August 2025

D2.1 – AI-based Services Catalogue and Regulatory Framework

EnerTEF: The future of energy through AI testing and experimentation

UST:

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Technical References

Project Number	101172887
Project Acronym	EnerTEF

Full Project Title	Common European-scale Energy Artificial Intelligence Federated Testing and Experimentation Facility
Topic	HORIZON-CL5-2024-D3-01-13
Funding Scheme	HORIZON EUROPE: RIA – Research and Innovation Action
Project Duration	1 November 2024 – 31 October 2027 (36 Months)
Project URL	www.EnerTEF.eu
Project Coordinator	NTUA

Deliverable	D2.1 – First Version of the AI-based Services Catalogue and Specifications of Existing Frameworks and Architectures

Work Package	WP2 - EnerTEF AI Living Labs – Definition and Requirements of Trustworthy AI Services and EnerTEF Architecture
Task	T2.1. Co-creation of a testing service catalogue for AI solutions and categorisation in nodes/satellites
Date of Delivery	31 August 2025
Actual Submission Date	
Dissemination Level	Public
Lead Beneficiary	LIST
Contributors	Jun Cao (LIST)
Reviewer(s)	EUROPEAN DYNAMICS LUXEMBOURG SA (ED), NATIONAL TECHNICAL UNIVERSITY OF ATHENS (NTUA)
Keywords	AI Service Catalogue, Regulatory Framework

Document History

Version	Date	Contributor(s)	Description
v0.1	25 June 2025	Jun Cao (LIST)	Table of Contents
v0.2	1 July 2025	(ED)	First draft
v0.5	18 July 2025	Jun Cao (LIST)	First draft
V0.6	21 July 2025	Andrej Čampa (COMS), Matija Čemažar (JSI)	Section 4
V0.6-REV	28 July 2025	Stratis Kanarachos (ED), Konstantinos Tsolakis (ED)	Review of 1st draft
V0.7	9 August 2025	Jun Cao (LIST)	Revision
V0.8	18 August 2025	Athanasios Fragkoulakis (NTUA)	Review
V0.9	26 August 2025	Jun Cao (LIST)	Revision

Consortium

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Executive Summary

D2.1 – "First Version of the AI-based Services Catalogue and Specifications of Existing Frameworks and Architectures" establishes the foundational framework for trustworthy AI deployment within the EnerTEF Testing and Experimentation Facility. This deliverable synthesizes critical work across five interconnected tasks to create a comprehensive catalogue of AI services specifically designed for European energy systems while ensuring full compliance with emerging regulatory frameworks.

Key Achievements

- **Comprehensive AI Services Catalogue**: This deliverable presents a structured taxonomy of AI services categorized for deployment across both node and satellite environments within the EnerTEF network. Through systematic co-creation processes involving energy sector stakeholders, the catalogue addresses real-world operational requirements including smart grid management, renewable energy forecasting, demand response optimization, and predictive maintenance applications.
- **Regulatory Compliance Framework**: Full integration with EU AI Act requirements and GDPR obligations ensures that all catalogued AI services meet the highest standards for deployment in critical energy infrastructure. The framework specifically addresses high-risk AI system classifications, conformity assessment procedures, and regulatory sandbox operational requirements, enabling innovation within established legal boundaries.
- **Trustworthy AI Technical Specifications**: Comprehensive technical frameworks guarantee AI system trustworthiness through explainable architectures, human oversight mechanisms, and rigorous evaluation methodologies. Performance specifications include >95% accuracy requirements, <100ms latency for real-time operations, and 99.9% availability standards for critical infrastructure applications.
- **European Framework Alignment**: Strategic alignment with existing European energy ecosystem frameworks ensures seamless interoperability and integration capabilities. The specifications enable AI services to operate within established infrastructure while contributing to broader European digital transformation objectives.
- **Federated Architecture Design**: An open, interoperable, and modular federated architecture enables scalable AI service deployment across the European energy TEF network while maintaining centralised governance and quality standards.

Strategic Impact

The AI services catalogue directly supports Europe's transition toward sustainable energy systems by providing validated, compliant, and operationally ready AI solutions. The framework enables energy sector stakeholders to deploy advanced AI capabilities with confidence in regulatory compliance, technical performance, and operational safety.

- **Innovation Enablement**: The regulatory sandbox framework facilitates controlled experimentation with cutting-edge AI technologies while maintaining strict safety and compliance standards. This approach accelerates innovation cycles while minimizing deployment risks.
- **Stakeholder Value Creation**: Co-creation methodologies ensure that catalogued AI services address specific stakeholder needs across the energy value chain, from grid operators to consumer service providers, maximizing adoption potential and operational impact.
- **FAIR Data Principles Integration**: All AI services incorporate comprehensive data management specifications supporting findability, accessibility, interoperability, and reusability, contributing to broader knowledge discovery and innovation within the European energy sector.

Implementation Readiness

D2.1 provides immediate implementation guidance through detailed technical specifications, deployment procedures, and compliance frameworks. The deliverable includes comprehensive evaluation methodologies, performance metrics, and quality assurance procedures that enable systematic AI service validation and deployment.

- **Resource Requirements:** Clear resource allocation frameworks support informed decision-making regarding AI service implementation, including personnel requirements, infrastructure specifications, and timeline expectations.
- **Risk Management:** Comprehensive risk assessment and mitigation strategies address technical, regulatory, and operational challenges, ensuring robust AI service deployment across diverse energy sector environments.
- **Continuous Improvement:** Living document approach with systematic update mechanisms ensures continued relevance and compliance as technology and regulatory landscapes evolve throughout the project lifecycle.

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List of Acronyms

AI	Artificial Intelligence
AIoD	AI-on-Demand Platform

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AIOTI	Alliance for the Internet of Things Innovation
BDVA	Big Data Value Association
BEMS	Building Energy Management Systems
BESS	Battery & Energy Storage Systems
CEEDS	Common European Energy Data Space
DER	Distributed Energy Resources
DOME	Digital Open Marketplace Ecosystem
DMP	Data Management Plan
DPIA	Data Protection Impact Assessment
DSO	Distribution System Operator
EDIHS	European Digital Innovation Hubs
EU	European Union
EV	Electric Vehicle
FAIR	Findable Accessible Interoperable Reusable
GSUC	Generic System Use Case
IAM	Identity Access Management
IDSA	International Data Spaces Association
MAE	Mean Absolute Error
MAPE	Mean Absolute Percentage Error
ML	Machine Learning
PV	Photovoltaic
RBAC	Role Based Access Control
RES	Renewable Energy Systems
RMSE	Root Mean Squared Error

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SGAM	Smart Grid Architecture Model
TEF	Testing Experimentation Facility
TSO	Transmission System Operator
WP	Work Package Explainable AI
XAI	

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1. Introduction

1.1. Purpose and Scope

This deliverable D2.1 presents the first version of the AI-based services catalogue and specification of existing frameworks and architectures for the EnerTEF project. Building upon the foundational work established across Work Package 2 (WP2), this document synthesizes critical elements of AI service co-creation, regulatory compliance, and technical framework alignment to establish a comprehensive foundation for trustworthy AI deployment in European energy systems.

The primary purpose of D2.1 is to provide a structured analysis and specification of AI services that will be developed, tested, and deployed within the EnerTEF Testing and Experimentation Facility. This catalogue serves as both a technical reference and a strategic roadmap, ensuring that all AI solutions developed within the project maintain alignment with European regulatory frameworks while meeting the specific operational requirements of energy sector stakeholders.

1.2. Context and Relationship to EnerTEF Objectives

The EnerTEF project aims to establish a comprehensive Testing and Experimentation Facility (TEF) for AI solutions in the energy domain, contributing to Europe's digital transformation while ensuring compliance with emerging regulatory frameworks. D2.1 represents a critical milestone in translating the project's high-level objectives into concrete, actionable specifications that will guide subsequent technical development and implementation phases.

This deliverable directly supports the project's core mission of building a [illegible] where relevant stakeholders will define the catalogue of trustworthy AI services and design the EnerTEF Reference Architecture. D2.1 also supports creating findable, accessible, interoperable, and reusable (FAIR) AI services by establishing clear categorisation frameworks, technical specifications, and compliance guidelines. The work presented here forms the foundation for all subsequent AI service development activities within the consortium, ensuring consistency, quality, and regulatory compliance across all project outputs.

1.3. Integrated Approach and Task Synthesis

D2.1 represents the synthesis of five interconnected tasks within WP2, each contributing essential components to the overall AI services framework:

- T2.1 Co-creation of Energy Service Catalogue provides the foundational service taxonomy and categorisation methodology, establishing how AI solutions will be classified and organized within both code and sandbox environments. This task ensures that the catalogue reflects real-world stakeholder needs through systematic co-creation processes involving energy sector operators, technology providers, and regulatory authorities.
- T2.2 Technical and Socio-Requirements for Trustworthy AI contributes the technical specifications and evaluation frameworks necessary to guarantee trustworthy AI deployment. The comprehensive framework developed in T2.2, including EU AI Act compliance mechanisms, GDPR integration, and technical performance specifications, provides the quality assurance backbone for all catalogued services.
- T2.3 Regional and EU-level Regulatory Framework establishes the legal and ethical compliance framework, particularly focusing on EU AI Act requirements for regulatory sandbox environments. This task ensures that all catalogued AI services operate within established legal boundaries while enabling innovation through controlled experimentation.

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- T2.4 (Alignment with Existing European Frameworks) provides critical interoperability specifications by analysing and aligning with existing European ecosystem frameworks and architectures. This alignment ensures that EnerTEF AI services can integrate seamlessly with established energy infrastructure and data management systems. T2.5 (Federated Architecture Design) contributes the technical architecture specifications for open,
- interoperable, and modular AI service deployment across the European energy TEF network. This federated approach enables scalable, distributed AI service delivery while maintaining centralized governance and quality standards.

1.4 Deliverable Structure and Content Overview

Following the established EnerTEF documentation framework and building upon the Data Management Plan structure, D2.1 is organized to provide comprehensive coverage of AI service specifications while maintaining clear traceability to regulatory requirements and technical standards.

The document structure reflects the integrated nature of the contributing tasks while ensuring accessibility for diverse stakeholder groups including technical developers, regulatory assessors, energy sector operators, and project evaluators. Each section builds progressively from foundational concepts to detailed technical specifications, enabling readers to engage with content appropriate to their specific roles and responsibilities.

Chapter 2 presents the comprehensive AI services catalogue, including detailed categorization frameworks for state and [illegible] deployments, service specifications, and stakeholder-driven requirements analysis derived from T2.1 co-creation activities.

Chapter 3 establishes the trustworthy AI technical framework, incorporating the evaluation methods, performance specifications, and quality assurance mechanisms developed in T2.2, with particular emphasis on EU AI Act compliance and GDPR integration.

Chapter 4 addresses the regulatory compliance framework, presenting the legal and ethical guidelines established in T2.3 for conducting AI experiments within regulatory sandbox environments, including specific procedures for EU AI Act adherence.

Chapter 5 details the alignment specifications with existing European frameworks and architectures, ensuring interoperability and integration capabilities as developed in T2.4, with particular focus on data exchange protocols and system integration requirements.

Chapter 6 presents the federated architecture design for the European energy TEF, incorporating the technical specifications and deployment models developed in T2.5, including scalability, security, and governance mechanisms.

Chapter 7 synthesizes the integrated framework, presenting implementation roadmaps, resource requirements, and success metrics that will guide subsequent project phases.

1.5 Relationship to Project Data Management and FAIR Principles

D2.1 maintains strict alignment with the project's Data Management Plan (DMP) and FAIR data principles, ensuring that all AI service specifications contribute to knowledge discovery and innovation within the European energy sector. The catalogue design inherently supports findability through comprehensive metadata standards and search capabilities, accessibility through open interfaces and standardized access protocols, interoperability through

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alignment with existing European frameworks; and Flexibility through modular service design and comprehensive documentation.

The specifications presented in this deliverable directly support the data management requirements outlined in the project DMP, particularly regarding the handling of diverse data types across technical work packages (WP2-WP5) and ensuring compliance with the EU Data Act framework. All AI services catalogued within this document include explicit data governance specifications, privacy protection mechanisms, and security requirements that align with both project-specific and regulatory data management obligations.

1.6 Stakeholder Engagement and Validation

The development of D2.1 has involved extensive stakeholder engagement through the consultation processes established in T2.1, ensuring that the resulting catalogue reflects real-world operational requirements and regulatory expectations. Key stakeholder groups including energy system operators, technology providers, regulatory authorities, and research institutions have contributed to the specification development through structured consultation processes, pilot testing activities, and formal validation procedures.

This stakeholder-driven approach ensures that D2.1 serves not only as a technical specification document but also as a practical implementation guide that addresses the diverse needs and constraints of the European energy sector. The validation processes embedded within each contributing task provide confidence that the catalogued AI services can be successfully deployed within existing operational environments while meeting all applicable regulatory requirements.

1.7 Living Document Approach and Future Development

Consistent with the project's commitment to adaptive management and continuous improvement, D2.1 represents the first version of an evolving specification framework that will be refined and expanded throughout the project lifecycle. The catalogue design incorporates mechanisms for systematic updates, stakeholder feedback integration, and regulatory adaptation to ensure continued relevance and compliance as both technology and regulatory landscapes evolve.

Future versions of this deliverable will incorporate lessons learned from pilot deployments, stakeholder feedback, regulatory updates, and emerging technological capabilities. This iterative approach ensures that the EnerTEF AI services catalogue remains at the forefront of innovation while maintaining the highest standards of trustworthiness, compliance, and operational effectiveness.

The specifications and frameworks presented in D2.1 therefore serve as both immediate implementation guidance and a foundation for long-term project success, supporting the EnerTEF consortium's mission to establish Europe as a global leader in trustworthy AI deployment within critical energy infrastructure.

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2. AI-based Services Catalogue

2.1 Introduction

The objective of the EnerTEF AI-based Services Catalogue is to develop and deploy a comprehensive ecosystem of AI solutions that accelerate the European energy transition through collaborative innovation and real-world validation. This catalogue has been developed through a structured co-creation process involving multiple stages: initial global living lab sessions with the entire consortium to establish common frameworks and requirements, followed by [illegible] and [illegible] workshops and living labs to define specific service requirements and technical specifications, publication of the first draft catalogue for stakeholder review and feedback, [illegible] global living lab presentations to refine and validate the services based on cross-consortium input, and culminating in the publication of the final catalogue [illegible], ensuring comprehensive stakeholder engagement and iterative refinement throughout the development process. [illegible] serves as the central collaboration platform throughout the living lab sessions, enabling real-time visual collaboration and structured ideation across geographically distributed consortium partners. This digital-first approach ensures that all consortium members can actively participate regardless of location, while maintaining a comprehensive visual record of the co-creation process that informs subsequent development stages.

The EnerTEF AI-based Services Catalogue represents a comprehensive ecosystem of [illegible] strategically distributed across 5 Testing Nodes and 2 Satellite TEFs throughout Europe, creating a federated network of innovation hubs that address critical challenges in modern energy systems. With approximately 8 services per Node and 3 services per Satellite, the catalogue spans five specialized domains: TEF BUILD ([illegible] services) focusing on building energy management, TEF TSO (4 services) emphasizing transmission grid coordination, TEF RES ([illegible] services) covering renewable energy systems, TEF EV (7 services) targeting electric vehicle integration, and TEF DSO ([illegible] services) concentrating on distribution grid automation. A defining characteristic of this ecosystem is that approximately [illegible] of services focus on Forecasting & Prediction, reflecting the critical importance of anticipatory capabilities in energy system management, with multi-horizon forecasting spanning from real-time prediction to long-term planning. Built upon trustworthy AI principles including [illegible], and robust security measures, the catalogue employs a collaborative co-design methodology with direct stakeholder involvement from DSOs, TSOs, municipalities, and technology providers, emphasizing real-world validation over synthetic environments. The federated architecture enables distributed learning, interoperability, and scalability while leveraging diverse data ecosystems including real-time operational data, historical datasets, and external sources, ultimately delivering immediate operational benefits through reduced costs, enhanced renewable integration, and improved grid stability while establishing the technological foundation for long-term European energy system transformation.

2.2 TEF BUILD Node

2.2.1 Overview

The TEF BUILD node focuses on Building Energy Management Systems (BEMS) insights, offering [illegible] AI-powered services designed to optimize energy consumption, enhance sustainability, and support data-driven decision-making for municipal buildings. All services are being developed by the City of Athens in collaboration with NTUA, targeting a portfolio of 300 municipal buildings.

[illegible]

AI Battery Storage Optimization & Simulation

Objective: Optimize battery sizing and operation for municipal buildings with PV installations to maximize self-consumption and financial returns.

Business Need

- Identifies optimal battery size and usage patterns to improve solar energy self-consumption and reduce energy waste.
- Supports investment decisions by simulating financial returns, payback periods, and savings under various scenarios.
- Reduces peak demand charges by shifting grid usage away from high-tariff periods.
- Increases energy resilience for municipal buildings by modelling backup and autonomy potential during outages.
- Aligns with sustainability goals by enabling better integration of renewable energy and reducing grid dependency.

Table 7 Battery Storage Optimization & Simulation

	Battery Storage Optimization & Simulation
Type of Analytics	• Optimization & Decision Support • Predictive & Prescriptive Analytics •
Key Performance Indicators	• Simulated energy and financial savings • Improvement of self-consumption rate
Data Available	• Building metadata (size, building category, year of construction) - 300 buildings • PV system data (installed capacity, annual production, PV area used, roof available for battery installation) - 300 buildings • Historical energy consumption bills - 300 buildings (monthly) • Historical energy consumption - 30 buildings with expansion potential (hourly) • External datasets (weather data, calendar data, energy market prices, battery technologies and prices) • Synthetic dataset of PV production (hourly basis simulation using yearly PV data and weather data)
KPI Targets	• Enhanced self-consumption rate (%) with battery • Financial savings on monthly basis • Payback period calculations

7) Building Demand Response Optimization

Objective: Enable municipal buildings to participate in demand response programs by identifying opportunities to reduce or shift electricity consumption during peak periods.

Business Need:

- Reduces peak electricity demand charges, lowering overall energy costs for municipal buildings.
- Enables participation in utility demand response programs, generating new revenue streams or financial incentives.
- Supports grid stability and resilience by helping balance supply and demand during critical periods.
- Aligns with sustainability goals by reducing reliance on fossil fuel-based peak generation.

Table 2 Building Demand Response Optimization

	Building Demand Response Optimization
[illegible]	• Optimization & Decision Support • Automation & Control Systems •
[illegible]	• Reward maximization (if reinforcement learning used) • Load reduction accuracy (measures how accurately the system predicts and achieves targeted load reduction during demand response events)
[illegible]	• Building metadata (size, building category, year of construction) - 500 buildings • PV system data (installed capacity, annual production, PV area used) - 500 buildings • Historical energy consumption bills - 500 buildings (monthly) • Historical energy consumption - 50 buildings with expansion potential (hourly) • External datasets (weather data, calendar data, energy market prices) • Synthetic dataset of PV production (hourly) from simulation using yearly PV data and weather data
[illegible]	• Recommended load changes per hour during event period • Estimated financial incentives or cost savings • Participation recommendations for market signals

8) Building Energy Consumption Anomaly Detection

Objective: Identify unusual patterns in municipal building energy usage to detect equipment malfunctions, energy waste, or operational inefficiencies.

Business Need:

- Detects unnoticed system failures or equipment malfunctions early before they cause high costs.
- Identifies abnormal energy consumption patterns such as leaks, operational inefficiencies, or user behaviour changes.
- Supports proactive maintenance and energy management, reducing downtime and avoiding costly reactive repairs.

Table 3 Building Energy Consumption Anomaly Detection

	Building Energy Consumption Anomaly Detection
Core Capabilities	• Monitoring & Anomaly Detection • Optimisation & Decision Support
Key Performance Indicators	• Precision, recall, F1-score • False positive rate
Data Involved	• Building metadata (GFA, building category, year of construction) - 500 buildings • Historical energy consumption bills - 500 buildings (monthly) • Historical energy consumption - 30 buildings with expansion potential (hourly) • External datasets (calendar days)
Key Outputs	Flagged buildings with potential anomalies Real-time alerts for immediate action Diagnostic insights for maintenance prioritisation

AI Building Energy Consumption Forecasting

Objective: Provide accurate short-term (7 days) and mid-term (1 month) energy consumption forecasts to support strategic planning and procurement.

Business Need:

- Enables accurate cost forecasting.
- Detects abnormal or unexpected energy consumption trends early.
- Supports proactive energy management and procurement strategies.

Table 4 Building Energy Consumption Forecasting

	Building Energy Consumption Forecasting
Core Capabilities	• Predictive & Prescriptive Analytics • Optimisation & Decision Support
Key Performance Indicators	• Mean Absolute Error (MAE) • Mean Absolute Percentage Error (MAPE) • Root Mean Square Error (RMSE)

	• Energy consumption variance
Data Needed	• Building metadata (size, building category, year of construction) - 500 buildings • Historical energy consumption bills - 500 buildings (monthly) • Historical energy consumption - 30 buildings with expansion potential (hourly) • External datasets (calendar days)
Key Outputs	• Time-series predictions of hourly energy consumption • Short-term (7 days) and mid-term (3 month) forecasts • Consumption variance analysis

11 Building PV Self-Consumption Optimization

Objective: Maximize the use of locally generated solar energy within municipal buildings through intelligent load-shifting strategies.

Business Need:

- Maximizes the use of on-site solar energy, reducing the need to purchase grid electricity.
- Supports sustainability and climate goals by reducing carbon emissions associated with external energy consumption.
- Enhances building energy autonomy and resilience against electricity price volatility or grid disturbances.
- Aligns with sustainability goals by reducing reliance on fossil-fuel-based peak generation.
- Optimizes operational schedules to better match energy demand with PV generation peaks.

Table 11 Building PV Self-Consumption Optimization

	Building PV Self-Consumption Optimization
Core Capabilities	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Optimization & Decision Support
Key Performance Indicators	• Self-consumption rate (%) - percentage of PV-generated electricity used on-site • Improvement over baseline - increase in self-consumption compared to current operation • Financial savings from the increase of self-consumption
Data Needed	• Building metadata (size, building category, year of construction) - 500 buildings • PV system data (installed capacity, annual production, PV area used) - 500 buildings • Historical energy consumption bills - 500 buildings (monthly)

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	• Historical energy consumption – 30 buildings with expansion potential (hourly) • External datasets (weather data, calendar data, energy market prices) • Synthetic dataset of PV production (hourly basis simulations using yearly PV data and weather data)
Key Outputs	• Forecasted hourly PV generation vs. consumption • Self-consumption rate improvements (%) • Load shifting recommendations with energy and financial savings estimation

b) Energy Efficiency Scoring

Objective: Assign quantitative efficiency scores to municipal buildings by comparing actual performance to similar buildings in the portfolio.

Business Need:

- Targeted retrofitting: Focus investments where they'll have the biggest impact.
- Tracking over time: See if upgrades or behaviour changes improve scores.
- Grant support: Use scores to justify funding for energy efficiency projects.

Table [illegible] Energy Efficiency Scoring

	Energy Efficiency Scoring
Use Case Category	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics •
Key Performance Indicators	• Scoring consistency (measures if similar buildings receive similar scores) Sensitivity to outliers (tests model's robustness to extreme consumption data)
Input Data	• Building metadata (size, building category, year of construction) – 500 buildings • Historical energy consumption bills – 500 buildings (monthly) • Historical energy consumption – 30 buildings with expansion potential (hourly)
Key Outputs	• Energy efficiency scores for each building • Building classification by energy consumption performance • Prioritization for retrofit planning

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2.2.3 Technical Infrastructure and Impact

Common Technical Stack: The TEF BUILD services are built upon a unified technical foundation that ensures consistency and interoperability across all municipal energy management applications. All services utilize Python as the primary programming language with FastAPI for backend APIs, supported by comprehensive ML libraries including pandas, NumPy, scikit-learn, and XGBoost for data processing and machine learning capabilities. Deep learning frameworks PyTorch and TensorFlow enable advanced AI model development, while Docker containers provide standardized deployment infrastructure. Data visualization is handled through matplotlib and plotly, ensuring clear presentation of energy insights and operational metrics.

Validation and Scalability Framework: The services employ a robust validation methodology combining real-world test cases with municipal buildings, simulated test environments, and cross-validation against industry benchmarks, complemented by continuous monitoring in production environments. Immediate scalability is achieved through integration of additional buildings as smart meter installations progress, coordination of multiple buildings as unified energy clusters, and cross-node integration within the broader EnerTEF ecosystem. Future enhancements include real-time anomaly detection with continuous smart meter feeds, reinforcement learning agents for adaptive demand response, edge computing deployment for reduced latency, and integration of emissions factors and decarbonization metrics.

Business Impact and Ecosystem Integration: The technical infrastructure delivers substantial business value through cost reduction via optimized energy procurement and reduced peak demand charges, enhanced sustainability through improved renewable energy integration, operational efficiency gains through predictive maintenance, and strategic investment support for energy efficiency upgrades. The services serve diverse end users including facility managers, municipal energy managers, DSOs, AI developers, and municipal leadership, positioning the TEF BUILD node as a critical component of the EnerTEF ecosystem that delivers practical solutions for municipal energy management while advancing AI technology integration in the energy sector.

This comprehensive AI services portfolio positions the TEF BUILD node as a critical component of the EnerTEF ecosystem, delivering practical solutions for municipal energy management while advancing the integration of AI technologies in the energy sector.

2.3 TEF TSO Node

2.3.1 Overview

The TEF TSO node focuses on Transmission System Operator coordination and grid management, offering four AI-powered services designed to enhance grid stability, fault detection, and TSO-DSO coordination. All services are being developed by various European organizations including [illegible], targeting critical transmission grid operations and system reliability.

2.3.2 Service Portfolio

1) AI-driven Fault Detection and Classification in Transmission Grids

Objective: Leverage AI technologies for rapid detection, localization, and classification of faults in transmission grids using protection relay recordings.

Business Need:

- Addresses the challenge of manual analysis of protection relay recordings following system disturbances.
- Eliminates the inefficient process of extracting relevant information from large datasets filled with non-critical events.
- Automates fault detection, localization, and classification to reduce time and expert effort required.
- Supports analysis of both trip events and non-trip disturbances for comprehensive grid condition assessment.
- Enables proactive identification of hidden or developing issues in the transmission network.

Table 7: AI-driven Fault Detection and Classification at Transmission Grids

	AI-driven Fault Detection and Classification at Transmission Grids
Core Capabilities	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Automation & Control Systems
Key Performance Indicators	• Classification accuracy • Response time for events • Reduction in required time for analysis (%)
Data Required	• Protection relay records (near-real-time and historical) • Topological data • Technical (asset) data • Operation logs • SCADA data • SQL databases, COMTRADE files format • Per-event data resolution
Key Outcomes	• Automated fault detection and classification • Fault localization information • Analysis of protection system response correctness • Reduced manual analysis time

II) Dynamic AI-enhanced Transmission Grid Stability Assessment

Objective: Evaluate grid stability using AI technologies based on grid state graphs and assessment of short circuit event likelihood in specific node neighbourhoods.

Business Need:

- Addresses critical scientific and operational challenge of real-time grid stability evaluation.
- Provides predictive assessment of potential failures by analysing accident likelihood across the network.
- Enables proactive decision-making to prevent outages or disruptions.
- Supports energy utilities and TSOs monitoring large-scale electrical networks.
- Valuable for smart grid technology providers integrating predictive maintenance features.
- Assists government agencies and regulators overseeing energy infrastructure safety.

[illegible]

	[illegible]
[illegible]	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Optimisation & Decision Support
[illegible]	• Classification accuracy • Incident likelihood confidence • Reduction in required time for analysis (%)
[illegible]	• Protection relay records (... real time and historical) • Topological data • Technical (asset) data • Operation logs • SCADA data • IEEE 39-bus system graphs • Real-time Energy Grid State Graphs • Per-event data resolution
[illegible]	• Grid stability scores for each network node • Overall network stability assessment • Predictive failure likelihood analysis • Real-time stability monitoring

3) ML-Based Outage Root Cause Identification

Objective: Use machine learning and GenAI to analyse SCADA event logs in real time, filtering noise and identifying root causes during planned and unplanned outages.

Business Need:

- Tackles critical issue of identifying root causes during unplanned outages due to overwhelming log data volumes.
- Addresses operator difficulty in sifting through noisy, redundant logs that slow response times.
- Automates real-time log analysis, filtering noise and surfacing key events.
- Significantly accelerates initial diagnosis enabling faster, more informed responses.
- Improves operational efficiency, reduces downtime, and enhances grid reliability during critical events.

Table XX: ML-Based Outage Root Cause Identification

	ML-Based Outage Root Cause Identification
[illegible]	• Optimization & Decision Support • Automation & Control Systems

Key Performance Indicators	- Accuracy and relevance of event clustering (evaluated by domain professionals) - Quality and usefulness of generated outage summaries (assessed by domain experts) - Time taken to analyse logs and generate insights during unplanned outages (alarms) - Reduction in time to identify root cause compared to manual analysis (alarms) - Confusion matrix for classification performance assessment
Data Required	- SCADA event logs (historical and real-time streams) - Outage events from MySQL database - Historical outage event metadata (timestamps, duration, location, resolution notes) - SQL/JSON or real-time JSON over MQTT format - Files from the extracted data set for SCADA event data ingestion
Key Outputs	- Real-time log analysis and alarm filtering - Root cause identification support - Concise incident summaries for operators - Automated event clustering and prioritization

F) Real-time Power Management for TSO-DSO Coordination

Objective: Model DSO network effects and simulate impacts of distributed energy resources (DER) and battery energy storage systems (BESS) on TSO network frequency and voltage.

Business Need:

- Addresses the challenge of multiple 5-20 MW BESS requests on 33kV feeders affecting TSO network
- Models and understands how DSO disturbances propagate to the TSO network
- Actively alerts operators about potentially disturbing events
- Balances and dampens demand/response effects in real time to enhance operational efficiency
- Prevents network issues and potential blackouts through proactive management

Table [illegible] Real-time Power Management for TSO-DSO Coordination

	Real-time Power Management for TSO-DSO Coordination
Tech Capabilities	- Optimisation & Decision Support - Automation & Control Systems
Key Performance	- Effectiveness of possible actions on the TSO arising from simulation (evaluated by domain professionals)

[illegible]	• Quality and usefulness of generated simulations (assessed by domain experts)
[illegible]	• Historical data for DSO consumption loads • Historical controllable assets data (possibly simulated) • Simulation environment of joined DSO/TSO network • Historical transformer and energy assets data (PV, BESS) • Network metadata and simulation environment • Real-time transformer loading streams (future phases) • SQL/CSV to real-time JSON over MQTT format • About 3GB estimated data size • Per 1-15 minute consumption measurements resolution •
[illegible]	• Real-time power management recommendations • TSO-DSO coordination alerts and notifications • BESS control optimization Network stability impact assessments

2.2.3 [illegible]

Common Technical Stack and Computational Requirements: All TEF TSO services are built upon a unified Python-based technical foundation that ensures consistency and interoperability across transmission grid operations. The services utilize core AI frameworks including TensorFlow, PyTorch, Scikit-learn, and XGBoost, enhanced with specialized libraries such as Pandapower for power system analysis and MLflow for ML lifecycle management. Data integration supports multiple formats including SQL databases, COMTRADE files, CSV, JSON, and real-time MQTT streams to accommodate diverse grid data sources. The computational environment requires mid to high-end workstations with CPU and GPU capabilities, supporting both Linux and Windows operating systems, with edge computing infrastructure for some services and secure cloud-based training for model deployment.

Validation Framework and Deployment Methodology: The services employ a comprehensive validation approach centered on real-world test cases as the primary validation method, complemented by simulated test environments particularly crucial for grid stability and TSO-DSO coordination scenarios. Cross-validation with industry benchmarks ensures performance standards, while domain expert evaluation provides critical operational relevance assessment. Deployment follows a gradual integration strategy, beginning with read-only access to critical systems and offline historical data analysis, progressing toward real-time capabilities through modular architecture designed for scalability across different grid operators.

Integration Challenges and Cybersecurity Framework: Technical integration presents significant challenges including compatibility with existing SCADA and Distribution Management Systems (DMS), real-time data access limitations, and cybersecurity compliance with Operational Technology (OT) systems. The operational environment maintains strict security protocols with read-only access policies, no modification capabilities for SCADA/DMS variables, and comprehensive compliance with grid security standards. Legacy system integration complexity and limited streaming capabilities require careful consideration during deployment, while maintaining the balance between AI capabilities and grid security requirements.

Scalability Strategy and Future Enhancements: Immediate scalability is achieved through modular architecture enabling cross-operator deployment across different TSOs and DSOs, with capabilities for additional network integration and enhanced simulation through machine learning model integration with rule-based logic. Future enhancements focus on migration from offline analysis to live system integration, replacement of rule-based systems with advanced ML models, and development of cross-border coordination capabilities for multi-TSO operations. Integration with asset management systems will provide enhanced [illegible] assessment and maintenance planning capabilities.

Business Impact and Stakeholder Ecosystem: The technical infrastructure delivers substantial operational benefits including reduced manual analysis time, faster fault detection and root cause identification, improved grid stability through predictive assessment, and enhanced TSO-DSO coordination. Primary stakeholders include transmission and distribution system operators, grid control centre operators, and system engineers, while secondary stakeholders encompass regulators, AI developers, energy research institutions, and government agencies. The infrastructure addresses key technical challenges including data access limitations, system integration complexity, real-time performance requirements, and operational challenges such as cybersecurity balance, operator acceptance, regulatory compliance, and data quality assurance for reliable AI performance.

This comprehensive AI services portfolio positions the TEF TSO node as a critical component of the EnerTEF ecosystem, delivering advanced solutions for transmission grid management while addressing the complex challenges of modern power system operations and the integration of AI technologies in critical infrastructure.

2.4 TEF RES Node

2.4.1 Overview

The TEF RES node focuses on Renewable Energy Systems, offering ten AI-powered services designed to optimize renewable energy generation, maintenance, and operational efficiency. The services span multiple renewable energy technologies including hydropower, photovoltaic (PV), wind power, and wave energy systems. These services are being developed by organizations including PPC (Public Power Corporation) and various AI companies, targeting critical renewable energy operations and system optimization.

2.4.2 Service Portfolio

1) AI-Powered Hydropower Short-Term Generation Forecasting

Objective: Predict day-ahead energy generation at hydropower plants with daily granularity using advanced AI models.

Business Need:

- Addresses critical need for accurate hydropower generation forecasts
- Overcomes challenges of inefficient water resource management and grid instability
- Enables optimized plant operations and improved grid integration
- Supports enhanced economic value through better energy trading
- Promotes sustainable water use practices

Table 11: AI-Powered Hydropower Short-Term Generation Forecasting

	AI-Powered Hydropower Short-Term Generation Forecasting

Core Capabilities	• Predictive & Prescriptive Analytics
Key Performance Indicators	• Forecasting accuracy (Mean Absolute Error - MAE) • Latency (ms) - time taken to return predictions for real-time conditions
Data Available	• Historical generation and water level data (CSV format; daily resolution, with documentation) • Open-source weather datasets from Open-Meteo (API format; hourly resolution, with documentation) • Historical dataset spanning 2013-2023 from HDAM
Key Outputs	• Daily and predicted daily energy generation (MWh) in CSV format • Day-ahead forecasts with daily granularity

3) AI-Driven Pumpback Optimization for Hydropower System

Objective: Optimize pumpback operations between hydro dam and adjacent hydro storage to maximize energy storage and generation efficiency.

Business Need:

- Addresses complexities of coordinating water transfer for optimal energy efficiency.
- Prevents wasted energy due to suboptimal timing and volume of water transfer.
- Reduces risk of water overflow posing environmental and safety hazards.
- Ensures sufficient water availability for storage hydro plant power generation.
- Minimizes operational costs from manual intervention and suboptimal decision-making.

Table 13 AI-Driven Pumpback Optimization for Hydropower System

	AI-Driven Pumpback Optimization for Hydropower System
Core Capabilities	• Predictive & Prescriptive Analytics • Optimization & Decision Support •
Key Performance Indicators	• Forecasting accuracy (Mean Absolute Error - MAE) • Pumpback efficiency ratio (% of water pumped resulting in usable stored energy) • Overflow risk reduction (%) - quantifies decrease in overflow events
Data Available	• Weather forecasts (precipitation, temperature) via API with hourly resolution • Historical water level data from HDAM plant and HPSA plant (CSV format; daily resolution)

Key Outputs	• Pump dispatch signals (commands or setpoints for pump operation) • Automated water transfer optimization recommendations

f) AI-Based PV Soiling Loss Assessment

Objective: Quantify energy losses of PV systems due to soiling and provide insights for optimal cleaning intervention timing.

Business Need

- Addresses significant problem of reduced energy production due to soiling accumulation.
- Prevents lost revenue from decreased energy output.
- Optimizes cleaning activity scheduling to avoid unnecessary costs or prolonged energy losses.
- Enables precise evaluation of true PV system performance.
- Supports accurate future energy production predictions.

Table [illegible]: AI-Based PV Soiling Loss Assessment

	AI-Based PV Soiling Loss Assessment
AI Core [illegible]	• Optimization & Decision Support
Key Performance Indicators	• Mean Absolute Error (MAE) or Root Mean Squared Error (RMSE) for soiling loss estimation • R-squared value indicating model fit quality
Input Data/Datasets	• Historical generation data from inverters (CSV format, 15-minute resolution, no documentation) Soiling sensor data (CSV format, 15-minute resolution, no documentation)
Key Outputs	• Soiling loss assessment results (CSV format) • Optimal cleaning intervention timing recommendations

g) AI-Powered Spare Parts Procurement Recommendations for PV Inverters

Objective: Predict potential inverter failures and recommend optimal spare parts procurement strategies using historical inverter and string data analysis.

Business Need

- Addresses challenges of managing spare parts inventory for PV inverters.
- Prevents high inventory costs due to overstocking unnecessary parts.

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- Reduces increased downtime from unavailability of critical components.
- Minimizes delays in repair and maintenance activities.
- Prevents lost energy production and revenue from extended outages.

Table [illegible]: AI-Powered Spare Parts Procurement Recommendations for PV systems

	AI-Powered Spare Parts Procurement Recommendations for PV Systems
Core Capabilities	• Optimisation & Decision Support
Key Performance Indicators	• Accuracy of failure prediction (Precision, Recall, F1 score) • MAE/RMSE of time-to-failure • Reduction in downtime due to spare parts availability
Data Provided	• Historical generation data from inverters (CSV format, 15-minute resolution, no documentation) • Historical generation data from strings (CSV format, 15-minute resolution, no documentation) • Operations log reports (monthly resolution, with documentation)
[illegible]	• Spare parts recommendations with predicted time-to-failure and procurement options (CSV format) • Inventory optimisation strategies

[illegible] AI-Powered Wind Power Short-Term Forecasting

Objective: Provide accurate forecasts of wind power generation using historical SCADA data and weather information

Business Need:

- Addresses inherent challenge of wind power variability and unpredictability.
- Prevents inefficient energy trading practices and lost revenue opportunities.
- Supports grid balancing and stability maintenance.
- Enables optimal scheduling of maintenance activities.
- Reduces downtime and operational costs.

Table [illegible]: AI-Powered Wind Power Short-Term Forecasting

	AI-Powered Wind Power Short-Term Forecasting
Core Capabilities	• Predictive & Prescriptive Analytics
Key Performance Indicators	• Forecast accuracy (MAE, RMSE, nRMSE for 1h, 6h, 24h forecasts) • Forecast delivery time (seconds)

Data Required	- Historical SCADA data (CSV format, hourly resolution), no documentation, including: o Timestamp, ambient wind direction and speed, temperature o Blade pitch angle, generator temperatures and RPM o Active/reactive power, production references o Grid, rotor, and gearbox information - Weather forecasts (Open API, hourly resolution, with documentation if available)
Key Outputs	- Wind power forecasts (CSV or JSON format) - Forecasted active power for wind farm and potentially per turbine - Uncertainty or confidence intervals for forecasts

(f) Wave Power Generation Short-Term Forecasting

Objective: Forecast energy production from wave power plants using AI techniques with real-time sensor data and weather forecasts.

Business Need:

- Addresses unpredictable wave conditions significantly impacting generation.
- Ensures efficient energy production through accurate real-time forecasting.
- Optimizes trading strategies and improves grid reliability.
- Supports operational planning and power trading decisions.

Table 20: Wave Power Generation Short-Term Forecasting

	Wave Power Generation Short-Term Forecasting
Core Capabilities	- Predictive & Prescriptive Analytics for wave energy trading, plant operation planning, and grid reliability.
KPI / Measurement Indicators	- Forecasting accuracy (Mean Absolute Error - MAE) - Response time for real-time operations
Data Required	- Real-time sensor data from wave plant turbines (power generation, weather conditions, wave size and frequency) - Historical wave power generation data - Historical wave weather data (wave size, frequency, wind speed) - Open-source weather forecasts - API, CSV, JSON formats with hourly resolution
Key Outputs	- 48-hour forecasts with hourly resolution through APIs - Strategic decision support for wave energy operations

7) Anomaly Detection for Preventive Maintenance in Offshore Renewables

Objective: Continuously analyse frequency and patterns in offshore renewable energy systems to predict component failure likelihood.

Business Need:

- Addresses harsh offshore conditions and hard-to-access infrastructure challenges.
- Enables early malfunction identification and efficient dispatch.
- Allows remote detection and prioritisation of maintenance tasks.
- Improves operational safety and reduces unexpected downtimes.
- Extends operational life of offshore assets.

Table 27 Anomaly Detection for Preventive Maintenance

	[illegible] Offshore Renewables
Tool Capabilities	• Monitoring & Anomaly Detection • Predictive Analytics • Automation & Decision Support • Data Integration & Interoperability
Key Performance Indicators	• Anomaly prediction accuracy (confusion matrix) • Mean time between failures (MTBF) improvement • Maintenance cost reduction estimates
Data Provision	• Real-time sensor data from wave plant turbines • Historical power generation and weather/wave data • Open-source weather forecasts • Optional: AI-based weather forecasts, proprietary datasets, maintenance records • API, CSV, JSON, SQL database formats with hourly or sub-hourly resolution
Tool Outputs	• Component failure likelihood predictions • Risk-based asset prioritisation • Preventive maintenance recommendations

8) Asset Control and Operational State Management for Offshore Energy Assets

Objective: Classify and manage operational states of offshore renewable energy assets, distinguishing between normal generation, derated, and safeguard states.

Business Need:

- Addresses need for precise control over operational states to prevent damage.

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- Reduces wear and optimizes generation efficiency.
- Enables remote identification of asset effective modes.
- Initiates safe transitions automatically when risk or non-productive states detected.
- Improves operational efficiency and asset lifetime.

Table [illegible]: [illegible]

	[illegible]
Core Capabilities	• Mode classification & state Decision Support • Health condition Monitoring • User Interface & Visualization
KPI / Performance Indicators	• Correct state classification rate • Safe transition workflow • Operational uptime ratio •
Data Envelope	• Real-time telemetry/sensor data • Operational mode logs • Open-source weather forecasts • Fault and alert history API, CSV, JSON, real-time streams with hourly or sub-hourly resolution
Key Outputs	• Control commands via API • Operational status monitoring • Automated state transition management

8) Fault Classification and Location in Offshore Renewables

Objective: Enable detection and localization of faults in offshore renewable energy systems using real-time sensor data processing.

Business Need:

- Addresses harsh offshore conditions and hard-to-access infrastructure.
- Enables effective fault identification and dispatch efficiency.
- Allows remote detection and prioritization of maintenance tasks.
- Improves operational safety and minimizes service disruption.
- Reduces operational downtime through timely maintenance dispatch.

Table [illegible]: Fault Classification and Location

	Fault Classification and Location in Offshore Renewables
Core Capabilities	• Fault classification • Fault location and identification • Corrective maintenance support

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Key AI Performance Indicators	- Number of fault detection identification types - Model robustness under variable offshore conditions - True positives and false positives [%]
Data Sources	- Real-time sensor data from wave point turbines - Historical power generation and weather/wave data - Open-source weather forecasts - Optional: AI-based weather forecasts, proprietary datasets - API, CSV, JSON formats with hourly or sub-hourly resolution
Key Outputs	- Fault detection and classification via API - Fault location identification - Maintenance prioritization recommendations

10) Performance Evaluation of Energy Forecasts for Offshore Energy Assets

Objective: Evaluate performance of energy forecasts by comparing predicted and actual energy outputs of offshore assets.

Business Need:

- Addresses essential need for planning and market operations evaluation
- Reduces penalties from imbalance markets
- Enhances grid integration of offshore renewable sources
- Supports energy analysts and system operators in identifying forecasting errors
- Enables improvement of future forecasting models

Table [illegible]: [illegible] Evaluation of Energy Forecasts

	Performance Evaluation of Energy Forecasts for Offshore Energy Assets
Core Functionality	- Performance evaluation - Estimation of performance deviation
Key Performance Indicators	- Mean Absolute Error (MAE) - Root Mean Square Error (RMSE) - Forecast bias (%) - Accuracy improvement over time
Data Required	- Forecasted energy production data (from internal or third-party sources) - Historical power generation and weather/wave data - Open-source weather forecasts - API, CSV, JSON, time series formats with hourly or sub-hourly resolution

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Key Outputs	• Performance metrics and charts through APIs • Critical KPIs including MAE, RMSE, and deviation trends • Exportable reports (PDF/CSV format)

3.4.3 Technical Infrastructure and Impact

Common Technical Stack and Development Environment: The TEF RES services are built upon a consistent Python-based technical foundation that ensures interoperability across diverse renewable energy technologies. Most services utilize FastAPI for backend APIs, supported by comprehensive ML libraries including pandas, NumPy, scikit-learn, XGBoost, and LightGBM, with PyTorch and TensorFlow providing deep learning capabilities. Data visualization is handled through matplotlib and plotly, while Docker containers enable standardized deployment with API-based integration. The development environment ranges from standard PC configurations to secure cloud-based infrastructure, incorporating simulation tools for hydrological and renewable energy modelling, and supporting both real-time and batch processing through RESTful API architectures.

Validation Framework and Integration Methods: The services employ a robust validation methodology emphasizing real-world test cases as the primary validation approach, particularly for operational renewable energy systems, complemented by simulated test environments for offshore and complex systems. Cross-validation with industry benchmarks ensures performance standards, while backtesting using historical data with known outcomes provides reliability assessment. Integration is achieved through API-based architectures supporting data ingestion and output delivery, containerized deployment for portability and consistency, and microservices architecture enabling scalable operations across cloud-based and on-premises environments with both offline and online operational modes.

Scalability Strategy and Future Enhancements: Immediate scalability is facilitated through cross-technology integration across multiple renewable energy technologies, modular architecture enabling reuse across different asset types, and API-driven architecture for independent component scaling. Geographic expansion supports additional renewable energy facilities and coordination between multiple installations, while integration with operation planning and power trading optimization tools enhances system-wide efficiency. Future enhancements focus on advanced AI-powered optimization tools, real-time adaptive learning capabilities, edge computing deployment for reduced latency, and evolution toward predictive maintenance, multi-asset coordination, and enhanced visualization interfaces.

Business Impact and Stakeholder Ecosystem: The technical infrastructure delivers substantial value through optimized energy generation and trading strategies, reduced maintenance costs via predictive approaches, improved asset utilization, and enhanced grid integration reliability. Economic benefits include increased revenue through better energy trading, reduced operational costs and downtime, optimized inventory management, and penalty reduction from imbalance markets, while environmental impact encompasses maximized renewable energy utilization and enhanced clean energy contribution. Primary stakeholders include asset owners and operators, transmission and distribution system operators, aggregators, and power traders, supported by secondary stakeholders including AI developers, regulators, industrial consumers, and energy research institutions.

Technology-Specific Challenges and Sector Insights: The infrastructure addresses diverse technical challenges including limited documentation for datasets, varying data resolution and granularity, integration of multiple data sources, and harsh environmental conditions affecting offshore systems. Operational challenges encompass integration with existing renewable energy infrastructure, real-time processing requirements, cybersecurity for critical energy infrastructure, and regulatory compliance across different jurisdictions. Sector-specific insights reveal distinct approaches: hydropower concentrates on water resource optimization with long-term historical data, photovoltaic services emphasize maintenance and high-frequency data analysis, wind power services utilize comprehensive SCADA

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data for trading optimisation, while wind offshore services address harsh environment challenges through multi-faceted forecasting, fault detection, and safety-critical operational state management.

This comprehensive AI services portfolio positions the TEF RES node as a critical component of the EnerTEF ecosystem, delivering specialized solutions for renewable energy optimization while addressing the unique challenges of different renewable energy technologies and their integration into modern energy systems.

2.5 TEF EV Node

2.5.1 Overview

The TEF EV node focuses on Smart Electric Vehicle (EV) Chargers and integration, offering seven AI-powered services designed to optimise EV charging behaviour, energy management, and grid interaction within smart energy communities. All services are being developed by EMG or new partners, targeting the critical intersection of electric vehicle adoption, renewable energy integration, and smart grid operations.

2.5.2 Model Catalogue

1) Private/Public EV User Charging and Usage Profiles Prediction

Objective: Forecast day-ahead charging behaviour and energy demand patterns of private and public EV users based on historical usage data and contextual information.

Business Need:

- Critical for grid stability and efficient energy use planning.
- Enables smart charging strategy development and deployment.
- Supports DSOs in peak shaving and infrastructure upgrade planning.
- Empowers aggregators to better engage EV users in flexibility markets.
- Reduces forecasting errors in EV-related energy consumption.

Table 21 Private/Public EV User Charging and Usage Profile Prediction

	Private/Public EV User Charging and Usage Profile Prediction
Data Capabilities	• Predictive & Prescriptive Analytics
Key Performance Indicators	• Mean Absolute Error (MAE) for charging prediction accuracy • Recall on charging event detection • User segmentation clustering accuracy • Response time for inference operations
Data Provided	• Smart meter and EVSE data (private, internal) – 15-minute resolution • User demographic and behavioural data (anonymised, internal) • Weather forecast and traffic data (Open Meteo, public APIs) JSON, CSV formats accessible via APIs or batch upload

	- Metadata dictionaries provided for each data source
Key Outputs	- Predicted charging profiles (time series of demand, probability of charging events) Day-ahead EV charging behaviour forecasts - Proactive load balancing recommendations

J) EV-Driven Demand Forecasting in Energy Communities

Objective: Forecast electricity demand in energy communities with strong focus on EV charging behaviour, integrating smart meter data, EV usage patterns, and external variables.

Business Need

- Addresses rapid growth of EV adoption introducing uncertainty into local energy demand profiles.
- Overcomes limitations of traditional forecasting methods in capturing dynamic EV charging behaviour.
- Supports infrastructure planning and demand-side management strategies.
- Enables local flexibility market participation and grid impact mitigation.
- Prevents transformer overloading and costly grid reinforcements.

Table [illegible] EV-Driven Demand Forecasting in Energy Communities

	EV-Driven Demand Forecasting in Energy Communities
Data Capabilities	- Predictive & Prescriptive Analytics
[illegible]	- Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) of forecasts - [illegible] - [illegible]
[illegible]	- Smart meter and EVSE data (smaller intervals) / 15-minute resolution - User demographics and behavioural data (anonymised, opt-in) - Weather forecast and traffic data (Open Meteo, public APIs) - JSON, CSV formats accessible via APIs or batch upload - Metadata dictionaries provided for each data source
Key Outputs	- Aggregated and disaggregated demand forecasts across multiple time horizons - Smart scheduling recommendations for EV charging - Grid impact mitigation strategies - Alignment guidance with local renewable generation

K) Localised PV Generation Forecasting for Smart Energy Communities

Objective: Deliver high-resolution forecasts of solar PV generation tailored to energy community configurations, including individual rooftops, shared PV systems, and EV-coupled infrastructures.

Business Need:

- Addresses intermittency challenges in energy communities relying on variable solar PV generation.
- Essential for optimizing energy flows and reducing curtailment.
- Enables coordination of flexible assets like EVs with renewable generation.
- Supports demand response, storage scheduling, and market participation.
- Improves overall energy resilience and autonomy at community level.

Table [illegible] Localized PV Generation Forecasting for Smart Energy Communities

	Localized PV Generation Forecasting for Smart Energy Communities
Data Capabilities	• Predictive & Prescriptive Analytics
Key Performance Indicators	• Root Mean Square Error (RMSE) and Normalized Mean Absolute Error (NMAE) for 1-hour, 6-hour, and day-ahead horizons • Forecast bias assessment • Latency and uptime of forecast service
Data Exploited	• Historical PV output data (internal, community-owned systems) – 15-minute resolution • Weather forecasts (Open-Meteo, COSMO, [illegible]) • Geographic, PV system metadata (tilt, azimuth, capacity – internal) • JSON, CSV formats accessible via APIs or batch upload • Metadata dictionaries provided for each data source
Key Insights	• Short- and medium-term PV generation predictions • Intelligent scheduling support for battery charging and EV loads • Peer-to-peer energy trading optimization • Enhanced self-consumption strategies

Wind Generation Forecasting for EV-Integrated Energy Communities

Objective: Provide high-resolution short- and medium-term forecasts of wind power generation within EV-integrated energy communities using localized wind turbine data and meteorological inputs.

Business Need:

- Addresses increasing complexity of balancing supply and demand in communities with local wind power and EVs.
- Prevents underutilized/excess energy and grid instability from wind generation variability.
- Enables predictive scheduling of EV charging and storage systems.
- Supports cost savings, carbon reduction, and improved grid interaction.

- Empowers communities to operate with greater autonomy and flexibility.

Table 14: Wind Generation Forecasting for EV-Integrated Energy Communities

	Wind Energy Generation Forecasting for EV-Integrated Energy Communities
TEF Capabilities	• Predictive & Prescriptive Analytics
KPIs & Performance Indicators	• Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Mean Absolute Percentage Error (MAPE) over different forecast horizons • Uptime and latency of forecast APIs • Forecast bias and coverage rate assessment
Data Provided	• SCADA data from wind turbines (private, internal) - 15-minute resolution • Weather forecast models (ECMWF, Open-Meteo - public/open) • Site metadata (turbine specifications, location, altitude - internal) • JSON, CSV formats accessible via APIs or batch upload • Metadata dictionaries provided for each data source
AI Outputs	• Coordinated wind energy utilization for EV charging, battery storage, and household consumption • Community-level energy balancing recommendations • Demand shaping strategies under variable wind conditions

3) Battery & EV EMS Optimization for PV Self-Consumption

Objective: Optimize charging and discharging of stationary batteries and electric vehicles to maximize on-site PV self-consumption in residential and community energy systems.

Business Need:

- Addresses opportunities and operational challenges created by EV adoption and rooftop solar.
- Prevents low-value PV export and costly peak loads from uncoordinated EV charging.
- Enables unified Energy Management System (EMS) strategies treating EVs and batteries as coordinated flexibility assets.
- Maximizes self-consumption, reduces energy bills, and prepares for local energy market participation.
- Respects EV driver mobility requirements while optimizing energy flows.

Table 15: Battery & EV EMS Optimization for PV Self-Consumption

	Battery & EV EMS Optimization for PV Self-Consumption
TEF Capabilities	• Predictive & Prescriptive Analytics • Optimization & Decision Support

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Key Performance Indicators	• PV self-consumption ratio improvement • Battery round-trip efficiency optimization • Grid import/export reduction measurements • State of Charge (SOC) trajectory stability • Forecast-optimization latency assessment
[illegible]	• PV generation forecasts (open weather APIs, system metadata) - 15-minute resolution • Load forecasts from smart meter data (internal, household level) • Battery parameters (capacity, charge/discharge limits - internal) • Tariff data or market signals (optional, internal or open) • JSON, CSV formats accessible via APIs or batch upload
Use Cases	• Intelligent energy flow scheduling to reduce grid dependency • Peak tariff avoidance strategies • Local flexibility services coordination • Seamless EV integration as mobile storage units

8) AI-Enhanced Multi-Agent Testing for V2G Applications

Objective: Simulate and test AI-enhanced multi-agent systems for Vehicle-to-Grid (V2G) applications, enabling experimentation with decentralized coordination strategies and market participation.

Business Need:

- Addresses dependency of V2G success on robust, trustworthy multi-agent behaviour across distributed EVs
- Enables stakeholder evaluation of performance, fairness, compliance, and safety before real-world deployment
- Ensures AI agents operate reliably under uncertainty and market dynamics
- Supports development of decentralized control strategies for EV fleets
- Validates grid service delivery capabilities of coordinated EV systems

Table 13: AI-Enhanced Multi-Agent Testing for V2G Applications

	AI-Enhanced Multi-Agent Testing for V2G Applications
Core Capabilities	• Predictive & Prescriptive Analytics • Optimization & Decision Support
Key Performance Indicators	• Economic efficiency (cost savings, arbitrage revenue) • Grid compliance (response time, capacity delivered) • Agent robustness (performance under noise/failure conditions) • AI transparency/interpretability metrics
[illegible]	• EV fleet data (State of Charge, availability - internal) - 15-minute resolution

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	- Market signals (price forecasts, flexibility events – internal or public APIs) - Grid constraints and balancing signals (TSO/DSO – testbed-specific or synthetic) - JSON, CSV formats accessible via APIs or batch upload - Metadata dictionaries provided for each data source
Key Outcomes	- Multi-agent system performance validation - Decentralised coordination strategy testing - Agent decision-making behaviour analysis - Market participation simulation results

7) EV-Centric Flexibility and Ancillary Services Optimisation for CO2 and Cost Reduction

Objective: Orchestrate electric vehicles and other flexible assets to deliver grid-supportive ancillary services and local demand optimisation, targeting CO_2 emissions reduction and economic savings.

Business Need

- Addresses rapidly growing but underutilised source of grid flexibility in EVs.
- Overcomes challenges of intelligent coordination across heterogeneous assets, user behaviours, and regulatory conditions.
- Enables AI-driven tools that unlock EV flexibility for ancillary services.
- Reduces emissions during peak periods and lowers energy costs.
- Provides scalable, user-friendly flexibility without sacrificing mobility needs.

Table 27 EV-Centric Flexibility and Ancillary Services Optimisation for CO2 and Cost Reduction

	EV-Centric Flexibility and Ancillary Services Optimisation for CO2 and Cost Reduction
TEF Capabilities	- Predictive & Prescriptive Analytics - Optimisation & Decision Support
Key AI Infrastructure Features	- Simulated or real access to flexible loads and assets - Price and emissions forecast API access capability - Ability to simulate frequency response or DSO flexibility calls
Data Provided	- Asset-level flexibility metadata (internal, site-specific) – 15-minute resolution - Real-time and forecasted electricity prices (open/market APIs) - CO_2 intensity signals (ENTSO-E, Tomorrow's Carbon Intensity API – open) - Load and generation forecasts (internal/derived) - JSON, CSV formats accessible via APIs or batch upload
Key Outcomes	- Dynamic EV charging and discharging schedules based on real-time market signals - Carbon intensity forecast integration - Automated participation in flexibility markets

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	- Low-carbon grid services contribution

[illegible]

Unified Technical Stack and Development Environment: All TEF EV services are built upon a consistent and modern technical foundation utilizing Python as the backend programming language with FastAPI for service delivery, ensuring seamless integration across electric vehicle and energy management applications. The services support JSON and CSV data formats across [illegible] with batch upload, with API-based integration methods enabling seamless deployment through Docker container compatibility and microservices architecture for independent scaling. The development environment features a GPU-enabled server with 64 GB RAM hosted on CERTH cluster infrastructure, complemented by cloud backup and development environments on AWS supporting federated training capabilities, with high-end GPU (V100) resources available for training and a combination of real-time and batch processing capabilities.

Validation Framework and Cross-Node Integration: The services employ a comprehensive validation strategy centred on real-world data with [illegible] focus across all services, utilizing historical smart charging datasets from pilot sites and simulation of grid-level impacts via DSO digital twins. Cross-validation with industry benchmarks ensures performance standards while supporting integration across the broader EnerTEF ecosystem including renewable energy forecasting (TEF-RES), distribution grid automation coordination (TEF-DSO), transmission system operator coordination (TEF-TSO), and building energy management integration (TEF-BUILD). The scalability approach emphasizes compatibility across multiple TEF nodes through modular architecture enabling horizontal scaling, federated learning capabilities for distributed training, and community-level deployment with grid interaction capabilities.

Business Impact and Market Transformation: The technical infrastructure delivers substantial operational benefits including enhanced grid stability through predictive EV charging management, reduced peak loads and infrastructure upgrade costs, improved renewable energy integration, and optimized demand-side management strategies. Economic impacts include reduced energy procurement costs through smart charging, avoided peak tariff charges, increased revenue from flexibility market participation, and lower infrastructure costs through demand management, while environmental benefits include CO_2 emissions reduction, enhanced clean energy utilization efficiency, and support for decarbonization goals. Market transformation is facilitated through accelerated EV adoption via optimized charging experiences, enhanced V2G market readiness, improved business models for EV fleet operators, and enhanced seamless EV integration in energy communities.

Technical Challenges and Advanced Solutions: The infrastructure addresses complex data integration challenges including real-time data [illegible] requiring adaptive processing solutions, integration of multiple data sources with varying formats, real-time processing requirements for grid interaction, and privacy preservation in federated learning scenarios. Solutions include scalable cloud infrastructure with elastic capacity, standardized API interfaces, edge computing capabilities for real-time processing, and privacy-preserving machine learning techniques. System integration complexities are managed through multi-agent system architectures for distributed coordination, real-time optimization algorithms with constraint handling, user preference learning and mobility pattern recognition, and grid-aware control algorithms with stability guarantees.

Future Innovation Pathways and Ecosystem Development: The technical foundation supports advanced future capabilities including Vehicle-to-Everything (V2X) integration beyond grid services, autonomous vehicle integration with energy management, blockchain-based peer-to-peer energy trading, and advanced AI techniques including reinforcement learning. Market development opportunities encompass Energy-as-a-Service offerings for EV owners,

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community energy market platforms, carbon credit optimisation through smart charging, and mobility-energy service bundling. Regulatory evolution integration includes dynamic pricing mechanism integration, regulatory sandbox participation for V2G services, cross-border energy trading facilitation, and carbon accounting integration for emissions optimisation, positioning the TEF EV node as a critical enabler of electric vehicle integration within smart energy systems.

This comprehensive AI services portfolio positions the TEF EV node as a critical enabler of electric vehicle integration within smart energy systems, delivering practical solutions for the coordination of EVs with renewable energy sources, grid operations, and community energy management while advancing the transition toward sustainable mobility and energy systems.

2.5 TEF DSO Node

2.5.1 Overview

The TEF DSO node focuses on Distribution Grid Automation, offering three AI-powered services designed to enhance grid monitoring, state estimation, and model-based control systems for DSOs. These services are being developed by RWTH Aachen and Distribution Grid Operators (SWW), targeting critical distribution grid operations including real-time state estimation, forecasting, and advanced control system optimisation.

2.5.2 Service Portfolio

1) AI-Enhanced Model-Based Ancillary Services

Objective: Improve the accuracy and prediction capability of dynamic models used in model-based control systems employed by DSOs for various grid management applications.

Business Need:

- Addresses uncertainties in model-based control systems used for Energy Management Systems (EMS), flexibility services, and congestion management.
- Overcomes inaccurate predictions from traditional models that lack real-time learning capabilities.
- Enhances operational efficiency by improving model accuracy for critical grid operations.
- Supports better decision-making in flexibility services and congestion management.
- Reduces operational risks through more reliable prediction models.

Table [illegible]: AI-Enhanced Model-Based Ancillary Services

	1) Enhanced Model-Based Ancillary Services
[illegible]	• Optimisation & Decision Support
[illegible]	• Model prediction accuracy (Mean Absolute Error - MAE) • Real-time performance for the number of 3-phase buses •
[illegible]	Real-time sensor data from distribution grid ([illegible]), 15 min resolution, with documentation)

	• Historical generation and/or load profiles (CSV format, 15-minute resolution, with documentation) • Real-time generation and/or load profiles (API/MQTT/UDP/IEC61850/others, 15-minute resolution, with documentation) • Distribution grid topology (CIM or MATPOWER format, with documentation)
Key Outcomes	• Enhanced dynamic models with improved prediction accuracy • 24-hour low-voltage power flow and losses predictions • Optimized power flow/control [illegible]

2) AI State Estimation Forecast

Objective: Estimate utilization, power flow, current flow, and voltage magnitude of all grid elements based on measurements, billing information, grid model, and weather data with forecasting capabilities.

Business Need:

- Provides DSOs with essential information for grid planning and operating purposes.
- Enables comprehensive understanding of grid usage and performance.
- Supports proactive grid management through state estimation and forecasting.
- Facilitates infrastructure planning and capacity management decisions.
- Enhances grid reliability through accurate state monitoring and prediction.

Table [illegible]: AI State Estimation Forecast

	2) AI State Estimation Forecast
Service Classification	• Monitoring & Anomaly Detection • Optimization & Decision Support • Automation & Control Systems
Key Performance Indicators	• Accuracy (Mean Absolute Error / MAE) • Response time for new measurements •
Data Provision	• Real-time measurements of substations, feeders, and generators (V, I, P, Q, S) • Real-time weather data • Historical power profiles of substations • Grid model (CIM-CGMES format)
Key Outcomes	• Current electrical state of the grid through API • Utilization, power flow, current flow and voltage magnitude estimates for all grid elements • Forecasted grid states for planning purposes

T1.4: State Estimation

Objective: Estimate utilization, power flow, current flow, and voltage magnitude of all grid elements based on real-time measurements, billing information, grid model, and weather data.

Business Need:

- Provides DSOs with critical real-time grid state information for operational decision-making.
- Enables comprehensive monitoring of grid performance and utilization.
- Supports real-time grid management and control operations.
- Facilitates immediate response to grid conditions and anomalies.
- Enhances operational efficiency through accurate state estimation.

Table [illegible]: State Estimation

	T1 State Estimation
Core Capabilities	• Monitoring & Anomaly Detection • Optimization & Decision Support • Automation & Control Systems
Key Performance Indicators	• Accuracy (Mean Absolute Error - MAE) • Response time for new measurements
Data Inputs	• Real-time measurements of substations, feeders, and generators (V, I, P, Q, S) • Real-time weather data • Historical power profiles of substations • Grid model (CIM-CGMES format)
Key Outputs	• Estimate electrical state of the grid through API • Real-time utilization, power flow, current flow, and voltage magnitude for all grid elements • Immediate grid state information for operational control

[illegible]

Common Technical Stack and Development Environment: All [illegible] DSO services are built upon consistent Python-based technical foundations with varying deployment architectures tailored to distribution grid automation requirements. The services utilize PostgreSQL databases (version 16.0 for service 1, standard versions for services 2&3), FastAPI framework for service 1 with standard APIs for services 2&3, and Jupyter Notebooks with [illegible] for enhanced user interface capabilities in service 1. Deployment is standardized through Docker containers and API calls, supporting multiple communication protocols including API/MQTT/[illegible] for comprehensive grid system integration. The development environment features a private Kubernetes cloud at RWTH Aachen for service 1, while services 2&3 utilize secure cloud-based model hosting, all supporting Docker containerization and direct integration with DSO APIs and SCADA systems.

Integration Architecture and Operational Environment: The services employ sophisticated integration architecture supporting multiple communication protocols for real-time data streaming capabilities and seamless integration with existing DSO SCADA systems through Docker containerization for enhanced portability. The operational environment enables integration with DSO's existing infrastructure, real-time measurement processing of high-frequency data (1ms to 1s), and comprehensive grid model integration supporting CIM-CGMES, CIM, and MATPOWER formats. Weather data integration enhances accuracy while addressing technical requirements including access to DSO's API for real-time data, SCADA system integration, and handling of various data formats and communication protocols for comprehensive grid state awareness.

Validation Framework and Scalability Strategy: The services employ real-world test cases as the primary validation method across all services, complemented by simulated test environments for comprehensive testing scenarios and direct DSO API integration for operational system validation. Immediate scalability is differentiated by service type: Service 1 features distributed co-simulation or Hardware-in-the-Loop setups with Kubernetes deployment for horizontal scaling, while Services 2&3 support horizontal scaling through parallelized computation of grid sections and extension to multiple DSO networks. Future enhancements focus on integration with emerging grid technologies, enhanced AI models for improved prediction accuracy, cross-grid coordination and optimization, and integration with renewable energy sources and smart grid components.

Business Impact and Grid Modernization Value: The technical infrastructure delivers substantial operational benefits including enhanced grid state visibility and monitoring, improved decision-making through accurate state estimation, better congestion management and flexibility services, and reduced operational risks through predictive capabilities. Economic impact encompasses reduced operational costs through improved efficiency, better asset utilization, prevented outages through proactive state estimation, and optimized maintenance schedules, while supporting informed infrastructure upgrade decisions and capacity planning based on accurate utilization data. The infrastructure drives grid modernization through enhanced grid observability via AI-powered state estimation, improved model-based control systems, real-time grid state awareness for operational decisions, and predictive capabilities for proactive grid management.

Technical Challenges and System Integration Solutions: The infrastructure addresses complex data integration challenges including multiple communication protocol integration, real-time processing of high-frequency measurements, grid model format compatibility, and weather data integration for enhanced accuracy. Solution approaches include multi-protocol communication interfaces, real-time processing capabilities with low latency, standardized grid model interfaces, and weather API integration for comprehensive data fusion. Service differentiation is achieved through specialized focus areas: Service 1 emphasizes model accuracy improvement for control systems with early deployment and rapid iteration, while Services 2&3 provide comprehensive grid state monitoring with real-time and forecasted capabilities, supporting the broader energy transition through better integration of variable renewable energy sources, enhanced flexibility services for grid balancing, and improved congestion management with high renewable penetration.

This comprehensive AI services portfolio positions the TEF DSO node as a critical component of the EnerTEF ecosystem, delivering advanced solutions for distribution grid automation while addressing the complex challenges of modern power distribution systems and supporting the transition toward smart, automated grid operations.

2.7 TEF H2 Satellite

2.7.1 Overview

The TEF H2 satellite focuses on Hydrogen Energy systems, offering three AI-powered services designed to optimize hydrogen technology integration, fuel cell performance, and energy management across various applications. These

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services are being developed by UTBM (Université de Technologie de Belfort-Montbéliard), targeting critical hydrogen energy challenges including predictive maintenance, microgrid integration, and hybrid vehicle energy management.

[illegible]

1) Data-Driven Predictive Modelling for Fuel Cell Performance and Degradation

Objective: Provide predictive analytics for fuel cell systems using data-driven models to forecast performance degradation and identify potential failures in advance.

Business Need:

- Addresses fuel cell system degradation over time due to operational and environmental factors.
- Enables proactive maintenance by predicting degradation before performance is affected.
- Reduces operational risks and cuts maintenance costs significantly.
- Increases system uptime and extends overall fuel cell system lifespan.
- Supports intelligent real-time monitoring and decision support for fuel cell operations.

Table 11: Data-Driven Predictive Modelling for Fuel Cell Performance and Degradation

	Data-Driven Predictive Modelling for Fuel Cell Performance and Degradation
Type of Solution	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics
KPIs	• Root Mean Square Error (RMSE) for prediction accuracy • Mean Absolute Error (MAE) for degradation forecasting
Data Required	• Operational data (real-time & historical) from onboard sensors and fuel cell controllers • Voltage, current, and power output measurements • Temperature and humidity (internal and ambient) monitoring • Fuel flow rate and pressure data • Load cycles and start-stop events with runtime duration • Data resolution per second or per minute with existing documentation for structure
Expected Outputs	• Performance degradation predictions and failure identification • Proactive maintenance recommendations via API or text/CSV format • Real-time monitoring insights for fuel cell system optimization

2) AI-Driven Active Control for More Efficient Hydrogen Integration in Microgrids

Objective: Enable intelligent control of hydrogen technologies within microgrids by coordinating real-time operation of electrolyzers, fuel cells, and other energy storage systems.

Business Need:

- Enables real-time optimization of hydrogen production, storage, and consumption.
- Significantly improves energy efficiency and reduces dependence on diesel backup systems.
- Maximizes return on investment in hydrogen infrastructure.
- Supports industrial and grid operator decarbonization aspirations.
- Enhances energy resilience through optimal hybrid renewable-hydrogen systems.
- Addresses climate goals and energy transition policy requirements.

Table 32: AI-Driven Hybrid Control for More Efficient Hydrogen Integration in Microgrids

	AI-Driven Hybrid Control for More Efficient Hydrogen Integration in Microgrids
Type of AI Solution	• Optimization & Decision Support • Automation & Control Systems
Key Performance Indicators	• Root Mean Square Error (RMSE) for control optimization • Mean Absolute Error (MAE) for system performance prediction
Data Required	• High-quality real-time and historical data across multiple domains • Energy demand and renewable generation data • Hydrogen system status (electrolysers, fuel cells, storage) • Weather forecasts and electricity market price information • Data from SCADA systems, IoT sensors, forecasting tools, and asset management systems • Data resolution: per minute, with existing documentation for structure
Key Outputs	• Optimal energy flow coordination between hydrogen and electrical systems • Real-time control commands via API for electrolyser and fuel cell operation • Enhanced efficiency and reduced renewable intermittency • Grid stability support through intelligent hydrogen system management

11 AI-Driven Energy Management for Fuel Cell Hybrid Electric Vehicles

Objective: Optimize power flow in Fuel Cell Hybrid Electric Vehicles (FCHEVs) by intelligently balancing energy use between fuel cell and battery systems.

Business Need:

- Addresses essential need for efficient energy management in fuel cell hybrid vehicles.
- Reduces hydrogen consumption and extends component lifespan.
- Lowers operational costs through dynamic adaptive control.
- Improves vehicle range, reliability, and sustainability.
- Supports key priorities for clean, cost-effective transportation solutions.
- Enables better performance across diverse driving conditions.

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Table [illegible]: AI-Driven Energy Management for Fuel Cell Hybrid Electric Vehicles

	AI-Driven Energy Management for Fuel Cell Hybrid Electric Vehicles
Core Capabilities	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Optimization & Decision Support • Automation & Control Systems
Key Performance Indicators	• Improvement in vehicle range due to optimized energy management • Powertrain efficiency through optimization of fuel cell and battery power distribution
Data [illegible]	• Fuel cell performance data (voltage, current, temperature) • Battery state of charge and power demand information • Vehicle operational data (speed, acceleration, driving conditions) • Driving environment data (slope, traffic, GPS location) • Data from onboard vehicle sensors, ECU logs, and telematics systems • Data resolution per second with evolving documentation for structure
Key Outputs	• Optimized power flow control between fuel cell and battery • Enhanced vehicle efficiency and reduced hydrogen consumption • Extended component lifespan through intelligent energy management • Real-time energy flow control integration with vehicle systems

[illegible] Technical Implementation and [illegible]

Common Technical Stack and Development Environment: All hydrogen energy services are built upon consistent technical foundations utilizing Python and MATLAB programming languages with a hybrid development framework combining Python for data processing and MATLAB for advanced modelling capabilities. The system employs API-based integration as the primary deployment method, supported by MATLAB/Simulink simulation and testing tools for synthetic operational scenarios. The development environment requires high-performance computing resources or cloud-based compute instances, complemented by digital twin environments for testing predictive performance and comprehensive validation through real-world test cases and simulated test environments.

Integration Architecture and Operational Environment: The services feature sophisticated integration architecture supporting multiple deployment methods including API integration, SCADA integration for direct control system connections, vehicle ECU integration for automotive applications, and cloud-edge hybrid processing capabilities. The operational environment addresses complex integration requirements encompassing fuel cell control systems, monitoring dashboard connectivity, SCADA/EMS system compatibility, and vehicle control system integration with real-time data processing capabilities. Technical solutions include standardized API interfaces, real-time processing with low latency, flexible data resolution handling, and multi-platform integration architecture to coordinate multi-domain data across energy, transport, and environmental systems.

Validation Framework and Scalability Strategy: The services employ real-world test cases as the primary validation method, complemented by simulated test environments for comprehensive scenario testing and cross-validation with industry benchmarks for performance comparison. Immediate scalability features services designed for reproducibility across similar applications with modular architecture enabling deployment in different hydrogen systems and integration potential with other TEF nodes for comprehensive energy management. Future enhancements focus on advanced AI algorithms for improved prediction accuracy, enhanced integration with renewable energy forecasting, expanded vehicle fleet management capabilities, and integration with hydrogen supply chain optimization.

Business Impact and Grid Modernization Value: The technical infrastructure delivers substantial operational benefits including reduced maintenance costs through predictive maintenance, enhanced system uptime and reliability, improved energy efficiency across hydrogen applications, and extended component lifespan through optimized operation. Economic impact encompasses lower maintenance costs through predictive approaches, reduced operational risks and unplanned downtime, optimized hydrogen consumption and energy efficiency, and maximum return on hydrogen infrastructure investment. The infrastructure drives market development by supporting hydrogen economy advancement, enhancing competitiveness of hydrogen technologies, improving business cases for hydrogen adoption, and supporting clean energy transition goals while providing environmental benefits through reduced dependence on diesel backup systems, enhanced renewable energy integration, and lower carbon emissions supporting decarbonization goals across industries.

This comprehensive AI services portfolio positions the TEF H2 satellite as a critical component of the hydrogen energy ecosystem within EnerTEF, delivering specialized solutions for hydrogen technology optimization while supporting the broader energy transition goals through advanced AI-driven approaches to hydrogen system management and integration.

2.8 TEF DHC Satellite

2.8.1 Overview

The TEF DHC node focuses on District Heating and Cooling Networks, offering three AI-powered services designed to optimize energy consumption, forecast demand, and enhance operational efficiency through digital twin technology. These services are being developed by Veolia, targeting critical challenges in district heating/cooling network management including real-time optimization, predictive analytics, and intelligent operational decision-making.

2.8.2 Service Portfolio

1) Energy Consumption Optimization

Objective: Apply AI algorithms to optimize energy consumption at both district level (boiler rooms) and building level (substations) using advanced technology to manage and improve facility energy efficiency.

Business Need:

- Reduces operational costs through intelligent energy management.
- Improves energy efficiency across district heating/cooling networks.

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- Achieves sustainability goals through optimized resource allocation.
- Enhances overall facility performance and operational effectiveness.
- Supports cost reduction initiatives and environmental objectives.

Table [illegible]: Energy Consumption Optimization

	Energy Consumption Optimization
Core Capabilities	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Optimization & Decision Support • Automation & Control Systems • Data Integration & Interoperability • User Interface & Visualization
Key Performance Indicators	• Energy performance improvement at district and substation levels • Percentage reduction in energy consumption (kWh) • Energy cost savings (€/month or €/year) • Energy production optimization metrics
[illegible]	• Operational data from DHCN infrastructure (temperature, flow rates, pressure, energy consumption, weather data) • Real-time data streams through [illegible] platform • SQL databases storing historical operational data • Over 700 variables collected every 15 minutes • Data collected at 15-minute intervals at both district level (boiler room) and building level (substations) • Comprehensive variables map for documentation and metadata
[illegible]	• Optimized set points through [illegible] devices • Real-time energy consumption control and adjustment • Enhanced energy efficiency across the network • Automated operational parameter optimization

D Energy Demand Forecasting

Objective: Predict future energy consumption patterns in DHCN networks using historical data, weather forecasts, and building usage patterns to optimize energy distribution and reduce operational costs while maintaining user comfort levels.

Business Need:

- Reduces operational costs through accurate demand prediction.
- Improves efficiency in district heating systems through better planning.
- Enables proactive energy management and resource allocation.
- Supports optimal energy distribution strategies.
- Maintains user comfort while minimizing energy waste.

[illegible]

	[illegible]
[illegible]	- Monitoring & Anomaly Detection - Predictive & Prescriptive Analytics - Optimization & Decision Support - Automation & Control Systems - Data Integration & Interoperability - User Interface & Visualization
[illegible]	- Forecast accuracy (Mean error % between simulated data and real demand data) - Effective prediction time horizon (hours/days) - Operational cost reduction through improved forecasting
[illegible]	- Operational data from DHCN infrastructure (temperature, flow rates, pressure, energy consumption, weather data) - Real-time data streams through Nalagrade platform - SQL databases storing historical operational data - Over 700 variables collected every <5 minutes - Data collected at 15-minute intervals at both district level (boiler rooms) and building level (substations) - Comprehensive variables map for documentation and metadata
[illegible]	- Accurate energy demand predictions for optimal planning - Set points optimization through TREND devices - Enhanced operational efficiency through predictive insights - Improved resource allocation and energy distribution strategies

3) Digital Twin DHCN Optimization

Objective: Combine artificial intelligence with Digital Twin technology to optimize district heating/cooling networks by creating virtual simulations to analyse and improve production scenarios, helping managers make better operational decisions.

Business Need

- Reduces operational costs through intelligent simulation and optimization
- Improves efficiency in district heating systems through virtual modelling
- Enables advanced scenario analysis and operational planning
- Supports data-driven decision-making for network management
- Enhances system understanding through comprehensive digital representation

[illegible]

	[illegible]
[illegible]	• Monitoring & Anomaly Detection • Predictive & Prescriptive Analytics • Optimisation & Decision Support • Automation & Control Systems • Data Integration & Interoperability • User Interface & Visualisation
Key Performance Indicators	• Model accuracy (% similarity between real and simulated behaviour) • Processing time for simulations (seconds/minutes) • Operational improvement through digital twin insights
[illegible]	• Operational data from DHCN infrastructure (temperature, flow rates, pressure, energy consumption, weather data) • Real-time data streams through Hubgrade platform • SQL databases storing historical operational data • Over 700 variables collected every 15 minutes • Data collected at 15-minute intervals at both district level (boiler rooms) and building level (substations) • Comprehensive variables map for documentation and metadata
[illegible]	• Virtual network simulation for scenario analysis • Optimised operational strategies through digital twin modelling • Enhanced decision-making support for network managers • Real-time operational adjustments through TREND devices

[illegible]

Common Technical Stack and Development Environment: All district heating/cooling network services are built upon consistent technical foundations utilising Python for user interface and AI algorithms, SQL database infrastructure for data storage and management, and the Hubgrade platform for real-time data streaming capabilities. The system enables direct hardware integration through 31 TREND devices for sensor data collection and control implementation, eliminating the need for backend APIs through direct device integration. The development environment operates on a coordinated M14-M36 development schedule, requiring SQL database infrastructure, TREND device network, Hubgrade platform integration, and Python development environment for comprehensive AI algorithm implementation.

Integration Architecture and Operational Environment: The services feature sophisticated integration architecture supporting real operational environment deployment through a 12-month demonstration period with direct TREND device integration for data collection and control. The operational environment addresses complex requirements including integration of over 700 variables from diverse sensors, real-time data processing with 15-minute intervals,

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and coordination between district-level and building-level data systems. Technical solutions include the Indigigrade platform for standardized data streaming, SQL database architecture for efficient data management, comprehensive TREND device network for consistent data collection, and advanced variables mapping for systematic data organization across the entire network infrastructure.

Validation Framework and Scalability Strategy: The services employ multiple validation methods including standard energy datasets for benchmarking against industry standards, real-world test cases through 12-month demonstration in operational environments, and cross-validation with industry benchmarks for performance comparison with existing solutions. Immediate scalability features modular architecture for easy deployment to new district heating/cooling networks, standardized integration approach using TREND devices, scalable data management through SQL database architecture, and replicable AI algorithms across different network configurations. Future enhancements focus on smart building systems integration for enhanced data collection, integration with renewable energy systems for sustainable operations, advanced analytics capabilities for deeper operational insights, and enhanced automation features for reduced manual intervention.

Business Impact and Grid Modernization Value: The technical infrastructure delivers substantial operational benefits including significant reduction in operational costs through optimized energy consumption, improved energy efficiency across district and building levels, enhanced resource utilization through predictive analytics, and reduced waste through accurate demand forecasting. Economic impact encompasses measurable energy cost savings, reduced operational overhead through automation, optimized maintenance scheduling, and enhanced competitiveness in the district heating/cooling market. The infrastructure drives sustainability through reduced energy consumption supporting carbon reduction goals, optimized resource utilization minimizing environmental impact, enhanced integration potential with renewable energy sources, and support for circular economy principles while providing advanced digital twin capabilities for virtual simulation, predictive modelling, enhanced system understanding, and strategic decision-making support for network development and operational excellence.

This comprehensive AI services portfolio positions the TEF DHN node as a critical component of the EnerTEF ecosystem, delivering specialized solutions for district heating and cooling network optimization while supporting broader energy efficiency and sustainability goals through advanced AI-driven approaches to thermal energy management.

2.5 TEF IND Greece

2.5.1 Overview

The TEF IND node focuses on industrial flexibility, offering four AI-powered services designed to optimize manufacturing operations, energy efficiency, and sustainability across industrial processes. These services are being developed by LMS (Laboratory for Manufacturing Systems), targeting critical challenges in industrial energy management including production scheduling, process planning, digital twin modelling, and supply chain optimization.

2.5.2 Service portfolio

1) AI-Assisted Scheduling of Production towards Energy Efficiency Increase

Objective: Utilize AI to optimize production scheduling in manufacturing, integrating energy efficiency as a key criterion alongside time-related metrics for improved operational performance.

Business Need:

- Addresses manual or inefficient scheduling processes that lead to resource conflicts, downtime, and asset underutilization.
- Eliminates inefficiencies that increase operational costs, reduce productivity, and introduce human error.
- Integrates energy efficiency as a scheduling criterion for smarter resource allocation.
- Reduces operational costs and supports sustainability goals and ESG targets.
- Enables automated optimization of task and resource allocation for improved service delivery.

Table 27 AI-Assisted Scheduling of Production towards Energy Efficiency Services

	AI-Assisted Scheduling of Production towards Energy Efficiency Services
Core Capabilities	- Optimization & Decision Support
Key Performance Indicators	- Response time for real-time adjustments - Increase in energy efficiency - Reduction in time-related KPIs - Applicability & Adaptation metrics
Data Provisioning	- Proprietary datasets from plant operations (API, CSV, JSON formats, hourly resolution, existing documentation) - Proprietary datasets for orders (API, CSV, JSON formats, hourly resolution, existing documentation) - Unknown data size with structured documentation available
Test Outputs	- Optimized production schedule plans via JSON and REST API - Energy-efficient resource allocation strategies - Automated scheduling with real-time adaptation capabilities

7) Energy-Efficient Process Planning Optimizer

Objective: Optimize manufacturing process plans by selecting processes, their sequences, and parameter values with energy efficiency as a key decision criterion alongside time, cost, and quality factors.

Business Need:

- Addresses growing pressure to reduce energy consumption due to rising costs and environmental regulations.
- Overcomes traditional process planning that overlooks energy efficiency considerations.
- Integrates energy consumption metrics into production planning phases.
- Reduces operational costs through lower energy usage and improved environmental sustainability.
- Ensures regulatory compliance with energy and emissions standards while supporting ESG performance.

Table 28 Energy-Efficient Process Planning Optimizer

	Energy-Efficient Process Planning Optimizer

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Core Capabilities	• Optimization & Decision Support
Key AI Performance Indicators	• Response time for real-time adjustments • Increase in energy efficiency • Reduction in time-related KPIs • Applicability & Adaptation metrics
Data Provision	• Proprietary datasets from plant operations (API, CSV, JSON formats, hourly resolution, existing documentation) • Proprietary datasets for orders (API, CSV, JSON formats, hourly resolution, existing documentation) • Unknown data size with structured documentation available
Key Outputs	• Optimized process plans with energy-efficient sequences via JSON over REST APIs • Energy-conscious process parameter recommendations • Integrated optimization considering time, cost, quality, and energy factors

f) AI Manufacturing Process & Modeller (Digital Twin)

Objective: Model manufacturing process behaviour using AI to facilitate both operation and design of manufacturing lines through optimization and what-if scenario analysis.

Business Need:

- Addresses limited visibility into real-time process performance in precision-dependent manufacturing.
- Prevents defects, reduces energy waste, and optimises overall system behaviour.
- Provides real-time virtual representation enabling live monitoring, simulation, and predictive optimisation.
- Optimizes energy use through better control and process tuning.
- Reduces defects and rework, saving energy and materials through intelligent defect prevention.

Table [illegible]: AI Manufacturing Process & Modeller (Digital Twin)

	AI Manufacturing Process & Modeller (Digital Twin)
Core Capabilities	• Optimization & Decision Support
Key AI Performance Indicators	• Response time for real-time adjustments • Increase in energy efficiency • Reduction in time-related KPIs • Applicability & Adaptation metrics
Data Provision	• Proprietary datasets from process characteristics (API, CSV, JSON formats, hourly resolution, existing documentation)

[illegible]	• Historical process variables and performance indicators (API) • CSV, JSON, or streaming; potentially millisecond resolution) • Real-time data for adaptation and active learning Large unknown data size with potentially unknown structure for some datasets
Key Outcomes	• Digital twin models of manufacturing processes via ISON over REST APIs • Real-time process monitoring and optimisation recommendations • Predictive insights for defect prevention and energy efficiency

4) Sustainable Supply Chain Optimiser

Objective: Optimise resource flow within supply chain networks by integrating sustainability metrics such as energy efficiency, consumption, and CO2 emissions alongside traditional time and cost factors.

Business Need

- Addresses complex supply chain networks that traditionally focus only on cost and time optimisation.
- Overcomes overlooked energy consumption, carbon footprint, and sustainability performance issues.
- Eliminates inefficient logistics routes with high fuel and energy use.
- Enables compliance with environmental regulations and achievement of sustainability goals.
- Optimises routes, loads, inventory management, and space utilization for reduced emissions.

Table 43 Sustainable Supply Chain Optimiser

	Sustainable Supply Chain Optimiser
Core Capabilities	• Optimisation & Decision Support
Key Performance Indicators	• Response time for real-time adjustments • Accuracy in prediction • Reduction in production-level KPIs through optimisation actions • Applicability & Adaptation metrics
Data Inventory	• Proprietary datasets for suppliers (API, CSV, JSON formats, hourly resolution, existing documentation) • Proprietary datasets for orders and parts (API, CSV, JSON formats, hourly resolution, existing documentation) • Unknown data size with structured documentation available
Key Outcomes	• Optimised supply chain resource flows via JSON over REST APIs • Sustainable logistics and transportation recommendations • Energy-efficient inventory and distribution strategies

2.5.2 Technical Infrastructure and Impact

Common Technical Stack and Development Environment: All manufacturing optimization services are built upon consistent technical foundations utilizing Java SPRING for backend APIs, MySQL for database management, and Angular for user interface development, with Python/C/C++ backend core components available for Service 3. The system employs JSON over REST APIs for comprehensive data integration with input/output capabilities, operating on a coordinated M18-M19 development schedule including structured testing phases. The development environment supports optional secure cloud-based model hosting and API access, edge computing infrastructure at manufacturing facilities, and integration with production, process physics, and supply chain simulators, while maintaining standard development infrastructure for API and database management without dedicated computational resources during development.

Integration Architecture and Operational Environment: The services feature sophisticated integration architecture supporting API-based integration as the primary deployment method using JSON over REST APIs, with optional industrial deployment limited to industry or provider API access and edge computing infrastructure at manufacturing facilities. The operational environment addresses complex manufacturing requirements including facility data integration, real-time processing capabilities for production optimization, historical data management and analysis systems, and supply chain network connectivity for comprehensive optimization services. Technical solutions include standardized API interfaces for data integration, flexible data processing architectures adaptable to varying data characteristics, real-time processing capabilities with appropriate timing management, and modular data integration approaches for different manufacturing environments.

Validation Framework and Scalability Strategy: The services employ multiple validation methods including real-world test cases as the primary focus for operational validation, simulated test environments for comprehensive scenario testing, and standard energy datasets for Service 3 including industry benchmarking and cross-validation with industry benchmarks for performance comparison. Immediate scalability features potential application to non-industrial users, modular architecture enabling deployment across different manufacturing sectors, and standardized API interfaces for broad compatibility across diverse industrial environments. Future enhancements focus on enhanced real-time adaptation capabilities, advanced machine learning algorithms for improved optimization, integration with IoT and Industry 4.0 technologies, and enhanced sustainability metrics and environmental impact assessment capabilities.

Business Impact and Grid Modernization Value: The technical infrastructure delivers substantial operational benefits including reduced operational costs through optimized scheduling and process planning, enhanced energy efficiency across manufacturing operations, improved resource utilization and reduced waste, and better coordination between production planning and execution. Economic impact encompasses lower energy consumption through optimized operations, reduced material waste and rework through better process control, optimized inventory and logistics costs, and improved overall equipment effectiveness while providing strategic benefits including enhanced competitiveness, better sustainability profile supporting ESG goals, and compliance with environmental regulations. The infrastructure drives sustainability through direct energy efficiency improvements across manufacturing processes, reduced carbon footprint through optimized supply chain operations, minimized material waste through better process control, and support for circular economy principles while enabling advanced digital twin applications for real-time process modelling, predictive analytics, what-if scenario analysis, and comprehensive integration of environmental impact metrics in manufacturing and supply chain decisions.

This comprehensive AI services portfolio positions the TEF IND node as a critical component of the EnerTEF ecosystem, delivering specialized solutions for industrial energy efficiency and sustainability while supporting the broader goals of smart manufacturing and industrial digitalization through advanced AI-driven approaches to industrial operations optimization.

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3. Trustworthy AI Framework - Evaluation methods, standards, and quality assurance (UST)

3.1 Introduction

EnerTEF's AI services must be developed and deployed under a rigorous trustworthiness framework to ensure they are reliable, ethical, and compliant with all relevant standards. This task establishes a comprehensive approach addressing both technical and social aspects of trustworthy AI, including how systems are evaluated and validated. Drawing on European guidelines for Trustworthy AI, we consider seven key requirements – from human oversight and technical robustness to privacy, transparency, fairness, societal well-being, and accountability. In practice, this means EnerTEF will emphasize transparency in AI operations, carefully govern the AI's degree of autonomy, enforce high data quality standards, safeguard privacy and intellectual property, and ensure strong security measures. We outline below the framework's main components, evaluation methods, and alignment with industry standards to guarantee that EnerTEF's AI services are trustworthy and meet rigorous validation and quality assurance benchmarks.

3.2 Regulatory Compliance Framework

3.2.1 Transparency and Explainability

Transparency is crucial for building trust in AI systems. EnerTEF will require that each AI service can explain its decisions and make clear what data it uses and how it processes information. In line with EU guidelines, transparency entails traceability, explainability, and open communication about the AI's functioning. Practically, this involves maintaining detailed documentation of model design and data sources, providing explanations for AI recommendations, and enabling auditability. For instance, high-risk AI systems in the EU must disclose their capabilities, limitations, and the logic behind their decisions. EnerTEF will incorporate explainable AI (XAI) techniques and traceability mechanisms so that stakeholders (developers, end-users, and auditors) can understand and retrace how an AI result was produced. This not only aids compliance with upcoming regulations but also builds user confidence. By making AI decisions interpretable, EnerTEF ensures outputs are of high quality and free from hidden bias or errors. To operationalize transparency, EnerTEF will integrate model monitoring and reporting tools – for example, logging decision steps or providing feature attributions – and develop guidelines on how and when AI decisions are communicated to users. Ultimately, a transparent and explainable AI system allows users to trust the AI's recommendations, knowing they can get answers to "why did the AI do that?" and that those answers are satisfactory.

3.2.2 Human Oversight and AI Autonomy

Maintaining a human-centric approach is another pillar of trustworthy AI. EnerTEF will define clear limits on the autonomy of AI systems and ensure appropriate human oversight is in place. In practice, this means distinguishing between scenarios where the AI only provides recommendations versus those where it may take automated actions. Human-in-the-loop or human-on-the-loop mechanisms will be applied for critical decisions, so that humans can intervene or review AI outputs before final actions are taken. This aligns with the principle of human agency and oversight, which calls for AI to support human decision-making without undermining human autonomy. EnerTEF services will be designed such that users remain in control: AI systems will flag recommendations or predictions, but final judgments (especially those with significant safety, financial, or legal implications) will require human validation. For high-autonomy features, extra safeguards (like emergency stop or escalation to a human supervisor) will be implemented. By managing the degree of autonomy, EnerTEF ensures AI acts as a support tool – not an unchecked agent – thereby preventing unintended consequences from fully automated decisions. This careful oversight strategy is essential for compliance and for user acceptance, as users can trust that no critical action is taken by AI without a human's awareness and consent.

3.3.3 Data Quality and Bias Mitigation

Trustworthy AI depends on high-quality, well-curated data. EnerTEF will enforce strict data governance practices to scrutinise the provenance, validation, accuracy, and bias of all training and testing datasets. According to the EU AI Act's requirements, high-risk AI systems must utilise "high-quality, representative, and error-free datasets" for training, validation, and testing. In EnerTEF, every dataset will undergo a quality check, verifying accuracy, completeness, and relevance to the intended context. We will document the source and provenance of data and ensure it has been obtained and vetted properly (e.g. from trusted energy sector partners or public benchmarks). Bias mitigation strategies will be applied at data preparation stages – for example, analysing datasets for imbalance or systemic bias (such as under-representation of certain conditions or groups) and correcting these issues via augmentation or re-sampling. This addresses the ethical requirement of non-discrimination and fairness, which includes avoiding unfair bias in AI. In practice, EnerTEF will maintain a "bias log" for each AI model, recording identified biases and steps taken to mitigate them. Additionally, data will be subject to continuous validation: as models roll experiments, their outputs will be monitored for anomalies or drift that might indicate data issues or emerging bias. Where possible, we will incorporate automated data validation tools and bias detection frameworks that align with best practices (the EU AI Act explicitly mandates providers to assess and address potential biases in datasets). By upholding stringent data quality standards – checking that data is relevant, correct, and unbiased – EnerTEF ensures that AI models are trained on information that will lead to reliable and equitable outcomes. This rigor in data governance not only improves model performance but also is a foundation for user trust: stakeholders know that the AI's insights are drawn from sound and unbiased data.

3.3.4 Privacy and Data Governance

In the EnerTEF framework, data privacy is treated as a paramount concern alongside functionality. AI services will be designed to respect privacy regulations (like GDPR) and to clearly separate private or sensitive data from public data sources. This involves controlling who can access and use personal or confidential information. Concretely, EnerTEF will implement fine-grained access controls and data segregation mechanisms in the data infrastructure. For example, personal user data or proprietary operational data will reside in secure, access-restricted repositories, separate from open datasets used for general AI model training. The usage of any sensitive data will be logged and purpose-limited (used only for the specific experiment or service for which consent or permission was given). We will also apply data minimization and anonymization techniques where feasible – using aggregated or de-identified data to train AI models so that individual privacy is preserved. Adhering to the EU's trustworthiness guidelines on privacy and data governance means ensuring "respect for privacy, quality and integrity of data, and access to data". EnerTEF's data governance framework will include privacy impact assessments for AI services to evaluate risks and ensure compliance with GDPR's principles (lawfulness, purpose limitation, data minimization, etc.). For any cross-border or external data sharing, we will leverage trusted data exchange mechanisms (such as IDS-based data spaces or federated learning setups) so that raw private data does not need to leave its origin. In addition, all users contributing data to EnerTEF will retain control via explicit data usage agreements, and any AI models developed will be checked to avoid leakage of sensitive information. By embedding privacy considerations in design and by using robust data governance tools, EnerTEF ensures that private data remains protected and confidential throughout the AI lifecycle. This commitment to privacy not only complies with legal standards but is essential for maintaining user trust and social acceptance of AI services.

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2.2.7 Intellectual Property and Confidential Data Handling

Beyond personal privacy, protection of intellectual property (IP) and confidential data is a key aspect of trustworthiness in EnerTEF's AI framework. AI systems often rely on large datasets that may include copyrighted or proprietary content. Indeed, a significant portion of training data for modern AI (e.g. language models) comes from public internet sources and can inadvertently include copyrighted text, images, or other IP-protected works. To guarantee trust and legal compliance, EnerTEF will institute measures to respect IP rights in both data and AI outputs. This means any data contributed by companies or partners that is proprietary (e.g. industrial data, trade secrets, or licensed datasets) will be clearly labeled and handled under strict access permissions. We will ensure that AI developers using such data are aware of licensing restrictions and that models do not improperly expose or redistribute protected content. For example, if an AI service is trained on a proprietary dataset, we will verify that its outputs do not contain sensitive raw data or violate copyright (this can involve techniques like output filtering or confidentiality constraints during model training). EnerTEF's platform will likely incorporate an agreement where AI service developers must disclose and document the sources of training data and confirm they have the rights to use them, as well as abide by any usage limitations. In alignment with emerging regulations, providers of general-purpose AI models are expected to comply with copyright law and disclose training data sources; EnerTEF will thus maintain transparency about AI training materials and ensure all content is either open licensed, public domain, or used with permission. Additionally, data protection extends to safeguarding sensitive data like critical energy infrastructure data or business-sensitive information against misuse; any such data provided to the EnerTEF environment will be stored securely (encrypted at rest and in transit) and only used within the boundaries agreed by the data provider. By embedding IP and data protection protocols, EnerTEF not only prevents legal and ethical violations but also fosters an environment of trust for data providers: organizations can confidently contribute data, knowing the platform will protect their intellectual assets and proprietary information.

2.2.8 Security and Robustness Against Attacks

Security is a foundational technical requirement to keep AI services trustworthy. EnerTEF will adopt a "security-by-design" approach to protect AI systems from unauthorized access, tampering, and cyberattacks. This encompasses both traditional IT security measures and AI-specific robustness techniques. On the platform level, all AI service components will be secured through strong authentication, encryption, and network security controls. We will use enterprise-grade identity and access management (integrated with EnerTEF's IAM module) to ensure only authorized users and processes can access sensitive data or deploy AI models. All data exchanges (especially involving private or critical data) will be encrypted and monitored to prevent eavesdropping or data leaks. Regular security audits and penetration tests will be conducted on the EnerTEF platform and AI pipelines to identify and patch vulnerabilities before they can be exploited. Beyond these baseline security practices, EnerTEF's trust framework emphasizes technical robustness of AI models themselves. Models will be evaluated for resilience to attacks and adversarial manipulations, aligning with the EU's technical robustness criterion which includes "resilience to attack and security". This means we will test AI systems against possible adversarial inputs or perturbations (for example, maliciously crafted data that could fool a machine learning model) and harden them via techniques like adversarial training or input validation. If an AI service is safety-critical, we will implement a fallback or fail-safe plan – ensuring that if the AI output is uncertain or the system is under attack, it can revert to a safe mode or human control (this is also highlighted under the safety aspects of trustworthy AI). Moreover, EnerTEF will maintain an incident response procedure for AI, so that any security breach or model malfunction is quickly detected, reported, and mitigated. By ensuring AI services are secure and resilient by design, we protect both the system's integrity and the users who rely on its outputs. This relentless focus on security not only guards against hacking and data breaches but also contributes to the reliability and robustness of AI services – key ingredients for user trust and compliance with standards.

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3.3 Technical Framework for Trustworthy AI in Energy Systems

3.3.1 [illegible]

Explainable AI Architecture: Energy AI systems must incorporate explainability mechanisms enabling human operators to understand decision-making processes, EU Artificial Intelligence Act particularly for:

- **Smart Grid Operations**: Real-time grid stability decisions with interpretable control actions
- **Renewable Energy Forecasting**: Weather-to-energy conversion rationale with uncertainty quantification
- **Demand Response Management**: Consumer behaviour predictions with transparent optimization criteria
- **Asset Management**: Predictive maintenance recommendations with failure risk explanations

Human-AI Collaboration Framework: Implement graduated autonomy levels distinguishing between AI recommendations and independent actions:

- **Level 1**: AI provides recommendations with mandatory human approval
- **Level 2**: AI executes routine decisions with human oversight and intervention capability
- **Level 3**: AI operates autonomously with continuous monitoring and emergency stop mechanisms
- **Level 4**: Full autonomy reserved for non-critical applications with comprehensive audit trails

3.3.2 EnerTEE [illegible] Validation Pipeline [illegible]

Drawing from industry best practices in automated AI model testing and validation, the EnerTEE Services Catalogue incorporates a robust pipeline framework that ensures all AI solutions meet rigorous quality standards before deployment in energy transition applications.

Automated Validation Framework

The EnerTEE pipeline architecture implements automated testing workflows, ensuring model robustness, and accelerating deployment Automating AI Model Testing & Validation with Azure ML Pipelines through several integrated components:

- **Energy Data Preprocessing Pipeline**: Ensures clean, standardized energy datasets from various sources (smart meters, renewable generation, grid sensors) are properly formatted for AI model training and validation
- **Multi-Model Training Pipeline**: Trains energy-specific AI models using predefined configurations optimized for different energy transition scenarios (demand forecasting, renewable integration, grid optimization)
- **Performance Evaluation Pipeline**: Runs metrics-based validation (accuracy, precision, recall, F1-score, etc.) Automating AI Model Testing & Validation with Azure ML Pipelines with energy sector-specific KPIs such as prediction accuracy for energy demand, renewable output forecasting precision, and grid stability metrics
- **Energy Data Drift Detection Pipeline**: Monitors model performance against evolving data distributions Automating AI Model Testing & Validation with Azure ML Pipelines, particularly crucial for energy systems where consumption patterns, renewable generation profiles, and grid dynamics continuously evolve
- **Real-World Energy Scenario Testing Pipeline**: Validates AI models using actual energy consumption use cases, seasonal variations, and extreme weather conditions that impact renewable generation
- **Controlled Deployment Pipeline**: Deploys models only after passing predefined quality thresholds Automating AI Model Testing & Validation with Azure ML Pipelines specific to energy system reliability and safety requirements.

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These evaluation steps will be part of EnerTEF's quality assurance cycle for AI. We will likely integrate them into a "Trustworthiness Evaluation Toolkit" that developers must use when they onboard an AI service to the platform. The results (scores, reports) from these evaluations will be documented, and any service that fails to meet predefined trustworthiness criteria will require improvements before proceeding. This continuous evaluation echoes the approach of frameworks like NIST's AI Risk Management Framework, which guides organizations to "identify, mitigate, and minimize risks and negative impacts associated with AI systems as an essential step toward trustworthy AI". Similarly, EnerTEF will follow a risk-based evaluation – higher-risk AI applications (e.g. affecting critical energy infrastructure or human safety) will face more stringent verification and possibly external review.

Critically, EnerTEF's framework will align with emerging standards for AI trust and quality. For instance, the project will take into account ISO/IEC guidelines on AI trustworthiness and quality management. The new ISO/IEC 42001:2023 AI Management System standard provides a structured way to manage AI risks, addressing challenges like ethics and transparency and balancing innovation with governance. EnerTEF aims to comply with such standards by instituting an internal AI governance process – essentially a quality management system for AI development. We will ensure that our procedures (from data handling to model validation) meet or exceed the relevant harmonized standards once they are available, which will also facilitate compliance with the EU AI Act (which foresees the use of harmonised standards for demonstrating conformity). In addition, the Assessment List for Trustworthy AI (ALTAI) – a checklist derived from EU's seven requirements – may be used as a self-assessment tool for each service, to verify that nothing has been overlooked in terms of ethical and societal considerations. By integrating these standards and frameworks, EnerTEF not only evaluates trustworthiness at development time but also sets up a process for continuous monitoring and improvement. AI systems will be re-evaluated periodically (since models can evolve or data drift over time), and we will maintain accountability by logging all evaluations and decisions, supporting the accountability principle of trustworthy AI.

Through this robust evaluation framework and adherence to established standards, EnerTEF will guarantee that its AI services are rigorously validated and trustworthy before they are deployed. Users and stakeholders will have clear evidence – via documentation and certification – that each AI service meets high standards of quality, safety, fairness, and compliance. This not only fulfils the technical goals of the project but also addresses social and ethical expectations, ultimately fostering confidence in AI innovations in the energy sector.

2.4 Conclusion

By addressing the technical components (like robustness, security, and data integrity) alongside social and ethical components (like transparency, oversight, and fairness), EnerTEF's Task 2.2 framework ensures that AI services are trustworthy by design. Every stage – from data collection and model development to deployment and monitoring – is guided by trustworthiness criteria and standardized evaluation methods. The framework's emphasis on transparency in how AI systems work, controlled autonomy with human oversight, high data quality without bias, strong privacy and IP protections, and resilient security measures creates a holistic assurance of trust. Moreover, by grounding the approach in recognized standards and best practices, EnerTEF aligns itself with the cutting edge of AI governance and upcoming regulatory requirements. This will not only ensure compliance (e.g. with the EU AI Act, GDPR) but also position EnerTEF as a leader in delivering AI solutions that stakeholders can confidently adopt. In summary, Task 2.2 lays out the technical and social foundations for trustworthy AI in EnerTEF, with a clear framework of evaluation methods and standards that guarantee rigorous validation and sustained trustworthiness of all AI services developed under the project.

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4. Regulatory Compliance – EU AI Act, GDPR, and legal framework alignment (COMS)

EnerTEF provides a coordinated set of services focused on supporting the safe and effective use of artificial intelligence (AI) within the critical infrastructure domain, particularly the electrical power grid. To facilitate this, EnerTEF has established a network of TEF nodes across multiple EU countries and covering different domains of expertise. These TEF nodes enable the testing, validation, and demonstration of AI-based solutions using real or representative data from different energy business stakeholders, e.g., TSOs, DSOs, power generation companies, energy communities and others.

Each TEF node is equipped to support AI services for processing, analysing, and managing critical infrastructure data. This includes services developed by SMEs, research institutes, and other technology providers, which may involve forecasting, operational planning, monitoring, cybersecurity, and data-driven optimisation. These stakeholders may interact with sensitive data and develop applications that can be related to critical infrastructure.
The primary objective of Task T2.3 is to define a structured, practical, and legally grounded workflow for the development, testing, and eventual deployment of such AI services. This includes establishing procedures for data sharing, AI service development, regulatory compliance, and risk management, while identifying the roles and responsibilities of service providers, data owners, processors, and institutional users.
The outcome of Task T2.3 is guidance for EnerTEF users and developers, how to approach the creation of the energy-related AI tools, ensuring that potential risks related to improper management or regulatory non-compliance are properly addressed and mitigated.

4.1 Regulatory Sandbox

Innovation and research projects try to put new ideas and tools in operation as soon as possible. In the era when machine learning and AI-powered tools are on the rise of the hype curve, and some implications of the technology is still unknown, there is a need for testing the solutions in special environment as a digital sandbox – not only in the sense of functional and technological limitations, but also if they are compliant with regulations.

Innovation and research projects strive to transition emerging technologies into operational environments as early as possible. This is particularly relevant in domains where machine learning (ML), artificial intelligence (AI), blockchain, and other data-driven technologies are rapidly evolving but remain only partially understood in terms of their long-term societal, legal, and ethical implications. As such, there is a necessity to evaluate these solutions not only for their technical feasibility and functional performance – which is a usual approach in the application development – but also for their **regulatory compliance**, particularly when they interact with existing legal frameworks, involve sensitive personal data, or influence consumer rights and market structures. In the context of energy research and innovation

projects – such as EnerTEF – the introduction of novel services,
algorithms, or business models often entails regulatory uncertainty. For example, platforms that propose new roles in energy markets (e.g., prosumers, energy communities, aggregators), or that leverage AI or blockchain for automation, frequently lack clear classification within existing regulations. In such cases, the use of a **regulatory sandbox** becomes highly valuable. A regulatory sandbox is a **controlled testing environment**, established under the supervision of competent authorities, where innovative technologies or services can be developed, piloted, and evaluated without

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being immediately subject to the full set of regulatory obligations. This approach enables both regulators and technology providers to jointly explore the operational, legal, and societal implications of new solutions in a safe and time-bound setting.

The **EU Artificial Intelligence Act** (Article 57) [ ] explicitly recognises the role of regulatory sandboxes in supporting innovation. According to the Act, sandboxes shall provide a supervised environment for the development, training, testing, and validation of innovative AI systems, allowing such systems to be evaluated before being placed on the market or put into service. Sandbox participation is based on an agreed plan between the provider and the relevant authority and may include testing in real-world conditions under regulatory oversight. This framework is particularly important for services that: (i) interact with regulated markets or critical infrastructure; (ii) have potential impacts on end-user rights or costs; (iii) employ AI or distributed ledger technologies; or (iv) involve the processing of sensitive or high-risk personal data.

By facilitating structured, risk-mitigated experimentation, regulatory sandboxes serve as a critical mechanism to **bridge the gap between innovation and regulation**, ensuring that emerging technologies can be responsibly integrated into complex socio-technical systems without compromising legal compliance, user protection, or system integrity.

6.2 Relation of EnerTEF and A Regulatory Sandbox plan definition

The EnerTEF project forms a federation of TEFs, where each of them is developing the services for energy systems. Within the list of TEF nodes and its services the two of them – TEF BUILD and TEF TED – were selected to establish the regulatory sandbox environment for the service development and delivery. As introduced in a previous section our regulatory sandbox should [ ]:

"AI regulatory sandboxes established under paragraph 1 shall provide for a controlled environment that fosters innovation and facilitates the development, training, testing and validation of innovative AI systems for a limited time before their being placed on the market or put into service pursuant to a specific sandbox plan agreed between the providers or prospective providers and the competent authority. Such sandboxes may include testing in real world conditions supervised therein." From a technical perspective Regulatory Sandbox is something like a staging

environment or digital twin of the

infrastructure to test the application. However, the reader should understand that the purpose is different. It implicates the definition of a different **testing plan** in comparison to the unit-, integration- and field- test procedures. The sandbox allows the real-world testing of applications in a controlled setting, while ensuring that **potential risks** are identified and addressed before widespread use. In other words, if in the staging environment the testing plan includes tests, the regulatory testing plan should define risks, controls, timescales of testing and releasing requirements (e.g. exit strategy). The definition of the application risks, testing and releasing requirements can be very complex and

sometimes in novel

and state of the art AI applications cannot be fully defined in advance. This particular problem is solved by introducing competent stakeholders that can support technical, ethical, legislative and other aspects of regulation. The Article 57 explains the part as:

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"... Competent authorities shall provide, as appropriate, guidance, supervision and support within the AI regulatory sandbox with a view to identifying risks, in particular to fundamental rights, health and safety, testing, mitigation measures, and their effectiveness in relation to the obligations and requirements of this Regulation and, where relevant, other Union and national law supervised within the sandbox."

3.3 Experiments bound to the Regulatory Sandbox

The EnerTEF project establishes a federation of TEF nodes and satellites that will serve as a testing and development framework for future energy services. As already mentioned, some innovative solutions must be evaluated and classified according to their regulatory risk level and technology readiness. Services identified as low-risk or non-risk can be tested outside of a regulatory sandbox. However, those involving regulatory uncertainty, novel business models, or technologies such as AI or blockchain may require testing within a Regulatory Sandbox environment to ensure compliance with relevant legislation (e.g. AI Act, GDPR, energy market rules).

In this section, we outline which services are expected to require access to the Regulatory Sandbox, based on their risk profile, regulatory impact, and degree of innovation.

3.3.1 Service Process for Regulatory Sandbox Access

The Task 2.1 combined the catalogue of services (Unified Services Catalogue) to be developed and tested within the EnerTEF project. In addition to describing their functionality and requirements, each service must be classified to determine whether it should be developed or tested within a Regulatory Sandbox environment.

The classification focuses primarily on the function, impact, and data handling characteristics of a service – rather than the underlying technology. To assess whether a service requires testing in a sandbox, the following attributes must be considered:

1. **Automated Decision-Making, AI, or User Profiling** *(High risk)*
   Services incorporating automated decision-making, artificial intelligence, or user profiling may fall under the **high-risk category of the AI Act**, requiring additional safeguards and testing in a regulatory sandbox.
2. **Processing of Personal or Consumption Data** *(Medium–High risk)*
   If a service processes personal or energy consumption data, it is subject to **GDPR and Data Protection Impact Assessment (DPIA)** requirements. These services may require sandbox testing to ensure data protection compliance.
3. **Impact on Consumer Prices, Billing, or Incentives** *(High risk)*
   Services that influence customer billing, dynamic pricing, or financial incentives may fall under **energy market consumer protection regulations** and should be tested in a controlled regulatory environment.
4. **Use of Blockchain or Smart Contracts** *(Medium risk)*
   Services utilizing blockchain or smart contracts often operate in **regulatory grey areas**. Due to legal uncertainty and decentralization, these services are good candidates for sandbox testing.
5. **Influence on Grid or System Operations** *(High risk)*
   Services that affect grid balancing, flexibility markets, or system stability may trigger **TSO or DSO** regulatory conditions. Early testing under controlled conditions is advisable.

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4. **User Interface or Hardware-Only Innovations** (Low risk)

Applications or hardware solutions that only present existing data or provide improved sensing capabilities—without autonomous control, decision-making, or market interaction—generally **do not require sandbox involvement**.

Using the presented attributes a simple three-class risk tagging system has been define, see Table 41.

Table 41 Risk Tagging matrix

[illegible]	[illegible]	[illegible]
Red	[illegible]	• Use of autonomous decision-making or AI-driven [illegible] • Impacts energy markets, such as pricing, billing, or settlement • Affects real-time grid operations or critical infrastructure • Lacks sufficient legal clarity (e.g., emerging tech like [illegible])
Yellow	[illegible]	• Processes personal or non-[illegible] data [illegible] • Uses [illegible] • Influences operational decisions, but with human oversight or fallback • Potentially touches regulatory grey areas, but can be mitigated
Green	[illegible]	• Non-critical tool (dashboards, reporting) • UI enhancements, hardware sensors, or read-only data display • No control functions, no decision-making, no sensitive data • Purely simulation or lab use, with no effect on live systems

4.4 Decision process Templates

Decision process can be a complex task for a TEF user, depending on their technical, management or legislative background. To empower all EnerTEF user, we proposed a scoring matrix that is more suitable for regulatory experts or evaluators that can clearly compare many services quickly with numerical justification. The second proposed tool is a decision graph, that is probably more intuitive for non-technical stakeholders, and easier to present and explain to service developers and consortium partners. Finally, there is a hybrid approach, where TEF leaders and project coordinator will probably benefit the most, to prepare presentations and reports.

4.4.1 EnerTEF Regulatory Sandbox [illegible]

Service classification can be made on different approaches. In the task 3.3 a weighted table is proposed to prioritise factors and simplify the decision if the service requires regulatory sandbox. The Table 42 provides a possible factors and evaluation scores for each factor. The total score is 100, and all services that score 50+ would go into the sandbox environment. The services between 30-49 score, would need to be considered case by case.

Table 42 The EU Regulatory Sandbox Scoring Matrix

Criterion	Weight	
Use of AI / Automated Decision Making	30	30
Involvement of Personal Data	20	10
Legal Uncertainty / Market Novelty	10	10
Use of Distributed Tech (e.g. Blockchain)		
Consumer Impact (Pricing, Switching)		
Impact on Grid / System Operations		

The Table 42 presents a scoring model ensures that innovative energy services are evaluated systematically and proportionately, balancing innovation support with compliance needs.

4.4.2 EnerTEF Regulatory Sandbox Eligibility Decision Chart

To empower the users who are less familiar with regulations and can quickly walk through logic a decision flow chart is developed. The decision graph uses a bit different terminology, that is more intuitive, and the decision is explained by the path in the tree. The proposed decision tree (Figure 1 Proposed Regulatory Sandbox Decision Tree Figure 1) first considers all high-risk applications according to the AI Act Annex III[2], which include applications using or managing data in fields of Biometric, Critical infrastructure, Education, Essential services, Law enforcement, Migration and Administration of justice and democratic process. For EnerTEF, we focus on critical infrastructure, which Annex III defines it as:

"Critical infrastructure: AI systems intended to be used as safety components in the management and operation of critical digital infrastructure, road traffic, or in the supply of water, gas, heating or electricity."

Further, the decision tree has only a few more steps that focus on data privacy and real-time operation with the grid. After clearing out these, the person in charge understands how critical the application classification is, tagged by four colour tags, that were already introduced in Table 41. The decision tree could be also used for the application owners, who add the application to the catalogue. With three questions it is possible to determine the category of an app. For clarity, the category colour tags can be added next to the application listing in the catalogue, which would also reflect the risk level of each application.

[2] AI Act Annex III, URL: [illegible]

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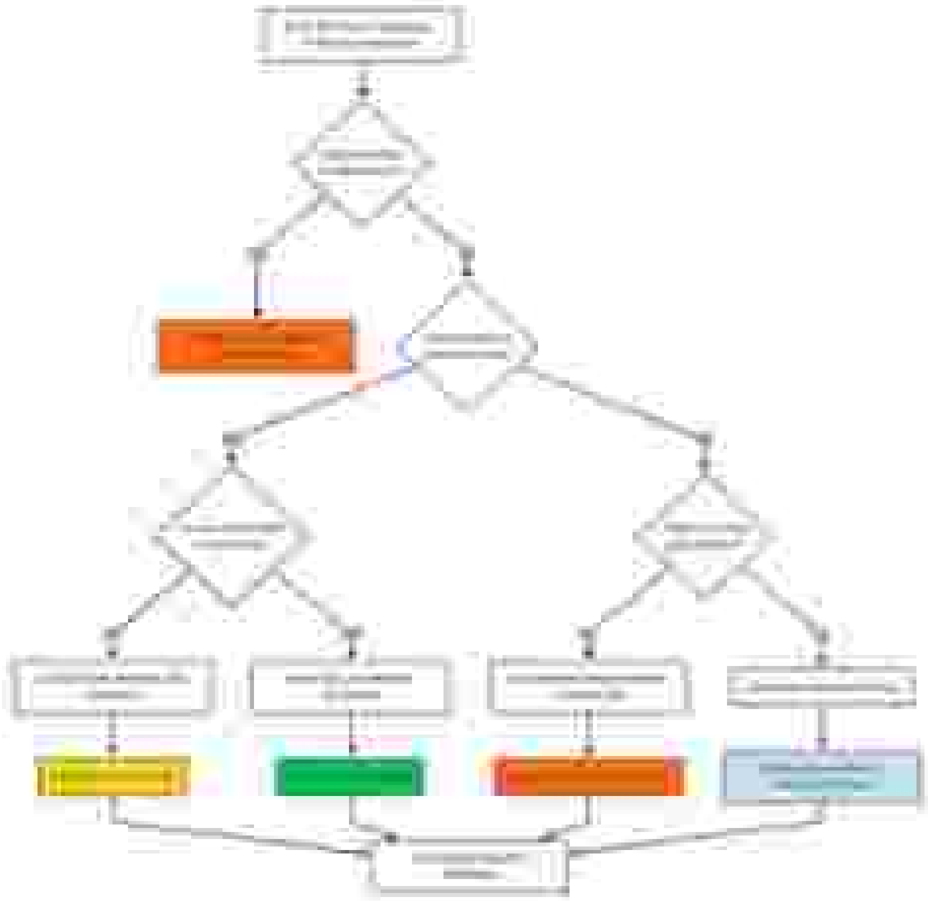

Figure x Proposed Regulatory Sandbox Decision Tree

[illegible]

This document proposes two classification approaches that define if particular application is bound to the Regulatory Sandbox workflow. For the evaluation it is important to understand how those two approaches are compatible with each other and if it is possible to translate one classification to another. To ease this task, the Table 43 provides a mapping between Scoring and Decision Tree approach.

Table 43 Combining the tagging and scoring approach

[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
"[illegible] with high caution"	Red flag	AI [illegible] grid operations	70–100	Yes – [illegible]
"[illegible] safeguards"	Yellow flag	Use of personal or commercial data, or [illegible]	35–69	Conditional / case-by-case
"Lower risk: proceed with caution tag"	Yellow flag	[illegible] data, limited impact	35–69	[illegible]

"Work includes human oversight + rollback plan"	Red or Yellow	Moderate/high impact, operational effect, no automated safeguards	30–49	Yes or conditionally sandboxed
"Classify as Informational Tool"	Green Fast	UI only traffic dashboards, no decisions or actuation	0–29	No sandbox needed
"Eligible for Low-Risk or Voluntary Sandbox"	Green Fast	Low impact, [illegible]	0–29	Not required, but possible

8.5 Conclusions and future work

- We defined the T2.3 work and legislation background for regulatory sandboxes. We proposed classification approaches to help users with understanding which applications are bound the Regulatory Sandboxes.
- In next period we will focus on collaboration with users and developers to get the feedback of the classification approach and we will provide a Regulatory sandbox Plan template – a template that will detail and include all required information for managing the Applications Regulatory Sandbox workflow.

Funded by the European Union
This project has received funding from the European Union's Horizon Europe Research and Innovation programme under the Grant Agreement No [illegible]

5. Framework Integration and Alignment with Existing Frameworks (NTUA)

5.1 Introduction

This section presents an analysis of the major European digital and energy-related frameworks that EnerTEF aims to align with, in order to ensure technical compatibility, policy coherence, and strategic relevance across the EU innovation ecosystem. The frameworks covered include energy data spaces, AI infrastructure platforms, digital innovation hubs, and related projects or architectures that set the foundation for cross-sectoral digital transformation. By reviewing the objectives, components, and strategic positioning of each initiative, this section identifies key touchpoints for EnerTEF's integration.

The purpose of this analysis is twofold: firstly, to understand the technical and operational standards adopted by leading EU initiatives in AI, energy, and data governance, and second, to evaluate how these standards and approaches can be leveraged or adopted within the design and operation of EnerTEF. The following subsections detail how EnerTEF can exploit these frameworks to enhance interoperability, data sharing, regulatory compliance, AI testing capabilities, and ecosystem collaboration. The goal is to ensure that EnerTEF does not operate in isolation, but as an integral component of Europe's broader digital and energy transition efforts.

5.2 Common European Energy Data Spaces (CEEDS)

The Common EU Energy Data Spaces is a Pan European attempt towards the development of a framework able to interact with several EU platforms and facilitate the sharing of energy data. Interoperability and security are primary requirements that CEEDS can deliver [3].

Major objectives of CEEDS are:

- Maximization of Energy Efficiency by facilitating the exploitation of several types of information. The scope is to coordinate more efficiently energy production with energy consumption by considering features and capabilities of distribution grid and storage.
- Facilitate attempts towards the formulation of novel business models related with i) modern management of smart grids, ii) increase in the capabilities of smart grids to host renewable energy sources and iii) efficient exploitation of flexibility sources (i.e. storage).
- Interoperability among Energy Markets to facilitate interaction among markets across borders by standardizing data models and by guaranteeing transparency.
- Facilitate Energy Consumers to control the information that they dispose and to personalize their services through the automation of flexibility use.

The major requirements that CEEDS fulfils are: i) Interoperability note as the capability to exchange data between services, smart grid components and operational platforms, ii) Data Sovereignty which related with data ownership and data privacy in terms of facilitating control on how the information that they own can be used and shared, iii) Secure Infrastructure which related with cybersecurity able to protect energy data from possible purposeful attacks and/or wrong use.

CEEDS facilitates the involvement of several stakeholders as: i) Energy Companies as Utilities, grid operators, and renewable energy producers able to use the aforementioned services, ii) Technology Providers which are developers of smart grid devices & components as: smart meters, IoT home automation solutions, and energy management platforms, iii) Governments & Regulators that exploit information to optimally design policies and monitor the progress of the targets that they set, iv) Consumers that gain the ability to personalize their energy services according to their requirements/preferences and achieve greater transparency in energy consumption and costs.

[illegible]

EnerTEF will exploit CEEDS towards: **Enhancement of its AI Testing Capabilities with High-Quality Energy Data**. To achieve this EnerTEF will acquire access to Real-World Energy Data through CEEDS. According to it EnerTEF can leverage CEEDS data to test AI models on services related with CEEDS areas which include real-time grid operations, forecasting, and flexibility optimization. In addition, CEEDS will facilitate interoperability testing for its AI Experiments which guarantee that AI algorithms which are tested work properly across different energy platforms. **Enhancement of Regulatory Compliance and Data Governance**. CEEDS proposes regulatory frameworks that can help EnerTEF service developers to ensure GDPR-compliant energy data usage and cybersecurity. In addition, CEEDS facilitates data Sovereignty & Security and in this way EnerTEF can implement privacy-preserving AI techniques. Finally, EnerTEF can enhance its energy policy testing by exploiting AI models that assess the impact of new energy regulations. **Support Novel Business Models and Market Expansion**. CEEDS can facilitate Monetization of Smart Grid AI Services by implementing AI-powered insights and analytics to energy providers, governments, and consumers through a Digital Open Marketplace. Furthermore, CEEDS facilitates EnerTEF to extend into smart buildings, EV charging networks, and energy-efficient manufacturing and develop in this way cross-sector AI applications.

5.2 AI on Demand Platform

The AIoD Platform is vendor independent and is designed to ensure a fair and democratic access to cutting-edge AI technologies made in Europe, enabling innovation at a large scale [4]. The vision is for it to become an AI "Lighthouse Project", so shaping a standard AI infrastructure for all stakeholders in the European industrial ecosystem. The platform is designed to facilitate stakeholders—such as businesses, researchers, policymakers, and developers—in accessing AI tools, services, and resources.

- Businesses and Industry Stakeholders can access AI Resources (a range of AI tools, datasets, algorithms, and models) to enhance their business operations. Indicative use cases can be found in the areas of healthcare, manufacturing, and finance. AIoD offers: i) collaboration opportunities (i.e. business to business partnerships), ii) Training programs and courses relevant with AI capabilities, iii) AI services on-demand which can be used ad-hoc from SMEs, iv) Funding and Innovation Support in terms of business consulting.
- Researchers and Developers can have access to Datasets and pre-trained Models to facilitate testing and experimentation through the platform and they can conduct collaborative research through interaction with other research groups with respect to the services that platform offers. They can also exploit available [illegible]

specialised AI tools available on the platform for evolving their algorithms. Finally, they can disseminate their findings, papers, and AI models and promote in this way their work. Policymakers and Regulators can monitor and realise though the platform the way that industry adopts AI and through this process they formulate regulations that address ethical, legal, and social concerns. In addition, AIoD facilitates compliance with European regulations, such as the General Data Protection Regulation (GDPR) and AI-specific legislation. Public Sector can improve through AIoD public services as digital administration, healthcare and transportation by offering advanced features as to optimised resource management, service delivery, and decision-making. More specifically Smart Cities can use AIoD to develop AI-enable traffic management, energy efficiency, and public safety systems. Digital Transformation and improvement of citizen engagement can be also improved through AIoD. SMEs and Startups can use the platform to access affordable AI services and resources without having to invest heavily in infrastructure and specialised knowledge. AIoD facilitates startups to innovate faster, create new business models, and stay competitive in rapidly changing markets. Furthermore, it enables Networking and Community and facilitates in this way the discovery of AI entrepreneurs and potential partners for joint ventures, collaborations, and funding opportunities. AI Solution Providers and Technology Vendors can showcase their products and services to a wide range of stakeholders, gaining exposure and expanding their market reach within Europe. They can establish Commercial Partnerships with other stakeholders (business-to-business relationships).

2.3.1 [illegible]

Indicatively ENERTEF can exploit the AI-on-Demand (AIoD) Platform by: Enhancing AI Testing Capabilities and Service

Development: ENERTEF can leverage the AIoD platform to access a broad
repository of cutting-edge AI tools, pre-trained models, and datasets that align with its energy-related use cases. This allows ENERTEF to test, benchmark, and validate AI algorithms under diverse conditions without the need for extensive in-house infrastructure. Particularly for scenarios like grid forecasting, predictive maintenance, or energy consumption optimization, AIoD provides ready-to-use components that accelerate development and experimentation cycles while ensuring technological competitiveness.
Strengthening Collaboration and Research Impact: By engaging with AIoD's collaborative research environment, ENERTEF can build strategic alliances with academic institutions, research labs, and fellow innovators. This opens opportunities for joint experiments, co-authored publications, and shared access to computational resources. Additionally, ENERTEF can contribute its own testbed results and energy-focused AI tools to the platform, thereby increasing its visibility, influencing AI research directions, and contributing to European efforts in standardization and AI sovereignty.
Supporting Policy Alignment and Ethical AI Deployment: ENERTEF can use the AIoD platform to monitor emerging trends in AI governance, ethics, and compliance. The built-in regulatory support mechanisms—especially those ensuring GDPR compliance and adherence to AI Act provisions—enable ENERTEF to validate its services in a legally sound and transparent manner. Furthermore, ENERTEF can simulate the societal and regulatory impact of its AI

solutions using policy modelling tools within AIoD, strengthening trust and preparing its services for real-world deployment across Europe.

Funded by the European Union
This project has received funding from European Union's Horizon Europe research and innovation programme under the Grant Agreement No. [illegible]

[illegible] European Digital Innovation Hubs (EDIHs)

EDIHs are one-stop support centres designed to help European businesses, especially SMEs and public sector organisations, integrate digital technologies into their operations [1]. EDIHs belong to the Digital Europe Programme whose objective is to accelerate the digital transformation across the EU. The major services and offerings of EDIHs are:

- Technology and Expertise Access which facilitates the interaction with novel digital technologies as AI, high-performance computing, cybersecurity, blockchain, IoT, and robotics. In addition, a major functionality is provision of the opportunity to SMEs to experiment with the digital technologies and commercially assess their offerings before investing in them.
- Skills and Training which include the offering of training programs to employees and business leaders to enrich their digital skills. Furthermore, EDIHs target the digital skills gap in various industries.
- Innovation and Ecosystem Building which concerns the development of innovation hubs that enhance the connection between SMEs and research institutions, investors, technology providers, and policymakers. More specifically EDIHs promote collaboration between digital solution service providers and SMEs.
- Financial and Business Support which includes the development of services that facilitate the preparation of funding applications and the steering of EU and national financial instruments. It helps businesses to develop digital transformation strategies and business models.
- Networking and Internationalisation concerns the interaction between SMEs, EU Digital Innovation Hubs and global digital networks. Cross-border collaborations and technology exchange across different regions and sectors is one of the key objectives in this area.

[illegible] EnerTEF using EDIH

EnerTEF will leverage EDIHs in multiple ways to maximize impact, collaboration, and sustainability. In a nutshell EDIHs will provide access to SMEs to provide experiments in the services that EnerTEF offers. The rest of this section analyses these ways indicating the ways that EnerTEF will examine to interacts with EDIHs.

Regarding NODE1 - TEF RES EnerTEF will examine the use of EDIHs for:

Connect stakeholders that operate offshore RES planning and acquire AI technology to facilitate testing towards the AI driven optimal deployment of generation technologies and/or in situ analytics monitoring which ensures precise asset positioning and performance monitoring.

Provision of experimentation resources (e.g. infrastructure, AI algorithms, etc.) towards i) RES (Wave, PV, Wind, Hydro) production forecasting and degradation estimation of ocean wave energy converters.
Facilitate connections among AI developers, investors and Energy Market Analysis & Trading service operators (e.g. analysing onshore and offshore data). Thus, EnerTEF will highly improve the AI tools that analyse energy market dynamics, forecast price trends, and automate trading strategies.

Facilitate RES operators to evolve and optimize though the use of AI their predictive maintenance services (AI power for early fault detection).

Regarding NODE2 - TEF EV EnerTEF will examine the use of EDIHs for:

The discovery of stakeholders that operate EV user charging and usage profiles prediction and the use of AI tools/libraries towards testing and experimenting with AI-based models for predicting EV charging.

The deployment of Energy demand forecasting in Energy Communities (ECOs) by exploiting AI-based algorithms able to integrate profile (generation) (residential, commercial, public, etc.) and other exogenous factors (weather forecasts, weather conditions, etc.).

Building of an ecosystem that unfolds around EV charging and the intelligent orchestration of other services (DERs, DR, BESS and EESCs within EEOs). Additionally, EnerTEF envisages the aligning AI solutions with regulatory and funding frameworks through facilitation of EDIHs.

The provision of necessary infrastructure to assess the optimality and the scalability of RES generation forecasting services in ECOs that utilize AI-based models for accurate RES generation prediction in ECOs.
The evaluation of intelligent flexibility and ancillary services that deploy AI-driven Demand-Side Management (DSM) functionalities, together with other grid-interactive functionalities of the energy assets, when providing flexibility and ancillary services to the distribution grid. Additionally, EnerTEF will examine the use of EDIHs to facilitate dissemination of this technology to SMEs that develop similar products/services.
Facilitate dissemination (discovery of relevant stakeholders) of Predictive maintenance of EV charging infrastructure that exploits AI-based models for assessing EV charging infrastructure performance and degradation.
Regarding NODE3 - TEF TSO EnerTEF will examine the use of EDIHs for:

Exploitation of their infrastructure and their technical support towards evaluation (from EnerTEF's stakeholders and/or third parties) of AI-driven fault detection and classification in transmission grids (rapid detection, localization and classification of faults).

Acting as intermediary between AI technology providers (Dynamic AI-enhanced transmission grid stability assessment service developers) and SMEs/public organizations that interested in monitor grid parameters, predicting and addressing potential instability issues in real-time.

Facilitate the build of an ecosystem towards Real-time power management for TSO-DSO Coordination (e.g. Optimum frequency and voltage regulation across transmission and distribution networks, etc.). More specifically EDIHs will facilitate connections between relevant service AI developers, research institutions, and investors, facilitating in this way dissemination of these services that EnerTEF delivers.
Facilitate the realization of best practices and policies that concern critical infrastructure and cybersecurity enhancement (Strengthens cybersecurity in critical energy infrastructure using AI-based solutions).
Regarding NODE4 - TEF DSO EnerTEF will examine the use of EDIHs for:

Exploitation of their infrastructure and their technical support towards evaluation of AI monitoring and control applications supported by CIM handling services that compose Distribution System Digital Twin.

Acting as intermediary between AI technology providers for microservices (e.g. EV charging) and SMEs/public organizations that interested in the development of Microservices Platform. EDIHs will be used towards composition of microservice architectures of distribution system operators.

Facilitate the replication of best practices and policies that concern data space integration for Distribution Grids (utilizing [illegible]'s MVP and [illegible] for data exchange).

Regarding NODES - TEF Buildings EnerTEF will examine the use of EDIHs for:

Development of Monitor and Consumption Forecast services which require AI towards modelling of the end user behaviour and the modelling of the appliances. EDIHs will facilitate these types of experiments by providing infrastructure and relevant technology. The development of an ecosystem that unfolds around building management and its interaction with smart grids will be also potentially facilitated from EDIHs.

Facilitating dissemination of Optimisation of Shiftable Building Assets through AI (scheduling shiftable loads, such as EVs and BEMS) based on day ahead forecasting of power production and energy demand. More specifically, EDIHs will bring ENERTEF in contact with relevant SMEs and stakeholders to experiment with this service.

Enabling Intelligent Demand Response Schemes are a critical service in smart grids and its interaction with energy markets is vital for their financial sustainability. More specifically, EDIHs will provide to EnerTEF best practices and policies towards the development of Demand Response Services.

Implementing and testing demand response scenarios using BEMS systems augmented with energy storage systems, addressing the unique energy dynamics of city-level infrastructure.

5.5 Digital Open Marketplace Ecosystem (DOME 4.0)

DOME 4.0 develops digital market platforms that small and medium-sized enterprises (SMEs) can use in a Business to Business (B2B) fashion. DOME 4.0 exploits and integrates several Industry 4.0 technologies as AI, blockchain, cloud computing, and big data and creates a novel digital marketplace for SMEs. It enhances the digital trading and the B2B interaction [illegible]. More specifically, DOME4.0 focuses on:

- **Digital Marketplace Integration** which concerns the development of an open digital marketplace ecosystem where businesses can i) interact, ii) discover clients, and iii) collaboratively produce. The proposed marketplace can host product and service developers.
- **Smart Supply Chain** which enables vertical smart and efficient supply chain solutions by exploitation IoT (real-time monitoring) and AI technologies (optimization of assets through forecast of demand) to track inventory, predict demand, and improve logistics management.
- **Blockchain for Trust and Transparency** (by incorporating blockchain to ensure transparency and security in digital transactions). More specifically, smart contracts automatically derive terms resolve disputes while record is kept consistently.
- **AI-Powered Decision Making** which is the use of AIs to facilitate businesses intelligence and deliver services as i) forecast of market trends (i.e. predict changes in demand), ii) identification of business opportunities, iii) improvement of customer experiences.
- **Interoperability** noted as the smooth interaction with existing digital business platforms (i.e. financial software, inventory management, etc.) to facilitate SMEs to connect to the proposed digital marketplace ecosystem with low overhead and cost.
- **Cloud Infrastructure and Data Analytics** to ensure the secure data storage to provide novel services as modelling of customer behaviour, extraction of market trends, and assessment of operational performance.

3.5.1 Synergies between ENERTEF and DOME 4.0

Digital Open Marketplace Ecosystem (DOME) can enhance ENERTEF in multiple ways by fostering collaboration, resource sharing, and commercialization. More specifically but not exclusively DOME will facilitate ENERTEF in the following ways.

DOME will be Marketplace for ENERTEF's AI Models & Tools. ENERTEF will create a repository of AI models, datasets and tools that researchers, startups, and enterprises can access towards the enhancement of the dissemination of the services that ENERTEF will offer in its test bed. In addition, DOME will provide typical benchmark datasets for testing AI algorithms of ENERTEF's services.

DOME will provide Cloud-Based AI Testing as a Service. More analytically it will offer on-demand AI testing environments through the marketplace. A critical objective towards DOME's exploitation is the provision of access to synthetic data generation, adversarial testing, and model validation to assess complex services that ENERTEF envisages.

DOME will provide Regulatory & Ethical Compliance Hub and it will integrate compliance-as-a-service tools for AI regulation testing. ENERTEF will offer to its clients through DOME the capability to provide a certification marketplace for AI models that meet ethical and performance standards (submission of AI models for automated regulatory assessment).

3.6 Other TEFs

Other Testing and Experimentation Facilities [?] have been developed in various sectors, such as CitCom.ai, TEF-Health [9], AI-MATTERS [10], and AgrifoodTEF [11]. These will be presented in the following subsections.

3.6.1 CitCom.ai

It is the Artificial Intelligence Testing and Experimentation Facility (AI TEF) whose objective is to advance smart and sustainable cities and communities. The framework has started in 2023 and it is the one of the four AI TEFs that Europe deploys and it is the only one that falls in ENERTEF's area. It concerns the experimentation with AI services towards smart cities.

The objectives of CitCom.ai can be categorized in three major categories. The first is Testing and Validation and it facilitates field trials for AI service developers. It allows experimentation with algorithmic solution and relevant infrastructure. Major goal here are efficiency and security before the commercial deployment. The second is Policy and Regulation which concerns the development and the validation of policies that in some cases are national or regional while in some other cases concern a specific sector/domain.

The facility is organized into three thematic "super nodes," each addressing specific challenges:

- **North Supernode ("POWER")**: Focuses on energy systems, environmental solutions, cybersecurity, ethics, and edge learning. This node comprises nine partners across Finland, Sweden, and Denmark.
- **Central Supernode ("MOVE")**: Addresses mobility and logistics challenges in urban settings, with partners located in Belgium, the Netherlands, Luxembourg, and France.
- **South Supernode ("CONNECT")**: Aims to connect citizens, infrastructures, AI, and robotics services securely, focusing on innovations that enhance local infrastructures and cross-sectoral services. Partners in this node are based in Italy, Spain, Poland, and Germany.

In a nutshell the major services that CitCom.ai offers are: i) **Data Quality** Testing which ensures that data sets the models are derived through adequate and unbiased data sets towards their high levels accuracy and fairness and ii) **Regulatory Navigation Support** which facilitates AI service developers to realise and navigate through various regulatory frameworks. In a nutshell the facility provides access to 28 test sites across Europe and facilitates 28 different experiments.

[illegible]

TEFHEALTH facilitates integration of AI and robotics into the healthcare sector. It envisages the provision of technical and scientific support to AI services providers' related healthcare sector. Its major objectives can be categorised as i) Accelerating Market Introduction through validation services, ii) Ensuring Trustworthy AI through compliance with regulations (i.e. safety, ethics) and interoperability standards and iii) Enhancing Healthcare Systems exploitation of AI and robotics.

[illegible]

AI-MATTERS is an initiative that enhances the resilience and flexibility of the European manufacturing sector by integrating advanced AI, robotics, and intelligent autonomous systems into production processes.

The major activities of AI-MATTERS include: i) Deployment of latest AI and robotics innovations to facilitate flexible and resilient manufacturing, ii) Support of SMEs to access TEFs and iii) Enhancement of EU Competitiveness by marketing cutting-edge technologies.

Its Services include: i) Testing and Validation of AI and robotic solutions in real field trials, ii) Compliance Support which concerns the alignment of novel services with regulatory frameworks, iii) Technology Transfer which concerns exploitation and use of AI solutions by providing expertise and resources to advance a solution from development to deployment and iv) Collaboration Networks which connect (facilitate business to business relationships) innovators with industry leaders, research institutions.

2.5.4 The European Testing and Experimentation Facilities for Agri-Food Innovation (AgrifoodTEF)

Built as a network of physical and digital facilities across Europe, the EU project agrifoodTEF provides services that help assess and validate third party AI and Robotics solutions in real-world conditions, aiming to foster sustainable and efficient food production. AgrifoodTEF offers validation tools to innovators so they can develop their ideas into market products and services. More specifically AgrifoodTEF aims to support innovators on services relating with farming and food processing by providing customized tools and services for testing and validating their AI and robotics solutions under real-world conditions.

2.5.5 Interaction with the European TEFs

EnerTEF will try to actively engage with the European TEFs by leveraging their expertise in AI validation, regulatory compliance, and real-world testing. These TEFs provide structured environments where AI-driven solutions are tested for performance, security, and ethical considerations before being deployed at scale. By studying CitCom.ai, TEFHealth, AI-MATTERS, and AgrifoodTEF, EnerTEF will gain valuable insights into best practices for AI experimentation, including access to benchmarking datasets, testing methodologies, and compliance frameworks that align with EU regulations. This interaction allows us to refine our AI models and technologies to ensure they meet industry-specific requirements and societal needs.

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This project has received funding from European Union's Horizon Europe Research and Innovation programme under the Grant Agreement No. [illegible]

Beyond technical validation, the TEFs offer a unique opportunity for EnerTEF to study and adopt governance models for AI development and deployment. Each TEF operates within a specific sector—smart cities, healthcare, manufacturing, and agrifood—providing a structured approach to regulatory compliance and policy alignment. By engaging with these facilities, we can learn how to implement ethical AI principles, manage data sharing policies, and establish trustworthy AI systems. Furthermore, collaborating with their extensive networks of industry partners, startups, and researchers allows us to build strategic partnerships that enhance the scalability and adaptability of our AI solutions across multiple domains.

Lastly, EnerTEF can benefit from the TEFs' experience in fostering AI ecosystems and commercializing innovations. By examining their approaches to technology transfer, industry collaboration, and AI marketplace integration, we can develop a more robust strategy for connecting AI developers with end users. The TEFs' expertise in supporting small and medium enterprises (SMEs) and facilitating AI adoption across industries provides a blueprint for us to design a Digital Open Marketplace Ecosystem (DOME) where AI solutions can be tested, validated, and commercialized efficiently. Through knowledge sharing workshops, pilot projects, and joint experiments, we can continuously enhance our methodologies and contribute to the broader European AI ecosystem.

5.3 Related Projects

5.3.1 International Data Spaces Association (IDSA)

The International Data Spaces Association (IDSA) brings together over 130 member companies and institutions from more than 20 countries, aiming to create a global standard for secure and sovereign data sharing across industries and borders [17].

Its mission is to enhance data economy with fairness and reliability. To achieve this, it must ensure that organizations can keep full control over and be in position to share them and trade with them at the same time. This concept, known as "data sovereignty," facilitates data owners to create requirements and policies towards efficient interaction with their data users.
The major achievements of IDSA are:

- **IDS Reference Architecture Model (IDS-RAM)** which is a framework that sketches roles, processes, and components to maintain the security of data exchange.
- **IDSA Rulebook** which is a guide that clarifies the legal, operational, functional, and technical agreements that participants in a data space must consider.
- **Data Space Connector** which is software that facilitates stakeholders to connect to data spaces, facilitating controlled and secure data sharing.
- **Certification Services**, which assess the processes to ensure that components and participants meet the established standards for secure data exchange.

Finally, IDSA recently established collaborations with various international initiatives and organizations, such as Gaia-X, to promote interoperability and the development of a unified data infrastructure in Europe and beyond.
EnerTEF will extensively examine interaction with the International Data Spaces Association (IDSA) in several strategic and technical ways as analyzed below.

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The first is the use of the IDS Reference Architecture. More specifically EnerTEF can adopt the IDS Reference Architecture Model (IDS-RAM) to structure its data sharing framework (i.e. definition of roles like Data Provider/Data Consumer and Broker, guarantee data sovereignty and control the admission to datasets that are shared, development of compatible data connectors).

The second is to examine implementation of IDS-Compliant Components. More specifically EnerTEF could: i) Use IDS connectors to enable secure data exchange between different testbeds or pilot sites, ii) Embed usage control policies so each partner defines how their data can be used, iii) Support interoperability with other data spaces, e.g., in energy, manufacturing, or smart cities.

The third is to Pilot Use Cases or Test Certification. In more detail IDSA encourages the development and validation of use cases. Thus, EnerTEF could i) propose pilot projects to demonstrate secure energy data exchange though IDSA exploitation and ii) test and certify its components through IDSA's certification program.

2.4.[illegible] Gaia-X

Gaia-X is a European initiative aimed at creating a federated and secure data infrastructure that ensures data sovereignty, transparency, and interoperability across borders and sectors. In more detail Gaia-X tries to bridge the gap between a diverse set of stakeholders as governments, industry, research institutions, and standardization bodies. Its objective is the development of a digital ecosystem that entails around data protection (GDPR), openness, and control over data usage [33]. Gaia-X can operate on top of cloud/edge providers, and it is able to act as a framework and set of standards that they can follow to ensure trustworthy and interoperable data services.

The major key goals of Gaia-X or in other words requirements that it fulfils are: i) data sovereignty which allows organizations to keep control over their data (i.e. direct their storage and control the admission to them while defining admission requirements), ii) interoperability which ensures that services and data are able to operate across services providers and data sectors, iii) Decentralization which avoids single point of dependency (i.e. proprietary service or platform) and iv) Federated Services which link cloud and data providers under common standards, without requiring a central hub.

Core Components are related directly with the above requirements. In a nutshell Gaia-X Federation Services (GXFS) are open-source software building blocks (e.g., for identity, access control, compliance) that enable the federation of services. In addition, Gaia-X Ecosystems are domain-specific data spaces (e.g., energy, health, etc.). Finally, Gaia-X Association (AISBL) is a Brussels-based non-profit organization that coordinates the development and governance of Gaia-X standards.

EnerTEF could interact with Gaia-X by aligning with its federated data space principles, participating in its ecosystems, and contributing to or adopting its open-source services.

More specifically EnerTEF can adopt Gaia-X Federation Services (GXFS) to enable secure, sovereign, and interoperable data exchange between energy test beds and facilities. It can use GXFS components for identity and trust, compliance, service discovery, and data contract management. In this context it can integrate these components to EnerTEF's test platforms to support federated access by stakeholders (utilities, startups, regulators, etc.).

EnerTEF can also examine to join a Gaia-X Energy Ecosystem. More specifically EnerTEF could engage with existing Gaia-X energy initiatives (e.g., GX4E – Gaia-X 4 Energy, SDXE – Sovereign Data Exchange for Energy) and interact with third parties that work on smart grid, renewables, or energy market projects. In this context EnerTEF can co-develop use cases, like peer-to-peer energy trading, grid optimisation, or cross-border energy data services. All these facilitate EnerTEF to gain visibility, partnership opportunities, and alignment with EU digital policies.

Finally, EnerTEF can Define and Publish Gaia-X Compliant Services. More specifically EnerTEF can turn its experimentation facilities (or a subset of them) into catalogued Gaia-X services. To achieve this, it must define service descriptions and metadata in the Gaia-X Service Registry. In addition, it must use self-descriptions and compliance labels to signal that EnerTEF's services meet Gaia-X standards for transparency and trust. In this case EnerTEF opens the door for others to discover and use its services both programmatically or through a data space.

2.7.2 Alliance for the Internet of Things Innovation (AIOTI)

AIOTI is a European industry association that facilitates promotion and dissemination of the development and adoption of the Internet of Things (IoT) in Europe. AIOTI interacts with digitalization and green strategies that EU develops and integrates [14]. It founded in 2015 by the European Commission as part of the Digital Single Market strategy. AIOTI's main objectives are:

- Facilitate the interaction among a diverse set of stakeholders towards holistic IoT innovation ecosystems.
- Facilitate the deployment and the integration of cross-sector IoT services (i.e. Smart Energy, Smart Manufacturing (Industry 4.0), Smart Mobility & Transport, Smart Cities, Data Spaces and Edge Computing, Semantic Interoperability & Standards, Security, Privacy, and Trust, etc.)
- Support and promote the standardisation and interoperability of IoT technologies through development and participation in relevant activities.
- Develop policies and regulatory frameworks for responsible (i.e. ethical) and sustainable (i.e. quality of service, financial sustainability) IoT development.

AIOTI interacts closely with European institutions, standard bodies, and industrial alliances. More specifically AIOTI includes tech companies, research institutions, SMEs, and public sector players from across Europe. AIOTI's members can i) join working groups and shape technical and policy discussions, ii) Collaborate on EU-funded projects (e.g., Horizon Europe) and iii) influence standards and regulations for IoT and AI.

EnerTEF's development of testing and experimentation facilities for energy can interact with AIOTI through the AIOTI's Smart Energy Working Group (WG).

Smart Energy Working Group (WG Energy) is a group under the umbrella of AIOTI which focuses on the efficient interaction among smart grid's components. More specifically the activities of WG Energy unfold around IoT-enabled smart grids, renewable integration, and demand-side flexibility. Its major requirements are the interoperability of energy devices, the compatibility among platforms, and the development of common data spaces. In addition, WG Energy contributes to policy and regulatory input on digitalization in energy systems, while it aligns energy systems with European Green Deal and digital strategy goals.

EnerTEF will assess its attendance in regular working group meetings to understand its recent objectives and contribute through its activities. More specifically, EnerTEF will examine its contribution to position papers, whitepapers, and reference architecture reviews of WG Energy. It will also propose pilot use cases, through its facilities, which could be promoted as a testing environment for smart energy systems. The goal of EnerTEF is to offer a use case around federated testing of smart grid scenarios using IoT and data sovereignty principles (e.g., with Gaia-X and IDSA).

Finally, EnerTEF will collaborate in general with AIOTI on funding and policy initiatives. In this context it will exploit the deep connections of AIOTI with: i) EU funding calls (e.g., Horizon Europe, Digital Europe) and ii) Stakeholders in standardization (e.g., ETSI, CEN-CENELEC). According to these EnerTEF and AIOTI will co-develop project proposals, position EnerTEF's facilities as a test and experimentation infrastructure (TEF) aligned with EU goals and help influence EU energy and digital infrastructure policy.

Big Data Value Association (BDVA)

BDVA is a pan-European industry-driven organization which focuses on data and AI innovation [?]. BDVA plays a key role in shaping Europe's data economy by aligning research, innovation, and industrial interests around big data, AI, and data spaces. More specifically, the major objectives of BDVA unfold around the following clusters: i) Foster a competitive European data and AI ecosystem, ii) Shape and implement the European data strategy, iii) Promote the development of data spaces, trustworthy AI, and data-driven innovation and iv) Act as a bridge between industry, academia, and policymakers.

There are several key activities along the lines of BDVA. Its Strategic Research & Innovation Agenda (SRIA) tries to connect industry with academia by defining the research priorities and the major challenges for data and AI in Europe. A critical focus is also Data Spaces & Interoperability that acts as a framework through which BDVA contributes to building European common data spaces in key sectors (e.g., health, energy, mobility). This is aligned with Gaia-X and IDSA whose similarities analysed above. In addition, BDVA focuses on AI and Big Data Standardization. In this context BDVA works with organizations like ETSI, ISO, and CEN/CENELEC to promote European values in AI and data governance. Finally, BDVA is involved in numerous Horizon Europe and Digital Europe projects, often as a partner, advisor, or coordinator.

BDVA includes over 200 European members which include large corporations (e.g., SAP, Siemens, IBM etc.), SMEs and startups, Research institutions and universities and public sector and digital innovation hubs.

EnerTEF can contribute to and benefit from BDVA's focused working groups, such as:

- **Data Space WG** which develops architecture and governance models for cross-sector data spaces. This Data Space WG will facilitate federated energy experimentation platforms that EnerTEF envisages.
- **AI and Data Technologies WG** which focuses on AI-driven innovation. It will facilitate several ENERTEF's services include analytics, forecasting and optimization.

In addition, EnerTEF can connect with the Data Spaces Support Centre (DSSC). More specifically, BDVA is a core partner in the DSSC, which coordinates the development of European data spaces. In this context EnerTEF's energy facilities could potentially: i) Contribute to the Energy Data Space blueprint, ii) Help define testing and validation environments for trustworthy data sharing and iii) Offer insights into interoperability, privacy, and sovereignty at the infrastructure level.

Finally, EnerTEF can exploit BDVA to showcase its work and facilitate in this way its dissemination strategy. More specifically it will: i) Present EnerTEF at BDVA organized events (e.g. the European Big Data Value Forum), ii) Contribute to white papers and position documents on data sharing and AI in energy and iii) Feature in the BDVA innovation hub and use cases.

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This project has received funding from European Union's Horizon Europe Research and Innovation programme under the Grant Agreement No. [illegible]

6 Federated Architecture – Technical specifications for the EnerTEF reference architecture (E0)

6.1 Introduction

This section presents the architectural foundation of the EnerTEF digital ecosystem. It outlines the key software components and their functional roles, the application scenarios they support, and the system-wide logic that orchestrates their interactions. The architecture is structured to provide a modular, interoperable, and scalable environment capable of supporting secure experimentation and deployment of AI services in the energy domain.

Key input for the Reference Architecture design is the creation of a Components Catalogue, describing each core building block of the EnerTEF platform in terms of its function, interfaces, and information flows. This is followed by the Application Scenarios, which exemplifies how users interact with the platform to fulfil the representative

operational

objective.

To illustrate system behaviour, we then describe how the components interconnect to realize the scenario, identifying key integration pathways, control flows, and data exchange mechanisms. A set of Generic System Use Cases (GSUC) is introduced to abstract recurring patterns of user-platform interactions, providing a foundation for functional validation and requirement mapping.

Finally, we present the architecture mapped onto the Smart Grid Architecture Model (SGAM) framework, offering a structured and standards-aligned view of the system across the five SGAM layers: Business, Function, Information, Communication, and Component. This mapping facilitates the alignment of the EnerTEF architecture with EU energy and digital interoperability standards and supports future extensions toward compliance with frameworks such as IDSA, GAIA-X, and BRIDGE.

6.2 Reference Architectural Design Methodology

The initial Reference Architecture of the EnerTEF digital ecosystem has been designed through a structured, layered, and standards-informed methodology to ensure modularity, interoperability, scalability, and compliance with European digital energy and Data Space initiatives.

The design approach followed these guiding principles:

- **User-Centric and Use Case-Driven:** Architecture requirements were derived from the needs of key user groups: AI service developers, energy sector end-users, and TEF node operators through representative business application scenarios.
- **Layered Architectural Decomposition (SGAM-based):** The Smart Grid Architecture Model (SGAM) was adopted for the design of the 1st EnerTEF logical concept model to ensure alignment with EU best practices in the digitalisation of energy systems. SGAM enabled a multi-layered breakdown — Business, Function, Information, Communication, Component — to clearly separate concerns and map system roles to standardised domains and zones.

- **Interoperability and Standards Alignment:** The design incorporated components such as Dataspace Connectors and standardised data models to enforce semantic and technical interoperability. It also considered alignment with frameworks such as IDSA, GAIA-X and BDVA, laying the foundation for future compliance.
- **Modularity and Federation:** The architecture supports the federation of independent TEF nodes, allowing them to contribute assets (e.g., datasets, DTs, HPC resources) in a modular manner. Centralised components (e.g., the Portal, IAM, Orchestrator) interoperate with decentralised local assets through well-defined interfaces.
- **Security and Access Control by Design:** Identity and Access Management (IAM) principles were embedded from the start, with integration to systems such as Keycloak for authentication and Role-Based Access Control (RBAC) across all modules and user roles.
- **Iterative and Incremental Development:** The architecture was refined through iterations with the entire EnerTEF consortium. Component capabilities were continuously validated against real-world workflows, ensuring traceability from user needs to technical design.

This methodology ensures that the resulting architecture is not only technically sound but also responsive to the needs of stakeholders, scalable for future extensions, and capable of supporting secure and trustworthy AI experimentation within the European energy ecosystem. This first version of the Reference Architecture will also form the basis for the Technical Reference (Software) Architecture which will be further refined in the continuous T2.5 efforts.

6.3 Architecture Models & Initiatives Alignment

The EnerTEF architecture is designed to align with key European frameworks and digitalisation initiatives to ensure interoperability, trustworthiness, and regulatory compliance across the energy and AI experimentation domains.

- **Smart Grid Architecture Model (SGAM):** The architecture adopts SGAM to ensure layered clarity (Business, Function, Information, Communication, and Component) and maps actors, domains, and zones consistently. This alignment facilitates integration with energy systems and compliance with EU energy digitalisation strategies.
- **IDSA (International Data Spaces Association):** The use of Dataspace Connectors and data governance mechanisms ensures alignment with IDSA principles, including data sovereignty, secure data exchange, and trusted data usage.
- **GAIA-X:** The platform design supports federated data infrastructure with decentralised control, trust frameworks, and interoperable services – key tenets of GAIA-X. Integration of identity and access management, transparency, and policy enforcement enables alignment.
- **Common European Energy Data Space (CEEDS):** The EnerTEF architecture aligns with CEEDS principles by adopting mechanisms for federated data exchange through standardised APIs and incorporating data and control plane protocols that ensure secure and interoperable communication across nodes. Furthermore, the architecture envisions the use of catalogues for the registration, publication, and discovery of data, services, and assets, supporting seamless integration, governance, and findability of resources.
- **BDVA (Big Data Value Association):** The EnerTEF platform fosters AI and big data experimentation, promoting data-driven innovation while adhering to principles like FAIR data (Findable, Accessible, Interoperable, Reusable) and secure AI model usage, in line with BDVA objectives.

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- **AIOTI, AIoD, and DOME**: The platform promotes collaboration between AI developers and infrastructure providers, contributing to AI and IoT experimentation environments that are open, federated, and modular, reflecting AIOTI and AIoD principles.

This alignment ensures that EnerTEF is not only technically robust and modular but also adheres to strategic European digital frameworks, maximising its relevance, sustainability, and potential for cross-border collaboration.

3.4 Component Catalogue

This section describes the components that will be developed in the context of the EnerTEF project and will form the EnerTEF building blocks for establishing the reference architecture. For each component the technological enabler (TE) is provided, the basic functionality, the I/O method, the actors to use it and the responsible partner. The tables below provide information of the EnerTEF central platform components and not the local assets, DTs and digital platforms (TE-10, TE-11, TE-12, TE-13) to be provided by TEF providers.

[illegible]

	Energy Data Models
Technological enabler	TE-1
Description	Ensure interoperability and homogenisation by extending energy ontologies.
Functionalities	• Ontology development • Data annotation
Sub-components	• Ontology development submodule • Data annotation submodule
Input Data description	Energy-specific data
Input data format	Structured (databases, tables, spreadsheets)
Data input method(s)	API input, file upload
Data output method(s)	API output, file export
Actors to use	• Data consumers: TEF Users • Data providers: TEF Asset Providers
Relevant software component	Interoperability Middleware
WP/Task	WP3/T3.1

[illegible]	FWIR

[illegible]

	[illegible]
[illegible]	TE-1
[illegible]	Ensure seamless, secure data exchange and sovereignty
[illegible]	• Secure Data transfer between a provider and a consumer • Support policy enforcement • Identity verification • Register available datasets and expose metadata
[illegible]	• Data connector GUI • Middleware integration APIs
[illegible]	TEF dataset to be transferred
[illegible]	Semi-structured (JSON, XML, YAML)
[illegible]	Through GUI or API allow users to provide data to be published
[illegible]	Through GUI or API show transferred data and procedures (interrogation, contract agreement)
[illegible]	• Data provider: TEF Asset Provider (TEF provider administrators data sources) • Data consumer (searches, agrees and consumes data): End Users
[illegible]	Interoperability Middleware
[illegible]	WP3/ T3.1.2
[illegible]	A0

[illegible]

	[illegible]
[illegible]	TE-2

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Description	Secure Access to TEF Resources by applying identity access policies
Functionalities	• Authentication • Authorization • Role based access control (RBAC)
Sub-components	•
Input data consumption	• User information • Organisation access policies • RBAC Data
Output data format	Standardised data exchanges (OAuth, LDAP etc.)
Data input interface	Through GUI or API allow users to enter data to be published
Data output interface	Through GUI or API show monitored data and procedure (investigation, contract agreement)
Envisaged users	All EnerTEF users
Related software components	• EnerTEF portal • TEF providers • TEF services and
WP/Task	WP3, T3.2
Leader	CUMS

Table 47: [illegible] component details

	[illegible]
[illegible]	T1.4
Description	Coordinate and monitor access to TEF resources
Functionalities	• Monitor TEF resource allocation • Schedule and prioritise access to TEF resources
Sub-components	• Resource monitoring module • Resource access prioritisation module

Input Data Information	• TEF nodes Telemetry Data • Resources list
Input Data Format	• Telemetry Data (semi-structured, JSON) • Resources list (semi-structured, JSON) • Access priorities (semi-structured, JSON)
User Input Method	Through GUI receive experiment resource requirements
[illegible] Method	GUI/UI for perusing access history, scheduling priorities
Actors/Roles	TEF Asset providers/Node admins: Monitor HPC resources, register assets
Related software Components	• EnerTEF Portal • Experimentation GUI
WP/Task	WP3/T3.3
Partner	[illegible]

[illegible]

	[illegible]
Technology Enablers	TE-3, TE-6, TE-7, TE-8
Objective	Execute AI experiments
Functionalities	• Data preprocessing • Run services from the service catalogue • Train AI models • Track performance of AI models • Serve AI models
Dependencies	• Experimentation Suite (ES) for designing the experiment • Datasets • Model registry: store AI models for reusability
Input Data Information	• Datasets (CSV, JSON) or dataset address in database • APIs for services, needed for input features • API for AI model and python code to train AI model • HPC resources available for experiment • Experiment information and metrics (JSON, CSV) • Trained model in object
Input Data Format	Metrics in influence database

[illegible]	• Dataset (csv, json) or dataset address in database • APIs for services, needed input features for sample • API for AI model and/ or python code via Jupyter notebook to • train AI model • API for HPC resources availability • Experiment information, tracking metrics via Jupyter notebook • input
[illegible]	• API AI model (pkl) Tracking information (CSV) Giving back resources to HPC (structured)
[illegible]	AI service providers
[illegible]	• Data connector • TEF nodes • HPC Orchestration • Marketplace
[illegible]	WP4/T4.3
[illegible]	RWTH

Table [illegible] EnerTEF [illegible] component details

	[illegible]
[illegible]	TE-9
[illegible]	One-stop shop for listing, purchasing and executing services on TEF nodes
[illegible]	• Register and authenticate users • Register services, assets, resources • Purchase services, assets, resources • Access resources • Design experiments
[illegible]	• Marketplace GUI • Transaction mechanism • Training material
[illegible]	• Service list: structured (DB) • Resource list: structured (DB)
[illegible]	User forms through portal GUI
[illegible]	Structured (database)

[illegible]	Through portal GUI show purchased services
Actors/ Users	• End-Users: Access services • AI service developers: Access service catalogue, request resources, design experiments TEF Asset provider: provide and monitor resources
[illegible]	Experimentation workbench HPC orchestrator IAM module
[illegible]	WP3/T3.3
[illegible]	ISI

Table 30 Regulatory Sandboxes Component Overview

	Regulatory Sandboxes
[illegible]	TF-18
[illegible]	Sandbox for supporting AI testing on legal and regulatory standards
[illegible]	• Description of Regulatory Sandboxes • Linking to compliance level • Classification, if application requires Sandboxing • Sandbox workflow report
[illegible]	• Template for developers • Template for regulatory persons
[illegible]	Manual, User forms
[illegible]	Descriptive (free text) and choice
[illegible]	Input in template document of portal
[illegible]	List of TEF/Sandboxes mapped to the regulations Document
[illegible]	Users Administrators Project Manager, Lead developers
[illegible]	Catalogue, Staging environment

[illegible]	WP7/T2
Leader	COMS, [illegible]

[illegible]

	[illegible]
[illegible]	TE-15
Description	Offer content-based suggestions to end users, linking them with [illegible] services
[illegible]	Organisation of services Recommendation of services based on the user
[illegible]	Catalogue
[illegible]	Text box, possible free text
[illegible]	Free text
[illegible]	One or multiple choices
[illegible]	List of recommendations
[illegible]	Users
[illegible]	Recommendation engine or [illegible] software
[illegible]	WP7/T7.4
Leader	COMS

[illegible] Business Application Scenario & Support Flow

This section describes a business application scenario on the EnerTEF Platform. The section will begin with the flow of actions for each category of users and then present the complete application scenario demonstrating the interaction of users between them on the EnerTEF integrated platform.

[illegible]

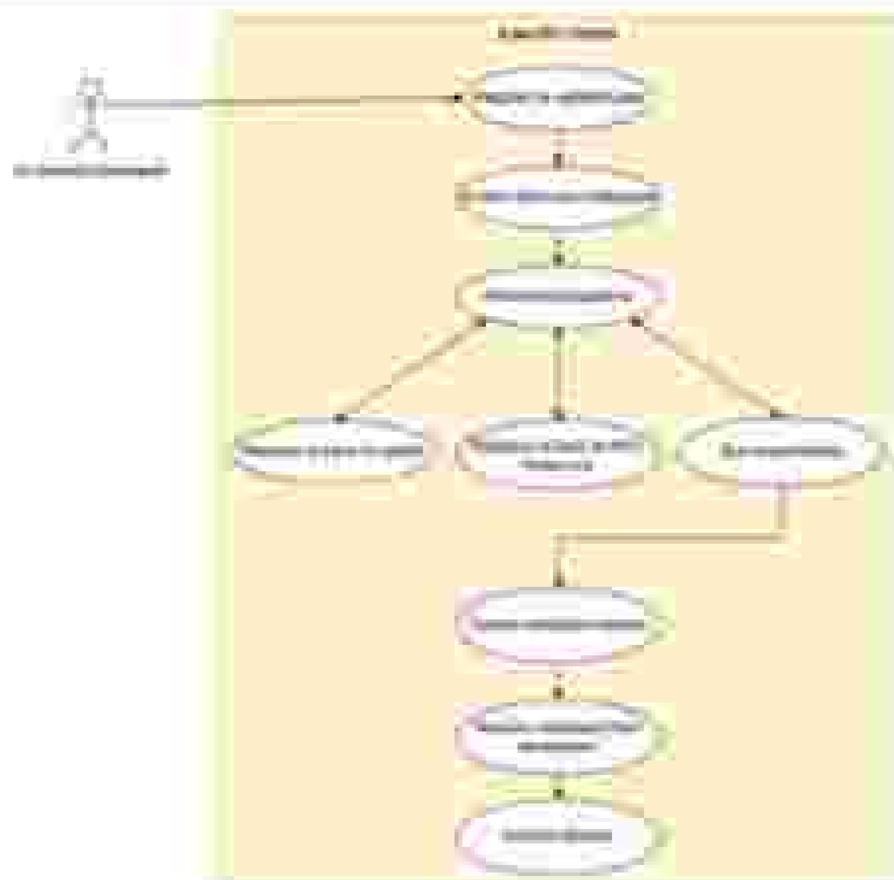
	[illegible]
Actor Description	Startups, SMEs, research teams, or technology providers offering AI-based solutions applicable to the energy sector.
Expected Activities	• Register and authenticate through the EnerTEF Portal's Access Management System (T3.3). • Access and browse the EnerTEF Services Catalogue; identify expertise-related challenges, and propose solutions to the relevant end-users. • Request access to EnerTEF Assets (Datasets, Digital Twins, Virtual Assets (T3.1)). • Configure and run experiments through the EnerTEF AI Experiment Workbench, request HPC resources, all via the Transaction Manager (T3.3). • Collect experiment outputs, refine solutions if necessary, and prepare intermediate validation reports aligned with the established KPIs. • Receive feedback from the end user and proceed with the implementation. • Present the final AI service on the Experiment Dashboard and notify the Transaction Manager upon submission.
Actor Diagram	

Table 33 End User (flow of actions)

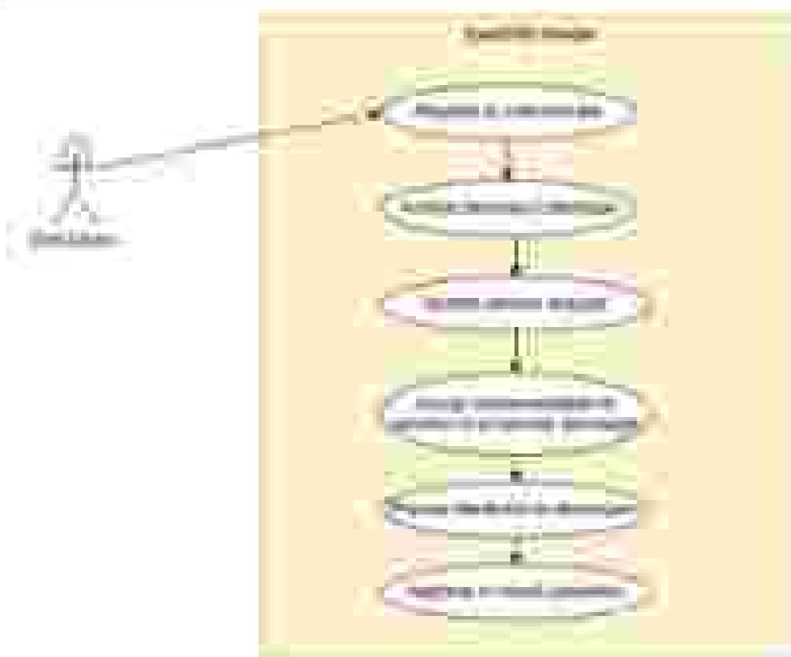
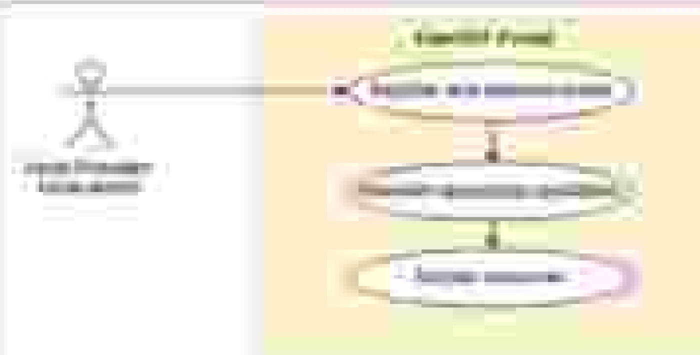
	End User
Actor Description	Stakeholders from the energy sector, including DSOs, TSOs, utilities, Renewable Energy Source (RES) operators, aggregators, and other energy-related entities. End-users may also have assets to provide, making them potential Asset Providers as well.
Goal / Actions	• Register and authenticate through the EnerTEF Portal's Access Management System (T1.3). • Access the EnerTEF Services Catalogue, which contains the existing set of validated AI service needs and testing opportunities, initially defined during the Co-Creation in Living Labs. • Submit new service needs (or modify the already defined services) directly through the Portal if additional or emerging challenges arise. • Accept the implementation of the solution to the Startup/SME that has expressed interest in carrying it out. • Provide feedback to AI service developers based on their interim reports. Approve or reject the validation of solutions based on test results and business/operational relevance via the Transaction Manager. Provide feedback to the AI Service Developers.
Flow Diagram	

Table 34 TEF Node Administrator (flow of actions)

	TEF Node Administrator

[illegible]	TEF Asset providers/Node administrators
[illegible]	Entities responsible for operating and maintaining the physical infrastructures, virtual environments, datasets, digital twins, and high-performance computing (HPC) resources federated into the EnerTEF Portal.
[illegible]	• Register and onboard their managed assets into the EnerTEF Portal ensuring proper metadata documentation (capabilities, access policies, operational parameters). • Maintain operational availability and performance of: Physical testing infrastructures, Digital assets (datasets, simulators, digital twins), HPC resources and cloud environments. • Integrate with the EnerTEF HPC Orchestrator (T5.4) to enable dynamic and seamless resource allocation to AI Service Developers conducting experiments. • Apply data governance and interoperability standards as required by the Data Governance, Data Space, Data Access and Semantic Interoperability Layer (T5.1, T5.2). • Support the secure and permissioned sharing of datasets and system telemetry with AI experiments, under GDPR and cybersecurity regulations.
[illegible]	

The figure below displays the entire application scenario to demonstrate the interaction of the different category of users between them on the EnerTEF Portal. End-users request the implementation of services and validate the results, Startups and SMEs develop services using EnerTEF resources and prepare reports and finally TEF asset providers provide assets and HPC resources. The EnerTEF Platform ensures smooth coordination among these roles to maintain a seamless workflow.

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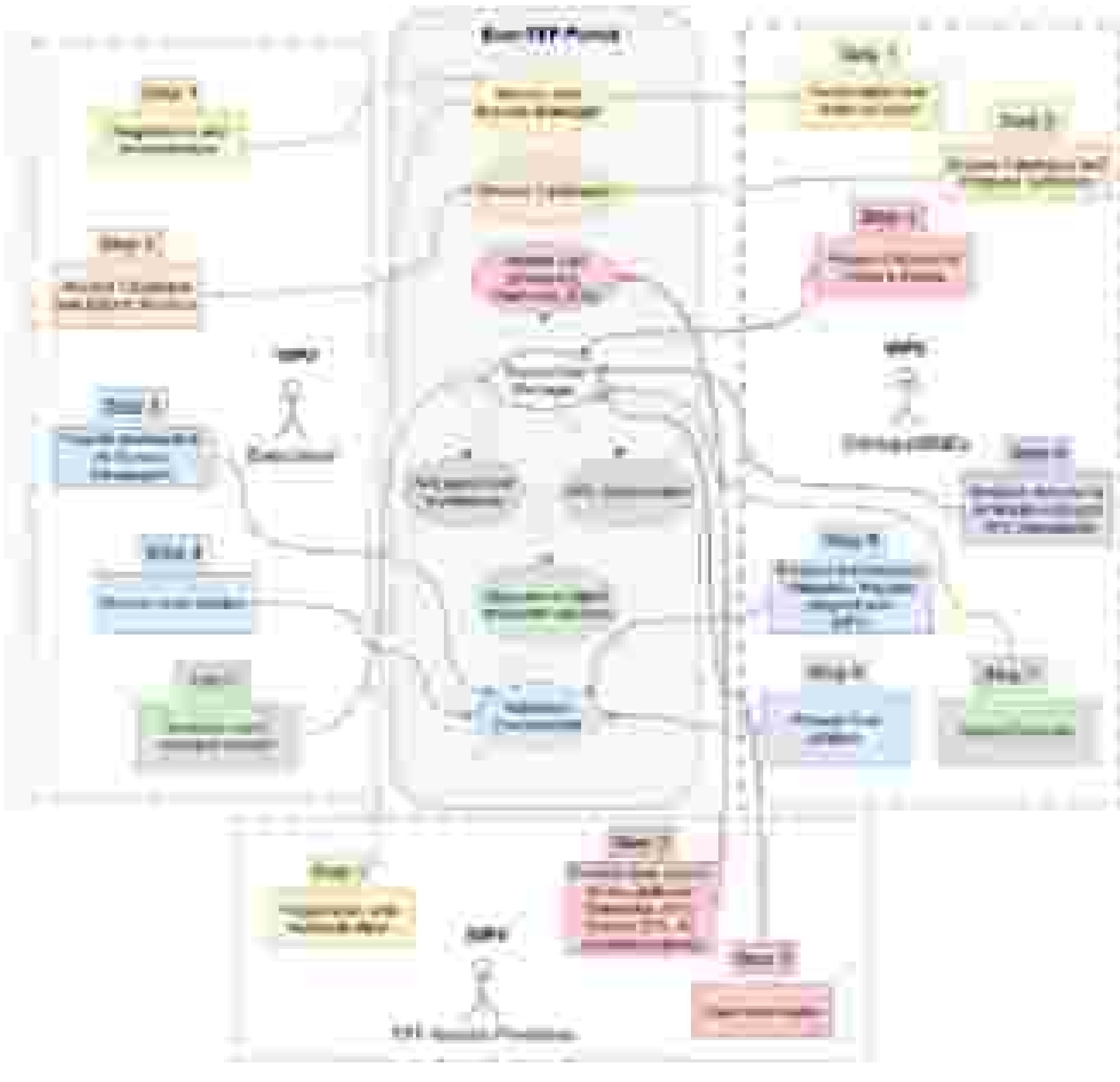

Figure 2 EnerTEF application [illegible]

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The figure below illustrates the logical data flow and interaction between the core EnerTEF building blocks (interoperability interfaces), highlighting how telemetry, control, and identity-related information traverses the system. This interconnection architecture enables seamless integration and orchestration of physical and virtual resources across TEF nodes. It captures the mechanisms required to fulfil key user capabilities, including resource discovery, access management, prioritised scheduling, service creation and validation, and execution of AI-enhanced services. Each component plays a pivotal role in ensuring coordinated, efficient, and secure access to TEF infrastructure.

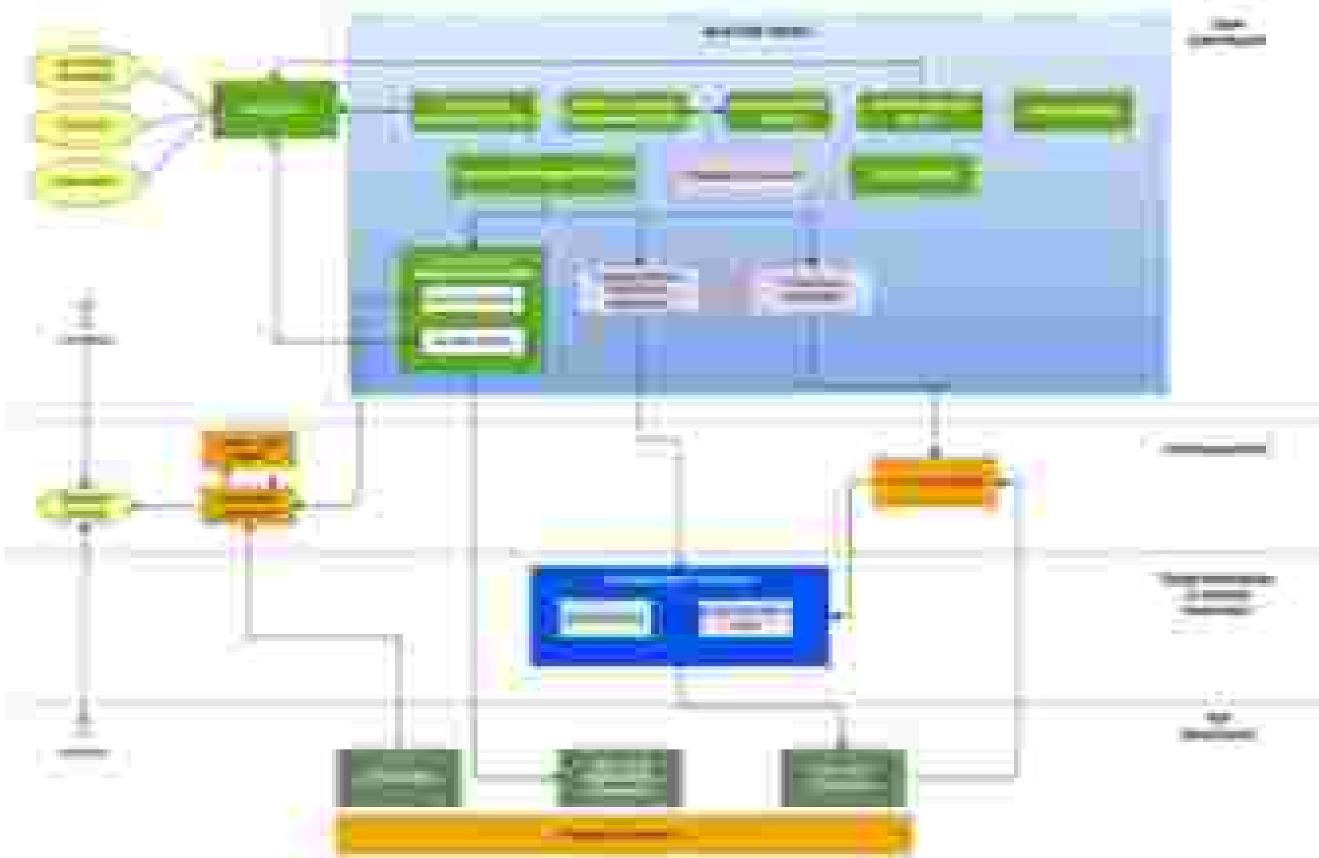

Figure [illegible] EnerTEF Platform logical Dataflow

- **EnerTEF Portal:** is the highest level user interface and single entry point of access for the EnerTEF modules. The EnerTEF Portal consists of the following submodules:
    - **User Access Management Module:** allows the user from registration and authentication. The User Access Management system will be integrated with the Identity Access Management (IAM) module for the creation and enforcement of access policies and role-based access control (RBAC, AI service developers, End Users, Node admins).
    - **Services Catalogue Management Module:** It provides basic Service Catalogue operation management with functionalities such as, creation of service requests, proposing solutions and assigning the solution development to startups and SMEs.

- **Recommendation toolbox:** suggests top ten services to users, providing all necessary details for an informed selection.
- **Asset Management module:** allows every operation on the Asset List, registering new assets (local platforms and DTs), their parameters and access policies in the EnerTEF platform.
- **Asset Access Management Module:** allows users to access EnerTEF assets: i) firstly to access EnerTEF local assets (DTs and platforms) by checking the asset's access policies with the IAM module and then redirecting users to the local platforms and DTs for using them, and ii) secondly to negotiate and consume TEF datasets by utilizing the Dataspace Connector.
- **Transaction Mechanism:** allows stakeholders to purchase EnerTEF resources, including local assets, platforms and DTs, HPC resources for conducting experiments and access to experimentation workbench for implementing services.
- **Experimentation Dashboard:** allows users to design their experiments, provide necessary description of the experiment (title, description, date, etc.), request the datasets they would like to use.
- **Orchestrator Dashboard:** displays and performs analytics on TEF resource monitoring data, resource allocation and service execution status.
- **Validation Dashboard:** allows users to provide feedback, monitor and validate service results, and finally validate the services according to their standards and KPIs.
- **Analytics Module:** collects data and performs analytics regarding the portal usage, transactions and services usage analytics.
- **Support Module:** allows end-users to create tickets regarding technical issues they are experiencing in the Portal, access issues, resource conflicts and disputes. It will also allow users and admins to track the progress of the issues and their status.

- **Interoperability Middleware**
  - **Dataspace connector:** Dataspace Connector allows the interrogation of a TEF dataset between the data provider (TEF provider) and data consumer (Portal's end users) ensuring data sovereignty and secure data exchange according to IDSA principles.
  - **Connector GUI:** The connector front-end responsible for all user dataspace interactions.
  - **Semantic Interoperability Enabler:** Transforms and homogenizes data across heterogeneous sources, ensuring semantic alignment and consistency. Supports standardised data representation (ontologies) for interoperability and integration.
- **HPC Orchestrator:** monitors, prioritizes and schedules access to HPC resources for executing services and performing experiments in the Experimentation Workbench.

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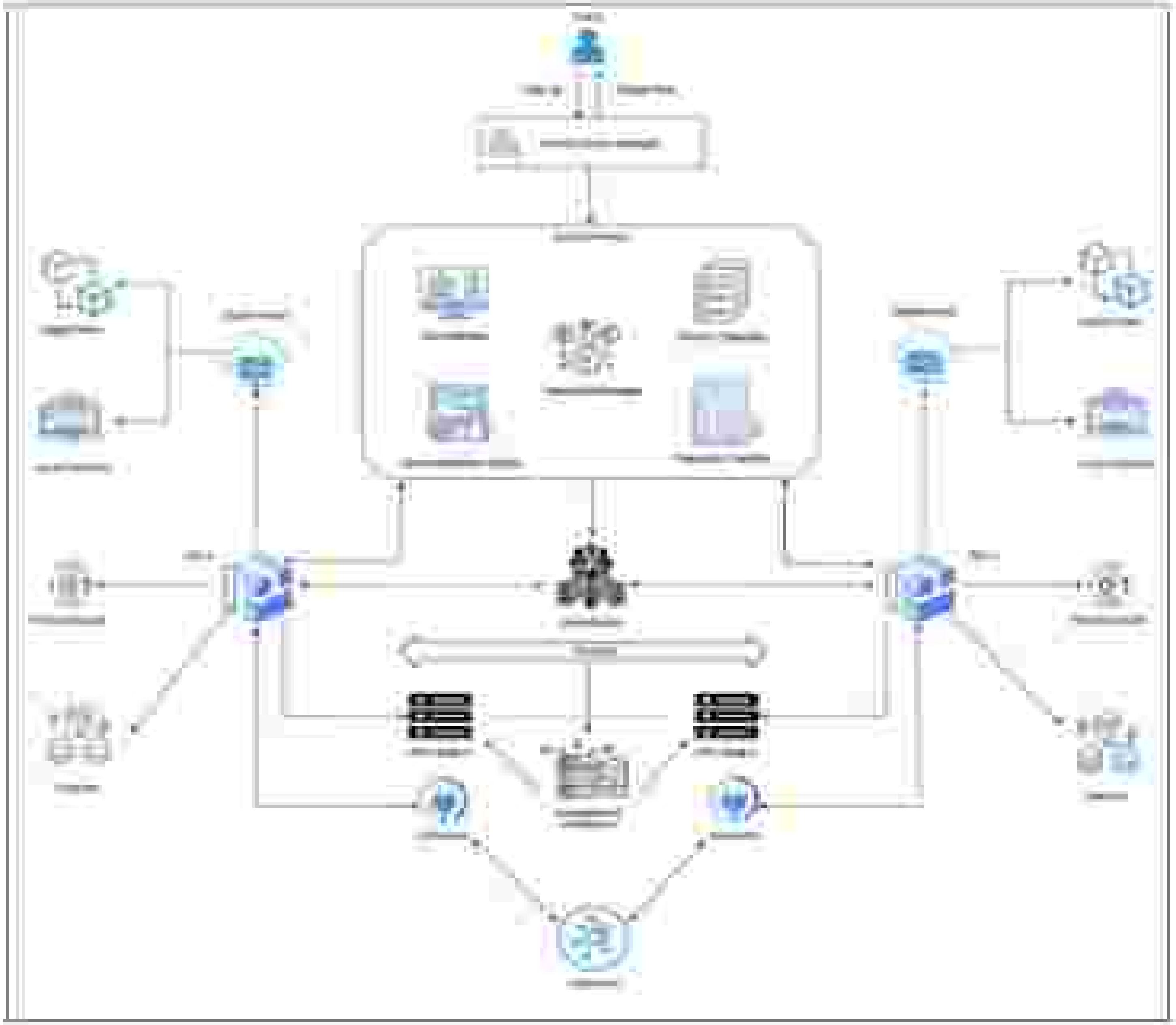
- **Experimentation Workbench:** allows users to perform experiments. Consists of firstly, the experimentation suite that allows users to perform their experiment step by step and, secondly, the model registry which allows users to store the trained models and the achieved KPIs.

TEF Nodes:

- **TEF datasets:** Data to be shared with end users for conducting experiments and training models
- **HPC resources:** for conducting experiments, training models and execute services
- **TEF assets:** includes TEF local platforms and DTs providing services that Portal's end-users can access.

The following figure depicts the development view displaying the component interconnection to achieve the desired functionalities of the application scenario based on the same logical business flow.



6.6 General System Use Cases from Business Flow

From the business flow and application domains formulated in the previous section the following general system use cases (GSUCs) are derived that will be elaborated in the subsequent deliverable D2.2 – "Final version of the AI-based services catalogue and EnerTEF's federated architecture".

Table [illegible]

[illegible]	[illegible]	[illegible]
User Registration	All	EnerTEF Portal, IAM
User Authentication	All	EnerTEF Portal, IAM
Access Service Catalogue	AI service developers, End Users	EnerTEF Portal, Service Catalogue Management Module
Submit new service request	End Users	EnerTEF Portal, Service Catalogue Management Module
Propose solutions	AI service developers	EnerTEF Portal, Service Catalogue Management Module
Perform transactions	AI service developers	Portal, Transaction Mechanism
Request access to assets	AI service developers	EnerTEF Portal, Transaction Mechanism, Asset Access Management Module, IAM
Request access to HPC resources	AI service developers	EnerTEF Portal, Transaction Mechanism, HPC orchestrator
Configure and perform experiments	AI service developers	EnerTEF Portal, Transaction mechanism, Experimentation Dashboard, Experimentation Workbench
Create validation reports	AI service developers	EnerTEF Portal, Validation Dashboard
Access feedback from users	AI service developers	EnerTEF Portal, Validation Dashboard
Assign service implementation to startup/SME	End-Users	EnerTEF Portal, Service Catalogue Management Module
Provide feedback to service developers	End-Users	EnerTEF Portal, Validation Dashboard
Approve or reject validation of solution	End-Users	EnerTEF Portal, Validation Dashboard
Register assets	Node Administrators/TEF Asset Providers	EnerTEF Portal, Asset Management Module, IAM
Monitor assets	Node Administrators/TEF Asset Providers	EnerTEF Portal, Asset Management Module, HPC orchestrator

6.2 SGAM of limited EnerTEF RA

EnerTEF aims to establish a Common European-scale Energy AI federated TEF, facilitating extensive utilization validation and uptake of AI tools and services across the energy sector so as to bridge the gap between demand and limited availability of rigorously tested AI products. The EnerTEF platform will bridge AI Service Developers (Startups, SMEs, researchers) with End Users (Energy sector stakeholders such as TSOs, DSOs, RES operators, utilities, aggregators) to accelerate the deployment of trustworthy AI solutions in real and near-real environments.

SGAM Model

The SGAM[5] was initially developed under the M/490 mandate from the European Commission (EC) to the European standardization organizations, CEN, CENELEC, and ETSI. Its primary goal was to identify existing technical standards relevant to Smart Grids and to highlight any gaps in current technologies and standardization efforts. SGAM serves as a framework to harmonize terminology, technologies, and objectives by providing a reference model that functions as a blueprint for designing future Smart Grid architectures.

The conceptual SGAM model consisting of five interoperability layers, each comprising six domains and five zones, is shown in the figure below.

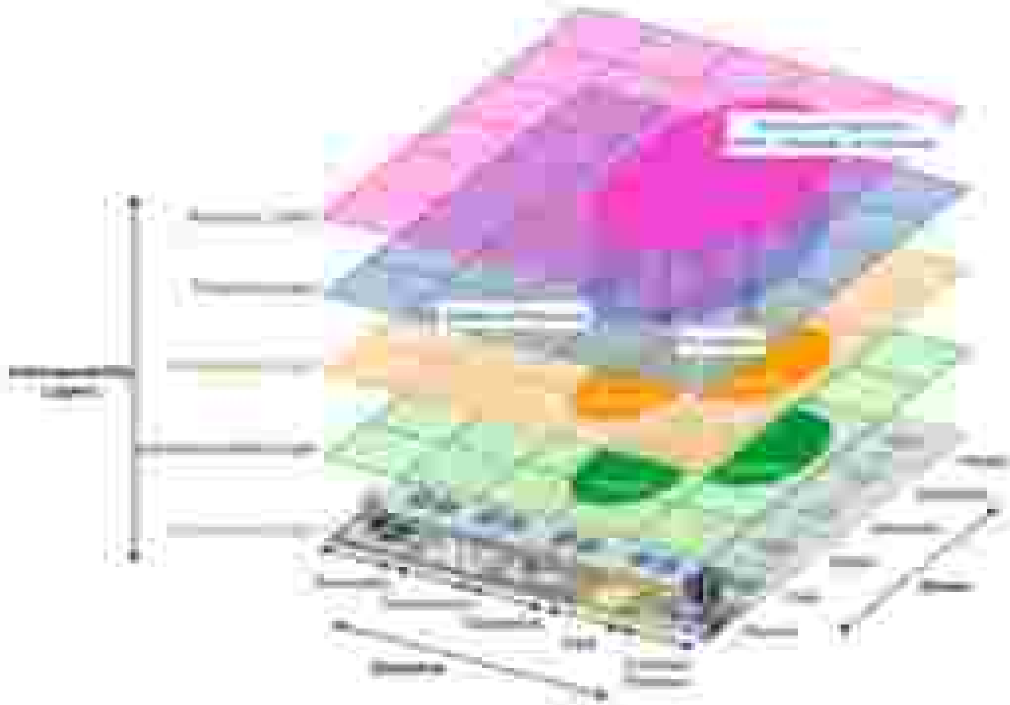


Figure 1 SGAM Model

The SGAM Domains reflect the stages of the energy conversion process, as outlined in the widely recognized NIST Conceptual Model[6]. These domains are defined as follows:

[4] URL: [illegible]
[5] Office of the National Coordinator for Smart Grid Interoperability. NIST Framework and Roadmap for Smart Grid Interoperability Standards Release 1.0; Technical Report; National Institute of Standards and Technology (NIST): Gaithersburg, MD, USA, 2010
[6] Smart Grid Coordination Group. Smart Grid Reference Architecture; Technical Report; CEN-CENELEC-ETSI: Brussels, Belgium, 2012

- **Bulk Generation:** Refers to the large-scale production of electricity using sources such as fossil fuels, nuclear energy, hydroelectric plants, offshore wind farms, and extensive solar facilities like photovoltaic (PV) and concentrated solar power (CSP) plants. These are typically linked to the transmission grid.
- **Transmission:** Involves the high-voltage infrastructure used to transport electricity across long distances.
- **Distribution:** Covers the systems responsible for delivering electricity from the transmission network to end users.
- **Distribution Energy Resources (DER):** Encompasses small-scale, decentralized electricity generation units connected to the public distribution network, usually ranging from 3 to 10 MW. These units can be managed directly by a DSO. **Customer Premises:** Includes all locations where electricity is consumed and potentially generated. These
- range from industrial and commercial sites to residential homes (e.g., factories, airports, shopping malls, and households). They may also host energy technologies like PV systems, electric vehicles (EVs), battery storage, and microturbines.

The *Zones*, which intersect with the SGAM Domains, represent the ICT-based control layers that manage the energy conversion process. Structured according to the automation pyramid, the Zones are defined as follows:

- **Market:** Represents the various market-related activities across the energy value chain, including energy trading, retail, and mass markets.
- **Enterprise:** Covers business and organizational operations, services, and infrastructure for stakeholders like utilities and energy providers. This includes functions such as asset management, logistics, workforce planning, training, billing, and customer relationship management.
- **Operation:** Focuses on the control and monitoring of power systems within each domain. Examples include Distribution Management Systems (DMS), Energy Management Systems (EMS) for generation and transmission, microgrid controllers, virtual power plant management platforms, and EV fleet charging coordination systems.
- **Station:** Acts as the aggregation point at the local level, responsible for tasks like data collection, function integration, substation automation, local SCADA systems, and plant-level supervision.
- **Field:** Involves devices used for real-time monitoring, protection, and control of the power system. This includes protection relays, bay controllers, and Intelligent Electronic Devices (IEDs) that collect and use data from the physical infrastructure.

• **Process:** Represents the actual physical and chemical processes in energy conversion—such as generating, transmitting, or consuming electricity. It includes all physical components directly involved, like generators, transformers, circuit breakers, lines, cables, loads, sensors, and actuators.

The following layers of the SGAM models are defined for the EnerTEF platform:

1. **Business Layer:** provides a business view of the EnerTEF platform and consists of all the end users along with their objectives. Particularly:
    - AI service developers: Startups, SMEs, research teams, or technology providers offering AI-based solutions applicable to the energy sector.

- End users: Stakeholders from the energy sector consuming services, including TSO/s, DSOs, utilities, RES operators, aggregators, and other energy-related entities. TEF asset providers-Node administrators:
- TEF providers, AI factories, entities responsible for providing assets, operating and maintaining the physical infrastructures, virtual environments, datasets, digital twins and high-performance computing (HPC) resources federated into the EnerTEF Portal.

2. **Function Layer**: describes the services of the EnerTEF platform. Particularly:

- Registration and authentication,
- Access to EnerTEF services catalogue, submit new service needs, assign implementation, approve or reject validation,
- Access to EnerTEF Assets (Datasets, DTs, Digital platforms),
- AI Experiment design and conduction,
- Experiment validation,
- Regulatory compliance,
- Feedback on services and experiments,
- Maintain operational availability of assets HPC resources and testing infrastructures

3. **Information Layer**: provides the necessary mechanism for data modeling and homogenization ensuring data integrity. Consists of all the syntax in an effort to describe the appropriate semantic vocabularies and design the needed metadata repository and data interoperability process. Our methodology will focus on SAREF4ENER, SAREF4BLDG.

4. **Communication Layer**: provides all the necessary protocols for securing data transfer between entities ensuring data sovereignty and protection. Particularly, Dataspaces will be leveraged that enable secure and controlled data exchange between participants. They enforce usage policies, manage data access, and ensure interoperability across systems. Data space Connectors are key to maintaining data sovereignty and trust in distributed environments. The Governance framework will be defined that sets the rules, policies, and structures that manage data sharing, access, and responsibilities among participants. It ensures trust, compliance, and alignment with legal and ethical standards. Effective governance enables secure and fair collaboration.

5. **Component Layer**: Consists of all the components that will be developed. Particularly:

- **EnerTEF central platform components**: including Portal, Experimentation module, HPC orchestrator, IAM module
- **EnerTEF local assets**: offerings from TEF nodes, datasets, DTs, Platforms, HPC Resources.

And finally, the EnerTEF reference architecture based on SGAM is visualized below. The full detailed EnerTEF reference architecture will be elaborated in D2.2 – "Finalization of the AI-based services catalogue and EnerTEF's reference architecture".

Figure [illegible] EnerTEF SGAM [illegible]

6.5 Conclusion & Future steps

The work conducted in this deliverable establishes the foundational architectural design of the EnerTEF platform. Through a detailed component catalogue, application concepts, generic system use case outline, and a layered SGAM-based representation, we have laid the groundwork for an interoperable, modular, and federated experimentation ecosystem aligned with key European digital and energy initiatives.

At this stage, the architecture serves as a functional baseline to guide the implementation of the platform's core components and services. However, several architectural elements remain under active development, particularly in the areas of interoperability, orchestration, data sovereignty, and standardised service interactions. In this phase (M18), the EnerTEF architecture demonstrates alignment with three key reference architecture standards: the Smart Grid Architecture Model (SGAM), the International Data Spaces Association (IDSA) reference architecture, and the GAIA-X framework. This ensures compliance with the project KPI for this milestone. Moving forward, the architecture will evolve to integrate additional standards, aiming for compliance to at least seven reference architectures by M48, ensuring robustness, interoperability and European alignment.

Looking ahead, the next critical milestone will be the formulation of the final EnerTEF Reference Architecture to be delivered in D2.2 – "Final version of the AI-based services catalogue and EnerTEF's federated architecture". This architecture will go beyond the current SGAM-based representation to offer a comprehensive, implementation-ready model capturing the platform's refined component interactions, data flows, governance, and compliance layers. The final reference architecture will be validated against relevant European and international standards and initiatives (e.g., IDSA, GAIA-X, [illegible], BDVA, [illegible]).

In parallel, the use cases introduced in this deliverable will be further developed and formally analysed in Deliverable D2.2 – "Final version of the AI-based services catalogue and EnerTEF's federated architecture", where they will be used to validate the architecture and demonstrate its applicability, completeness, and extensibility across real-world scenarios.

Through this iterative refinement, EnerTEF aims to deliver a scalable and standards-aligned architecture that facilitates trusted AI experimentation in the energy sector, while ensuring openness, compliance, and reusability across TEF nodes and stakeholders.

This project has received funding from European Union's Horizon Europe Research and Innovation programme under the Grant Agreement No. [illegible]

7. Conclusions

The D2.1 deliverable successfully establishes a robust foundation for trustworthy AI deployment within the European energy sector through the EnerTEF Testing and Experimentation Facility. By delivering a comprehensive AI services catalogue, fully integrated regulatory compliance framework, and federated architecture design, this work addresses the critical need for validated, compliant, and operationally ready AI solutions in energy infrastructure.

The strategic alignment with EU regulatory requirements, including the AI Act and GDPR, positions EnerTEF as a pioneering framework that balances innovation with safety and compliance. Through systematic stakeholder co-creation and adherence to FAIR data principles, the catalogue ensures that AI services meet real-world operational needs while maintaining the highest standards of trustworthiness, including >95% accuracy, <100ms latency, and 99.9% availability for critical applications. This deliverable represents a significant step toward Europe's sustainable energy transition, providing the technical specifications, compliance frameworks, and implementation guidance necessary for confident AI deployment across the energy value chain. The living document approach ensures continued relevance as both technological capabilities and regulatory landscapes evolve, while the regulatory sandbox framework enables controlled innovation within established safety boundaries. Moving forward, D2.1 serves as the cornerstone for subsequent project phases, enabling energy sector stakeholders to leverage advanced AI capabilities while maintaining full regulatory compliance, operational safety, and technical excellence. The framework's emphasis on interoperability, modularity, and scalability ensures that EnerTEF can adapt to emerging challenges and opportunities in Europe's evolving energy ecosystem.

Funded by the European Union

This project has received funding from the European Union's Horizon Europe research and innovation programme under the Grant Agreement No. [illegible]

8. References

[1] "Services Catalogue." [Online]. Available: https://enertef.eu/services-catalogue. [Accessed 2025].

[2] "EU Artificial Intelligence Act." [Online]. Available: https://artificialintelligenceact.eu/article/57/. [Accessed 2025].

[3] "[illegible]." [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/data-spaces. [Accessed 2025].

[4] "AI on Demand." [Online]. Available: https://www.ai4europe.eu/. [Accessed 2025].

[5] "EDIHs." [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/edihs. [Accessed 2025].

[6] "[illegible]." [Online]. Available: [illegible]. [Accessed 2025].

[7] "TEFs." [Online]. Available: https://digital-strategy.ec.europa.eu/en/policies/testing-and-experimentation-facilities. [Accessed 2025].

[8] "Citcom.ai." [Online]. Available: https://citcomtef.eu/. [Accessed 2025].

[9] TEF-Health. [Online]. Available: https://tefhealth.eu/home. [Accessed 2025].

[10] "AIMatters." [Online]. Available: https://ai-matters.eu/. [Accessed 2025].

[11] "AgrifoodTEF." [Online]. Available: https://agrifoodtef.eu/. [Accessed 2025].

[12] "IDSA." [Online]. Available: https://internationaldataspaces.org/. [Accessed 2025].

[13] "GAIA-X." [Online]. Available: https://gaia-x.eu/. [Accessed 2025].

[14] "AIOTI." [Online]. Available: https://aioti.eu/. [Accessed 2025].

[15] "BDVA." [Online]. Available: https://bdva.eu/. [Accessed 2025].

[16] "EnerTEF Grant Agreement." EnerTEF Consortium, 2024.

Funded by the European Union

This project has received funding from the European Union's [illegible] Programme under Grant Agreement No. [illegible]