reference architecture

1. **Perception Layer**: The Perception Layer is responsible for capturing real-time data from the physical environment, using IoT sensors, devices, and communication protocols. Key considerations include:
    - **Data Sources**: Determine the types of sensors and devices needed to capture accurate data relevant to each use case, such as emissions, energy usage, equipment status, or location.
    - **Processing Needs**: Assess whether data can be processed locally at the edge (e.g., using IoT gateways) or if it requires immediate transmission to centralized systems, especially for use cases requiring real-time analysis.

   - **Connectivity Solutions**: Select appropriate communication solutions, such as 4G/5G, low power wide area network (LPWAN), satellite, or Wi-Fi, based on the geographic spread and operational context of each use case.

2. **Data Layer**: The Data Layer handles data storage, organization, and management, ensuring data is accessible, consistent, and ready for analysis. Key technology requirements include:

   - **Data Storage Solutions**: Identify the optimal database types (e.g., relational, NoSQL, and time-series databases) based on the volume, variety, and velocity of data generated.
   - **Data Integration**: Use extract, transform, load (ETL) tools to aggregate, transform, and standardize data from diverse sources, ensuring uniformity and reliability across systems.
   - **Message Queues and Communication Protocols**: Implement message queues for reliable data flow and communication protocols (e.g., MQTT, HTTP) to maintain secure, real-time data transmission.

3. **Middleware Layer**: The Middleware Layer facilitates interoperability, data sharing, and integration, particularly for multi-stakeholder and cross-border applications. Core components include:

   - **Data Integration Middleware**: Select platforms that support seamless data exchange and transformations between various systems, ensuring compatibility and compliance.
   - **API Management**: Implement application programming interface (API) management tools to provide secure, controlled access to data, enabling integration with third-party applications and supporting regulatory requirements.
   - **Data models:** Define data models for sharing between various systems
   - **Data Spaces and Federation**: Consider using federated data spaces for secure, controlled data sharing, accommodating complex data privacy and access needs across entities.

4. **Business Layer**: The Business Layer is pivotal in orchestrating the core functionalities of ODPs, encompassing business rules, regulatory compliance, payment processing, and reporting systems. This layer ensures that operations align with organizational objectives and adhere to industry standards and legal mandates.

   - **Business Rules and Logic**: This component defines and enforces the operational protocols and workflows within the ODP, ensuring that processes are executed in accordance with organizational policies and strategic goals.

- **Regulatory Compliance/Reporting Systems**: The Business Layer integrates mechanisms to ensure that all operations comply with relevant laws, regulations, and industry standards. This includes implementing compliance checks, maintaining audit trails, and generating reports required by regulatory bodies.
- **Payment and Settlement Processing**: This function manages financial transactions within the ODP, handling tasks such as invoicing, payment processing, and settlement of accounts. It ensures that all financial operations are conducted securely, accurately, and in a timely manner, adhering to financial regulations and standards.

5. **Application Layer**: The Business Layer provides stakeholders with visualization, reporting, and data access capabilities, supporting strategic and operational decision-making:
    - **Visualization and Dashboards**: Implement visualization tools that offer real-time monitoring and display key metrics tailored to each use case.
    - **Analytics and Reporting**: Use analytics tools to generate detailed reports, track long-term trends, and meet compliance requirements.
    - **Blockchain for Data Validation**: Where applicable, incorporate blockchain to validate and record critical data points, offering transparency, auditability, and automated validation through smart contracts.
    - **End user apps:** Apps which allow users to interact with the platform
    - **Security management:** Provide a way ensure security and monitor both alerts and incidents.

This methodology ensures that each layer's technologies align with the specific functional and regulatory needs of each use case, creating a resilient, adaptable platform that supports accurate data management, interoperability, and compliance across sectors.

The analysis of each use case can be read independently from each other. Finally, the document ends with a section on security concerns across operational digital platforms.

Use case I: Electricity customers centric ODP

Use Cases I: Electricity customers centric ODP focus on empowering electricity customers through a cross-border ODP. This platform provides services such as automated supplier switching, participation in virtual energy communities, and demand-side flexibility procurement. By integrating renewable energy sources (RESs), controllable devices, and electric vehicles, the platform enables customers to contribute to grid stability, reduce energy costs, and actively participate in green transition programs. AI-driven tools support forecasting, decision-making, and personalized recommendations, ensuring that the platform aligns with varying regulations across EU member states while fostering sustainable energy practices.

Requirements

Developing a customer-centric ODP for electricity consumers requires a comprehensive framework to enhance energy management, optimize consumption, and integrate renewable energy sources. To achieve this, the following requirements need to be met:

1. **Data Acquisition and Integration**:
   - **Comprehensive Data Collection**: Implement systems to gather real-time data from Electric Vehicles (EVs), RES, controllable devices, and smart home systems.
   - **Market and Environmental Data Integration**: Incorporate electricity market data and accurate weather forecasts to inform energy management strategies.
   - **Seamless Data Transmission and Reception**: Utilize robust communication protocols to ensure efficient data exchange between devices, the ODP, and external data sources.
2. **Data Management and Processing**:
   - **Scalable Data Storage**: Deploy infrastructure capable of handling large volumes of diverse data, facilitating both real-time analytics and long-term historical analysis.
   - **Efficient Data Movement**: Establish high-throughput data pipelines to process and analyze incoming data swiftly, enabling real-time decision-making and predictive maintenance.
3. **System Integration and Interoperability**:
   - **Integration with EU Data Spaces**: Align data management practices with European Union data space initiatives to ensure regulatory compliance and facilitate cross-border data collaboration.

- **Smart Home Integration**: Ensure compatibility with existing smart home systems to enable centralized control and monitoring of energy-consuming devices.

4. **Advanced Analytics and Optimization**:

   - **Predictive Load Management**: Employ artificial intelligence (AI) algorithms to forecast grid load and optimize energy distribution, balancing supply and demand effectively.
   - **Automated Participation in Virtual Energy Communities**: Enable the platform to engage in energy trading and sharing within virtual communities, optimizing energy usage and costs.
   - **Energy Usage Recommendations**: Provide personalized suggestions to consumers for optimizing energy consumption based on usage patterns and predictive analytics.

5. **User Interaction and Administration**:

   - **Interactive User Interfaces**: Develop user-friendly platforms for stakeholders to interact with the ODP, access information, and control relevant aspects of the system.
   - **Visualization of Energy Patterns**: Offer tools to visualize energy consumption and generation patterns, enhancing consumer awareness and engagement.
   - **Automated Billing Systems**: Implement systems for accurate and timely billing, reflecting real-time energy usage and dynamic pricing models.
   - **Administrative Tools**: Equip administrators with tools to manage system configurations, user access, and monitor overall health and security.

Table 22**Error! Reference source not found.Error! Reference source not found.** provides an overview of the technical requirements and technologies needed for use case I. They will be discussed in detail in the following sections.

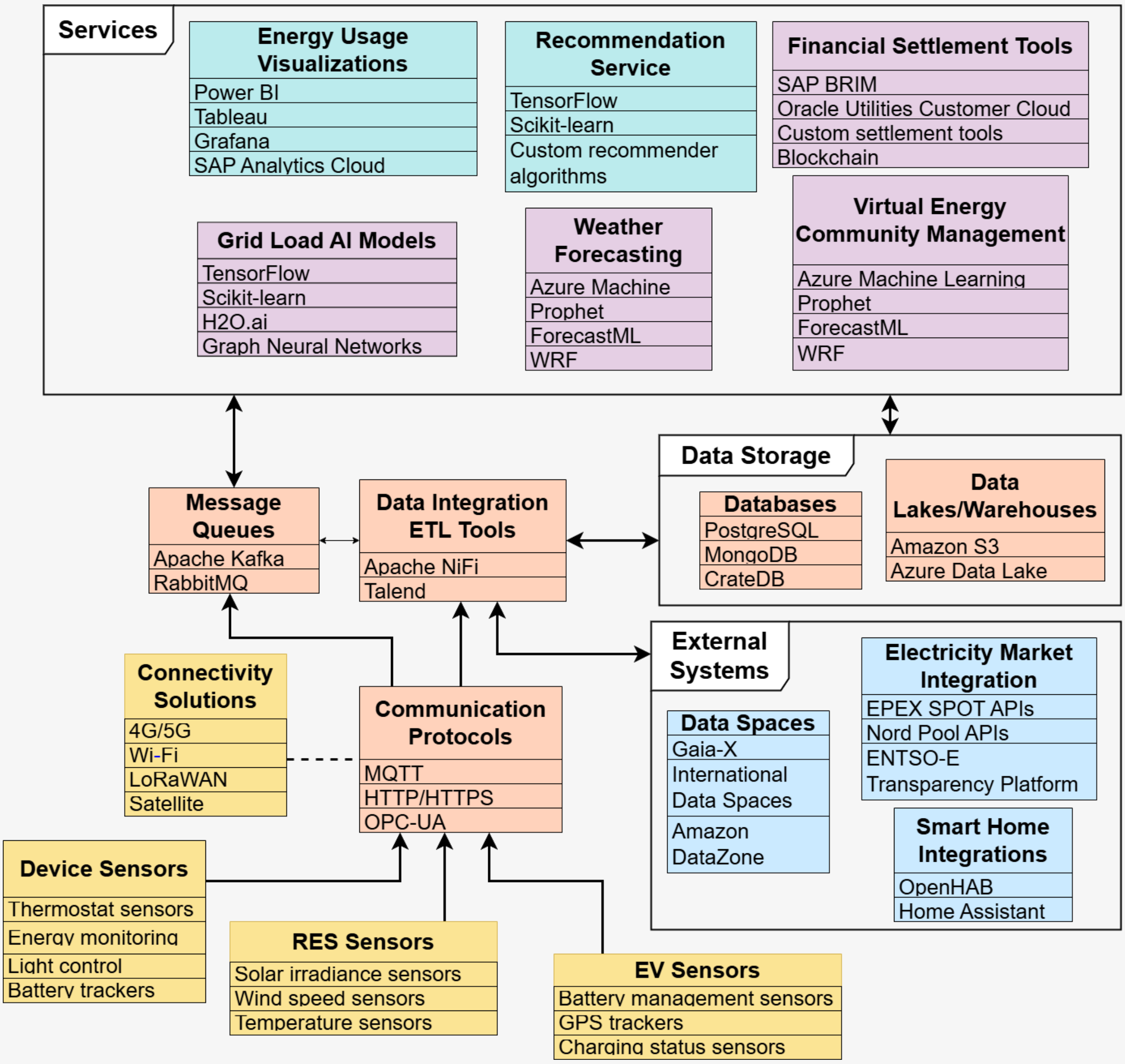
Table 22: Use case I requirements

Architectural Layer	Requirements	Type of Technology	Main Required Technologies
Perception Layer	Collect EV data	Ev sensors	Battery management sensors, GPS trackers, charging status sensors
	Collect RES data	RES sensors	Solar irradiance sensors, wind speed sensors, temperature sensors
	Collect data from controllable devices	Device sensors	Thermostat sensors, energy monitoring, light control, battery trackers
	Transmit data	Connectivity solutions	4G/5G, Wi-Fi, LoRaWAN, Satellite
Data Layer	Receive data	Communication Protocols	MQTT, HTTP/HTTPS, OPC-UA
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, MongoDB, CrateDB
	Store big data	Data Lakes/Warehouses	Amazon S3, Azure Data Lake
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend
Middleware Layer	Integrate with EU data spaces	Data spacFes	Gaia-X, International Data Spaces (IDS), Amazon DataZone
	Collect electricity market data	Electricity market integration	EPEX SPOT APIs, Nord Pool APIs, ENTSO-E Transparency Platform
	Integrate with smart homes	Smart home integrations	OpenHAB, Home Assistant
Business Layer	Predict grid load and provide optimisations	AI Models for Grid Load Prediction and Optimization	TensorFlow, Scikit-learn, H2O.ai, Graph Neural Networks
	Provide accurate weather forecasts	Weather Forecasting Algorithms	Azure Machine Learning, Prophet, ForecastML, WRF

	Automatically participate in virtual energy communities	Virtual Energy Community Management Tools	Siemens MindSphere, Schneider Electric EcoStruxure, ARIMA, Prophet, OpenADR, SAP Billing and Revenue Innovation Management (BRIM), Energy Web Chain, GridX
	Automated billing	Financial Settlement Tools	SAP Billing and Revenue Innovation Management (BRIM), Oracle Utilities Customer Cloud, custom settlement tools, blockchain (e.g., Hyperledger Fabric)
Application layer	Provide energy usage recommendations	Recommendation Service	TensorFlow, Scikit-learn, custom recommender algorithms.
	Visualise energy patterns	Energy Usage Visualizations	Power BI, Tableau, Grafana, SAP Analytics Cloud.

Figure 2 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 2: Use case I Technology Diagram



Perception layer

EV Sensors

Sensors embedded in EVs monitor battery status, charging cycles, and energy consumption. These sensors provide real-time data that allows the platform to adjust charging schedules based on grid conditions, availability of renewable energy, and customer preferences. This data is critical for aligning EV charging with periods of high renewable energy generation, reducing grid strain, and optimizing energy consumption.

Renewable Energy Sensors

Renewable energy systems such as solar panels and wind turbines are equipped with sensors to monitor energy generation, environmental conditions, and performance metrics. These sensors provide vital information on energy production and help predict energy availability. The integration of this data enables the platform to efficiently balance supply and demand by forecasting energy output and optimizing the use of renewable sources.

Controllable Device Sensors

Various controllable devices, including smart thermostats, energy meters, lighting control systems, and battery storage, are equipped with sensors to monitor energy use and adjust settings for efficiency. For instance, smart thermostats track room temperatures and adjust heating or cooling based on demand-response signals, while smart plugs and energy meters measure and control power consumption. These devices are essential for the platform’s energy optimization capabilities.

Connectivity Solutions

The Perception Layer employs advanced connectivity solutions to ensure seamless and reliable data transmission from sensors to the ODP. Connectivity solutions like 4G/5G, Wi-Fi, long range wide area network (LoRaWAN), and Satellite provide the necessary bandwidth and range for continuous monitoring and data collection, supporting real-time decision-making and enabling interactions across distributed devices.

By integrating data from EVs, RESs, and controllable devices, the Perception Layer facilitates a holistic view of energy flows, grid interactions, and consumer behavior. This enables customers to manage their energy consumption dynamically, reducing costs and supporting a sustainable energy grid. The data captured from these diverse sources is essential for driving personalized recommendations, optimizing energy use, and ensuring active participation in flexibility and demand-response programs.

Data layer

Communication Protocols

Communication protocols facilitate secure, real-time data exchange between sensors, smart appliances, distributed energy resources (DERs), and the Operational Digital Platform. Lightweight protocols like MQTT are ideal for telemetry from IoT devices, such as energy meters and EV chargers, while HTTP/HTTPS is used for secure interactions with energy market APIs and customer-facing applications. OPC-UA supports reliable communication with grid-connected systems, enabling the synchronization of customer-controlled devices with grid requirements.

Message Queues

Message queuing systems are critical for managing the high-frequency data streams generated by real-time energy monitoring and grid interactions. For example, EV chargers and renewable energy systems produce a continuous flow of timestamped data that must be processed without delay. Message queues buffer this data, ensuring that energy consumption patterns, DER outputs, and market signals are transmitted reliably to analytics systems for immediate decision-making.

Databases

Databases store structured and unstructured data, enabling historical tracking, analysis, and real-time decision-making. This data repository supports long-term analysis of energy patterns and is essential for identifying trends that inform grid management.

Databases allow for effective data organization and retrieval, essential for ongoing analysis, real-time decision-making, and long-term planning. They provide the storage backbone needed to support scalable, high-performance data operations.

Data Lakes/Warehouses

Data lakes provide a centralized repository for raw data collected from EVs, energy meters, renewable systems, and market interactions. This allows for flexible data exploration, such as analyzing historical trends in energy demand and renewable generation. Data warehouses, in contrast, organize structured data for fast, query-optimized analytics, enabling customer insights and decision-making for energy optimization and market participation.

Data Integration and ETL Tools

The wide variety of data sources in this use case—ranging from EV sensors to smart appliances and renewable energy systems—requires robust integration and ETL tools. These tools consolidate, clean, and standardize the data, ensuring consistent inputs for analytics and reporting. For instance, ETL processes can merge data from EV charging cycles with renewable energy availability, enabling dynamic optimization of charging schedules.

Middleware layer

Data Spaces

The middleware layer incorporates secure data spaces to enable seamless and compliant data exchange between stakeholders, such as customers, transmission system operators (TSOs), distribution system operators (DSOs), retailers, and aggregators. These data spaces ensure data sovereignty and facilitate cross-border interoperability, accommodating the diverse regulatory requirements of different EU member states. They also support the integration of virtual energy communities and demand-side flexibility markets, promoting collaboration while maintaining secure and controlled data sharing.

Electricity Market Integration

The middleware layer facilitates interaction with electricity market platforms, enabling access to trading mechanisms for power and flexibility in day-ahead, intraday, and balancing markets. It integrates real-time market signals into operational decision-making for both individual customers and virtual energy communities, ensuring that all actions comply with European electricity market standards. This capability is essential for enabling the ODP to dynamically align supply, demand, and grid operations.

Smart Home Integrations

Middleware tools in this layer enable direct integration with smart home systems, supporting real-time interaction with devices such as heating, ventilation, and air conditioning (HVAC) systems, EV chargers, and other controllable loads. These tools facilitate two-way communication between the ODP and connected devices, enabling automatic demand response and personalized energy management. By supporting a wide range of communication protocols and device ecosystems, the middleware ensures interoperability and scalability for interacting with smart devices in diverse home environments.

Business layer

AI Models for Grid Load Prediction and Optimization

The application layer employs advanced AI models to analyze historical and real-time data, enabling accurate predictions of grid load and energy demand. These models optimize energy dispatch, balance supply and demand, and enhance the integration of renewable energy sources by dynamically adjusting to fluctuating grid conditions. By leveraging machine learning and predictive analytics, these tools support proactive grid management and ensure stability while maximizing the use of green energy.

Weather Forecasting Algorithms

Weather forecasting algorithms are integrated into the application layer to predict meteorological conditions that influence renewable energy generation and grid load. By combining real-time weather data with historical patterns, these algorithms help grid operators and virtual energy communities anticipate fluctuations in renewable energy availability. This predictive capability enhances decision-making, ensuring that energy strategies align with changing environmental conditions.

Virtual Energy Community Management Tools

The application layer enables the management of virtual energy communities, facilitating the aggregation of distributed energy resources (DERs) and controllable loads into unified market-facing entities. These tools support community participation in electricity markets, automate bidding processes, and manage settlements for shared benefits. By integrating forecasting, optimization, and real-time market interactions, virtual energy community tools empower customers to actively contribute to energy markets while promoting renewable energy usage.

Financial Settlement Tools

Financial settlement tools within the application layer automate the billing and revenue distribution processes for energy usage, flexibility services, and market participation. These tools integrate data from various sources to calculate accurate financial transactions, ensuring compliance with cross-border regulations. By streamlining settlement processes, they provide transparency and efficiency, benefiting both individual customers and virtual energy communities.

Application layer

Recommendation Service

The business layer integrates AI-driven recommendation services to analyze energy consumption patterns, grid vulnerabilities, and renewable energy availability. By processing historical and real-time data, these services provide actionable insights to end-users, helping them optimize energy usage, reduce costs, and support grid stability. Recommendations are tailored to individual users and delivered through intuitive interfaces such as mobile apps or energy management systems (EMS), encouraging active participation in energy-saving initiatives and green transition efforts.

Energy Usage Visualizations

Energy usage visualizations are a key feature of the business layer, offering real-time dashboards and interactive tools to display consumption data, renewable energy contributions, and flexibility metrics. These visualizations empower users with insights into their energy behavior, enabling them to monitor trends, identify inefficiencies, and make data-driven decisions. By simplifying complex energy data into accessible visual formats, these tools enhance user engagement and awareness of energy management practices.

Use case II: AI-driven ODP for integration of EVs, ETs, RES and grid

Use Cases II: AI-driven ODP for integration of EVs, ETs, RES and grid focus on integrating RESs with dynamic weather adaptation and grid management to enhance energy sustainability and efficiency. By leveraging real-time weather data, AI-driven forecasting, and renewable energy monitoring, these use cases aim to optimize energy production, balance grid loads, and mitigate the intermittency of RESs. The inclusion of EVs further supports grid flexibility through dynamic charging and demand-response programs, fostering a transition toward a low-carbon energy system.

Requirements

Developing an AI-driven ODP for the integration of EVs, RESs, and the electrical grid necessitates a comprehensive set of requirements to ensure efficient, reliable, and sustainable operations. The following requirements are needed for the ODP to succeed:

1. **Data Acquisition and Management**:
    - **Comprehensive Data Collection**: Implement systems to gather real-time data from EVs, EV charge point infrastructure, RES installations, environmental sensors, weather forecasting services, and energy markets.
    - **Robust Data Communication**: Utilize secure and efficient protocols to transmit and receive data between various components, ensuring seamless integration and interoperability.
    - **Scalable Data Storage**: Deploy infrastructure capable of handling large volumes of diverse data, facilitating both real-time analytics and long-term historical analysis.
2. **System Integration and Interoperability**:
    - **Seamless Integration with Existing Systems**: Ensure compatibility with current grid management systems, EV charging networks, and RES controllers to leverage existing infrastructure.
    - **Compliance with EU Data Spaces**: Align data management practices with European Union data space initiatives to ensure regulatory compliance and facilitate cross-border data collaboration.
3. **Advanced Analytics and Optimization**:

- **Predictive Load Management**: Employ AI algorithms to forecast grid load and optimize energy distribution, balancing supply and demand effectively.
- **Dynamic Demand Response**: Enable the platform to react promptly to grid demands, adjusting EV charging schedules and RES outputs to maintain stability.
- **Optimal Routing for EVs**: Provide real-time navigation assistance for EV users, considering factors like battery levels, traffic conditions, and charging station availability.
- **Accurate Weather Forecasting**: Integrate precise weather data to predict RES generation and adjust operations accordingly.

4. **User Interaction and Administration**:
    - **Interactive User Interfaces**: Develop user-friendly platforms for stakeholders to interact with the ODP, access information, and control relevant aspects of the system.
    - **Charging Infrastructure Guidance**: Offer EV users directions to nearby charging points, including real-time availability and reservation options. This could be provided via smartphone apps or in car navigation systems.
    - **Operational Insights**: Provide comprehensive dashboards displaying system performance, energy usage, and other critical metrics for informed decision-making.
    - **Administrative Tools**: Equip administrators with tools to manage system configurations, user access, and monitor overall health and security.

Table 3**Error! Reference source not found.** provides an overview of the technical r equirements and technologies needed for use case II. They will be discussed in detail in the following sections.

Table 33: Use case II requirements

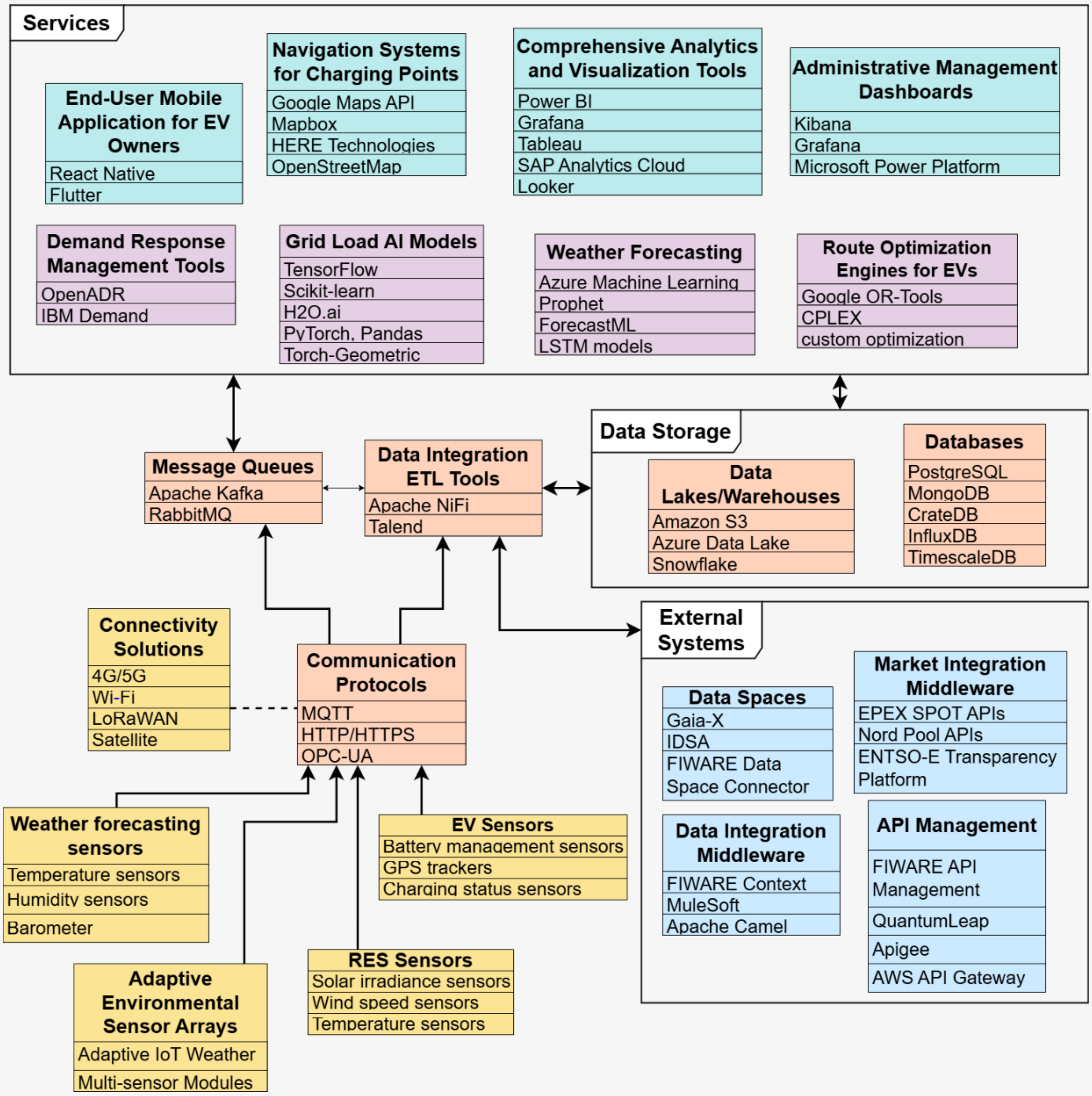
Architectural Layer	Requirement	Type of Technology	Main Required Technologies
Perception Layer	Collect data on vehicles	Ev sensors	Battery management sensors, GPS trackers, charging status sensors
	Collect data on RES	RES sensors	Solar irradiance sensors, wind speed sensors, temperature sensors
	Collect data on	Adaptive Environmental Sensor Arrays	Adaptive IoT Weather Nodes, Multi-sensor Modules

	environmental conditions		
	Collect data on weather conditions	Weather forecasting sensors	Temperature and humidity sensors, barometers, anemometers, rain gauges, weather stations
	Transmit data	Connectivity solutions	4G/5G, Wi-Fi, LoRaWAN, Satellite
Data Layer	Receive data	Communication Protocols	MQTT, HTTP/HTTPS, OPC-UA
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, MongoDB, CrateDB, InfluxDB, TimescaleDB
	Store big data	Data Lakes/Warehouses	Amazon S3, Azure Data Lake, Snowflake
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend
Middleware Layer	Integrate with existing systems	Data Integration Middleware	FIWARE Context Broker, MuleSoft, Apache Camel
	Provide clean APIs	API Management	FIWARE API Management, QuantumLeap, Apigee, AWS API Gateway
	Integrate with EU data spaces	Data Spaces	FIWARE Data Space Connector, Gaia-X, IDSA
	Collect market data	Market Integration Middleware	EPEX SPOT APIs, Nord Pool APIs, ENTSO-E Transparency Platform
Business Layer	Predict grid load and provide optimisations	AI Models for Grid Load Prediction and Optimization	TensorFlow, Scikit-learn, H2O.ai, PyTorch, Pandas, Scikit-learn, Torch-Geometric
	React to demands of the grid	Demand Response Management Tools	OpenADR, IBM Demand Response
	Provide optimal routes for vehicles	Route Optimization Engines for EVs	Google OR-Tools, CPLEX, custom optimization algorithms

	Provide accurate weather forecasts	Weather Forecasting Algorithms	Azure Machine Learning, Prophet, ForecastML, LSTM models
Application Layer	Enable users to interact with the ODP	End-User Mobile Application for EV Owners	Custom mobile app development frameworks (e.g., React Native, Flutter), integration with vehicle telematics and charging infrastructure APIs
	Provide directions to charging points	Navigation Systems for Charging Points	Google Maps API, Mapbox, HERE Technologies, OpenStreetMap
	Provide insights into the ODP	Comprehensive Analytics and Visualization Tools	Power BI, Grafana, Tableau, SAP Analytics Cloud, Looker
	Provide adminitration tools	Administrative Management Dashboards	Grafana, Kibana, Microsoft Power Platform

Figure 3 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 3: Use Case II Technology Diagram



Perception layer

EV Sensors

EV sensors capture critical data such as battery health, charging status, and the vehicle's global positioning system (GPS) location. This data allows the platform to monitor EV energy demands and adjust charging schedules according to grid load and RES availability, optimizing the energy network.

Real-time data from EV sensors is essential for understanding energy demands across the grid. By aligning EV charging patterns with grid requirements, the platform can prevent overloading and ensure a balanced energy supply.

RES Sensors

RES sensors monitor the performance of renewable energy sources, such as solar panels and wind turbines. They collect data on energy output and environmental conditions that influence production, helping the platform adjust energy flows based on renewable energy availability.

RES data helps predict the amount of renewable energy entering the grid, which is vital for balancing with EV demand. By analysing trends in RES output, the system can plan charging schedules and adjust grid interactions to optimize renewable energy use.

Adaptive Environmental Sensor Arrays

Advanced sensing systems designed to monitor a combination of environmental parameters critical to renewable energy generation and grid load balancing. These sensors integrate multiple functionalities into a single unit, enabling efficient data collection and processing for real-time energy optimization.

These sensors collect data on solar irradiance, wind speed, temperature, and humidity. They use self-calibration to maintain accuracy under dynamic environmental conditions, ensuring reliable inputs for forecasting energy production and grid adjustments.

Sensors combining multiple data sources have been used in EU Projects, such as Smart farming.[1]

Weather Forecasting Sensors

Weather sensors collect meteorological data that affects energy generation from RESs and impacts grid load patterns. For example, sensors measure temperature, humidity, and wind conditions, which are critical for predicting renewable energy availability.

Weather data enhances energy production forecasts by providing an accurate picture of conditions that impact RES output. This information is crucial for balancing grid load and planning EV charging in a way that aligns with renewable energy availability.

[1] https://digital-strategy.ec.europa.eu/en/policies/iot-investing

Connectivity Solutions

Connectivity solutions ensure that data captured by sensors can be continuously and securely transmitted to the ODP. Reliable connectivity options like 4G/5G, LPWAN, and Ethernet support data transfer in real-time, allowing for consistent monitoring and enabling timely responses to operational changes.

Data layer

Communication Protocols

Secure, standardized communication protocols enable real-time data exchange between EVs, RESs, and the central platform. These protocols manage data flow and ensure that data can be transmitted across the network safely and consistently.

Communication protocols ensure a stable and secure transfer of critical data, allowing the platform to respond in real-time to EV and RES conditions. This real-time capability is essential for adjusting grid load dynamically.

Message Queues

Message queues manage high-frequency data streams and maintain a consistent flow of data between the perception and processing layers, as well as within the processing layers themselves. They help manage the volume and speed of data collected from EVs, RESs, and external sources, ensuring that no data is lost or delayed. By buffering incoming data, message queues allow the platform to scale reliably, accommodating large data volumes in an organized manner even as the system grows. This capability is critical for timely analysis, decision-making, and responding to rapidly changing grid conditions.

The use of message queues enhances both scalability and reliability by ensuring that data flows smoothly under high load, preventing bottlenecks and maintaining data availability across the platform.

Databases

Databases store structured and unstructured data, enabling historical tracking, analysis, and real-time decision-making. This data repository supports long-term analysis of energy patterns and is essential for identifying trends that inform grid management.

Databases allow for effective data organization and retrieval, essential for ongoing analysis, real-time decision-making, and long-term planning. They provide the storage backbone needed to support scalable, high-performance data operations.

Data Lakes/Warehouses

Data Lakes and Warehouses serve as centralized repositories that aggregate vast amounts of diverse data, including real-time weather information, energy production metrics from RESs, and grid performance data. This centralization facilitates advanced analytics and machine learning applications, enabling operators to predict energy generation patterns, optimize grid stability, and effectively manage the variability inherent in renewable energy sources. By storing both structured and unstructured data, these systems support comprehensive analysis, informing decisions that enhance the integration of renewables into the energy mix.

Data Integration and ETL Tools

Data Integration and ETL Tools are essential for consolidating, cleansing, and standardizing data from multiple sources such as weather stations, RESs, and grid sensors. They ensure that the data feeding into analytics platforms is accurate and consistent, which is crucial for reliable forecasting and grid management. By automating data preparation processes, these tools enable timely insights, allowing operators to respond swiftly to changing conditions and maintain grid reliability amidst the dynamic inputs from renewable energy sources.

Middleware layer

Data Integration Middleware

Data integration middleware supports interoperability across diverse platforms, ensuring that data from EVs, RESs, and grid operators can be exchanged seamlessly and used by the platform.

Middleware allows for efficient, consistent data exchange and aggregation, essential for managing cross-border energy systems and integrating diverse data formats.

API Management

API management tools secure and control access to data, enabling streamlined data sharing between external platforms, time-series data retrieval, and stakeholders, e.g charging point operators, DSOs, electric truck (ET) owner companies etc.

API management provides secure, regulated access to system data, ensuring data consistency and facilitating integration with energy markets and external platforms.

Market Integration Middleware

This middleware connects the platform with European electricity trading markets, enabling EVs and RESs to participate in real-time energy trading and ancillary service markets.

Integrating with trading platforms allows EVs and RESs to buy or sell energy based on real-time conditions, enhancing grid stability and optimizing resource usage.

Business layer

AI Models for Grid Load Prediction and Optimization

AI models analyse historical and real-time data to predict grid load and optimize the distribution of energy across EV charging stations. These models apply machine learning techniques to forecast future demand, allowing grid operators to proactively allocate resources based on expected energy needs and renewable energy availability.

Predictive modelling is essential for maintaining grid stability by aligning energy supply with fluctuating renewable sources and demand from EVs. This approach helps avoid overloading the grid, maximizing the use of renewable energy, and minimizing the environmental impact of energy distribution.

Complex models, such as graph-based neural networks (using Torch-Geometric) and long short-term memory (LSTMs) networks are implemented to model the spatio-temporal dependencies to design more accurate models.

Demand Response Management Tools

Demand response management tools are used to dynamically adjust EV charging rates and RES integration based on real-time conditions. These tools enable automated adjustments to charging schedules and grid interactions to reduce peak load, preventing grid overload and enhancing the utilization of renewable resources.

By responding to real-time changes in grid load and renewable energy availability, demand response tools help align energy consumption with the most sustainable and cost-effective sources. This alignment supports efficient grid management and reduces the need for non-renewable energy sources.

Route Optimization Engines for EVs

Route optimization engines calculate optimal routes for EVs by taking into account available charging stations, energy constraints, and traffic conditions. These tools help EVs reduce energy usage by guiding them to the nearest available charging points, aligning with renewable energy availability and optimizing travel efficiency.

Optimized routing supports efficient energy use and reduces the overall carbon footprint of EV operations. By factoring in real-time data on charging station availability and energy constraints, these engines contribute to a more sustainable, grid-aligned approach to EV mobility.

Weather Forecasting Algorithms

Weather forecasting algorithms analyse meteorological data to predict conditions that impact renewable energy generation and grid load. By incorporating weather forecasts, these algorithms help grid operators plan energy distribution and adjust EV charging schedules in anticipation of RES fluctuations.

Accurate weather forecasting allows the platform to anticipate changes in RES output, supporting proactive grid management and aligning EV charging with periods of high renewable availability. This predictive capability optimizes renewable energy use and reduces reliance on non-renewable sources.

Application layer

End-User Mobile Application for EV Owners

The mobile application offers EV owners easy access to real-time information about charging station availability, optimal charging times, energy costs, and vehicle status. By integrating with charging infrastructure and vehicle telematics, the app provides a user-friendly way for EV owners to manage their charging needs efficiently.

A mobile app improves the user experience by giving EV owners valuable, real-time data to inform charging decisions. With accessible, on-the-go information, users can optimize their charging schedules, reducing costs and aligning with grid and renewable energy availability.

Navigation Systems for Charging Points

The navigation system provides turn-by-turn directions to available charging stations, incorporating real-time data on station availability and traffic conditions. This feature helps EV owners quickly locate charging points, reducing energy use associated with finding charging locations and ensuring efficient travel.

Efficient navigation reduces time spent searching for charging stations, decreasing unnecessary energy use and supporting a streamlined EV experience. By helping EVs find nearby charging stations, the platform optimizes energy use and aligns EV routes with grid needs. OpenStreetMap (OSM) is widely used in EU-supported projects, for example the European Comission had az OSM-based hackathon for sustainable cities in 2022.[2]

Comprehensive Analytics and Visualization Tools

Analytics and visualization tools provide dashboards, trend analysis, and reporting on metrics such as grid load, EV charging status, renewable energy output, energy costs, and sustainability achievements. These tools allow stakeholders to view real-time insights and monitor performance against sustainability and operational goals.

Real-time and historical insights from analytics tools support data-driven decision-making, enabling grid operators to make adjustments that optimize energy use and ensure grid reliability. These tools help track compliance with environmental standards and support long-term planning for sustainability.

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[2] https://commission.europa.eu/news/un-ec-and-openstreetmap-hackathon-sustainable-cities-2022-10-11_en

Administrative Management Dashboard

The Administrative Management Dashboard provides platform operators with a centralized interface to oversee system performance, configure settings, and ensure compliance with operational and regulatory standards. The tool enables administrators to monitor grid load, energy usage, renewable energy integration, and EV charging activity in real time, while also offering diagnostic tools for troubleshooting and optimization.

Administrators can track system health, generate compliance reports, manage role-based access, and receive alerts for critical events. The dashboard integrates with middleware, data layers, and API management platforms to provide a unified view of the platform. A robust administrative management tool ensures that the platform operates efficiently, with minimal downtime. It empowers operators to identify and resolve issues proactively, enforce security policies, and align operations with grid and energy market requirements, enhancing overall system reliability and resilience.

Use case III: Digitalisation of energy storage and reuse in Data Centers

Use Case III: Digitalisation of energy storage and reuse in Data Centers focuses on improving the energy efficiency and sustainability of data centers by integrating advanced energy storage, renewable energy systems, and waste heat reuse technologies. By digitalizing these processes through an ODP, this use case enables real-time monitoring, optimized energy management, and the provision of flexibility services to the grid. It aims to reduce operational costs, enhance energy utilization, and transform data centers into active contributors to sustainable energy systems.

Requirements

Digitalizing energy storage and reuse in data centers necessitates a tailored approach to enhance operational efficiency, sustainability, and resilience. To facilitate this, the following requirements need to be met:

1. **Real-Time Monitoring and Control**: Implement advanced sensors and control systems to monitor energy storage levels, power distribution, and environmental conditions within the data center. This enables immediate adjustments to energy flows, optimizing performance and preventing potential issues.
2. **Robust Data Communication**: Utilize high-speed, secure communication protocols to facilitate seamless data exchange between energy management systems, IT infrastructure, and facility operations. This integration ensures cohesive operation and efficient energy utilization.
3. **Scalable Data Storage Solutions**: Deploy scalable storage systems capable of handling vast amounts of data generated by monitoring equipment and operational logs. This supports comprehensive analysis and long-term data retention for compliance and optimization purposes.

4. **Efficient Data Processing Pipelines**: Establish high-throughput data pipelines to process and analyze incoming data swiftly, enabling real-time decision-making and predictive maintenance.
5. **Predictive Analytics for Energy Management**: Leverage machine learning algorithms to forecast energy demand and supply, facilitating proactive management of energy resources and enhancing sustainability efforts.
6. **User-Friendly Dashboards and Reporting Tools**: Develop intuitive interfaces that provide stakeholders with clear insights into energy consumption patterns, storage status, and system performance, aiding in informed decision-making.
7. **Emergency Response Mechanisms**: Implement automated protocols to manage power outages or equipment failures, ensuring continuity of operations and safeguarding critical data center functions.
8. **Compliance with Data Governance Standards**: Ensure that data management practices align with regional regulations, such as the European Union's data governance standards, to facilitate cross-border data collaboration and maintain compliance.

Table 44 provides an overview of the technical requirements and technologies needed for use case III. They will be discussed in detail in the following sections.

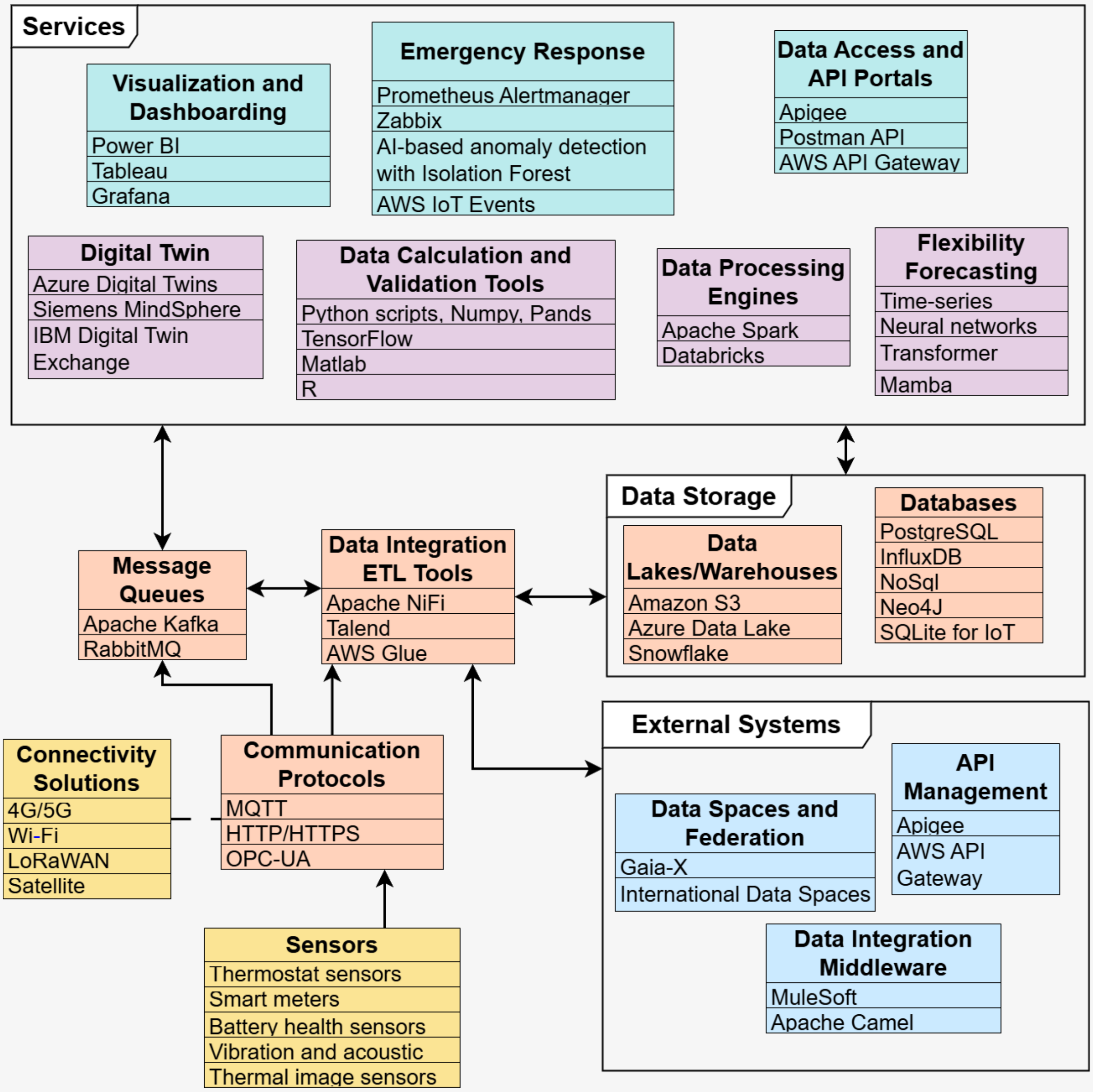
Table 44: Use case III requirements

Architectural Layer	Requirement	Type of Technology	Main Required Technologies
Perception Layer	React to the physical world	Sensors	Smart meters, temperature sensors, battery health sensors, vibration and acoustic sensors, thermal image sensors
	Transmit data	Connectivity Solutions	4G/5G, LPWAN, Ethernet, BLE, PoE
Data Layer	Receive data	Communication Protocols	MQTT, HTTP/HTTPS
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, InfluxDB, NoSQL, Neo4J, SQLite for IoT
	Store big data	Data Lakes/Warehouses	Amazon S3, Azure Data Lake, Snowflake
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend, AWS Glue

Middleware Layer	Integrate with existing systems	Data Integration Middleware	MuleSoft, Apache Camel
	Provide clear APIs	API Management Tools	Apigee, AWS API Gateway
	Integrate with EU data spaces	Data Spaces and Federation	Gaia-X, International Data Spaces (IDS)
Business Layer	Run simulations	Digital Twin	Azure Digital Twins, Siemens MindSphere, IBM Digital Twin Exchange
	Validate data	Data Calculation and Validation Tools	Python scripts, TensorFlow, Numpy, Pandas, Matlab, R
	Transform data	Data Processing Engines	Apache Spark, Databricks
	Predict future supply and demand	Flexibility Forecasting	Time-series analysis (ARIMA, Prophet), neural networks (LSTM), Transformer, Mamba
Application Layer	Provide insights into operations	Visualization and Dashboarding	Power BI, Grafana, Tableau
	Gracefully handle emergencies	Emergency Response	Prometheus Alertmanager, Zabbix, AI-based anomaly detection with Isolation Forest, Autoencoder models, AWS IoT Events
	Provide data for users	Data Access and API Portals	Apigee, Postman API Portal, AWS API Gateway

Figure 4 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 4: Use Case III Technology Diagram



Perception layer

Sensors

Sensors, such as smart meters and temperature sensors, monitor real-time metrics within the data center, offering insights into energy use, thermal conditions, and operational loads. These metrics form the foundation for tracking energy consumption patterns, identifying areas for improvement, and informing resource allocation decisions. Thermal conditions are also monitored using infrared imaging sensors.

Battery health sensors can monitor the spare batteries of data centers to avoid data loss. Vibration and acoustic sensors can detect anomalies of hardware thus enables engineers to prevent failure.

Connectivity Solutions

Connectivity solutions ensure that data captured by sensors can be continuously and securely transmitted to the ODP. Reliable connectivity options like 4G/5G, LPWAN, and Ethernet support data transfer in real-time, allowing for consistent monitoring and enabling timely responses to operational changes. BLE (Bluetooth Low Energy) is an energy-efficient, short-range communication for localized sensor networks and are useful for equipment monitoring in smaller zones, such as data centers. PoE (Power over Ethernet) combines power and data transmission over a single cable, simplifinig wires and reduces power reduncancy.

Data layer

Communication Protocols

Communication Protocols enable seamless, secure data exchange between data center devices and storage systems, ensuring that energy consumption, environmental metrics, and operational data flow reliably across the platform. By facilitating real-time and continuous data transfer, these protocols support efficient data processing and immediate availability of critical information, enabling the platform to analyze and respond to operational changes promptly. Communication protocols also standardize data transmission across varied devices and networks, enhancing compatibility and simplifying data integration across the data center's infrastructure.

Message Queues

Message Queues manage the flow of high-frequency data from sensors to storage and applications, buffering data to maintain a consistent and organized stream. By reducing latency and handling data volume fluctuations, message queues support continuous availability and allow the data platform to scale as the data center grows. This buffered flow is crucial for real-time analytics and operational responsiveness, as it ensures that data is available when needed without overwhelming the system during peak loads.

Databases

Databases provide a structured environment for storing both real-time and historical data on energy usage, environmental metrics, and operational efficiency. These storage solutions enable long-term tracking and analysis, allowing the platform to capture trends over time and support strategic decision-making. By maintaining a robust and easily accessible data repository, databases contribute to a stable foundation for reporting and predictive analytics, ensuring that data is preserved and retrievable for in-depth analysis.

Data Lakes/Warehouses

Data Lakes/Warehouses aggregate and centralize large volumes of diverse data, providing a scalable solution for long-term storage and advanced analysis. These systems allow the data center to store raw data from multiple sources in a single repository, supporting flexibility in data exploration and deeper analysis. By centralizing data, lakes and warehouses enable advanced analytics, allowing data center operators to derive insights from both structured and unstructured data, informing energy optimization and long-term planning.

Data Integration and ETL Tools

Data Integration and ETL Tools consolidate, clean, and standardize data from multiple sources, preparing it for downstream analysis. These tools ensure that data from various data center systems is consistent and accurate, which is essential for effective analytics and reporting. By automating the data preparation process, ETL tools enable efficient data flow into the platform, supporting timely decision-making and enhancing data quality for real-time insights and long-term trend analysis.

Middleware layer

Data Integration Middleware

Data Integration Middleware facilitates seamless data exchange between different systems within the data center and with external energy platforms. This middleware ensures that data from diverse sources, such as energy usage sensors and operational metrics, is accessible and usable across the platform. By enabling interoperability, data integration middleware supports a unified data environment, allowing the platform to provide comprehensive insights into data center operations.

API Management Tools

API Management Tools securely manage and control access to data via APIs, facilitating data sharing within the data center and with external stakeholders, e.g. DSOs, service providers, users etc. These tools allow the platform to handle high-volume data requests while ensuring scalability and data security. By centralizing API management, these tools enhance visibility into data interactions, supporting consistent and secure access across the platform.

Data Spaces and Federation

Data Spaces and Federation frameworks enable secure, compliant data sharing across organizational and geographic boundaries, ensuring data privacy, ownership, and control. These solutions allow the data center to share critical information with energy providers, regulatory bodies, and other stakeholders without compromising on data security. By supporting data sovereignty, data spaces ensure that shared data remains under the data center's control, meeting compliance requirements and facilitating trusted cross-border data exchange.

Business layer

Digital Twin

Digital twins provide a virtual model of the data center, allowing operators to simulate real-time operations and conduct predictive analysis. This technology enables proactive management by forecasting resource needs, optimizing energy usage, and identifying potential inefficiencies before they impact operations. Digital twins support strategic decision-making by offering a detailed, interactive view of the data center's energy dynamics.

Data Calculation and Validation Tools

Calculation and validation tools process raw data to provide accurate metrics on energy usage, storage capacity, and operational efficiency. These tools validate data consistency and reliability, ensuring that the platform can make informed decisions and meet compliance standards. They are essential for monitoring performance and maintaining accuracy in reporting.

Data Processing Engines

Data processing engines enable large-scale data transformations and support real-time analysis. By executing workflows that process energy data continuously, these engines allow the platform to adapt to changes in demand, ensuring operational agility and resource optimization. They are crucial for handling large volumes of data and responding to shifting operational needs.

Flexibility Forecasting

Flexibility forecasting uses predictive models to estimate energy storage needs and optimize resource allocation based on anticipated demand patterns. By enabling data center operators to prepare for changes in energy requirements, flexibility forecasting improves resource management and enhances the platform's overall responsiveness. More complex algorithms which can effectively handle large amount of heterogenous data are also implemented to provide accurate foracasting.

Application layer

Visualization and Dashboarding

Visualization and dashboarding tools display real-time data on energy metrics, operational performance, and environmental conditions. These tools present complex data in a user-friendly format, allowing data center operators to make informed decisions quickly. Dashboards provide insights into energy usage patterns, operational efficiencies, and areas for improvement, enabling effective monitoring and management.

Emergency Response

Emergency response systems provide real-time monitoring and alerting to detect critical incidents in the data center. These systems allow operators to respond quickly to anomalies, minimizing operational disruptions and ensuring data center stability. By enabling proactive incident management, emergency response tools help maintain service continuity and operational resilience.

Data Access and API Portals

Data access and API portals provide stakeholders with secure, managed access to energy usage and operational data. These portals enable stakeholders to retrieve specific data sets and interact with the platform via APIs, supporting data sharing and collaboration while maintaining security. API portals facilitate controlled access to valuable information, enhancing collaboration with partners and regulatory bodies.

Use case IV: Digital permits for drone-based inspections in linear infrastructures

Use Case IV: Digital permits for drone-based inspections in linear infrastructures aims to streamline and digitalize the permit process for drone-based inspections of linear infrastructures, especially in cross-border scenarios. By integrating blockchain technology into an ODP, the use case reduces regulatory delays and ensures compliance with legal requirements. The platform facilitates collaboration among stakeholders, automates permit validation, and supports faster, safer infrastructure inspections. This approach modernizes infrastructure management, improving efficiency and reducing disruptions.

Requirements

Implementing digital permits for drone-based inspections in linear infrastructures requires a comprehensive platform to ensure efficient data management, regulatory compliance, and operational optimization. The following key requirements are needed to complete the platform:

1. **Data Acquisition and Management**:

- **Comprehensive Data Collection**: Implement systems to gather real-time data from drones, including flight parameters, inspection imagery, and environmental conditions.
- **Weather Data Integration**: Incorporate accurate weather information to plan and adjust drone operations, ensuring safety and compliance with regulatory standards.
- **Robust Data Communication**: Utilize secure and efficient protocols to transmit and receive data between drones, control centers, and relevant authorities, ensuring seamless information flow.
- **Scalable Data Storage**: Deploy infrastructure capable of handling large volumes of data, including high-resolution images and videos, facilitating both real-time analysis and long-term archival.

2. **System Integration and Interoperability**:
    - **Blockchain Integration for Flight Permits**: Implement blockchain technology to manage and verify digital permits, ensuring transparency, security, and immutability in the authorization process.
    - **Flight Systems Compatibility**: Ensure seamless integration with existing flight management systems and air traffic control to coordinate drone operations effectively.
    - **Compliance with EU Data Spaces**: Align data management practices with European Union data space initiatives to ensure regulatory compliance and facilitate cross-border data collaboration.
3. **Operational Management and Compliance**:
    - **Automated Permit Management**: Develop systems to streamline the application, approval, and management of drone permits, reducing administrative burdens and expediting operational readiness.
    - **Flight Plan Verification**: Implement tools to assess and validate flight plans against regulatory requirements and operational constraints, ensuring safe and compliant drone operations.
    - **Blockchain-Based Compliance Checks**: Utilize blockchain to perform automated compliance verifications, providing an immutable record of adherence to regulations and operational standards.
4. **Optimization and User Interaction**:
    - **Inspection Optimization**: Leverage AI and machine learning algorithms to analyze collected data, optimizing inspection routes and schedules for efficiency and thoroughness.

- **Permit Visibility and Management**: Provide stakeholders with access to a user-friendly interface to view and manage drone permits, enhancing transparency and operational control.
- **Automated Compliance Reporting**: Develop systems to generate and distribute compliance reports automatically, ensuring timely communication with regulatory bodies and stakeholders.

Table 5 provides an overview of the technical requirements and technologies needed for use case IV. They will be discussed in detail in the following sections.

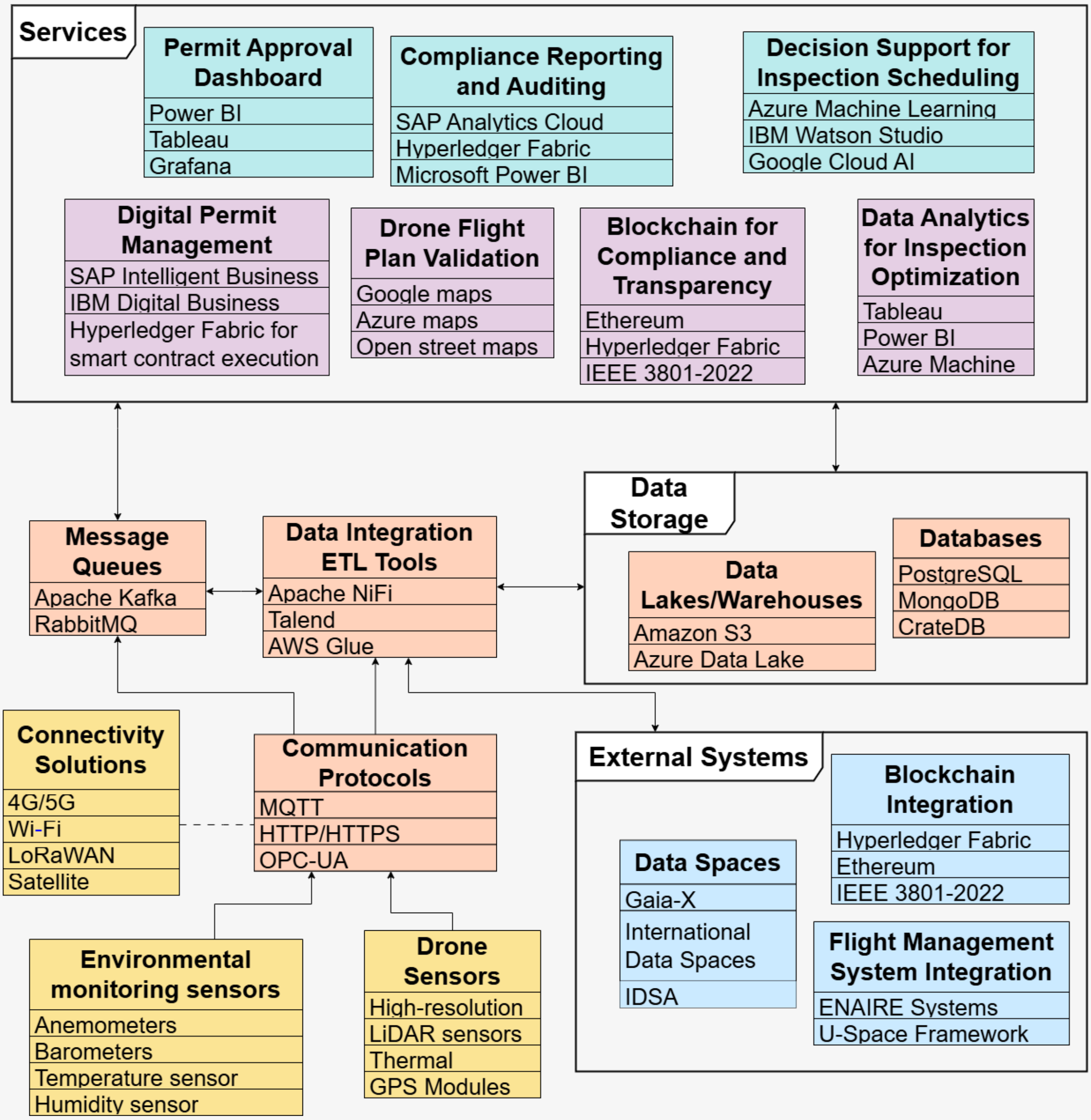
Table 55: Use case IV requirements

Architectural Layer	Requirement	Type of Technology	Main Required Technologies
Perception Layer	Collect drone data	Drone sensors	High-resolution imaging cameras, LiDAR sensors, thermal sensors, GPS modules
	Collect weather data	Environmental monitoring sensors	Anemometers for wind speed, barometers for pressure, temperature and humidity sensors
	Transmit data	Connectivity solutions	4G/5G modules, satellite communication systems, radio-frequency transceivers
Data Layer	Receive data	Communication Protocols	MQTT, HTTP/HTTPS, OPC-UA
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, MongoDB, CrateDB
	Store big data	Data Lakes/Warehouses	Amazon S3, Azure Data Lake
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend
Middleware Layer	Integrate with EU data spaces	Data Spaces	Gaia-X, International Data Spaces (IDS), IDSA Connectors
	Integrate with blockchain flight permits	Blockchain Integration	Hyperledger Fabric, Ethereum, IEEE 3801-2022 Standard for Blockchain-Based Electronic Contracts
	Integrate with flight systems	Flight Management System Integration	ENAIRE Systems (Spain), U-Space Framework

Business Layer	Manage drone permits	Digital Permit Management	SAP Intelligent Business Processes, IBM Digital Business Automation, Hyperledger Fabric for smart contract execution
	Verify flight plans	Drone Flight Plan Validation	Google maps, Azure Maps, open street maps
	Use blockchain for compliance checks	Blockchain for Compliance and Transparency	Ethereum, Hyperledger Fabric, IEEE 3801-2022 Standard for Blockchain-Based Electronic Contracts
	Provide inspection optimisations	Data Analytics for Inspection Optimization	Tableau, Power BI, Azure Machine Learning
Application Layer	Ability to view drone permits	Permit Approval Dashboard	Power BI, Tableau, Grafana
	Automatically provide compliance reports	Compliance Reporting and Auditing	SAP Analytics Cloud, Hyperledger Fabric, Microsoft Power BI
	Provide input on inspection scheduling	Decision Support for Inspection Scheduling	Azure Machine Learning, IBM Watson Studio, Google Cloud AI

Figure 5 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 5: Use Case IV Technology Diagram



Perception layer

Drone Sensors

Drones equipped with advanced sensors capture real-time data during inspections. These include high-resolution cameras for visual inspections, Light Detection and Ranging (LiDAR) for detailed 3D mapping, and thermal sensors for detecting structural anomalies or temperature-related issues. The sensors also provide critical flight data, such as altitude, speed, and position, enabling precise monitoring of inspection operations.

Environmental Monitoring Sensors

Environmental sensors monitor weather conditions, including wind speed, temperature, humidity, and precipitation, which are crucial for safe drone operation. These sensors provide real-time data to ensure that drones operate within optimal weather conditions, reducing risks during inspections.

Connectivity Solutions

Reliable connectivity is essential for real-time communication between drones, operators, and the Operational Digital Platform. Solutions include 4G/5G networks for urban or suburban operations, satellite communication for remote areas, and radio links for direct drone-to-ground station communication. These connectivity options ensure continuous data transmission for flight monitoring, compliance checks, and immediate decision-making.

Data layer

Communication Protocols

Communication protocols ensure secure, real-time data exchange between drones, sensors, regulatory systems, and the Operational Digital Platform. Lightweight protocols like MQTT facilitate telemetry from drones, including location, altitude, and sensor data, while HTTP/HTTPS is used for secure interactions with regulatory APIs and permit validation systems. For direct integration with aviation or infrastructure control systems, industrial protocols like DDS (Data Distribution Service) ensure robust communication.

Message Queues

Message queuing systems are critical for managing high-frequency data streams generated by drone operations and regulatory communications. For example, drones produce continuous data during inspections, such as video feeds, positional telemetry, and environmental readings. Message queues buffer this data, ensuring that it is transmitted reliably to the Operational Digital Platform for real-time permit validation, anomaly detection, and regulatory compliance checks.

Databases

Databases store structured and unstructured data collected from drone inspections, regulatory systems, and flight logs. This data repository supports historical tracking of inspection operations, permit validations, and compliance audits. Databases enable efficient organization and retrieval of data for ongoing analysis, real-time decision-making, and long-term planning, ensuring a scalable, high-performance foundation for operational transparency.

Data Lakes/Warehouses

Data lakes serve as centralized repositories for raw data collected during drone operations, including high-resolution imagery, LiDAR scans, and environmental metrics. This enables flexible exploration and deep analysis, such as reconstructing 3D infrastructure models or correlating inspection data with maintenance schedules. Data warehouses provide structured storage optimized for querying, enabling regulatory reporting and operational insights such as trends in permit validation efficiency or infrastructure condition over time.

Data Integration and ETL Tools

The diverse data sources in Use Case IV, ranging from drones to regulatory systems and infrastructure databases, require robust integration and ETL tools. These tools clean, consolidate, and standardize data, ensuring consistent and reliable inputs for analytics and compliance validation. For instance, ETL processes can merge flight data with regulatory permit approvals, enabling real-time compliance checks and operational optimization.

Middleware layer

Data Spaces

The middleware layer includes secure data spaces to facilitate coordination and data exchange between stakeholders such as infrastructure managers, air traffic controllers, and public authorities. These data spaces ensure compliance with national and regional regulations while maintaining data sovereignty. They enable real-time sharing of drone flight applications, inspection details, and validation statuses, streamlining the bureaucratic process for cross-border operations.

Blockchain Integration

The middleware leverages blockchain to validate, authenticate, and secure digital permits for drone operations. Blockchain ensures transparency and traceability in the permit approval process, reducing the risk of errors and enabling trust among stakeholders. Smart contracts automate the validation workflows, ensuring that all regulatory requirements are met before permits are issued.

Flight Management System Integration

Middleware tools integrate the platform with existing flight management systems to streamline airspace coordination. This integration ensures that real-time flight data is accessible to relevant stakeholders and that drone operations comply with regulations. It also supports communication with air traffic control and flight monitoring systems.

Business layer

Digital Permit Management

The application layer incorporates tools to manage the end-to-end lifecycle of digital permits for drone-based inspections. This includes generating permit requests, validating compliance with regulatory requirements, and issuing approvals or rejections. Automated workflows reduce manual effort and processing time while ensuring adherence to cross-border regulations.

Drone Flight Plan Validation

The application layer supports the validation and optimization of drone flight plans, ensuring compliance with airspace restrictions, weather conditions, and other regulatory constraints. By integrating with real-time data sources such as weather forecasting and air traffic control systems, it ensures operational safety and efficiency.

Blockchain for Compliance and Transparency

Blockchain technology ensures transparency, traceability, and security in the permit management process. Smart contracts automate compliance checks, logging all interactions and validations in an immutable ledger. This reduces the risk of fraud and simplifies auditing.

Data Analytics for Inspection Optimization

Advanced analytics tools process historical and real-time data to optimize drone inspections, prioritize maintenance schedules, and forecast infrastructure vulnerabilities. Insights derived from analytics ensure that inspections are timely and focused on critical infrastructure areas.

Application layer

Permit Approval Dashboard

The business layer provides a centralized dashboard for stakeholders to monitor and manage the digital permit approval process. This includes real-time visibility into the status of permit applications, requests for additional compliance information, and the final validation or rejection of permits. The dashboard simplifies communication among stakeholders, enhancing transparency and reducing delays.

Compliance Reporting and Auditing

The business layer provides comprehensive tools for compliance reporting, enabling stakeholders to generate detailed records of all permit-related activities. Blockchain-based auditing ensures the integrity of these records, offering a transparent and immutable trail of actions for regulatory purposes.

Decision Support for Inspection Scheduling

Decision support tools analyze historical data and real-time inputs (e.g., weather conditions, regulatory constraints) to recommend optimal times for inspections. These tools assist stakeholders in minimizing operational disruptions and ensuring timely maintenance of critical infrastructure.

Use case V: Smart Ports Operations

Use case V: Smart Ports Operations addresses the digital transformation of port operations to enhance efficiency, security, and sustainability. By integrating AI-driven cameras, drones, and environmental sensors with advanced analytics and decision-support systems, it aims to optimize cargo handling, resource allocation, and environmental compliance. The use case also emphasizes stakeholder collaboration and transparent reporting to align port activities with global trade and sustainability goals.

Requirements

Enhancing port operations through digitalization requires a comprehensive platform that integrates real-time monitoring, data management, predictive analytics, and compliance measures. In order for the platform to support this, it needs to adhere to the following requirements:

1. **Real-Time Monitoring and Data Acquisition**:
    - **Operational Monitoring**: Implement advanced sensors and IoT devices to continuously monitor port activities, including vessel movements, cargo handling, and equipment status.
    - **Environmental Monitoring**: Deploy systems to track environmental conditions such as weather, air quality, and water levels, ensuring safety and regulatory compliance.
    - **Secure Data Transmission**: Utilize robust communication protocols to ensure reliable data exchange between both internal and external systems.
    - **Comprehensive Data Integration**: Aggregate data from diverse sources into a unified platform, facilitating seamless information flow and operational coherence.
2. **Data Management and Processing**:

- **Scalable Data Storage**: Implement infrastructure capable of handling large volumes of structured and unstructured data, supporting both real-time analytics and historical data analysis.
- **Efficient Data Movement**: Establish high-throughput data pipelines to process and transfer data swiftly across systems, minimizing latency and ensuring data integrity.
- **Edge Computing Integration**: Leverage edge computing to process data locally at the source, reducing bandwidth usage and enabling faster decision-making.

3. **Predictive Analytics and Optimization**:
   - **Predictive Maintenance**: Utilize machine learning algorithms to anticipate equipment failures and schedule timely maintenance, reducing downtime and operational costs.
   - **Operational Optimization**: Analyze data to optimize port operations, such as berth allocation, cargo loading/unloading, and resource utilization, enhancing efficiency and throughput.
   - **Scenario Planning**: Develop simulation tools to model various operational scenarios, aiding in strategic planning and risk management.
4. **Security and Compliance**:
   - **Security Incident Detection**: Implement systems to identify and respond to security threats, ensuring the safety of port infrastructure and data.
   - **Automated Compliance Reporting**: Develop mechanisms to generate compliance reports automatically, adhering to regulatory standards and facilitating audits.
   - **Regulatory Insights**: Provide stakeholders with up-to-date information on compliance requirements and regulations, ensuring informed decision-making.
5. **User Interaction and Operational Insights**:
   - **Comprehensive Operational Overview**: Offer dashboards that provide real-time visibility into port operations, enabling stakeholders to monitor performance and identify areas for improvement.
   - **Security Overview**: Provide tools to monitor security status across the port, ensuring proactive management of potential threats.
   - **Operational Improvement Recommendations**: Leverage data analytics to identify inefficiencies and suggest actionable improvements to port operations.

Table 6 provides an overview of the technical requirements and technologies needed for use case V. They will be discussed in detail in the following sections.

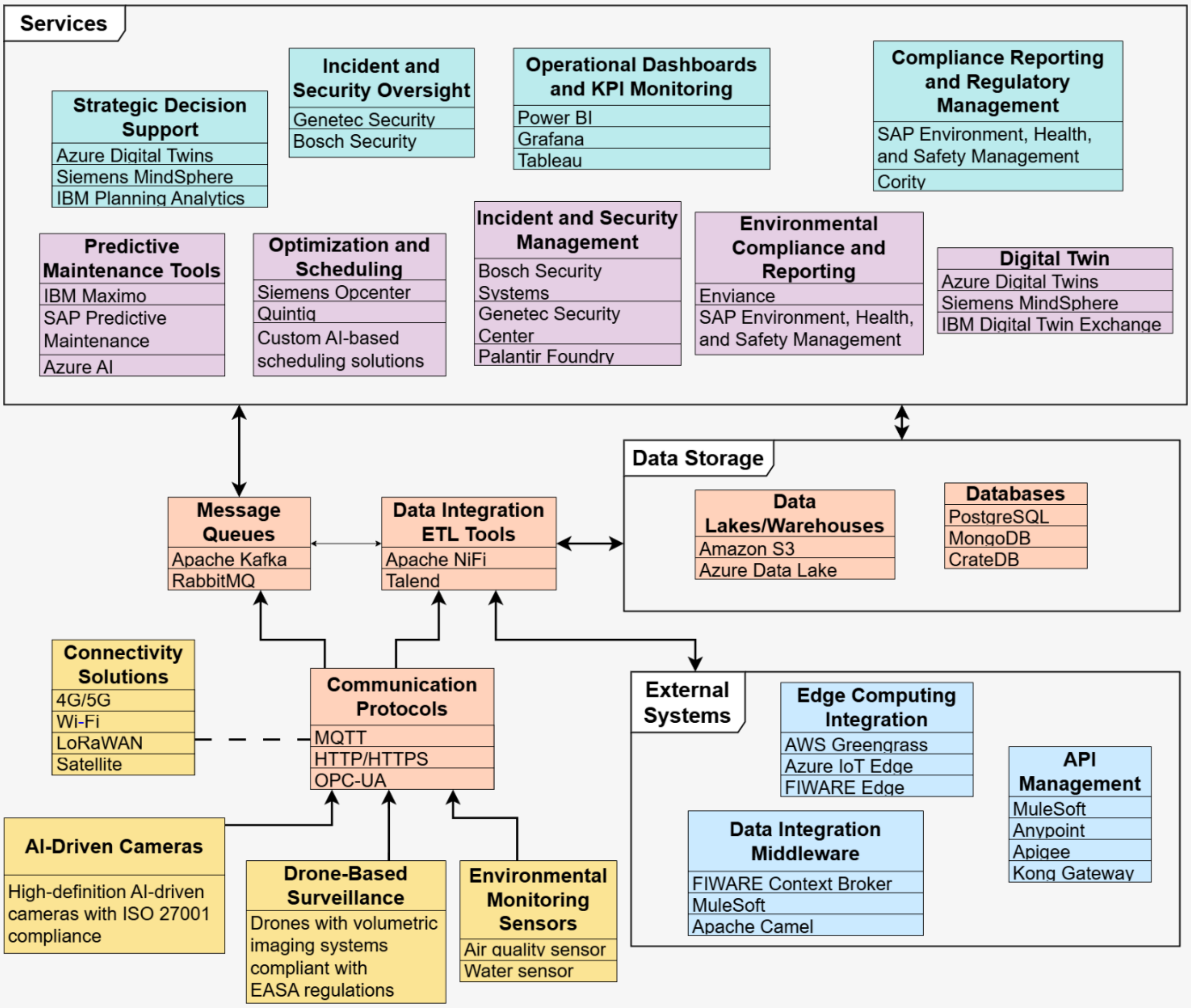
Table 66: Use case V requirements

Architectural Layer	Requirement	Type of Technology	Main Required Technologies
Perception Layer	Monitor port operations	AI-Driven Cameras	High-definition AI-driven cameras with ISO 27001 compliance
	Monitor port operations	Drone-Based Surveillance	Drones with volumetric imaging systems compliant with EASA regulations
	Monitor environmental conditions	Environmental Monitoring Sensors	ISO 14001-compliant air quality and water monitoring sensors
	Transmit data	Connectivity Solutions	Ethernet, 4G/5G, LPWAN
Data Layer	Receive data	Communication Protocols	MQTT, HTTP/HTTPS, OPC-UA
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, MongoDB, CrateDB
	Store big data	Data Lakes/Warehouses	Amazon S3, Azure Data Lake
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend
Middleware Layer	Integrate data from different sources	Data Integration Middleware	FIWARE Context Broker, Apache Camel, Talend
	Provide clean APIs	API Management	Apigee, MuleSoft Anypoint, Kong Gateway
	Integrate with edge computing	Edge Computing Integration	AWS Greengrass, Azure IoT Edge, FIWARE Edge

Business Layer	Provide predictive maintenance	Predictive Maintenance Tools	IBM Maximo, SAP Predictive Maintenance, Azure AI
	Provide port optimisations	Optimization and Scheduling	Siemens Opcenter, Quintiq, custom AI-based scheduling solutions
	Identify security incidents	Incident and Security Management	Bosch Security Systems, Genetec Security Center, Palantir Foundry
	Automatic compliance reporting	Environmental Compliance and Reporting	Enviance, SAP Environment, Health, and Safety Management (EHS)
	Provide scenario planning	Digital Twin for Port Operations	Azure Digital Twins, Siemens MindSphere, IBM Digital Twin Exchange
Application Layer	Provide overview over operations	Operational Dashboards and KPI Monitoring	Power BI, Tableau, Grafana
	Provide insights into compliance and regulations	Compliance Reporting and Regulatory Management	SAP Environment, Health, and Safety Management (EHS), Cority
	Provide an overview over security	Incident and Security Oversight	Genetec Security Center, Bosch Security Incident Manager
	Provide improvements to operations	Strategic Decision Support	Azure Digital Twins, Siemens MindSphere, IBM Planning Analytics

Figure 6 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 6: Use Case V Technology Diagram



Perception layer

AI-Driven Cameras

Intelligent camera systems are strategically deployed throughout the port to monitor critical activities, including ship docking, cargo handling, and crane operations. These cameras provide real-time video feeds and use AI algorithms to detect anomalies, enhancing situational awareness and safety. They support proactive incident management by identifying unauthorized access or operational inefficiencies.

Drone-Based Surveillance

Drones equipped with advanced sensors and imaging technologies conduct aerial surveys of the port. They capture high-resolution data for volumetric measurements of stockpiles, environmental monitoring, and infrastructure inspections. This capability supports inventory management and operational planning.

Environmental Monitoring Sensors

These sensors track air and water quality within the port, monitoring emissions and pollutants. They enable the port to maintain compliance with environmental standards and swiftly address threshold breaches.

Connectivity Solutions

Reliable communication systems ensure the seamless transmission of data from sensors, cameras, and drones to the central FIWARE digital platform. Connectivity options are chosen based on the port's infrastructure and include Ethernet for fixed installations, 4G/5G for mobile assets, and LPWAN for long-range, low-power communication.

Data layer

Communication Protocols

Communication protocols ensure secure and efficient data exchange between sensors, drones, port management systems, and the Operational Digital Platform. Lightweight protocols like MQTT are used for telemetry from IoT sensors, such as cargo tracking devices and environmental monitors. HTTP/HTTPS facilitates secure communication with external systems, including logistics platforms and regulatory authorities, while industrial protocols like OPC-UA ensure robust data transfer within port infrastructure systems.

Message Queues

Message queuing systems manage the high-frequency data streams generated by real-time port operations. For instance, drones capturing aerial imagery, cargo tracking systems transmitting updates, and environmental sensors monitoring emissions generate continuous data that needs to be buffered and processed without delay. Message queues ensure reliable data delivery to analytics and management systems for immediate operational insights.

Databases
Databases store structured and unstructured data from port operations, enabling efficient organization and retrieval for analysis and reporting. Structured data includes cargo manifests, berth schedules, and regulatory compliance logs, while unstructured data encompasses drone imagery, video feeds, and sensor logs. These databases support real-time decision-making and long-term trend analysis for optimizing port operations.

Data Lakes/Warehouses
Data lakes provide centralized storage for raw, unprocessed data collected from IoT sensors, drones, and operational systems. This supports flexible exploration, such as analyzing historical emissions data or reviewing drone footage for infrastructure inspections. Data warehouses, in contrast, organize structured data for rapid querying and reporting, enabling insights into cargo throughput, berth utilization, and compliance with environmental standards.

Data Integration and ETL Tools
Smart ports rely on diverse data sources, including cargo tracking systems, environmental monitors, and regulatory databases. ETL tools consolidate, clean, and standardize this data, ensuring consistency and reliability. These tools are critical for integrating data across multiple sources, enabling analytics that optimize resource allocation, improve operational efficiency, and support regulatory compliance.

Middleware layer

Data Integration Middleware
This layer integrates data from diverse sources, such as AI-driven cameras, drones, environmental sensors, and operational systems. By standardizing and aggregating data streams, the middleware enables interoperability between heterogeneous devices and systems. It supports real-time data fusion for comprehensive situational awareness and operational insights.

API Management
Secure and efficient APIs connect port systems, stakeholders, and external platforms. Middleware handles the flow of data between systems like cargo management, inventory tracking, and port logistics platforms, ensuring consistent access and communication. API gateways enable controlled data sharing with stakeholders, such as shipping companies and environmental agencies, while maintaining compliance with security and privacy regulations.

Edge Computing Integration
Edge computing middleware preprocesses data locally from AI cameras, drones, and sensors, reducing latency and optimizing bandwidth usage. This capability ensures that critical decisions, such as security incident responses or operational adjustments, are made quickly without relying entirely on centralized systems.

Business layer

Predictive Maintenance Tools

By analysing data from sensors, drones, and equipment logs, predictive maintenance tools identify potential failures before they occur. These applications optimize the maintenance schedule for critical infrastructure such as cranes, conveyor belts, and energy systems, reducing downtime and extending equipment lifespans.

Optimization and Scheduling

Optimization tools automate scheduling for port resources, such as berth allocation, crane assignments, and cargo movement. These applications use real-time and historical data to minimize bottlenecks, optimize throughput, and improve turnaround times for ships and cargo. They also support dynamic rescheduling in response to changing conditions, such as delays or equipment outages.

Incident and Security Management

Applications in this category analyze data from AI cameras, drones, and sensors to detect security breaches, operational anomalies, or environmental threshold violations. They provide alerts and recommendations for incident response, ensuring timely action to maintain safety and compliance. Automated workflows ensure that security protocols and incident management steps are consistently followed.

Environmental Compliance and Reporting

Environmental management applications track emissions, water quality, and energy usage, ensuring compliance with sustainability standards. They generate reports for regulatory bodies and stakeholders, documenting the port's adherence to environmental policies and identifying opportunities for reducing the environmental footprint.

Digital Twin for Port Operations

Digital twin applications create virtual models of port infrastructure and processes, allowing operators to simulate scenarios, test optimizations, and forecast outcomes. This enables data-driven decision-making for improving operational efficiency, managing risks, and planning future expansions.

Application layer

Operational Dashboards and KPI Monitoring

The Business Layer includes real-time dashboards that visualize key performance indicators such as berth occupancy, crane utilization, cargo throughput, and environmental metrics. These dashboards empower port managers and stakeholders to monitor operational performance and identify inefficiencies or opportunities for improvement. Customizable interfaces ensure that relevant stakeholders can access tailored views of the data.

Compliance Reporting and Regulatory Management

The Business Layer ensures that the port adheres to local and international regulations by automating compliance reporting for environmental, safety, and operational standards. These tools generate detailed reports for regulators and stakeholders, documenting emissions, waste management, and energy consumption, while providing recommendations for improving sustainability.

Incident and Security Oversight

Business-layer tools facilitate oversight of security incidents and operational anomalies by integrating alerts and reports from the application layer. These systems help coordinate response actions, ensure that standard operating procedures are followed, and document incident resolution for audits and future improvements.

Strategic Decision Support

Strategic decision support tools leverage insights from digital twins and predictive analytics to inform long-term planning, such as infrastructure upgrades, capacity expansion, and sustainability initiatives. These tools enable port authorities to simulate various scenarios and assess the potential impact of changes on operations and financial performance.

Use case VI: Carbon footprint in logistic operations

Use Case VI: Carbon footprint in logistic operations focuses on creating an ODP to provide accurate, standardized, and verifiable data on the carbon footprint (CF) of logistics operations, particularly in port activities. It aims to integrate data from manufacturers, port operators, logistics companies, and maritime transport services to calculate and track the CF of goods transported. This use case addresses the complexity of global supply chains, the lack of standardized CF measurement methods, and the need for reliable CF data to support decision-making.

The platform promotes transparency and competitiveness by enabling users to compare transportation options based on cost, time, and carbon emissions. By leveraging advanced technologies such as IoT sensors, blockchain for data validation, and data analytics, the ODP supports sustainability in logistics operations. It empowers consumers, companies, and port authorities to make informed choices and align with environmental goals, contributing to the green transition in the logistics sector.

Requirements

Developing a comprehensive system to monitor and reduce the carbon footprint in logistics operations requires a robust platform that integrates data collection, processing, analysis, and reporting. To achieve this, the following requirements are necessary:

1. **Data Acquisition and Integration**:

- **Comprehensive Data Collection**: Implement systems to gather real-time data from ships, trucks, and port facilities, including fuel consumption, operational activities, and equipment usage.
- **Seamless Data Transmission and Reception**: Utilize secure and efficient communication protocols to ensure reliable data exchange between various components of the logistics network.
- **Integration with Existing Systems**: Ensure compatibility with current logistics management systems to leverage existing infrastructure and facilitate cohesive operations.
- **Compliance with EU Data Spaces**: Align data management practices with European Union data space initiatives to ensure regulatory compliance and facilitate cross-border data collaboration.

2. **Data Management and Processing**:
   - **Scalable Data Storage**: Deploy infrastructure capable of handling large volumes of structured and unstructured data, supporting both real-time analytics and historical data analysis.
   - **Efficient Data Movement**: Establish high-throughput data pipelines to process and transfer data swiftly across systems, minimizing latency and ensuring data integrity.
   - **Automated Data Processing**: Implement automation tools to streamline data validation, transformation, and analysis, reducing manual intervention and enhancing accuracy.
3. **Carbon Footprint Calculation and Validation**:
   - **Accurate Emissions Calculation**: Utilize standardized methodologies to calculate carbon emissions from various logistics activities, ensuring consistency and reliability in reporting.
   - **Data Validation Mechanisms**: Implement protocols to verify the accuracy and trustworthiness of collected data, maintaining the integrity of carbon footprint assessments.
4. **Visualization and Reporting**:
   - **Comprehensive Metrics Visualization**: Develop dashboards to visualize carbon emissions and logistics performance metrics, providing stakeholders with clear insights into operations.
   - **User Access to Data**: Ensure that relevant stakeholders have access to pertinent data through user-friendly interfaces, supporting transparency and collaborative decision-making.

- **Automated Compliance Reporting**: Generate and distribute compliance reports automatically, adhering to regulatory standards and facilitating audits.

5. **Analysis and Optimization**:

- **In-Depth Carbon Footprint Analysis**: Conduct thorough analyses to identify emission hotspots and opportunities for reduction within the logistics network.
- **Operational Improvement Recommendations**: Leverage data analytics to suggest actionable improvements to logistics operations, enhancing efficiency and sustainability.

Table 7 provides an overview of the technical requirements and technologies needed for use case VI. They will be discussed in detail in the following sections.

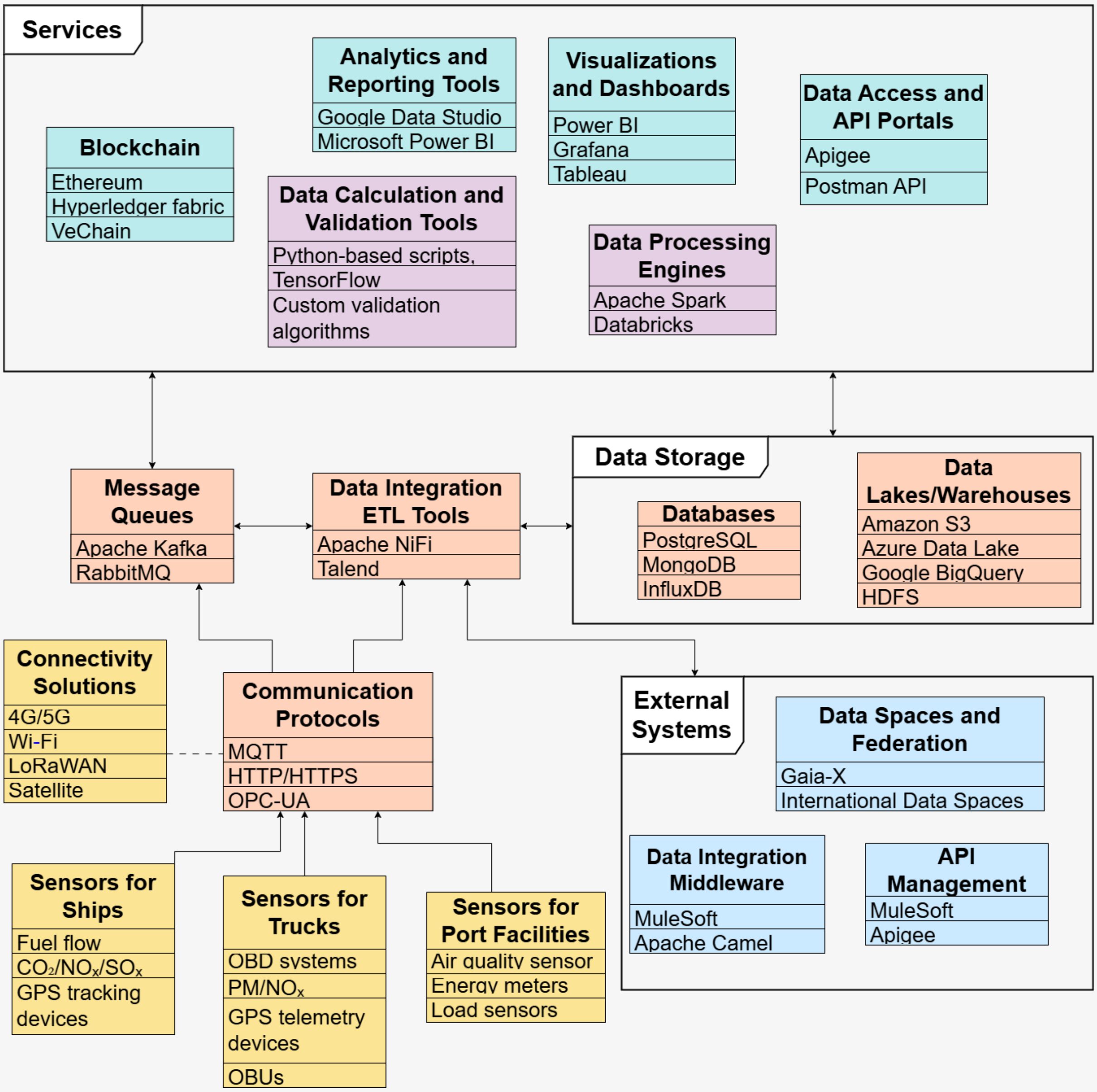
Table 77: Use case VI requirements

Architectural Layer	Requirement	Type of Technology	Main Required Technologies
Perception Layer	Collect data on ships	Sensors for Ships	Fuel flow meters, $CO_2/NO_x/SO_x$ emissions sensors, GPS tracking devices
	Collect data on trucks	Sensors for Trucks	OBD systems, PM/NO_x sensors, GPS telemetry devices, OBUs
	Collect data on port facilities	Sensors for Port Facilities	Air quality sensors, energy meters, load sensors
	Transmit data	Connectivity Solution	4g/5g, LPWAN, Satellite, WiFi
Data Layer	Receive data	Communication Protocols	MQTT, HTTP, OPC-UA
	Communicate data	Message Queues	Apache Kafka, RabbitMQ
	Store data	Databases	PostgreSQL, MongoDB, InfluxDB
	Store big data	Data Lakes or Warehouses	Amazon S3, Azure Data Lake, Google BigQuery, HDFS
	Move data	Data Integration and ETL Tools	Apache Nifi, Talend
Middleware Layer	Integrate with existing systems	Data Integration Middleware	MuleSoft, Apache Camel
	Provide clean APIs	API Management Tools	Apigee, AWS API Gateway

	Integrate with EU data spaces	Data Spaces and Federation	Gaia-X, International Data Spaces (IDS)
Business Layer	Validate data and calculate carbon footprint	Data Calculation and Validation Tools	Python-based scripts, TensorFlow, custom validation algorithms, PyTorch
	Automate data processing	Data Processing Engines	Apache Spark, Databricks
Application Layer	Visualize carbon and logistics metrics	Visualizations and Dashboards	Power BI, Grafana, Tableau
	Provide data for users	Data Access and API Portals	Apigee, Postman API Portal
	Analyse carbon footprint and provide required reports	Analytics and Reporting Tools	Google Data Studio, Microsoft Power BI
	Ensure accuracy and trustworthiness of data	Blockchain	Ethereum, hyperledger fabric, VeChain

Figure 7 provides an overview over how these technologies could interact. It shows how data will flow from sensors using communication protocols through ETL tools and messages queues into some form of data storage or directly to the desired service. The same is the case for external systems. It is important to stress that this is simply to give an idea of how the technologies could interact and is not a solution architecture.

Figure 7: Use Case VI Technology Diagram



Perception layer

Ships

Ships are a critical part of international logistics, and their fuel consumption and emissions contribute significantly to the overall carbon footprint. Monitoring these elements is essential for accurate tracking and reporting in a cross-border logistics network. The following sensors are necessary:

- **Fuel Flow Sensors**: Measure the rate of fuel consumption in real-time, providing data on fuel usage during transit. This information is crucial for calculating emissions and understanding fuel efficiency.
- **Emission Sensors**: Sensors for monitoring specific exhaust gases, such as CO_2, NO_x, and SO_x, are essential to measure the environmental impact directly associated with each voyage. These sensors can capture emissions data based on the fuel type and engine operation mode.
- **GPS and Route Tracking Sensors**: GPS sensors provide continuous location tracking, allowing for route optimization and verification of the ship's actual path versus planned routes. This data can be used to assess carbon impact across different regions or routes.
- **Onboard Units (OBUs):** specialized electronic devices installed in vehicles, such as trucks, to collect, process, and transmit real-time data about the vehicle's performance, location, and environment. By integrating OBUs as sensors in trucks, the platform gains a robust capability for real-time monitoring and decision-making, supporting advanced functionalities such as dynamic routing.

Trucks

Trucks are often a significant source of emissions in the logistics network, especially in last-mile delivery and regional transport. Monitoring emissions and fuel consumption in trucks helps logistics operators assess and minimize environmental impact. Key sensors for trucks include:

- **Onboard Diagnostic (OBD) Sensors**: OBD systems measure multiple vehicle parameters, including fuel consumption, engine efficiency, and exhaust gas temperature. Through real-time data on engine performance, OBD sensors provide a detailed view of fuel usage and emissions.
- **Particulate Matter and NO_x Sensors**: Specific sensors for tracking particulate matter and NO_x levels in truck exhaust are essential for capturing emissions data related to urban and highway driving. These sensors enable a closer analysis of carbon impact under different driving conditions.

- **GPS Tracking and Telemetry Sensors**: GPS trackers on trucks monitor real-time location and travel distance, which are essential for understanding route efficiency. Telemetry sensors can additionally capture acceleration, deceleration, and idling times, offering insights into driving behavior that impacts emissions.

Port Facilities

Ports are hubs for numerous logistics activities, and emissions from equipment such as cranes, trucks, and ships docked at the port contribute to the overall carbon footprint. Port facilities require a network of sensors to monitor emissions from both stationary and moving equipment, enabling comprehensive environmental tracking. Key sensors include:

- **Fixed Emission Sensors**: These sensors are strategically placed at key points within the port (e.g., docks, loading zones) to monitor air quality and track emissions of CO_2, NO_x, and other pollutants. This data provides a baseline for environmental impact within the port area.
- **Fuel and Energy Consumption Sensors**: Many ports now use electric or hybrid cranes and machinery; fuel and energy sensors on these machines measure energy consumption during operations, supporting accurate tracking of emissions related to port activities.
- **Operational Activity Sensors**: Sensors attached to cranes, forklifts, and other port machinery record operational metrics such as lift loads, operational hours, and machine idle times. This data is used to estimate emissions from equipment operations more accurately.

Connectivity Solutions

Connectivity solutions ensure that data captured by sensors can be continuously and securely transmitted to the ODP. Reliable connectivity options like 4G/5G, LPWAN, and Ethernet support data transfer in real-time, allowing for consistent monitoring and enabling timely responses to operational changes.

Data layer

Databases

Databases are essential in the Data Layer for storing structured and unstructured data related to emissions, fuel usage, and operational activities. In Use Case VI, these databases must handle high-volume, time-series data that provides insights into emissions patterns over time and across various logistics operations.

Data Lakes and Warehouses

Data lakes and warehouses play a crucial role in the Data Layer by consolidating data from multiple sources for long-term storage and batch analysis. In Use Case VI, a data lake can accommodate raw, unstructured data from sensors, while a data warehouse can store processed and structured data, making it easier to generate reports and analyze trends in carbon emissions.

Data Integration and ETL Tools

Data integration and ETL tools are responsible for aggregating and standardizing data from various sources, preparing it for further analysis. In Use Case VI, these tools are crucial for combining data from trucks, ships, and port facilities, ensuring consistent data formats that can be efficiently processed and analyzed.

Message Queues

Message queues manage the flow of data from sensors and acquisition points to storage and processing systems, ensuring that data is transmitted reliably and without loss, even when high volumes of real-time data are involved. In Use Case VI, message queues allow data from emissions and GPS sensors to be processed asynchronously, ensuring the system remains responsive and scalable.

Communication Protocols

Communication protocols facilitate the secure and efficient transmission of data between IoT devices, data acquisition platforms, and databases within the Data Layer. Protocols such as MQTT, HTTP, and OPC-UA are essential for ensuring that data from sensors reaches storage and processing systems reliably.

Middleware layer

Data Integration Middleware

Data integration middleware is essential for enabling communication and data exchange across disparate systems and platforms within the logistics network. This middleware standardizes data and ensures interoperability, allowing data from sensors on ships, trucks, and port facilities to be combined and utilized for comprehensive carbon footprint calculations.

API Management Tools

API management tools allow for secure, efficient access to data and services across different parts of the logistics network. These tools provide centralized control over API usage, supporting data sharing with consumers, manufacturers, logistic operators and regulatory agencies while ensuring compliance with security and usage policies.

Data Spaces and Federation

Data spaces and federated platforms are used to securely share carbon footprint data across different stakeholders, including logistics partners, regulators, and third-party platforms. Data spaces facilitate controlled, cross-border data exchange, allowing Use Case VI to provide secure access to verified emissions data without exposing sensitive internal data. Additionally, data spaces enable the acquisition of non-sensor data, such as fuel type, transportation schedules, and supplier data, which are essential for accurate carbon footprint calculations. By integrating non-sensor information, data spaces help create a more complete picture of emissions and environmental impact, enhancing the quality and accuracy of carbon assessments.

Business layer

Data Calculation and Validation Tools

Data calculation and validation tools are fundamental in converting data—such as fuel consumption, GPS coordinates, and emissions levels—into precise carbon footprint metrics. These tools perform essential calculations, applying formulae and algorithms to generate accurate CO_2 estimates based on input data. Validation steps ensure that data is consistent and meets expected thresholds, flagging any anomalies for review before further processing.

For Use Case VI, the integrity of carbon footprint data depends on accurate calculation and validation. With emissions data gathered from multiple sources and regions, validation is essential to detect errors or inconsistencies that could skew results. These tools ensure that the platform provides reliable emissions metrics, allowing logistics managers to make informed decisions.

Data Processing Engines

Data processing engines enable efficient handling of high-volume data from diverse logistics assets, processing data either in real time or in batches to meet operational demands. These engines automate the data flow, allowing the platform to aggregate, transform, and process emissions data continuously, thereby providing up-to-date carbon footprint metrics for real-time monitoring and historical analysis.

In Use Case VI, the volume of data from logistics operations is substantial, especially when tracking emissions and fuel consumption across geographically dispersed assets. Data processing engines support the system's scalability, ensuring that all incoming data can be processed efficiently without delays, which is essential for maintaining accurate, real-time carbon footprint calculations.

Application layer

Visualizations and Dashboards

Visualization and dashboard tools provide a real-time, interactive view of carbon footprint metrics, enabling stakeholders to monitor emissions, fuel usage, and other key environmental indicators as they occur. Dashboards present data in a user-friendly format, allowing logistics managers to quickly identify patterns, pinpoint high-emission activities, and make immediate operational adjustments to reduce environmental impact.

In Use Case VI, dashboards allow logistics managers to respond to emissions metrics in real time, ensuring that any increase in carbon footprint can be addressed quickly. Visualizations provide an intuitive way to interpret complex data and help teams monitor daily trends and activity across logistics operations.

Analytics and Reporting

Analytics and reporting tools in the Business Layer enable a deeper analysis of emissions trends, allowing stakeholders to generate compliance reports and conduct long-term evaluations of the logistics network's environmental impact. These tools support strategic planning by offering insights into carbon footprint patterns and forecasting emissions under different operational scenarios. Customizable reporting capabilities ensure that reports meet specific regulatory requirements and corporate sustainability goals.

For Use Case VI, analytics and reporting tools allow logistics managers to go beyond real-time monitoring and gain a comprehensive understanding of emissions patterns over time. These tools are crucial for regulatory compliance, as they enable organizations to demonstrate their environmental performance and track progress toward sustainability objectives.

Data Access and API Portals

Data access and API portals facilitate secure, controlled data sharing with external stakeholders, including regulatory agencies, business partners, and third-party platforms. These portals allow authorized users to access carbon footprint data in a standardized format, supporting compliance verification and enhancing transparency in emissions reporting. APIs also provide a streamlined method for integrating carbon data with external systems.

In Use Case VI, API portals are essential for securely sharing verified emissions data with consumers, manufacturers, logistic operators and regulatory agencies. This capability is especially important in cross-border logistics networks where data-sharing standards may vary, as it allows organizations to comply with regional requirements while maintaining data integrity.

Blockchain for Data Validation and Transparency

Blockchain enhances data integrity by securely recording emissions metrics, preventing tampering and ensuring that each data point is traceable. In a logistics network with multiple stakeholders, blockchain provides an auditable, decentralized ledger that records each entry, supporting data transparency and compliance with environmental standards.

Smart Contracts for Automated Validation:
Smart contracts on the blockchain automatically validate emissions data, triggering alerts if metrics deviate from expected ranges, and securely recording carbon offset transactions to ensure compliance.

Security considerations across use cases

Effective security across any Operational Digital Platform is critical for maintaining data integrity, confidentiality, and availability in each layer. Each layer presents unique challenges and requires a tailored approach to safeguard against potential threats. The following outlines the essential security considerations across the platform's layers, ensuring a resilient, secure environment.

Perception Layer

In the Perception Layer, safeguarding data from sensors and securing connectivity solutions are foundational to protecting data integrity and confidentiality as it moves through the platform. Data encryption during transmission, often through TLS/SSL, helps prevent interception, while role-based access controls restrict access to sensor data and connectivity settings to authorized personnel only. To further reinforce security, regular audits and continuous monitoring of both sensor networks and connectivity points are essential for detecting any unauthorized access attempts or tampering, thus maintaining a secure data flow from the outset.

Data Layer

The Data Layer requires a robust approach to encryption, access control, and data validation to protect the high-volume data moving through communication protocols, message queues, databases, data lakes, and/or data warehouses. Encrypting data at both rest and in transit is crucial for safeguarding sensitive information across storage and transfer systems. Implementing role-based access restrictions in databases, message queues, and storage ensures that permissions are carefully managed, reducing risk exposure to only necessary personnel. Additionally, comprehensive activity logging and monitoring provide visibility into data interactions, enabling the detection of anomalies or unauthorized access attempts. To support data consistency, ETL tools and integration workflows apply secure API configurations and validation processes, while regular backups and integrity checks enhance resilience and prepare the system for quick recovery in the event of a data breach or loss.

Middleware Layer

The Middleware Layer secures data exchanges and integration by combining encryption, access control, and authentication across data integration middleware, API management tools, and data spaces. Encryption safeguards data during exchanges, while role-based access controls restrict middleware functions to authorized users, ensuring that sensitive data remains protected throughout integration processes. API management tools use strong authentication protocols, such as OAuth, alongside rate limiting to prevent unauthorized access and misuse, promoting safe and efficient handling of data requests. Logging of all integration activities enhances visibility and accountability, while in data spaces, federated identity management enforces strict access policies, especially valuable for secure cross-border data sharing.

Application Layer

In the Application Layer, a comprehensive approach to encryption, access management, and model validation supports secure data processing, simulation, and forecasting. Encryption protects sensitive data in digital twin models, data processing engines, and forecasting algorithms, while role-based access controls limit access and prevent unauthorized modifications to these tools. Activity logging and monitoring across calculation, validation, and processing tools provide accountability and help quickly identify unusual patterns or unauthorized changes. Additionally, regular validation of forecasting models ensures their reliability and accuracy, preserving data integrity and protecting predictions from tampering.

Business Layer

The Business Layer requires secure access control and encryption for its tools, from visualization dashboards to emergency response systems and API portals, as it interfaces with internal and external stakeholders. Role-based access control safeguards sensitive data within dashboards, while encryption during transmission and at rest protects the confidentiality of shared information. Logging of user interactions with dashboards, API portals, and alert systems offers traceability and helps detect unauthorized access or suspicious activity. Emergency response protocols are also routinely tested and validated to ensure dependable performance during critical events, protecting ODP stability and enabling prompt responses to potential incidents.

Cross border considerations

There are few cross-border considerations which impact technology decisions. Most technologies operate over the internet and is therefore not limited by geographical areas. The main impacts on technologies are standards, regulations and policies, which can differ across countries. These concerns will be addressed in a later deliverable.

Conclusion

The D3.1 Technology Landscape and Technical Requirements deliverable provides a comprehensive analysis of the technological ecosystem essential for Operational Digital Platforms (ODPs) in addressing the complexities of modern energy, transport, and logistics systems. By dissecting six critical use cases, the document identifies and evaluates a wide spectrum of technologies across architectural layers, emphasizing their functional, operational, and strategic relevance.

The analysis showcases how advanced technologies are pivotal in achieving the scalability, interoperability, and modularity required for these ODPs. AI-driven models for predictive analytics, blockchain for immutable data validation, IoT frameworks for real-time data acquisition, and edge computing for localized decision-making emerge as foundational components. Each of these technologies is carefully mapped to specific use case needs, ensuring tailored solutions that align with functional requirements.

The deliverable also highlights the interdependencies within the technological stack, such as the seamless integration of perception-layer IoT devices with data processing engines and middleware platforms, ensuring real-time insights and operational agility. Furthermore, it underscores the importance of cloud computing, federated data spaces, and advanced ETL tools in enabling secure, efficient, and cross-border data management.

By addressing cybersecurity considerations and adhering to EU data governance standards, the analysis ensures that the proposed solutions not only meet technical requirements but also align with regulatory frameworks and societal expectations.

This technology-centric approach provides a robust foundation for the next phases of the BEGONIA project, where these insights will drive the development of solution architectures and proof-of-concept implementations. The identified technologies and frameworks will play a critical role in transforming the energy, transport, and logistics sectors, setting a precedent for scalable, sustainable, and secure digital infrastructures.

Annex I: Technology Options for BEGONIA - A Comparative Overview

As elaborated throughout this deliverable, the BEGONIA project envisions the development of advanced Operational Digital Platforms (ODPs) that facilitate cross-border integration of energy and transport systems. To support this ambitious goal, it is essential to carefully evaluate and select appropriate technologies that meet the diverse requirements of our various use cases. Given the scope and complexity of BEGONIA, numerous technology options are under consideration across various functional layers of the proposed ODP architecture. This appendix provides a detailed comparative analysis of these considered technologies across various functional areas.

A Framework for Technology Selection:

Table A.1 provides a structured framework to understand the technical landscape for BEGONIA. It presents key technologies categorized by their core function, enabling stakeholders to compare options based on their specific project needs. The table provides insights into their operational characteristics, technical advantages, and suitability for BEGONIA's diverse use cases.

The table lists each technology with the following key elements:

- **Technology:** The specific name of a technology platform or protocol.
- **Core Function:** A brief description of the technology's primary purpose and application.
- **Use Case Suitability:** Scenarios within the BEGONIA project where each technology is most applicable. This helps contextualize how each option aligns with specific operational needs.
- **Advantages:** The main benefits and strengths that each technology brings, such as scalability, security, and efficiency.
- **Cross-Border Considerations:** Specific challenges, requirements or factors to consider with regards to cross-border deployment including compliance with different regulations, ensuring seamless interoperability, and maintaining data integrity and sovereignty.

The use case analyses in the main body of this document discuss the broad technological needs of the project; here in the appendix, each technology is examined in closer detail. This level of analysis provides a necessary guide for the BEGONIA teams in selecting the technologies for implementation.

The technology options considered span the various functional layers of the proposed Operational Digital Platform, including data communication, storage, processing, forecasting, visualization, blockchain, and digital twin solutions.

Using this comparative analysis table:

Table A.1 serves as a practical reference for all BEGONIA partners and stakeholders. The table format is designed to enable quick and efficient comparisons between different technologies. The "Cross-Border Considerations" column is especially critical, providing guidance to the implementation teams while selecting technologies to ensure adherence to regulations, enable seamless interoperability, and provide robust data protection for the BEGONIA project. This section provides further granularity and detail to inform the selection of technologies.

By providing this detailed comparative analysis, the main body of the deliverable can maintain its focus on the overarching architecture and functional needs, while providing the project with a rich and extensive overview of the technologies under consideration. This comprehensive approach will be vital in ensuring the successful implementation of a scalable, interoperable, and secure ODP for the BEGONIA project.

Table A.1: Comparative Analysis of Technology Options for BEGONIA Use Cases

Category	Technology	Core Function	Use Case Suitability	Advantages	Cross-Border Considerations
Communication	MQTT	Lightweight Messaging	Remote devices, low-bandwidth environments, sensor data.	Efficient, minimal resource usage, continuous data flow.	Standard protocol, generally interoperable; ensure consistent implementation across borders.
	HTTP/HTTPS	Secure Web-Based Data Transfer	Comprehensive data exchange, cloud integration, API interactions.	Widely compatible, secure, standard web transport.	Ensure compliance with data privacy regulations (e.g., GDPR) and secure communication across borders.
	OPC-UA	Industrial Data Communication	Industrial IoT, high-security requirements, real-time control systems.	Secure, real-time transmission, built-in encryption.	Address differences in industrial automation standards across different countries.
Message Queues	Apache Kafka	High-Throughput Data Streams	Large, continuous data streams, scalability needs.	Optimized for high-throughput, fault tolerance.	Performance may vary across network boundaries; ensure sufficient bandwidth availability for cross-border message transfer.
	RabbitMQ	Flexible Data Routing	Lower-volume data transfers, simpler configurations.	Flexible, easy to set up, effective routing.	Potentially better suited for less complex cross-border integrations due to easier setup and management
Databases	PostgreSQL	Structured Data Storage	Complex queries, transactional data, situations requiring ACID compliance.	Robust, ACID-compliant, well-suited for structured data.	Standard SQL, ensure schemas are well-defined for cross-border data integration.
	MongoDB	Unstructured Data Storage	Handling diverse data types from multiple sources.	Flexible schema, scalable, adaptable to various data structures.	Data sovereignty challenges for data stored across different legal regions
	InfluxDB	Time-Series Data Storage	Real-time analytics, IoT monitoring, infrastructure observability.	Optimized for time-stamped data, efficient ingestion and retrieval.	Time-zone differences must be handled while processing data
Data Lakes/ Warehouses	Amazon S3	Scalable Data Storage	Large volumes of data, cost-effective storage, integration with AWS analytics.	Scalable, cost-effective, seamless AWS integration.	Data transfer costs and compliance challenges for large volumes of cross-border data transfers.

	Azure Data Lake	Analytics-Optimized Data Storage	Big data processing, integration with Microsoft tools, organizations with Microsoft ecosystem.	Specifically optimized for analytics, seamless Microsoft integration.	Potential vendor lock-in, ensure compatibility with tools from other ecosystem to ensure interoperability
	Google BigQuery	Near-Real-Time Analytics	Data-driven environments requiring fast query response times.	Near-real-time analytics, advanced querying capabilities.	Network latencies can affect response times for large cross-border datasets, manage storage costs
Data Tools	Python-based Scripts	Customized Data Processing	Tailored calculations, flexible validation, complex calculations.	Highly adaptable, allows for customized analysis and validation.	Ensure consistent libraries are used across implementation teams for the Python environment.
	TensorFlow	Complex Modeling, ML	Predictive modeling, large-scale data processing, real-time forecasting & validation.	Supports machine learning, ideal for complex models and high-volume data.	Ensure standardized training and deployment of ML models. May require specialised hardware for implementation
Data Engines	Apache Spark	Real-Time Data Processing	Scalable data workflows, distributed data processing, real-time data analysis.	Scalable, real-time data processing, suitable for big data tasks.	Cross-border data distribution strategies and resource management are important.
	Databricks	Simplified Data Pipeline Management	Managed environment for data processing and machine learning.	Simplifies data pipeline management, built-in ML tools.	Cost implications, consider data residency implications of using a cloud platform.
Forecasting	Azure ML	End-to-End Machine Learning	Forecasting models, automated machine learning, seamless integration with Azure.	AutoML capabilities, integrates with Azure, comprehensive cloud-based platform.	Data governance and management across legal jurisdictions and ensuring ML models are portable.
	Prophet	Time-Series Forecasting	Time series data with seasonality and trends, business forecasting.	Open-source, intuitive interface, handles missing data well.	Consistent time-series data collection/formatting required for cross-border analysis.
	forecastML	Flexible Multi-Step Forecasting	Flexible model-building, using different machine learning algorithms in R or Python.	Customizable, offers flexible model-building and visualizations.	Ensure consistent data handling formats for cross-border applications.

Visualization	Power BI	Comprehensive Data Visualization	Existing Microsoft ecosystems, detailed emissions reporting, custom visualizations.	User-friendly, strong data integration capabilities.	Ensure consistency with cross-border reporting and data access policies.
	Grafana	Real-Time Monitoring	Continuous emissions tracking, real-time data display.	Flexible, open-source, specialized in real-time monitoring.	Implement consistent visualization templates across different regions.
Analytics & Reporting	Google Data Studio	Straightforward Reporting	Basic analytics, organizations seeking accessible, low-cost options.	Free, easy to use, suited for basic analytics.	Limited integration capabilities with complex data workflows across different locations.
	Microsoft Power BI	Advanced Analytics & Reporting	Long-term emissions tracking, predictive analysis, complex reporting.	Deeper insights, powerful data manipulation, advanced reporting capabilities.	Ensure data is available across all relevant regions for consistent reporting.
Blockchain	Ethereum	Public Validation, Transactions	Organizations seeking public validation of emissions data, transparent transactions.	Widely adopted, open-source, transparency and trust.	Data privacy must be addressed, gas fees may be a concern.
	Hyperledger Fabric	Private Networks, Secure Access	Enterprises prioritizing control over shared data.	Secure, permissioned access, ideal for enterprise applications.	Permissioned access limitations can create barriers for cross-border public access.
	Azure Digital Twins	Digital Twin Creation, Real Time Monitoring	Organizations needing comprehensive digital models, real-time monitoring and control.	Comprehensive digital models, scalable integration with Azure services.	Data residency and compliance must be handled. Vendor lock in could be a concern
Digital Twins	Siemens MindSphere	Industrial IoT Connectivity	Industrial infrastructure, device connectivity, data management & analytics.	Connects physical infrastructure with the digital world, good device management, enables end-to-end digital twins	Vendor lock-in, ensure consistent deployment standards.
	IBM Digital Twin	Multi Stakeholder data sharing	Organizations needing collaboration in their digital twins, asset management.	Enables digital twin data sharing across	Compatibility with different systems from different stakeholders has to be taken care of.

					stakeholders, asset management.	