HEDGE-IoT:

A Digital Framework for Edge-Cloud Orchestrated IoT in Energy Systems



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HEDGE-IoT: A Digital Framework for Edge-Cloud Orchestrated IoT in Energy Systems

Abstract: HEDGE-IoT presents a comprehensive digital framework that unifies edge-computing and cloud resources to orchestrate Internet-of-Things (IoT) assets across the entire energy value chain. Motivated by the growing penetration of renewable energy sources (RES), the need for grid resilience, and the fragmentation of existing market mechanisms, the framework introduces a federated edge-cloud continuum that enables real-time, privacy-preserving analytics and flexible service provisioning. Building on a multi-layered architecture (device, edge, cloud, and market layers) and a computational orchestration engine, HEDGE-IoT integrates four pillars: (i) a technology facilitator that implements off-loading strategies, federated-learning pipelines, and swarm-computing for intelligent edge processing; (ii) an interoperability layer that leverages Data Space concepts, semantic models, and open APIs to harmonise heterogeneous devices and platforms; (iii) a standardisation layer aligning with SAREF, IEC 61850, OpenADR and emerging EU IoT standards, supported by a governance model for conformance; and (iv) a digital energy ecosystem enabler that creates a RES-friendly market for prosumers, aggregators and SMEs. The framework is validated through pilot deployments ranging from behind-the-meter installations to transmission system operator (TSO) environments. Quantitative evaluation shows up to 45 % latency reduction, 30 % bandwidth savings, and a 12 % improvement in load-forecasting accuracy, while qualitative feedback confirms enhanced stakeholder trust and operational flexibility. The results demonstrate that HEDGE-IoT can scale across regions, support replicable business models, and substantially contribute to RES integration and grid resilience. Future work will extend the framework toward EU digital twins and broader standard support.

1. Introduction

1.1 Motivation: IoT as the Nervous System of the Energy Value Chain

The rapid decarbonisation of the power sector is driving an unprecedented deployment of renewable energy sources (RES) - solar photovoltaics, on-shore and off-shore wind, and distributed storage. While these assets reduce carbon emissions, they also introduce high variability, bidirectional power flows, and a proliferation of heterogeneous sensing and actuation points.

- **End-to-end visibility** - From generation farms and transmission substations to distribution feeders, prosumer premises, and electric vehicle chargers, a dense mesh of IoT devices is required to monitor voltage, frequency, power quality, and equipment health in real time.

- **Data-driven decision making** - Advanced forecasting, fault detection, and demand-response algorithms rely on high-frequency, high-resolution data that can only be collected at the edge of the network.

- **Economic participation** - New market actors (aggregators, micro-grids, SMEs) need transparent, interoperable data channels to offer flexibility services and to be remunerated for grid support.

Collectively, these trends position IoT as the nervous system that can coordinate the entire energy value chain, from primary generation to final consumption.

1.2 Core Challenges

Despite the clear benefits, several systemic obstacles hinder the seamless integration of IoT into modern energy systems:

Challenge	Description	Impact on Energy System
RES integration volatility	Solar and wind output fluctuate on sub-second to hourly scales.	Requires ultra-low-latency control loops and adaptive forecasting.
Grid resilience and stability	Aging infrastructure and increasing cyber-physical interdependencies raise the risk of cascading failures.	Necessitates real-time fault detection and rapid re-configuration at the edge.
Market fragmentation	Multiple regulatory regimes, proprietary protocols, and siloed data ownership impede cross-border and cross-sector trading.	Limits the formation of aggregated flexibility pools and hampers economies of scale.
Scalability of data pipelines	Billions of sensor readings per day strain centralized cloud architectures.	Leads to bandwidth bottlenecks, higher latency, and increased operational costs.
Privacy and data sovereignty	Energy consumption patterns are highly sensitive, especially for residential prosumers.	Calls for privacy-preserving analytics and compliance with GDPR-like regulations.

These challenges are echoed throughout the publication, for instance in **Section 2** (Background and Related Work) which surveys existing smart-grid IoT solutions and highlights their inability to jointly address variability, resilience, and market openness.

1.3 Vision: A Federated Edge-Cloud Continuum

The HEDGE-IoT framework proposes a **federated edge-cloud continuum** that unifies the disparate layers of the energy ecosystem:

1. **Edge-first data acquisition and preprocessing** - Sensors and micro-controllers perform local filtering, anomaly detection, and feature extraction, reducing raw data volume before transmission.

2. **Dynamic off-loading to the cloud** - Computationally intensive AI/ML workloads (e.g., deep load-forecasting models) are elastically migrated to cloud resources when latency constraints permit, while latency-critical control loops remain at the edge.

3. **Federated learning across stakeholders** - Model updates are shared in a privacy-preserving manner, enabling collective intelligence without exposing raw consumption data.

4. **Marketplace-enabled orchestration** - An open market layer (see **Section 7**) brokers compute, storage, and flexibility services among prosumers, aggregators, TSOs/DSOs, and third-party service providers.

By treating edge and cloud as **co-equal participants** in a shared computational fabric, HEDGE-IoT directly tackles the challenges outlined above:

- **RES variability** is mitigated through near-real-time edge analytics that can react within sub-second windows.
- **Grid resilience** is enhanced by distributed fault-diagnosis agents that continue operating even under partial network outages.
- **Market fragmentation** is reduced by a common data-space abstraction (detailed in **Section 5**) that standardises semantics and access rights across actors.

1.4 Contributions of This Paper

The remainder of the publication builds on this introductory foundation:

- **Section 3** details the multi-layered architecture that materialises the edge-cloud continuum.
- **Sections 4-6** elaborate on the three pillars - Technology Facilitation, Interoperability, and Standardisation - that operationalise the vision.
- **Sections 8-10** address AI/ML pipelines, orchestration mechanisms, and security-by-design principles required for trustworthy deployment.
- **Sections 11-13** provide a rigorous evaluation of scalability, pilot implementations, and quantitative results.

Together, these contributions demonstrate how a federated edge-cloud approach can unlock the full potential of IoT assets, delivering a resilient, RES-friendly, and market-open energy system.

2. Background and Related Work

2.1 Smart-grid IoT Landscape

Domain	Typical IoT assets	Communication stack	Primary use-cases	Representative projects / platforms
Transmission	Phasor Measurement Units (PMUs), breaker status sensors	IEC 61850-based IEC 60870-5-104, 5G URLLC	Wide-area monitoring, state estimation	ENTSO-E **Grid-Vision**, EU-H2020 **TWIN-GRID**
Distribution	Smart meters, voltage regulators, DER inverters, EV chargers	DLMS/COSEM, LoRaWAN, PLC, Wi-Fi	Load profiling, demand-response, fault localisation	**OpenADR**, **FIWARE**-based **SmartDSO**
Behind-the-meter	Home energy management systems, IoT thermostats, PV-optimisers	Thread, Zigbee, Matter, BLE	Household load shaping, self-consumption optimisation	**EU-AIOTI** Living Lab, **M-Power** pilot

Key observations (consistent with the **four principal challenges** identified in Section 1):

1. **Heterogeneity** - devices span multiple protocols and data models, impeding seamless aggregation.

2. **Latency sensitivity** - real-time protection and voltage control require sub-100 ms response, which many cloud-centric pipelines cannot guarantee.

3. **Data-volume explosion** - high-frequency PMU streams (up to 30 Hz) and smart-meter granularity (15 min-1 s) generate petabytes per year, stressing centralized storage.

4. **Privacy & sovereignty** - residential consumption data are subject to GDPR and national data-space regulations, limiting raw data export to cloud providers.

These trends motivate a shift from monolithic cloud analytics toward **edge-first** processing, a premise that underpins the HEDGE-IoT continuum.

2.2 Edge-Centric AI/ML for Energy Applications

Edge AI/ML technique	Typical workload	Latency / Compute profile	Notable implementations
TinyML inference (e.g., quantised CNNs)	Fault detection on inverter data	10 ms, < 1 W	**TensorFlow-Lite for Microcontrollers** on ARM Cortex-M4
On-device reinforcement learning	Adaptive voltage-regulation set-points	50 ms, moderate RAM	**Edge-RL** prototype for voltage-droop control
Streaming analytics (e.g., Apache Flink-Stateful Functions)	Real-time load forecasting at sub-station	10-100 ms, multi-core edge server	**Flink-Edge** in the **SmartGrid-Edge** testbed
Graph Neural Networks (GNNs)	Topology-aware stability assessment	100-200 ms, GPU-enabled edge	**PyG-Edge** demo on NVIDIA Jetson AGX

State-of-the-art research (e.g., *M. Ghasemi et al., 2023*; *EU-H2020 "Edge-Power"*) demonstrates that moving inference to the edge reduces round-trip latency by 60-80 % and cuts upstream bandwidth by up to 90 %. However, most works treat the edge as a **static compute silo**; dynamic off-loading to the cloud, load-balancing across heterogeneous edge nodes, and coordinated model updates are still open problems - issues that the **Technology Facilitator Pillar** (Section 4) explicitly addresses.

2.3 Federated Learning in Power Systems

FL aspect	Current practice in energy domain	Open challenges
Model aggregation	Centralised parameter server (e.g., FedAvg) for load-forecast models across DSOs	Heterogeneous data distributions (non-IID) degrade convergence; communication overhead on low-bandwidth links
Privacy preservation	Differential privacy added post-aggregation	Trade-off between privacy budget ( ) and forecasting accuracy; limited evaluation on real-world grid data
Cross-border collaboration	Bilateral data-sharing agreements (e.g., ENTSO-E "Data Hub")	Legal constraints under GDPR and national data-space rules; lack of a common semantic layer
Edge-cloud orchestration	Ad-hoc scheduling of FL rounds on a single edge gateway	No systematic resource-aware placement; risk of over-loading edge devices during peak grid events

Recent EU projects such as **FLEUR** (2022) and **FL-Grid** (2023) showcase prototype FL for short-term load forecasting, yet they stop short of integrating **federated learning with a marketplace for compute resources**. HEDGE-IoT's **federated learning pipelines** (Section 8) close this gap by coupling FL with the **market layer**, enabling participants to lease edge compute while preserving data sovereignty.

2.4 Data-Space and Semantic Interoperability Initiatives

Data-space concepts (e.g., International Data Spaces, Gaia-X) propose **sovereign data exchange** through standardized contracts, usage policies, and semantic vocabularies. In the energy sector, two complementary strands have emerged:

1. **Energy-specific ontologies** - SAREF-4-Energy, CIM (Common Information Model) extensions, and the **Open Semantic Framework (OSF)** for grid assets.

2. **Marketplace-oriented data-space platforms** - **AIOTI** "IoT-Data-Space" reference architecture, **ENTSO-E** "Data Hub" pilot, and the **EU-Data-Space for Energy** (2024) initiative.

These efforts provide **interoperability building blocks** (semantic models, policy enforcement) but often remain **isolated**: a data-space for DERs does not automatically interoperate with a TSO-level data-hub, and the **orchestration of compute resources** across the space is not covered. Section 5 (Interoperability Pillar) builds on these standards, extending them with **edge-aware service descriptors** and **dynamic policy negotiation** required for the HEDGE-IoT continuum.

2.5 European Policy and Standardisation Landscape

Initiative / Body	Scope	Relevant Deliverables	Alignment with HEDGE-IoT
AIOTI (Alliance for IoT Innovation)	EU-wide IoT ecosystem, reference architecture	AIOTI RI 2022, "IoT-Data-Space" guidelines	Provides the **semantic and governance framework** adopted in the Interoperability Pillar.
ENTSO-E	Transmission system operators, cross-border coordination	**Data Hub** (2021), **Grid-Vision** roadmap	Supplies the **high-level grid data models** (CIM) that HEDGE-IoT maps to SAREF for edge consumption.
European Commission - Digital Europe Programme	Funding for digital infrastructure, AI, and data spaces	**Data Spaces for Energy** (2023-2026)	Offers **financial and regulatory support** for the marketplace layer and federated learning pilots.
CEN-CENELEC - IEC 61850, IEC 62351	Communication and security standards for substations	IEC 61850-7-4 (data models), IEC 62351-3 (security)	HEDGE-IoT's **edge-cloud gateway** implements these protocols to ensure backward compatibility.
ISO/IEC 20546 (Big Data) & ISO 26262 (Functional Safety)	General data-management and safety requirements	Guidelines for data quality, risk assessment	Influence the **security-by-design** and **trust management** mechanisms described in Section 10.

While these initiatives collectively cover **standards, data-sovereignty, and market mechanisms**, none provide a **holistic, layered architecture** that simultaneously addresses **real-time edge analytics, federated learning, and a compute marketplace**. This lacuna is the primary motivation for the HEDGE-IoT framework.

2.6 Identified Gaps and Motivation for HEDGE-IoT

1. **Fragmented edge-cloud integration** - Existing solutions either keep analytics at the edge (tinyML) or push everything to the cloud; **dynamic, policy-driven off-loading** across a continuum is missing.

2. **Limited federated learning orchestration** - Current FL pilots lack **resource-aware scheduling**, **incentive mechanisms**, and **semantic alignment** with grid data models.

3. **Absence of a unified data-space for compute services** - Data-space initiatives focus on **data exchange**, not on **compute brokerage** (e.g., renting edge GPU cycles for model training).

4. **Scalability under regulatory constraints** - GDPR-compliant pipelines exist, but they do not scale to **continental-wide deployments** where multiple TSOs, DSOs, and prosumers must interoperate.

5. **Standard-gap for edge-centric market participation** - IEC 61850 and SAREF describe *what* data are exchanged, but not *how* edge resources are discovered, priced, and contracted.

HEDGE-IoT is expressly designed to fill these gaps:

- The **multi-layered architecture** (Section 3) introduces a **market layer** that treats edge compute as a tradable commodity, extending the data-space concept.

- The **Technology Facilitator Pillar** (Section 4) implements **adaptive off-loading** and **swarm-computing** mechanisms that respect latency constraints highlighted in Section 1.

- The **Interoperability Pillar** (Section 5) harmonises SAREF, CIM, and AIOTI semantic models, enabling **cross-domain federation** of both data and compute.

- The **Standardisation Pillar** (Section 6) aligns the framework with IEC 61850, OpenADR, and emerging EU IoT standards, ensuring regulatory compliance and facilitating large-scale roll-out.

By systematically addressing the shortcomings identified above, HEDGE-IoT positions itself as the **first end-to-end, federated edge-cloud continuum** tailored for the evolving European energy ecosystem.

3. Overall Architecture of the HEDGE-IoT Framework

3.1 Multi-Layered Structural Overview

The HEDGE-IoT framework is organized as a **four-tier continuum** that mirrors the physical and logical strata of modern energy systems:

Layer	Primary Actors & Assets	Core Functions	Typical Deployment
Device Layer	Smart meters, PMUs, DER inverters, behind-the-meter sensors, EV chargers	Sensing, actuation, local preprocessing (e.g., TinyML inference)	Embedded firmware, micro-controllers, PLCs
Edge Layer	Edge gateways, micro-data-centers, sub-station compute nodes, mobile edge (e.g., 5G MEC)	Real-time analytics, control loops, policy enforcement, federated-learning (FL) client side	Distributed across distribution network, near-real-time latency (< 10 ms)
Cloud Layer	Centralised data-labs, high-performance clusters, AI-service platforms	Global model training, long-term storage, cross-border market clearing, advanced optimisation	Public-cloud, sovereign-cloud, or TSO-owned data-centres
Market Layer	Flexibility service aggregators, prosumer platforms, compute-service brokers, regulatory registries	Service discovery, pricing, SLA negotiation, compute-resource brokerage, data-space contracts	Federated marketplace (digital twin of the energy market)

This hierarchy directly addresses the **four principal challenges** identified in *Section 1 - Introduction* (renewable variability, grid resilience, market fragmentation, scalability & privacy) by **localising latency-critical tasks** at the Device/Edge tiers while **leveraging the Cloud for heavy-weight analytics and cross-border coordination**.

3.2 Device Layer - Sensing and First-Stage Conditioning

1. **Heterogeneous Protocol Support** - The layer embraces IEC 61850, OpenADR, MQTT, and emerging SAREF-based semantic models (see *Section 6 - Standardisation Pillar*).

2. **Edge-First Pre-Processing** - TinyML classifiers run on-device to filter out noise, detect faults, and generate **event-driven telemetry**. This reduces upstream bandwidth by up to 90 % (as highlighted in *Section 2 - Background and Related Work*).

3. **Secure Identity & Consent** - Each device embeds a cryptographic identity (X.509) and a consent flag that the Market Layer can query for GDPR-compliant data-sharing (see *Section 10 - Security, Ethics, and Trust Management*).

3.3 Edge Layer - Distributed Intelligence Hub

The Edge Layer is the **computational glue** that binds the Device and Cloud tiers:

- **Real-Time Control Loop** - Sub-second latency control (e.g., voltage regulation, demand-response actuation) is executed locally, satisfying the **ultra-low-latency** requirement for renewable variability.

- **Federated-Learning Client** - Edge nodes host FL participants that train local model updates on private data, then forward encrypted gradients to the Cloud (see *Section 8 - AI/ML and Federated Learning at the Edge*).

- **Swarm-Computing & Off-Loading** - When a node detects resource saturation, it can **dynamically off-load** workloads to neighbouring edge nodes or the Cloud via the **Computational Orchestration Engine** (described in 3.6). This fulfills the "dynamic, policy-driven edge-cloud off-loading" gap identified in *Section 2*.

3.4 Cloud Layer - Global Analytics and Market Coordination

The Cloud tier provides **elastic compute** and **global visibility**:

- **Central Model Aggregation** - FL server aggregates encrypted updates, retrains global models (e.g., load-forecasting, fault-prediction) and redistributes them to the Edge.

- **Cross-Border Market Clearing** - Leveraging the **Data-Space** semantics (see *Section 5 - Interoperability Pillar*), the Cloud hosts a **compute-service marketplace** where participants can publish/consume compute capacity, thereby addressing the market fragmentation challenge.

- **Long-Term Storage & Auditing** - Immutable logs of transactions, model versions, and policy decisions are stored in a GDPR-compliant ledger, enabling traceability for regulators.

3.5 Market Layer - Compute-Service Brokerage and Incentive Alignment

The Market Layer extends traditional energy-market concepts to **compute resources**:

- **Marketplace Catalog** - Edge and Cloud providers publish **resource descriptors** (CPU, GPU, memory, latency guarantees) conforming to the **SAREF-4-IoT** profile (see *Section 6*).

- **Dynamic Pricing Engine** - Prices are adjusted in real time based on demand, renewable forecast, and network congestion, creating an **incentive-aware FL orchestration** (gap #2 from *Section 2*).

- **Contractual Data-Space Agreements** - Semantic contracts define data-sovereignty rules, usage limits, and revenue sharing, ensuring compliance with EU data-space initiatives (AIOTI, Gaia-X).

3.6 Computational Orchestration Engine (COE) - The Continuum Binder

At the heart of the architecture lies the **Computational Orchestration Engine**, a **policy-driven, AI-enhanced scheduler** that continuously evaluates where a workload should execute:

Decision Dimension	Edge-Side Metric	Cloud-Side Metric	Market Influence
Latency	Real-time queue depth, network RTT	Average processing time, network bandwidth	SLA price signals
Resource Availability	CPU/GPU utilisation, battery state (for mobile edge)	Elastic pool capacity, spot-instance pricing	Market-driven bidding
Data-Sovereignty	Local data residency flag	Cross-border data-transfer policies	Regulatory compliance cost
Energy Efficiency	Local renewable generation forecast	Cloud-side PUE (Power Usage Effectiveness)	Carbon-credit pricing

The COE operates in three **feedback loops**:

1. **Discovery Loop** - Continuously harvests resource advertisements from Edge nodes and Cloud providers via the Market Layer's API.

2. **Placement Loop** - Runs a **multi-objective optimisation** (Pareto front of latency, cost, and carbon) to decide placement; the result is a **deployment manifest** pushed to the target node.

3. **Adaptation Loop** - Monitors runtime KPIs (e.g., QoS violations, energy price spikes) and triggers **re-orchestration** (migration, scaling, or fallback to local control).

By integrating **policy engines** (e.g., OPA - Open Policy Agent) with **reinforcement-learning** based workload predictors, the COE ensures that the edge-cloud continuum behaves as a **single logical compute fabric**, fulfilling the vision of a "federated edge-cloud continuum" introduced in *Section 1*.

3.7 End-to-End Data Flow

1. **Sensing** - Devices generate raw measurements → lightweight on-device inference → event packets.

2. **Edge Ingestion** - Edge gateway aggregates, enriches with context (e.g., topology, local forecasts), and forwards to the **COE**.

3. **Orchestration Decision** - COE evaluates policies, selects execution venue (edge, neighbouring edge, or cloud).

4. **Compute Execution** - Selected node runs the workload (e.g., FL client update, fault detection).

5. **Result Propagation** - Outcomes (control commands, model updates) are pushed back to devices; aggregated results are stored in the Cloud for historical analytics and market settlement.

6. **Marketplace Settlement** - Compute usage is recorded, priced, and settled through the Market Layer's ledger, closing the economic loop.

This pipeline guarantees **low-latency responsiveness** for critical grid operations while **maximising resource utilisation** and **preserving data sovereignty**, thereby delivering a coherent, scalable, and market-driven IoT fabric for the energy sector.

4. Technology Facilitator Pillar

4.1 Computational-Sharing Model

The HEDGE-IoT framework adopts a **continuum-wide resource pooling** concept that treats edge, fog, and cloud compute as a single elastic pool (see the **four-tier continuum** described in Section 3). The model is built on three orthogonal dimensions:

Dimension	What is shared	How it is advertised	Governance
CPU / GPU cycles	Real-time control kernels, inference services, FL client updates	Standardised SAREF-4-IoT descriptors published in the **compute-service marketplace** (Section 3)	Policy-driven quotas, carbon-aware pricing, GDPR-compliant data-sovereignty tags
Memory & storage	Time-series buffers, model checkpoints, intermediate feature maps	Capability advertisements include latency class (e.g., <5 ms for protection-grade loops) and persistence guarantees	Lease contracts enforce eviction policies and audit logs stored in the immutable Cloud layer
Network bandwidth	Streamed sensor feeds, model deltas, swarm-message gossip	Edge nodes expose *bandwidth-budget* tokens that are consumed by off-loading requests	Dynamic throttling based on grid-state (e.g., high-wind periods) to avoid congestion

The **Computational Orchestration Engine (COE)** introduced in Section 3 continuously reconciles these dimensions against a multi-objective optimisation function that balances latency, cost, carbon intensity, and data-sovereignty constraints. The result is a **resource-aware placement matrix** that can be updated at sub-second intervals, enabling the edge to act both as a consumer and a provider of compute.

4.2 Off-loading Strategies

Off-loading in HEDGE-IoT is **policy-driven and context-aware**, directly addressing the "dynamic, policy-driven edge-cloud off-loading" gap identified in Section 2. Four complementary strategies are defined:

1. **Latency-First Off-load** - Critical protection-grade functions (e.g., fault isolation, voltage-ride-through) are kept on-site; only non-time-critical pre-processing (e.g., feature extraction) is off-loaded to a *neighboring edge* with a lower latency budget.

2. **Cost-Optimised Off-load** - When market prices for compute drop (as signalled by the marketplace), batch-oriented workloads such as periodic model aggregation are migrated to the Cloud layer to exploit economies of scale.

3. **Carbon-Aware Off-load** - The COE incorporates real-time carbon intensity signals from the energy market; workloads are shifted to edge sites powered by renewable generation whenever possible, reducing the overall carbon footprint of AI inference.

4. **Data-Sovereignty Off-load** - For data subject to national GDPR constraints, the COE enforces *data-locality* policies, ensuring that any processing that could expose raw measurements remains within the jurisdiction-bound edge cluster.

Each strategy is expressed as a **rule-set** in the COE's policy engine, allowing operators to prioritize any combination of latency, cost, carbon, or legal constraints. The engine also supports *fallback* paths: if a preferred edge node becomes unavailable (e.g., due to a fault), the workload is automatically re-routed to the next best candidate, preserving grid resilience (see the resilience discussion in Section 1).

4.3 AI/ML Federated-Learning Pipelines

Federated Learning (FL) is the cornerstone for **collective intelligence without raw data movement** (Section 3). The pipeline is split into three logical stages, each mapped to a specific layer of the continuum:

Stage	Execution Layer	Core Activities	Key Enablers
Local Training	**Edge Layer** (tiny-ML containers)	On-device gradient computation on streaming sensor windows; differential privacy noise injection	TinyML runtimes, secure enclaves, SAREF-4-IoT model metadata
Secure Aggregation	**Hybrid Edge-Cloud** (peer-to-peer gossip + Cloud aggregator)	Encrypted model delta exchange using additive homomorphic encryption; Byzantine-resilient consensus	Swarm-computing gossip protocol (see 4.4) and Cloud-based aggregation service
Global Model Update	**Cloud Layer**	Weighted averaging, hyper-parameter tuning, versioning; publishing new model artefacts to the marketplace	Immutable audit logs, model-registry APIs, policy-driven version rollout

Incentive-aware FL orchestration (a gap highlighted in Section 2) is realised through the marketplace: edge nodes earn *compute-credits* proportional to the amount of useful gradient contribution (measured by a contribution-score derived from Shapley value approximations). Credits are settled in real-time against the operator's flexibility market participation, creating a virtuous loop where better models enable more accurate demand-response actions, which in turn generate additional credits.

The pipeline also supports **heterogeneous model architectures** (e.g., GNNs for topology-aware load forecasting, CNN-RNN hybrids for fault detection) by allowing each edge node to submit *model-compatible* updates defined in a shared ONNX schema. This flexibility is essential for the diverse asset portfolio described in Section 1 (PMUs, smart meters, behind-the-meter DERs).

4.4 Swarm-Computing Mechanisms

Swarm computing extends the edge's capability from isolated nodes to **self-organising collectives** that can jointly execute complex analytics (e.g., distributed state estimation) while preserving locality. The mechanism builds on three primitives:

1. **Gossip-Based Discovery** - Edge nodes broadcast *resource beacons* containing compute capacity, latency class, and data-sovereignty tags. Beacons are aggregated using a lightweight epidemic protocol, forming a **dynamic neighbourhood graph** that the COE consumes for placement decisions.

2. **Task Fragmentation & Replication** - Large workloads (e.g., Monte-Carlo contingency analysis) are split into *micro-tasks* that can be executed in parallel across the swarm. Redundant execution is employed for fault tolerance; results are merged using a majority-vote reducer.

3. **Consensus-Driven State Sharing** - Critical grid state (e.g., frequency deviation) is maintained via a **Byzantine Fault-Tolerant (BFT) ledger** replicated across the swarm. This ledger provides a tamper-evident source of truth for control loops that must survive partial network partitions.

Swarm computing directly supports the **grid-resilience** objective from Section 1 by enabling *distributed fault detection* and *rapid re-configuration* without relying on a central cloud orchestrator. Moreover, the swarm's **energy-aware scheduling** (nodes powered by local PV prioritize compute) aligns with the carbon-aware off-loading strategy described in 4.2.

4.5 Policy & Incentive Engine

The **Policy & Incentive Engine (PIE)** sits atop the COE and translates high-level stakeholder objectives (e.g., "minimise latency for protection-grade services", "maximise revenue from compute sharing") into concrete placement and pricing rules. Its main components are:

- **Policy Repository** - Stores declarative policies expressed in a domain-specific language (DSL) that references the four optimisation dimensions (latency, cost, carbon, sovereignty). Policies can be scoped per *actor* (TSO, DSO, prosumer) and per *service* (load forecasting, demand-response).

- **Incentive Calculator** - Computes real-time credits for edge participants based on contribution metrics (FL gradient quality, swarm task completion, bandwidth saved). Credits are settled through the marketplace's tokenised ledger, ensuring transparency and auditability.

- **Compliance Monitor** - Continuously checks that active placements respect regulatory constraints (e.g., GDPR-locality) and triggers remedial re-placement when violations are detected.

By integrating PIE with the **compute-service marketplace** (Section 3), HEDGE-IoT creates a closed loop where *technical performance* (latency, accuracy) and *economic incentives* co-evolve, thereby fulfilling the "market-driven IoT fabric" vision introduced in the Introduction.

4.6 Summary of the Technology Facilitator Pillar

The Technology Facilitator Pillar operationalises the HEDGE-IoT vision through:

- A **computational-sharing model** that abstracts edge, fog, and cloud resources into a unified pool, advertised via standardised descriptors.

- **Policy-driven off-loading strategies** that dynamically balance latency, cost, carbon impact, and data-sovereignty.
- **Federated-learning pipelines** that enable privacy-preserving collective model training while rewarding contributors through a compute-service marketplace.
- **Swarm-computing mechanisms** that provide resilient, distributed analytics and control at the grid edge.
- An overarching **Policy & Incentive Engine** that aligns technical decisions with market incentives and regulatory compliance.

Together, these mechanisms create the *intelligent processing substrate* required for ultra-low-latency grid services, scalable AI/ML, and a thriving compute marketplace - core enablers for the resilient, RES-friendly energy ecosystem described throughout the paper.

5. Interoperability Pillar

5.1 Data-Space Foundations for Energy-IoT

The Interoperability Pillar builds on the **Data-Space** paradigm introduced in the EU-wide AIOTI and Gaia-X initiatives (see *Section 2 - Background and Related Work*). A Data-Space is a federation of sovereign data-nodes that exchange information under mutually agreed usage policies, supported by machine-readable contracts (e.g., IDS-Core). In HEDGE-IoT the Data-Space is instantiated as a **Energy-Data-Space (EDS)** that spans:

Actor	Role in the EDS	Typical Assets
TSOs/DSOs	Data-space operator, policy arbiter	PMUs, SCADA, grid-state archives
Prosumers & SMEs	Data providers & consumers	Smart meters, PV inverters, EV chargers
Edge-cloud operators	Compute-service brokers	Edge nodes, fog clusters, public clouds
Marketplace	Service-level agreement (SLA) registry & pricing engine	Compute-service marketplace (see *Section 3 - Overall Architecture*)

Each node publishes a **self-describing connector** that advertises its data assets, access constraints, and provenance metadata. The connector conforms to the IDS-Information Model, enabling automated discovery and policy-driven negotiation without manual configuration. This approach directly addresses the market-fragmentation challenge highlighted in the *Introduction* by providing a **single logical view** over heterogeneous physical assets.

5.2 Semantic Interoperability Layer

Heterogeneity in the energy IoT domain is two-fold: (i) diverse communication protocols (IEC 61850, OpenADR, MQTT, CoAP) and (ii) divergent data models (device-specific telemetry vs. market-grade time series). To achieve **semantic interoperability**, HEDGE-IoT adopts a layered ontology stack:

1. **Core Energy Ontology (CEO)** - derived from IEC 61850-SCL and the SAREF-4-IoT extension (see *Section 6 - Standardisation Pillar*). CEO defines generic concepts such as *Measurement*, *Asset*, *ControlCommand*, and *FlexibilityProduct*.

2. **Domain-Specific Extensions** - e.g., *RenewableGeneration*, *DemandResponse*, *GridStability*. These extensions are published in the EDS registry and can be versioned independently.

3. **Mapping Profiles** - lightweight JSON-LD contexts that map vendor-specific payloads (e.g., a proprietary "Watt-Reading" field) to CEO concepts. Mapping profiles are stored as reusable artefacts in the marketplace, allowing any edge node to **auto-translate** incoming streams into the common semantic model.

The semantic layer is enforced at the **Edge API Gateway** (see *Section 3*), which validates incoming messages against the relevant JSON-LD context and enriches them with provenance tags (timestamp, source-ID, consent flag). This guarantees that downstream services - whether local control loops, federated-learning clients (*Section 4*), or market-clearing engines - operate on a **uniform, machine-interpretable data set**.

5.3 Open API Stack

Interoperability is realized in practice through a **REST-ful + gRPC** API suite that is openly documented in an OpenAPI 3.0 specification. The stack comprises three logical families:

API Family	Primary Function	Example Endpoints
Data-Ingestion API	Push telemetry from devices to the edge layer	`POST /ingest/{assetId}` (JSON-LD payload)
Data-Discovery & Catalog API	Query available data assets, contracts, and semantic profiles	`GET /catalog/assets?type=Measurement`
Compute-Service Marketplace API	Publish/consume compute offers, retrieve pricing, negotiate SLA	`POST /marketplace/offers`, `GET /marketplace/quotes`

All APIs are **policy-aware**: each request carries a signed JWT that encodes the caller's identity, consent scope, and data-usage rights. The edge-side **Policy Enforcement Point (PEP)** validates the token against the contract stored in the Data-Space, rejecting any operation that violates the data-sovereignty constraints defined in *Section 1* (e.g., GDPR-compliant consent handling).

The open nature of the API stack enables **plug-and-play integration** of third-party platforms (e.g., commercial DER management systems) and encourages ecosystem growth without requiring bespoke adapters.

5.4 Governance, Trust, and Auditing

A robust governance model is essential to sustain the federated data-exchange fabric. HEDGE-IoT adopts the **Data-Space Governance Framework** (DSP-GOV) comprising:

1. **Contract Registry** - immutable ledger (based on a permissioned Hyperledger Fabric network) that records all data-usage contracts, pricing terms, and revocation events.

2. **Dynamic Trust Scores** - each participant receives a trust rating derived from historical compliance (e.g., timely SLA fulfillment, correct provenance tagging). Trust scores are exposed via the **Trust-API** (`GET /trust/{actorId}`) and feed into the **Policy-Driven Off-loading Engine** (see *Section 4*), biasing placement decisions toward high-trust edge nodes.

3. **Audit Trail Service** - every data exchange is logged with cryptographic hashes, enabling post-hoc verification by regulators or auditors. The service integrates with the **Computational Orchestration Engine** to provide real-time compliance dashboards for market operators.

These mechanisms ensure that the **semantic and technical interoperability** does not compromise data sovereignty, aligning with the privacy-by-design principles highlighted in the *Introduction*.

5.5 Alignment with the Technology Facilitator and Standardisation Pillars

The Interoperability Pillar is tightly coupled with the other two pillars:

- **Technology Facilitator (Section 4)** - The **Semantic Mapping Engine** and **Open API Gateway** are the concrete artefacts that expose the unified computational-sharing model to heterogeneous devices. By translating device-level telemetry into the common CEO ontology, the facilitator can safely off-load workloads to any edge or cloud node that advertises compliance with the same semantic contract.
- **Standardisation (Section 6)** - All semantic artefacts (CEO, extensions, JSON-LD contexts) are derived from **SAREF-4-IoT**, **IEC 61850**, and **OpenADR** specifications. The open API definitions are published under an **OpenAPI-compatible license**, encouraging reuse and alignment with emerging EU IoT standards. This ensures that any future amendment to the underlying standards can be propagated automatically through the **Versioned Ontology Registry** without breaking existing integrations.

5.6 Summary

By **embedding Data-Space concepts**, enforcing a **semantic interoperability layer**, and exposing a **standardised open API stack**, the Interoperability Pillar guarantees that every IoT asset - regardless of vendor, protocol, or location - can participate in the HEDGE-IoT continuum. The combination of policy-driven contracts, trust-enhanced orchestration, and alignment with EU standards creates a **trustworthy, market-open data fabric** that underpins the resilient, RES-friendly energy ecosystem envisioned throughout the paper.

6. Standardisation Pillar

6.1 Alignment with Established Energy-IoT Standards

The **Standardisation Pillar** builds directly on the semantic foundations introduced in the *Interoperability Pillar* (Section 5). By re-using the **Core Energy Ontology (CEO)** - a layered ontology that extends **SAREF-14-IoT** with IEC 61850-based concepts - the HEDGE-IoT framework guarantees that every device, edge node, and cloud service can be described with a single, machine-readable vocabulary.

Standard	Role in HEDGE-IoT	Mapping in the CEO
SAREF-14-IoT	Provides the base class hierarchy for sensors, actuators, and computational resources.	Directly imported as the "Device" and "ComputeResource" packages of the CEO.
IEC 61850 / IEC 62351	Supplies the communication model for substation automation and the security profile for grid-level data exchange.	IEC 61850 data objects (e.g., *Logical Nodes*, *Data Sets*) are represented as extensions of the CEO's *GridComponent* class; IEC 62351 security attributes are attached as ontology annotations.
OpenADR 2.0b	Enables automated demand-response (DR) signalling between TSOs/DSOs and flexible resources.	OpenADR *Event* and *Report* messages are mapped to the CEO's *DemandResponse* extension, allowing DR services to be advertised in the compute-service marketplace.
AIOTI Reference Architecture	Defines the high-level functional blocks (e.g., *Connectivity*, *Data Management*, *Service Enablement*).	The four-tier continuum (Device → Edge → Cloud → Market) mirrors the AIOTI layers, and each functional block is instantiated as a reusable component in the HEDGE-IoT service catalogue.

By anchoring all resource descriptors, data-exchange contracts, and marketplace listings to these standards, HEDGE-IoT ensures **semantic interoperability** across heterogeneous vendors while preserving the **regulatory compliance** required by the EU's Digital Europe Programme.

6.2 Integration of Emerging EU IoT Standardisation Initiatives

The EU is actively developing a suite of IoT-specific standards under the **European Interoperability Framework (EIF)** and the **European Standardisation Organisations (CEN/CENELEC/ETSI)**. HEDGE-IoT adopts a **future-proof extension strategy** that allows new specifications to be incorporated without disrupting existing deployments:

1. **EU-IoT-SFA (Smart Functionality Architecture)** - Provides a common model for *function-as-a-service* (FaaS) in energy systems.
   HEDGE-IoT registers each edge-hosted AI/ML micro-service as an SFA-compliant function, exposing its input/output contracts through the marketplace API.
2. **EN 303 645 (Security for Consumer IoT)** - Defines baseline security requirements (secure boot, firmware updates, vulnerability disclosure).
   The **Policy & Incentive Engine (PIE)** (Section 4) enforces EN 303 645 compliance as a placement constraint; non-conforming nodes are automatically excluded from critical control loops.
3. **ISO/IEC 30141 (IoT Reference Architecture)** - Aligns with the AIOTI reference model but adds a detailed *security* and *privacy* viewpoint.
   HEDGE-IoT maps the ISO/IEC 30141 *Security* and *Privacy* viewpoints to the **trust-score** mechanism described in Section 5, ensuring that trust calculations are grounded in an internationally recognised framework.

These emerging standards are version-controlled in the **Standardisation Registry** (see 6.4) and are referenced in the **OpenAPI 3.0** specifications of the marketplace, guaranteeing that any new normative document can be consumed by existing clients without code changes.

6.3 Governance Model for Ecosystem-Wide Conformance

A **multi-stakeholder governance body** - the *HEDGE-IoT Standardisation Council (HISC)* - is established to steward conformance, evolve the ontology, and manage certification. The council comprises representatives from:

- **TSOs/DSOs** (national grid operators) - ensure grid-level reliability and regulatory alignment.
- **Edge-Cloud Service Providers** - contribute compute-resource descriptors and performance benchmarks.

- **Device Manufacturers** - supply SAREF-based device models and IEC 61850 mappings.
- **Regulators & Data-Space Authorities** - oversee GDPR, data-sovereignty, and market-fairness aspects.
- **Academic & Research Institutions** - provide independent validation of standard updates and emerging AI/ML techniques.

The governance process follows a **four-phase lifecycle**:

Phase	Activities	Deliverables
1. Proposal	Stakeholders submit a *Standardisation Change Request (SCR)* with technical rationale and impact analysis.	SCR document (publicly archived).
2. Review	HISC technical working groups evaluate semantic compatibility, security implications, and backward-compatibility.	Review report, optional *Request for Comments (RFC).*
3. Ratification	Formal voting (2/3 majority) and legal endorsement by the EU Digital Services Board.	*Standardisation Amendment* (versioned).
4. Publication & Certification	Updated ontology, API schemas, and conformance test suites are released; certified compliance badges are issued to participants.	Updated **Standardisation Registry**, certification badge (e.g., "SAREF-14-IoT-Compliant").

All decisions, voting records, and amendment histories are stored on a **permissioned ledger** (aligned with the trust-score mechanism of Section 5), guaranteeing transparency and auditability for regulators and market participants.

6.4 Conformance Management and Continuous Compliance

To operationalise the governance outcomes, HEDGE-IoT implements an **automated conformance pipeline** that runs continuously in the Cloud Layer:

1. **Schema Validation** - Every new resource descriptor (device, edge node, compute service) is validated against the latest **JSON-LD** schema derived from the CEO. Non-conforming submissions are rejected with detailed error reports.
2. **Security Profile Checks** - Using the **EN 303 645** rule set, the pipeline scans firmware images, container manifests, and runtime configurations for mandatory security controls (e.g., signed updates, secure boot).
3. **Trust-Score Re-calculation** - After each successful validation, the node's trust score is updated; the score feeds directly into the **Computational Orchestration Engine (COE)** (Section 4) to influence placement decisions.
4. **Periodic Audits** - A scheduled audit (quarterly) re-executes the validation suite against the *deployed* artefacts, detecting drift or deprecated standards. Findings are automatically logged in the **Immutable Contract Registry** (Section 5) and trigger remediation workflows.
5. **Marketplace Certification Badge Service** - Certified entities expose a `/certification` endpoint that returns a signed badge (JWT) indicating the exact standard versions they comply with. Consumers (e.g., DR aggregators) can query this badge before invoking services, ensuring end-to-end compliance.

Through this pipeline, conformance becomes a **runtime property** rather than a one-off certification, aligning with the dynamic, policy-driven nature of the HEDGE-IoT continuum.

6.5 Benefits of the Standardisation Pillar

- **Inter-operability at Scale** - Uniform SAREF-14-IoT and IEC 61850 semantics enable plug-and-play integration of millions of heterogeneous devices without bespoke adapters.
- **Regulatory Alignment** - Embedding EN 303 645 and GDPR-derived consent models ensures that the framework can be deployed across EU Member States with minimal legal friction.
- **Marketplace Trust** - Certified resource descriptors and immutable trust scores foster confidence among prosumers, aggregators, and cloud providers, reducing transaction costs and accelerating market adoption.

- **Future-Proofing** - The modular governance process allows rapid incorporation of emerging EU IoT standards, guaranteeing that HEDGE-IoT remains compatible with the evolving Digital Europe ecosystem.

In sum, the Standardisation Pillar provides the **normative glue** that binds the technology facilitator (Section 4) and interoperability (Section 5) pillars into a coherent, standards-compliant, and governable digital energy ecosystem.

7. Digital Energy Ecosystem Enabling Pillar

7.1 Resilient, RES-Friendly Energy Ecosystem

The HEDGE-IoT continuum (Section 3) binds **Device → Edge → Cloud → Market** layers into a single, self-optimising fabric. By keeping latency-critical control loops on the Edge (tinyML filtering, real-time voltage regulation) and delegating only non-critical analytics to the Cloud, the framework satisfies the **renewable variability** challenge identified in the Introduction.

- **Ultra-low latency** - Edge-resident controllers react to frequency or voltage excursions within 10 ms, a latency budget unattainable with pure cloud processing.

- **Distributed fault detection** - Swarm-computing mechanisms (Section 4) enable peer-to-peer health monitoring of DER inverters and PMUs; when a node fails, neighbouring edge agents automatically assume its control responsibilities, preserving grid stability.

- **Carbon-aware placement** - The Policy-Driven Off-loading Strategies (Section 4) include a *Carbon-Aware* policy that preferentially schedules compute on renewable-powered edge sites, reducing the overall carbon footprint of the control infrastructure.

Together, these capabilities create a **RES-friendly ecosystem** where high-penetration solar and wind can be accommodated without compromising reliability.

7.2 New Flexibility Services Enabled by the Continuum

The compute-service marketplace (Section 3) publishes standardized resource descriptors (SAREF-14-IoT) that can be consumed by flexibility-as-a-service (FaaS) applications. This opens three novel service categories:

Flexibility Service	Edge Role	Cloud Role	Market Impact
Real-time Demand-Response (DR)	Local load curtailment via OpenADR-compatible edge agents (Section 5)	Aggregated DR signal optimisation and settlement	Enables sub-second DR participation for residential prosumers
Virtual Power Plant (VPP) Coordination	Peer-to-peer swarm control of clustered DER	Global optimisation of VPP dispatch and market bidding	Provides a scalable, market-ready VPP layer for aggregators
Grid-Edge Frequency Regulation	Fast frequency response from battery-edge controllers	Long-term frequency trend analysis and incentive pricing	Turns otherwise idle storage into a revenue-generating ancillary service

The **Federated-Learning pipelines** (Section 4) continuously improve forecasting models for these services while preserving data privacy, ensuring that flexibility offers remain accurate and trustworthy.

7.3 Fostering Market Participation of Prosumers, Aggregators, and SMEs

The **Digital Marketplace Layer** (Section 3) transforms every edge node into a potential *service provider*:

- **Prosumers** can expose surplus generation or storage capacity as compute or flexibility resources. The **Policy & Incentive Engine (PIE)** (Section 4) translates the quality of their contributions (e.g., forecast accuracy, response time) into real-time credits, creating a direct economic incentive.

- **Aggregators** gain a unified view of distributed assets through the **Energy-Data-Space federation** (Section 5). They can dynamically compose portfolios of edge resources, negotiate contracts, and settle transactions using the marketplace's immutable ledger.

- **SMEs** (e.g., local energy service firms, micro-grid operators) can publish specialised AI/ML micro-services (fault detection, predictive maintenance) as *compute-as-a-service*. The **Standardisation Pillar** (Section 6) guarantees that these services are described with a common ontology, reducing integration effort and accelerating time-to-market.

By aligning technical performance (latency, carbon, data-sovereignty) with **economic rewards** (credits, market prices), the framework lowers entry barriers and encourages a vibrant, competitive ecosystem.

7.4 Synergy with the Three Enabling Pillars

Pillar	Contribution to the Digital Energy Ecosystem	Reference
Technology Facilitator (Section 4)	Provides the elastic computational pool, policy-driven off-loading, and incentive-aware FL that underpin resilient services and market-driven flexibility.	Section 4 - Key Findings
Interoperability (Section 5)	Supplies the semantic backbone (CEO, SAREF-14-IoT) and open APIs that allow heterogeneous devices, edge platforms, and market actors to interoperate seamlessly.	Section 5 - Key Findings
Standardisation (Section 6)	Guarantees that all descriptors, contracts, and security profiles conform to EU-wide standards (SAREF, IEC 61850, OpenADR), fostering trust and regulatory compliance across borders.	Section 6 - Key Findings

The three pillars act in concert: interoperability creates the *language* for exchange, standardisation enforces *trust* and *compliance*, and the technology facilitator supplies the *compute* and *incentive* mechanisms that turn this shared language into a **live, market-driven energy ecosystem**.

7.5 Summary of Ecosystem Benefits

- **Resilience** - Distributed edge intelligence and swarm-based fault tolerance keep the grid stable under high RES penetration.
- **Flexibility** - Real-time, market-priced services (DR, VPP, frequency regulation) become available to all participants, unlocking previously untapped flexibility.
- **Inclusivity** - Prosumers, aggregators, and SMEs can monetize assets and AI services through a transparent, standards-based marketplace.
- **Sustainability** - Carbon-aware orchestration and renewable-powered edge sites reduce the environmental impact of the control infrastructure itself.

These outcomes collectively realise the **RES-friendly, resilient, and market-open digital energy ecosystem** envisioned in the HEDGE-IoT framework.

8. AI/ML and Federated Learning at the Edge

8.1 AI/ML Use Cases at the Edge

The HEDGE-IoT continuum enables three high-impact AI/ML services that directly address the four principal challenges identified in **Section 1 - Introduction** (renewable variability, grid resilience, market fragmentation, scalability & privacy).

Use case	Edge role	Cloud role	Primary benefit	Alignment with HEDGE-IoT pillars
Load forecasting (short-term, 5-15 min horizon)	TinyML models ingest local smart-meter and PV inverter data, perform feature extraction and a first-stage forecast.	Global model aggregation in the Cloud refines parameters using data from thousands of nodes, producing a high-accuracy ensemble forecast.	Reduces forecast RMSE by up to **30 %** (as shown in the pilot of **Section 13**), enabling tighter dispatch of RES and lowering reserve requirements.	*Technology Facilitator* - federated-learning pipeline; *Interoperability* - semantic data descriptors (CEO) for load profiles; *Standardisation* - IEC 61850 measurement objects.
Fault detection & localisation	Edge nodes run streaming anomaly detectors (e.g., GNN-based edge-graph models) on PMU and breaker status streams, generating alerts within **10 ms** (see **Section 7**).	Cloud aggregates alerts to compute system-wide fault trees, validates root-cause hypotheses, and disseminates corrective set-points.	Cuts fault-diagnosis latency by **70 %**, supporting the ultra-low-latency control loops required for grid resilience.	*Technology Facilitator* - swarm-computing for distributed detection; *Interoperability* - IEC 61850/62351 security attributes; *Digital Energy Ecosystem* - market-grade reliability services.
Demand-Response (DR) optimisation	Edge controllers evaluate local flexibility (battery SOC, flexible loads) and generate candidate DR schedules using reinforcement-learning agents.	Cloud-level optimisation coordinates thousands of edge schedules, respecting market constraints and carbon-aware policies (see **Section 4 - Policy-Driven Off-loading Strategies**).	Increases DR participation by **45 %** and reduces peak-load by **12 %**, creating new revenue streams for prosumers (cf. **Section 7**).	*Technology Facilitator* - incentive-aware FL for DR policy learning; *Interoperability* - OpenADR event models; *Standardisation* - OpenADR 2.0b mapping.

These use cases illustrate how **edge-first processing** (Section 3) delivers ultra-low latency and bandwidth savings, while **cloud-assisted global intelligence** improves model accuracy and market-level coordination.

8.2 Federated Learning Workflow Across the Continuum

The federated learning (FL) pipeline described in **Section 4 - Technology Facilitator Pillar** is instantiated for each AI/ML service as follows:

1. **Client Initialization (Edge)**
   - TinyML containers on edge nodes load the latest global model version (e.g., a LSTM for load forecasting).
   - Local data are pre-processed according to the **Core Energy Ontology (CEO)** defined in **Section 5 - Interoperability Pillar**, ensuring uniform feature semantics.
2. **Local Training**
   - Edge devices perform a few epochs of stochastic gradient descent on their private datasets, respecting the **policy-driven off-loading strategies** (Latency-First, Data-Sovereignty) from **Section 4**.
   - Training is sandboxed in a secure enclave; intermediate gradients are encrypted with homomorphic encryption (HE) keys derived from the **Permissioned Ledger** (Section 5).
3. **Secure Aggregation**
   - Gradients are transmitted to a **peer-to-peer gossip layer** that performs a first-level aggregation among neighbouring edge nodes, reducing uplink traffic by up to **90 %** (see **Section 2 - Background**).
   - The partially aggregated result is then forwarded to the **Cloud Aggregation Service** where a **Secure Multi-Party Computation (SMPC)** protocol merges contributions from all participants, guaranteeing that no raw data ever leave the originating edge.

4. **Model Update & Distribution**
   - The global model is versioned and stored in the **Compute-Service Marketplace** (Section 3).
   - Edge nodes subscribe to model update notifications via the marketplace API (Section 5) and pull the new model when policy permits (e.g., respecting data-sovereignty constraints).
5. **Incentive & Credit Allocation**
   - The **Policy & Incentive Engine (PIE)** (Section 4) evaluates the quality of each node's contribution (e.g., gradient norm, validation loss reduction) and issues **credits** that can be traded in the marketplace, linking AI performance to economic rewards (as highlighted in **Section 7**).

This workflow preserves **privacy by design** (no raw data leaves the edge), complies with **GDPR and national data-sovereignty** requirements (Section 1), and continuously improves model accuracy through collective learning.

8.3 Privacy-Preserving Mechanisms

Mechanism	Where it is applied	Benefit
Homomorphic Encryption (HE)	Encrypts local gradients before transmission to the gossip layer.	Enables aggregation on ciphertexts, eliminating the need to decrypt at intermediate nodes.
Secure Multi-Party Computation (SMPC)	Cloud-side aggregation of encrypted gradients.	Guarantees that the global model can be reconstructed only when a quorum of edge participants collaborates, preventing single-point data leakage.
Differential Privacy (DP) Noise Injection	Optional per-client addition of calibrated Laplace noise to gradients.	Provides formal privacy guarantees (-DP) while allowing the COE to balance accuracy vs. privacy based on market-driven policies (Section 4).
Policy-Based Data-Sovereignty Tags	Embedded in the CEO metadata for each dataset (Section 5).	The Computational Orchestration Engine respects jurisdictional constraints during placement, ensuring that data never cross prohibited borders.
Permissioned Ledger Auditing	All model versioning, credit transactions, and consent records are immutably logged.	Enables regulators and market participants to audit compliance without exposing raw measurements.

These mechanisms are orchestrated by the **Computational Orchestration Engine (COE)** (Section 3) which dynamically selects the appropriate privacy stack based on the **Policy & Incentive Engine** rules.

8.4 Integration with Orchestration, Marketplace, and Standards

- **Resource-aware Placement** - The COE (Section 3) evaluates latency, cost, carbon intensity, and data-sovereignty to decide whether a training round runs entirely on-edge, off-loads to a nearby fog node, or leverages cloud elasticity. This aligns with the **multi-objective placement problem** described in **Section 4**.
- **Marketplace Monetisation** - Model updates and inference services are advertised as **compute-as-a-service** assets in the **Compute-Service Marketplace** (Section 3). Consumers (e.g., DSOs requesting DR optimisation) can purchase inference slots, while edge owners receive credits via the **PIE** (Section 4).
- **Standard-Based Interoperability** - All AI/ML payloads conform to the **SAREF-14-IoT** extensions (Section 6) and use **OpenAPI 3.0** specifications (Section 5) for model distribution, ensuring plug-and-play integration across heterogeneous vendors.
- **Feedback Loop to Orchestration** - Performance metrics (forecast error, detection latency, DR participation) are fed back to the COE, which updates its placement policies in near-real-time, closing the loop between AI performance and resource management (see **Section 9 - Orchestration and Computational Management**).

8.5 Summary of Impact

- **Accuracy Gains** - Federated learning reduces load-forecast RMSE by up to **30 %** and improves fault-detection true-positive rates by **15 %** compared with isolated edge models (validated in **Section 13**).

- **Latency & Bandwidth Savings** - Edge-first inference delivers sub-10 ms response times; gossip-based aggregation cuts upstream traffic by **90 %** (Section 2).

- **Privacy & Compliance** - No raw measurements leave the edge; GDPR, data-sovereignty, and sector-specific security standards (IEC 61850/62351) are honoured (Sections 1, 5, 6).

- **Economic Incentives** - Credits for high-quality model contributions create a new revenue stream for prosumers and SMEs, fostering inclusive market participation (Section 7).

Collectively, these AI/ML and federated-learning capabilities realise the **edge-cloud intelligence** envisioned in the HEDGE-IoT framework, delivering a resilient, RES-friendly, and market-open energy system.

9. Orchestration and Computational Management

9.1 Resource Discovery and Contextualisation

The **Computational Orchestration Engine (COE)** introduced in *Section 3 - Overall Architecture of the HEDGE-IoT Framework* continuously discovers compute, storage, and networking capabilities across the four-tier continuum (Device → Edge → Cloud → Market).

- **Active probing** - lightweight heart-beat messages are broadcast over the open gRPC-based APIs defined in *Section 5 - Interoperability Pillar*. Each edge node advertises a **SAREF-14-IoT** descriptor (see *Section 6 - Standardisation Pillar*) that includes: processing class (TinyML, GPU, FPGA), current load, energy source (renewable / grid), jurisdictional tags, and security posture.

- **Passive enrichment** - telemetry from the **Energy-Data-Space (EDS)** federation (Section 5) supplies semantic tags (e.g., "high-voltage substation", "prosumer-home") that the COE uses to enforce data-sovereignty policies defined in the **Policy & Incentive Engine (PIE)** (Section 4).

- **Trust-score integration** - the immutable contract registry on the permission-ed ledger (Section 5) continuously updates a node's trust score; the COE incorporates this score when ranking candidate resources (Section 6).

The result is a **global resource catalogue** that is always up-to-date, privacy-aware, and compliant with GDPR and national data-sovereignty constraints.

9.2 Multi-Objective Workload Placement Engine

Building on the **Unified Computational-Sharing Model** (Section 4), the placement engine solves a **multi-objective optimisation problem** at each scheduling interval:

$$\min \{\alpha \cdot \text{latency} + \beta \cdot \text{cost} + \gamma \cdot \text{carbon} + \delta \cdot (1 - \text{trust})\}$$

- **Latency-First** - guarantees sub-10 ms response for real-time control loops (Section 7).

- **Cost-Optimised** - selects the cheapest compute-as-a-service offer from the marketplace (Section 4).

- **Carbon-Aware** - prefers edge sites powered by renewable energy, as flagged in the SAREF descriptor (Section 6).

- **Data-Sovereignty** - enforces jurisdictional constraints by excluding resources outside the data-owner's legal domain (Section 5).

The optimisation is performed by a **distributed heuristic** (a hybrid of Ant-Colony for latency-critical paths and a Linear-Programming relaxation for cost-driven batches). The heuristic runs on the COE's control plane in the cloud layer, but can be **off-loaded to a high-capacity edge fog node** when cloud connectivity degrades, ensuring resilience (Section 7).

9.3 QoS Guarantees and SLA Enforcement

QoS is expressed through **Service Level Agreements (SLAs)** stored as smart-contract objects on the permissioned ledger (Section 5). Each SLA contains:

Metric	Target	Monitoring Agent
End-to-end latency	10 ms (critical) / 200 ms (batch)	Edge-resident latency probe
Throughput	10 Gbps (aggregated)	Cloud-side telemetry
Availability	99.99 %	Distributed heartbeat
Carbon intensity	50 gCO /kWh (optional)	Energy-source tag

The COE continuously **re-evaluates placement** against these targets. If a violation is imminent (e.g., rising latency on a congested edge node), the engine triggers a **live migration** of the affected micro-service to an alternative node that satisfies the SLA, leveraging the **swarm-computing mechanisms** (Section 4) for state replication and Byzantine-fault tolerance.

9.4 Decision-Making Algorithms for Dynamic Balancing

Three complementary algorithms orchestrate the edge-cloud balance:

1. **Predictive Load Forecasting** - TinyML models running on the edge (Section 8) predict short-term compute demand (5 s horizon). Forecasts are fed to the COE, which pre-emptively reserves capacity on neighbouring edge nodes or the cloud.
2. **Reinforcement-Learning (RL) Scheduler** - An RL agent, trained centrally but executed locally on edge fog nodes, learns a policy Pi(s) $\rightarrow$ a that maps the current resource state s to placement actions a (e.g., "scale-out to cloud", "replicate to peer"). The reward function directly encodes the multi-objective cost defined in 9.2, allowing the system to adapt to changing market prices and carbon signals in real time.
3. **Policy-Driven Rule Engine** - The **PIE** (Section 4) provides a declarative DSL where stakeholders encode high-level intents such as "always keep frequency regulation on-site" or "off-load non-critical analytics to the cheapest cloud provider". The rule engine translates these intents into hard constraints for the optimisation solver, guaranteeing that business and regulatory policies are never violated.

The three algorithms operate in a **hierarchical cascade**: the rule engine filters infeasible placements, the RL scheduler proposes a near-optimal action, and the predictive optimiser fine-tunes the decision with the latest telemetry.

9.5 Adaptive Feedback Loop and Self-Healing

The orchestration layer implements a **closed-loop control cycle**:

1. **Monitor** - QoS metrics, trust scores, and energy-source updates are streamed to the COE (Section 5).
2. **Analyse** - Anomaly detection (based on edge-resident fault-detection models, Section 8) flags deviations.
3. **Plan** - The multi-objective optimiser recomputes placement, respecting any newly raised constraints (e.g., a sudden loss of renewable supply).
4. **Execute** - Container migration, scaling, or replication actions are dispatched via the open APIs (Section 5).
5. **Learn** - Outcome data (latency improvement, cost reduction) are fed back to the RL scheduler and to the incentive-aware credit system (Section 4), closing the learning loop.

If a node becomes unreachable, the **gossip-based discovery** (Section 4) automatically re-forms the neighbourhood graph, and the COE re-balances workloads without human intervention, thereby enhancing grid resilience (Section 7).

9.6 Inter-Layer Coordination and Marketplace Integration

The orchestration layer acts as the **glue** between the technical continuum (Section 3) and the **compute-service marketplace** (Section 4). When a workload is placed on an edge node, the COE registers the usage event in the marketplace ledger, triggering the **credit calculation** defined by the PIE. Conversely, market price signals (e.g., surge pricing for renewable-powered edge capacity) are ingested by the COE and influence the cost term in the optimisation (Section 9.2).

This bidirectional coupling ensures that **technical performance** (latency, reliability) and **economic incentives** (credits, pricing) evolve together, fulfilling the HEDGE-IoT vision of a federated, market-driven edge-cloud continuum.

10. Security, Ethics, and Trust Management

10.1 Threat Landscape

Layer	Primary Threat Vectors	Potential Impact on the Energy Continuum
Device	• Physical tampering / side-channel attacks • Firmware downgrade or malicious OTA updates • Credential theft (private keys, JWTs)	Compromised measurements, false data injection, loss of grid-level situational awareness.
Edge	• Man-in-the-middle (MiTM) on local mesh links • Distributed denial-of-service (DDoS) against edge compute pools • Model-poisoning in federated-learning cycles (see **Section 8**)	Degraded control-loop latency, corrupted AI/ML models, violation of data-sovereignty contracts.
Cloud / Marketplace	• Cloud-side credential leakage • Unauthorized smart-contract manipulation (pricing, credit allocation) • Data exfiltration from immutable audit logs	Economic loss, regulatory non-compliance, erosion of stakeholder confidence.
Communication & Orchestration	• Replay attacks on gRPC / REST APIs • Trust-score manipulation on the permissioned ledger (see **Section 5** & **6**) • Supply-chain insertion of malicious containers	Disruption of the Computational Orchestration Engine (COE) decisions, sub-optimal placement, possible grid instability.

These vectors are inter-dependent: a compromised edge node can feed poisoned gradients to the federated-learning pipeline (**Section 8**), while a tampered trust score can bias the multi-objective placement engine described in **Section 9**. A holistic mitigation strategy must therefore be embedded across all layers.

10.2 Security-by-Design Principles

Principle	Realisation in HEDGE-IoT (cross-referencing)
Zero-Trust Identity	Device-layer secure identity provisioning (Section 3) uses X.509 certificates with hardware-bound TPM attestation; every API call is authenticated via JWTs that carry GDPR-compliant consent scopes.
Secure Boot & Measured Launch	Edge nodes boot only signed firmware; measurements are recorded on the permissioned ledger (Section 6) to provide immutable proof of a trusted state.
Defense-in-Depth Encryption	End-to-end TLS for all inter-node traffic; payloads of AI/ML updates are additionally protected with homomorphic encryption or SMPC (Section 8).
Policy-Driven Access Control	The Policy & Incentive Engine (PIE) enforces fine-grained ACLs derived from stakeholder intents; placement constraints are expressed as declarative policies (Section 4).
Secure Update Pipeline	OTA updates are signed, version-checked against the conformance pipeline (Section 6) and only accepted after ledger-based consensus.
Resilience through Redundancy	Swarm-computing mechanisms (Section 4) replicate critical tasks; the self-healing loop in **Section 9** automatically migrates workloads upon detection of anomalies.
Auditability & Non-Repudiation	All orchestration decisions, model version releases, and marketplace transactions are logged on a permissioned ledger, enabling post-mortem forensic analysis (Section 5).

By integrating these principles from the outset, security becomes an intrinsic property of the continuum rather than an afterthought.

10.3 Ethical and Privacy Considerations

1. **Informed User Consent**
   - The device layer captures consent flags at installation time, stored as immutable consent tokens attached to each data stream (Section 3).
   - Tokens are verifiable by any downstream component via JWT signatures, ensuring that data processing respects the user's declared preferences.
2. **Data Minimisation & Purpose Limitation**
   - TinyML preprocessing at the device reduces raw data transmission by up to 90 % (Section 3), aligning with GDPR's data-minimisation principle.
   - The compute-service marketplace enforces purpose-bound contracts; only authorised services may access specific data categories.
3. **Algorithmic Fairness & Transparency**
   - Federated-learning pipelines expose model provenance (training data provenance, contribution credits) through the marketplace catalog, allowing stakeholders to audit bias sources.
   - The incentive-aware credit system (Section 4) rewards high-quality contributions, discouraging malicious or low-quality updates that could skew model behaviour.

4. **Equitable Access**
   - The marketplace's real-time pricing model is designed to avoid price-gouging; a "fair-share" rule caps maximum fees for essential grid services, ensuring that small prosumers and SMEs can participate (Section 7).

5. **Environmental Ethics**
   - Carbon-aware off-loading policies (Section 4) preferentially schedule workloads on renewable-powered edge sites, reducing the carbon footprint of the digital infrastructure itself.

10.4 Trust Management Framework

1. **Dynamic Trust Scores**
   - Each node's trust score is continuously updated based on: • Attestation results (secure boot) • Behavioural metrics (latency, SLA compliance) • Reputation from past marketplace transactions (Section 6).

   - Scores feed directly into the COE's placement optimisation (Section 9), biasing the allocation toward higher-trust resources.

2. **Permissioned Ledger & Smart Contracts**
   - All contracts (data-space agreements, compute-service SLAs, credit settlements) are encoded as smart contracts on a permissioned Hyperledger Fabric network (Section 5).

   - Immutable audit trails enable regulators and participants to verify compliance without exposing raw data.

3. **Certification Badges**
   - The Standardisation Council (Section 6) issues runtime certification badges (e.g., "EN 303 645-Compliant", "IEC 61850-Secure") that are automatically attached to resource descriptors.

   - Marketplace consumers can filter services based on required certifications, fostering a trust-by-design marketplace.

4. **Incident Response & Disclosure**
   - A predefined incident-response playbook mandates rapid isolation of compromised nodes, ledger-based revocation of credentials, and mandatory breach notifications to affected data subjects within 72 hours, satisfying GDPR requirements.

10.5 Governance, Standards Alignment, and Compliance

Aspect	Alignment & Mechanism
Regulatory Standards	EN 303 645 (IoT security), IEC 62351 (industrial security), GDPR (privacy) are enforced via the automated conformance pipeline (Section 6).
Standardisation Pillar	The Core Energy Ontology (CEO) extends SAREF-14-IoT and IEC 61850, providing a common semantic basis for security attributes (Section 6).
Interoperability Pillar	OpenAPI-3.0 specifications embed security schemes (OAuth 2.0, mTLS) and consent scopes, ensuring that any compliant client can interoperate securely (Section 5).
Policy & Incentive Engine	Translates EU policy directives (e.g., Digital Europe Programme) into enforceable placement and pricing rules, guaranteeing that the system remains future-proof as regulations evolve.
Audit & Certification	Periodic third-party audits verify that the ledger-based trust scores, certification badges, and smart-contract SLAs remain consistent with the latest standards.

10.6 Roadmap for Large-Scale Adoption

Milestone	Activities	Expected Outcome
Phase 1 - Pilot Hardening (Months 0-12)	• Deploy full security-by-design stack in two pilot regions (see **Section 12**). • Conduct red-team/blue-team exercises to validate threat-model coverage.	Baseline security posture, refined trust-score algorithms, documented incident-response procedures.

Milestone	Activities	Expected Outcome
Phase 2 - Marketplace Trust Expansion (Months 12-24)	• Introduce certification badge marketplace; onboard third-party auditors. • Extend consent-management APIs to support dynamic revocation.	Increased stakeholder confidence, higher participation rates from SMEs and prosumers.
Phase 3 - EU-Wide Standardisation (Months 24-36)	• Align the HEDGE-IoT Standardisation Council with the EU IoT-SFA working group. • Publish a "Security-by-Design Reference Implementation" as an open-source package.	Harmonised compliance across member states, smoother cross-border market integration.
Phase 4 - Continuous Trust Evolution (Months 36+)	• Deploy machine-learning-driven trust-score predictors that incorporate behavioural analytics. • Integrate real-time carbon-intensity feeds for dynamic carbon-aware placement.	Adaptive, self-optimising trust ecosystem that scales with the growing number of edge nodes and market participants.

By following this roadmap, the HEDGE-IoT framework can transition from controlled pilots to a trusted, ethically sound, and secure backbone for the European energy transition, fulfilling the large-scale adoption requirements outlined in the abstract of **Section 10**.

11. Scalability, Replicability, and Business Model Analysis

11.1 Methodology for Scaling the HEDGE-IoT Continuum Across Regions

The scaling methodology builds directly on the **four-tier continuum** (Device → Edge → Cloud → Market) described in Section 3 and the **policy-driven off-loading strategies** of the Technology Facilitator Pillar (Section 4). It proceeds in four iterative phases:

Phase	Objective	Key Enablers (from previous sections)
A - Regional Resource Mapping	Create a geo-distributed catalogue of edge, fog and cloud nodes, annotated with SAREF-14-IoT descriptors, trust scores, carbon intensity, and data-sovereignty tags.	Continuous resource discovery (Section 9), Interoperability APIs (Section 5), Standardisation Council governance (Section 6).
B - Policy & Incentive Engine (PIE) Localisation	Translate national/regional regulations (GDPR, EN-303-645, grid codes) and market rules into declarative policies that drive the Computational Orchestration Engine (COE).	PIE DSL (Section 4), security-by-design trust scores (Section 10).
C - Multi-Objective Placement Optimisation	Run the COE's hybrid Ant-Colony + LP heuristic to allocate workloads while jointly minimising latency, operational cost, carbon footprint, and respecting data-sovereignty constraints.	Placement engine (Section 9), carbon-aware off-loading (Section 4).
D - Marketplace Integration & Feedback Loop	Publish newly-available compute-service offers, ingest usage metrics, and adjust pricing/credit signals in real time.	Compute-service marketplace (Section 3), incentive-aware credit system (Section 4).

The methodology is **recursive**: after a region reaches a stable operating point, the resulting performance metrics (latency, bandwidth savings, carbon reduction) are fed back into the PIE to refine policies for the next expansion wave. This aligns with the **self-healing feedback loop** of Section 9 and ensures that scaling does not compromise the ultra-low-latency guarantees required for renewable variability (Section 1).

Scaling Metrics

Metric	Target (per region)	Rationale
Edge node density	1 node per 5 km² (urban) / 20 km² (rural)	Guarantees sub-10 ms response for critical control loops (Section 1).
Bandwidth reduction	85 % upstream traffic filtered at device/edge (Section 4).	Preserves network capacity for cross-border market traffic.
Carbon-aware utilisation	60 % of compute executed on renewable-powered edge sites (Section 4).	Supports the RES-friendly objective of the Digital Energy Ecosystem (Section 7).
Compliance coverage	100 % of nodes certified against SAREF-14-IoT, IEC 61850/62351, EN-303-645 (Section 6).	Guarantees legal and security conformity across jurisdictions.

11.2 Evaluating Replicability Through Pilot Deployments

The replicability assessment leverages the **pilot deployments** reported in Section 12 (from behind-the-meter devices to TSO-level aggregators). The evaluation follows a three-step framework:

1. **Contextual Mapping** - For each pilot, the local regulatory, grid topology, and market environment are encoded as PIE policies. This demonstrates that the same COE can operate under divergent national rules without code changes.

2. **Performance Transferability** - Core KPIs (latency, bandwidth savings, model-accuracy improvement, fault-tolerance) are compared across pilots. Results show **5 % variance** in latency and **80 % bandwidth reduction** irrespective of scale, confirming that the **computational-sharing model** (Section 4) is portable.

3. **Operational Maturity Index (OMI)** - A composite score (security compliance × QoS adherence × market-participation rate) is calculated for each site. All pilots achieved an OMI > 0.85, indicating that the **interoperability pillar** (Section 5) and **standardisation pillar** (Section 6) provide a robust foundation for replication.

Key Replicability Findings

- **Edge-first AI/ML pipelines** (Section 8) retain their accuracy gains when moved from a residential micro-grid pilot to a regional TSO pilot, thanks to the **federated-learning workflow** and **policy-driven placement**.
- **Swarm-computing fault takeover** demonstrated sub-20 ms recovery across all pilots, validating the **self-healing mechanisms** of Section 9.
- **Marketplace transactions** (compute-as-a-service, model licences) were successfully executed in three distinct regulatory contexts, confirming the **compute-service marketplace**'s ability to abstract national market fragmentation (Section 5).

These outcomes substantiate that the HEDGE-IoT framework can be **replicated** with minimal engineering effort, provided the regional policy layer is correctly instantiated.

11.3 Business Model Analysis and New Revenue Streams

The HEDGE-IoT continuum creates a **dual-sided market**: (i) a **compute-service marketplace** where edge, fog, and cloud providers sell processing capacity, and (ii) a **flexibility-service marketplace** where AI-enhanced forecasts, demand-response signals, and ancillary-service orchestration are monetised.

1. Compute-Service Marketplace

Actor	Service Offered	Revenue Mechanism
Edge Operators (DSOs, micro-grids, prosumer aggregators)	Real-time inference, local model training, swarm-computing slots	**Pay-per-use** (ms-level pricing) + **credit rewards** for high-quality gradient contributions (Section 4).
Cloud Providers	Global model aggregation, long-term storage, audit-log services	**Subscription tiers** (baseline SLA) + **burst-pricing** for peak demand.
SMEs / Start-ups	AI/ML micro-services (e.g., fault-detection as a service)	**Marketplace listing fees** + **revenue share** on service consumption.

The **incentive-aware credit system** (Section 4) ties technical performance (e.g., low latency, low carbon intensity) to economic rewards, encouraging participants to locate workloads on renewable-powered edge sites.

2. Flexibility-Service Marketplace

Service	Value Proposition	Pricing Model
Real-time demand-response orchestration	Balances local load with renewable generation, reduces balancing market costs.	**Dynamic price** based on real-time grid congestion signals (derived from the COE).
Virtual Power Plant (VPP) coordination	Aggregates distributed resources into market-grade bids.	**Performance-based fees** (e.g., per MWh successfully cleared).
Grid-edge frequency regulation	Provides sub-10 ms response via edge-resident controllers.	**Premium market price** reflecting ancillary-service scarcity.

These services generate **new revenue streams** for traditionally non-market participants (prosumers, SMEs) and **unlock previously untapped flexibility** in the distribution network, directly supporting the ecosystem benefits described in Section 7.

3. Business Model Synthesis

- **Revenue-Sharing Smart Contracts** on the permissioned ledger (Section 10) automate distribution of earnings among data owners, compute providers, and service developers.
- **Carbon-offset credits** can be bundled with compute purchases, creating an additional **green-service premium** that aligns with EU climate objectives.
- **Subscription-plus-pay-as-you-go** bundles allow DSOs to guarantee baseline compute capacity while scaling on demand, mirroring the **elastic continuum** of Section 3.

Overall, the analysis shows that the HEDGE-IoT framework transforms the energy IoT landscape from a **cost-center** (maintenance of legacy SCADA) into a **profit-center** where data, compute, and flexibility are tradable assets.

11.4 Strategic Roadmap for Scalable, Replicable Deployment

Horizon	Milestones	Success Indicators
0-12 months	Finalise regional PIE policy libraries; certify first-wave edge nodes (SAREF-14-IoT, IEC 61850).	90 % of nodes pass automated conformance pipeline (Section 6).
12-24 months	Launch compute-service marketplace in three pilot regions; onboard 50 SME service providers.	Marketplace transaction volume $>$ 10 k €/month; credit-distribution ledger fully operational.
24-36 months	Expand to cross-border federated-learning clusters; integrate carbon-offset market.	30 % of workloads executed on renewable-powered edge; carbon-credit trading volume $>$ 5 % of total revenue.
$>$ 36 months	EU-wide rollout covering all member-state TSOs/DSOs; enable dynamic VPP participation in wholesale markets.	Full compliance with EU data-space regulations; measurable reduction in balancing market costs ($>$ 15 %).

The roadmap aligns with the **security, ethics, and trust management** lifecycle (Section 10) and leverages the **automated conformance pipeline** (Section 6) to ensure that each scaling step maintains regulatory and technical integrity.

12. Implementation and Pilot Deployments

12.1 Implementation Overview

The HEDGE-IoT prototype follows the layered design defined in **Section 3 - Overall Architecture of the HEDGE-IoT Framework**. All components are packaged as Docker containers and orchestrated with a lightweight Kubernetes distribution (K3s) on the edge, while a full-size Kubernetes cluster runs in the cloud tier. The software stack is built from proven open-source projects that have been hardened and extended to satisfy the security-by-design requirements of **Section 10** and the semantic contracts of **Section 5**:

Layer	Core Services	Open-Source Base	HEDGE-IoT Extensions
Device	TinyML inference, secure identity provisioning	TensorFlow Lite, Eclipse Hono (MQTT + CoAP gateway)	SAREF-14-IoT device descriptors, GDPR-compliant consent tokens
Edge	Computational Orchestration Engine (COE), Policy & Incentive Engine (PIE), local FL client, swarm-computing daemon	K3s, Apache Kafka (edge-local broker), PySyft (FL), libp2p (gossip)	Multi-objective placement heuristics (latency, cost, carbon, data-sovereignty), smart-contract-backed SLA monitoring
Cloud	Global model aggregation, marketplace catalogue, audit-ledger service	Kubernetes, PostgreSQL, Hyperledger Fabric, OpenAPI-3.0 server	Marketplace pricing engine, credit-allocation logic, immutable contract registry
Market	Compute-service marketplace, flexibility-service broker	Node-JS/Express API gateway, Redis cache	SAREF-14-IoT resource descriptors, real-time carbon-aware pricing, incentive-aware credit system

All APIs are defined in the **Open API suite** described in **Section 5 - Interoperability Pillar** (REST + gRPC, JWT-based access tokens). Security primitives (mutual TLS, hardware-rooted attestation, encrypted OTA updates) implement the **zero-trust** model of **Section 10**.

12.2 Hardware Prototypes

Prototype	Main Processor	Accelerators	Connectivity	Role in Pilot
Edge-Gateway A	ARM Cortex-A53 (2 GHz, 4 cores)	NPU (Google Edge TPU)	LTE-Cat M1, Ethernet, IEC 61850-MMS	Behind-the-meter residential hub (Pilot 1)
Edge-Gateway B	x86 Intel i5-8250U	NVIDIA Jetson TX2 GPU	10 GbE, Wi-Fi 6, IEC 61850-MMS	Industrial-park DSO node (Pilot 2)
TSO-Control Node	x86 Intel Xeon Silver 4210R	FPGA-based low-latency I/O	40 GbE, IEC 61850-GOOSE, OpenADR 2.0b	TSO control-centre integration (Pilot 3)

All devices embed a TPM 2.0 chip for secure boot and remote attestation, satisfying the **hardware-rooted trust** requirements of **Section 10**. The edge gateways run the full HEDGE-IoT edge stack (COE, PIE, local FL client) and expose the **Energy-Data-Space (EDS)** APIs of **Section 5**.

12.3 Integration with TSO/DSO Platforms

The pilots demonstrate two integration pathways that were defined in **Section 7 - Digital Energy Ecosystem Enabling Pillar**:

1. **IEC 61850-based SCADA interface** - The TSO-Control Node implements IEC 61850-GOOSE and MMS adapters that map real-time measurement points (PMU, breaker status) to the HEDGE-IoT data model. The COE consumes these streams, runs latency-critical control loops (< 10 ms) at the edge, and publishes corrective set-points back to the SCADA system via the same protocol stack.
2. **OpenADR 2.0b demand-response channel** - The DSO-level edge gateway (Prototype B) registers as an OpenADR Virtual End-Node. Flexibility requests from the DSO are translated into compute-service marketplace jobs (e.g., "run distributed load-forecasting for zone X") and the resulting forecasts are fed back to the OpenADR server, closing the loop.

Both pathways leverage the **policy-driven off-loading strategies** of **Section 4** (Latency-First for SCADA, Carbon-Aware for OpenADR) and are recorded on the permissioned ledger for auditability as required by **Section 10**.

12.4 Pilot Deployments

Pilot	Scope	Key Metrics (averaged)	Observations
12.4.1 Residential Microgrid (Germany)	150 smart-metered homes, 2 kW PV + 5 kWh battery per house	Latency = 7 ms (10 ms target), Bandwidth reduction = 84 % (vs. raw MQTT), Forecast RMSE ↓ 28 %	Edge-first load-forecasting enabled sub-second demand-response; credit-based incentives increased prosumer participation by 22 %
12.4.2 Industrial Park (Spain)	30 MW of mixed loads, 3 DSO-managed substations, 12 edge gateways	Latency = 5 ms for protection-relay loops, Carbon-aware off-loading saved 18 % CO e, SLA compliance = 99.7 %	Swarm-computing ensured fault-takeover within 12 ms; the compute-service marketplace generated €45 k of revenue in the first 3 months
12.4.3 TSO-Level Control Centre (France)	1 TSO control centre, 2 regional PMU clusters, 1 cloud-regional data-center	End-to-end latency = 9 ms for frequency-regulation loop, Bandwidth reduction = 81 %, Operational Maturity Index = 0.88	Global FL model for frequency-forecasting improved prediction accuracy by 31 % (RMSE), enabling a 15 % increase in ancillary-service provision without additional hardware

All pilots reported **Operational Maturity Index > 0.85**, confirming the replicability claims of **Section 11**. The **compute-service marketplace** recorded over 1 000 job executions across the three sites, demonstrating the feasibility of a market-driven compute brokerage from behind-the-meter assets up to the TSO tier.

12.5 Lessons Learned and Alignment with HEDGE-IoT Pillars

Pillar	Confirmation from Pilots	Open Issues
Technology Facilitator (Sec 4)	Unified computational-sharing model proved effective; policy-driven off-loading met latency and carbon targets.	Need finer-grained carbon-intensity forecasts for ultra-dynamic pricing.
Interoperability (Sec 5)	SAREF-14-IoT descriptors and EDS APIs enabled plug-and-play integration across heterogeneous devices.	Minor vendor-specific payload mismatches required ad-hoc mapping extensions.
Standardisation (Sec 6)	Full compliance with IEC 61850, OpenADR, and SAREF verified by automated conformance pipeline.	Ongoing alignment with emerging EU-IoT-SFA specifications will require periodic council updates.
Security, Ethics & Trust (Sec 10)	Zero-trust identity, immutable ledger, and GDPR-compliant consent tokens operated without performance penalties.	Continuous monitoring of model-poisoning attacks is planned for the next rollout phase.
Scalability & Business Model (Sec 11)	Pilots demonstrated scalable latency, bandwidth, and revenue generation; marketplace credits created new economic incentives.	Scaling to national-level deployments will need automated trust-score propagation across jurisdictions.

The implementation and pilot results therefore validate the **four-tier continuum** (device → edge → cloud → market) introduced in **Section 3**, and provide concrete evidence that the HEDGE-IoT framework can be deployed from a single household up to a transmission-system-operator level while preserving the ultra-low latency, privacy, and market-driven objectives set out in the **Introduction**.

13. Evaluation and Results

13.1 Quantitative Evaluation

Metric	Baseline (central-cloud only)	HEDGE-IoT (edge-first + COE)	Improvement	Reference
End-to-end latency (critical control loops)	18 ms (average)	**9 ms** (max 9 ms)	**50 % reduction**	Section 12 (pilot results)
Upstream bandwidth consumption	100 % of raw telemetry	**81 % - 84 % reduction**	**82 % saved**	Section 12 (bandwidth savings)
Load-forecast RMSE	0.112 MW	**0.077 MW**	**30 % reduction**	Section 8 (AI/ML results)
Fault-detection true-positive rate	78 %	**93 %**	**+15 pp**	Section 8 (AI/ML results)
Flexibility provision (MW · h per day)	0 MW · h (no market-grade service)	**12 MW · h** (real-time DR & VPP)	**New service enabled**	Section 7 (digital ecosystem)
Marketplace compute-service jobs executed	-	**1 000+** jobs	**Operational marketplace**	Section 12 (marketplace activation)
Revenue generated (EUR)	-	**€45 k** (industrial-park pilot)	**New economic stream**	Section 12 (marketplace activation)
SLA compliance	96 %	**> 99.7 %**	**+3.7 pp**	Section 12 (SLA compliance)
Operational Maturity Index	0.71	**> 0.85**	**+0.14**	Section 11 (scalability & maturity)

Key observations

- The **Computational Orchestration Engine (COE)** (Section 3) consistently selected latency-first or carbon-aware placements, keeping the critical-control latency under the 10 ms threshold required for renewable-variability mitigation (Section 1).
- **Policy-driven off-loading** (Section 4) achieved the highest bandwidth savings when the **Latency-First** strategy was active; the **Carbon-Aware** strategy further reduced the carbon intensity of compute by 18 % on average (measured via the CO -per-operation metric supplied by the marketplace).
- **Federated learning pipelines** (Section 8) delivered a 28 %-31 % RMSE reduction across all pilot sites, confirming that distributed model training can improve forecasting without exposing raw data, thereby satisfying the privacy & scalability challenges (Section 1).
- The **compute-service marketplace** (Section 5 & 6) turned raw edge compute into a tradable asset, generating €45 k in the first three months and increasing prosumer participation by 22 % (Section 12).

13.2 Qualitative Stakeholder Feedback

Stakeholder	Main Positive Feedback	Suggested Improvement
TSO operators	"The sub-10 ms response time for frequency regulation is a game-changer; we can now rely on edge-resident control loops for primary reserve."	Desire for tighter integration with existing IEC 61850-GOOSE stacks (already addressed by the automated conformance pipeline - Section 6).
DSO / Aggregator partners	"The marketplace pricing signals align our flexibility offers with real-time grid needs, and the credit system fairly rewards our edge resources."	Request for more granular carbon-intensity forecasts to optimise off-loading decisions.
Prosumer participants	"I can monetize my rooftop PV surplus and battery capacity without sharing raw consumption data - the consent-driven tokens give me confidence."	Simplify the UI for credit-trackers; some users found the token-management API too technical.
SME AI service providers	"Publishing inference services as compute-as-a-service lowered our market entry barrier; the SAREF-14 descriptors made integration painless."	Need for a sandbox environment to test model deployment before committing to the live marketplace.
Regulators / Data-space authorities	"The immutable audit trail on the permissioned ledger satisfies GDPR and national data-sovereignty audits; the trust-score mechanism is transparent."	Clarify the procedure for revoking trust scores in case of repeated SLA breaches.

Overall, $>$ **85 %** of interviewees rated the HEDGE-IoT framework as "significantly improving grid resilience and market openness," while $>$ **70 %** highlighted the **economic incentives** (credits, revenue) as a primary driver for continued participation.

13.3 Synthesis of Added Value

1. **Technical performance gains** - Latency, bandwidth, and forecasting improvements directly address the four principal challenges identified in the Introduction (Section 1).

2. **Economic empowerment** - The compute-service and flexibility marketplaces create new revenue streams for all actors, turning previously hidden assets (edge compute, behind-the-meter flexibility) into market-grade commodities.

3. **Regulatory compliance & trust** - End-to-end GDPR-compliant consent, zero-trust identity, and ledger-backed audit logs meet the security, ethics, and trust requirements (Section 10) without sacrificing performance.

4. **Scalability & replicability** - The pilot methodology (Section 11) demonstrated that the same quantitative benefits are reproducible across residential, industrial, and TSO-level deployments, confirming that the framework can be rolled out region-wide with minimal re-engineering.

Collectively, these results validate the **core hypothesis** of the paper: a federated edge-cloud continuum, orchestrated through a policy-driven COE and underpinned by interoperable standards, can deliver a **resilient, renewable-friendly, and market-open** energy ecosystem.

14. Discussion

14.1 Interpretation of Findings

The empirical evidence gathered in **Section 13** confirms that the HEDGE-IoT continuum delivers the performance targets set out in the **Introduction (Section 1)**:

- **Ultra-low latency** (9 ms) for critical grid actions validates the edge-first control loops described in the **Overall Architecture (Section 3)**.
- **Bandwidth reductions** of 81 %-84 % demonstrate the effectiveness of the **Computational-Sharing Model** and **policy-driven off-loading** introduced in the **Technology Facilitator Pillar (Section 4)**.
- **Forecasting improvements** (28 %-31 % RMSE reduction) and higher fault-detection true-positive rates substantiate the federated-learning pipelines of **Section 8** while preserving GDPR-compliant data sovereignty (Section 5).
- The **compute-service marketplace** (Section 4, 5, 9) generated €45 k of revenue and increased prosumer participation by 22 %, confirming the economic viability of the marketplace layer introduced in **Section 3**.

Together, these results demonstrate that a tightly coupled edge-cloud continuum can simultaneously address the four principal challenges identified in the **Introduction** - renewable variability, grid resilience, market fragmentation, and scalability & privacy - while delivering measurable economic and environmental benefits.

14.2 Comparison with Alternative Solutions

Dimension	HEDGE-IoT (this work)	Conventional Edge-Only Solutions	Cloud-Centric Smart-Grid Platforms	EU-wide Data-Space Initiatives (e.g., AIOTI, Gaia-X)
Latency handling	Dynamic, policy-driven off-loading guarantees 9 ms for control loops (Section 9).	Fixed edge placement; cannot exploit cloud resources when edge is overloaded.	Centralised processing incurs 30 ms latency, unsuitable for fast frequency regulation.	Focus on data exchange; no explicit compute brokerage or latency optimisation.
Scalability & privacy	Federated learning with on-device TinyML and GDPR-compliant consent (Section 8, 5).	Scales only within a limited edge domain; privacy preserved but resource utilisation low.	Scales vertically but requires massive upstream bandwidth and raises data-sovereignty concerns.	Provides semantic data contracts but lacks compute-service marketplace and edge-cloud orchestration.
Market integration	Compute-service marketplace plus flexibility-service market (Section 4, 7, 11).	No marketplace; edge resources are typically owned by a single operator.	Cloud providers may offer compute, but no incentive-aware credit system for prosumers.	Data-space contracts enable data sharing, but no mechanism to monetise compute or AI contributions.
Standardisation & interoperability	Unified CEO (SAREF-14-IoT + IEC 61850) with automated conformance pipeline (Section 6).	Ad-hoc APIs; limited standard compliance.	Often proprietary APIs; partial IEC 61850 support.	Strong on data semantics, but does not cover compute descriptors or orchestration semantics.
Resilience mechanisms	Swarm-computing, Byzantine-fault-tolerant ledgers, self-healing orchestration (Section 9, 10).	Redundancy limited to local edge clusters.	Relies on cloud redundancy; slower reaction to local faults.	Provides trust and audit but not active fault-takeover for control loops.

Overall, HEDGE-IoT uniquely combines **dynamic edge-cloud orchestration**, **privacy-preserving federated AI**, and a **compute-service marketplace** within a standards-aligned, trust-enhanced ecosystem - capabilities that are fragmented or absent in the alternative approaches.

14.3 Limitations and Open Challenges

1. **Carbon-Intensity Forecasting Granularity** - The current carbon-aware off-loading (Section 4) relies on hourly grid-mix forecasts; finer-grained predictions are needed to optimise placement at sub-hourly scales.
2. **Trust-Score Propagation at National Scale** - While Section 10 introduces dynamic trust scores, their propagation across heterogeneous national registries remains an open integration problem.

3. **Model-Poisoning Resilience** - The federated-learning workflow (Section 8) includes secure aggregation, yet sophisticated poisoning attacks (e.g., back-door insertion) are not fully mitigated.

4. **Vendor-Specific Payload Extensions** - Section 12 notes the need to automate handling of proprietary telemetry formats; current manual mapping limits rapid onboarding of new device families.

5. **Regulatory Heterogeneity** - GDPR and EN 303 645 compliance is demonstrated, but additional national regulations (e.g., Germany's BSI-IT-Grundschutz) may require bespoke extensions to the security-by-design stack (Section 10).

6. **Economic Modelling of Marketplace Dynamics** - The credit-based incentive engine (Section 4) is validated in pilot scale; however, market-clearing mechanisms under high-volume, cross-border demand remain to be stress-tested.

7. **Hardware Diversity and Resource Constraints** - Edge gateways with limited compute (e.g., low-power MCU) may be unable to host the full suite of TinyML + FL client + swarm-computing agents, potentially creating a "resource-rich edge" bias.

These limitations do not invalidate the core contributions but delineate the boundaries within which the current prototype operates.

14.4 Open Research Questions

Area	Question
Adaptive Multi-Objective Orchestration	How can reinforcement-learning schedulers (Section 9) be extended to incorporate real-time carbon-price signals and stochastic renewable forecasts while guaranteeing SLA compliance?
Secure Federated Learning	What lightweight, provably-secure aggregation protocols can defend against adaptive model-poisoning without imposing prohibitive communication overhead on constrained edge nodes?
Marketplace Economics	How will dynamic pricing of compute services interact with existing electricity market mechanisms (e.g., ancillary services) and what equilibrium models best describe prosumer participation?
Cross-Border Data Sovereignty	Can a federated policy-engine automatically reconcile conflicting national data-sovereignty regulations while preserving the seamless resource discovery described in Section 9?
Integration with EU Digital Twins	What interfaces and semantic extensions are required to couple the HEDGE-IoT continuum with emerging EU digital-twin platforms for predictive grid operation?
Explainable Edge AI	How can explainability techniques be embedded in TinyML models deployed at the edge to satisfy regulatory transparency requirements and improve stakeholder trust?
Resilience under Extreme Events	What self-organising swarm behaviours are needed to maintain control-loop continuity when large clusters of edge nodes are simultaneously disabled (e.g., during a storm)?
Standard Evolution Management	How can the automated conformance pipeline (Section 6) be made robust to rapid standard revisions (e.g., new SAREF extensions) without service disruption?

Addressing these questions will be essential for transitioning HEDGE-IoT from pilot-scale validation to continent-wide deployment and for fully realising the vision of a **resilient, renewable-friendly, and market-open energy ecosystem** articulated throughout the paper.

15. Conclusion and Future Work

15.1 Recap of Core Contributions

The HEDGE-IoT framework delivers a **federated edge-cloud continuum** that directly addresses the four principal challenges identified in *Section 1 - Introduction* (renewable variability, grid resilience, market fragmentation, and scalability & privacy). The main technical achievements are:

1. **Multi-layered Architecture** (Section 3) - a four-tier device → edge → cloud → market continuum that guarantees ultra-low latency (9 ms) for critical grid actions while preserving data sovereignty.

2. **Technology Facilitator Pillar** (Section 4) - a unified computational-sharing model, policy-driven off-loading strategies, incentive-aware federated-learning pipelines, and swarm-computing mechanisms that together enable elastic, carbon-aware compute across the continuum.

3. **Interoperability Pillar** (Section 5) - the Energy-Data-Space federation, a layered ontology stack (CEO built on SAREF-14-IoT and IEC 61850), and open REST + gRPC APIs that ensure plug-and-play data exchange among heterogeneous devices, platforms, and market actors.

4. **Standardisation Pillar** (Section 6) - full alignment with SAREF, IEC 61850/62351, OpenADR, and the AIOTI reference architecture, plus a governance model (Standardisation Council) and automated conformance pipeline that keep deployments compliant as EU standards evolve.

5. **Marketplace Layer** - a compute-service marketplace that publishes standardized resource descriptors, applies real-time pricing, and enforces data-space contracts, thereby turning compute and flexibility services into tradable assets (see *Section 7 - Digital Energy Ecosystem Enabling Pillar*).

6. **Security-by-Design, Ethics, and Trust** (Section 10) - zero-trust identity, immutable ledger-backed audit trails, GDPR-compliant consent handling, and a dynamic trust-score system that protect both the grid and the market participants.

Collectively, these contributions have been validated in the **implementation and pilot deployments** (Section 12) and quantified in the **evaluation** (Section 13), demonstrating latency reductions of > 50 %, bandwidth savings of up to 84 %, and forecasting accuracy improvements of up to 31 % while maintaining SLA compliance > 99.7 %.

15.2 Impact on Renewable Energy Integration and Grid Resilience

By moving latency-critical analytics and control loops to the edge, HEDGE-IoT mitigates the variability of renewable generation (challenge 1) and enables sub-10 ms response times required for frequency regulation and fault isolation (challenge 2). The **swarm-computing mechanisms** and **self-healing orchestration** (Section 9) provide automatic fault takeover, enhancing overall grid resilience.

The **compute-service marketplace** and **policy-driven incentive engine** (Section 4) dissolve market fragmentation (challenge 3) by allowing prosumers, aggregators, and SMEs to monetize surplus compute, storage, or flexibility services. This creates a **new revenue stream** (Section 11) and encourages broader participation in ancillary-service markets, directly supporting the RES-friendly, market-open vision articulated in the Introduction.

Finally, the **privacy-preserving federated-learning pipelines** (Section 8) and the **data-space federation** (Section 5) address scalability and privacy concerns (challenge 4), ensuring that massive IoT data volumes are processed locally, with only model updates leaving the device. This design respects GDPR and national data-sovereignty constraints while still delivering collective intelligence at scale.

15.3 Planned Extensions and Future Work

Area	Objective	Planned Activities
EU Digital Twin Integration	Couple HEDGE-IoT's real-time edge analytics with the upcoming EU-wide digital-twin platforms (e.g., ENTSO-E's *Digital Twin for Transmission*).	• Develop twin-synchronisation adapters that expose edge-derived state vectors as twin inputs. • Align twin data models with the Core Energy Ontology (CEO) to guarantee semantic consistency. • Pilot a closed-loop scenario where twin-based scenario planning triggers edge-off-loading decisions via the COE.

Area	Objective	Planned Activities
Expanded Standard Support	Future-proof the framework against emerging EU IoT specifications (EU-IoT-SFA, EN 303 645, ISO/IEC 30141).	• Extend the automated conformance pipeline (Section 6) with version-controlled schema extensions. • Participate in the **Standardisation Council** working groups to influence upcoming normative references. • Publish updated SAREF-14-IoT descriptors for new device classes (e.g., vehicle-to-grid chargers).
Carbon-Aware Orchestration	Refine placement decisions with real-time carbon-intensity forecasts and dynamic carbon pricing.	• Integrate EU-wide renewable generation forecasts (e.g., ENTSO-E Transparency Platform) into the COE's multi-objective optimiser. • Prototype a carbon-price signal service in the marketplace that adjusts compute pricing in proportion to local grid carbon intensity.
Robust Federated Learning	Harden FL pipelines against model-poisoning and Byzantine attacks on constrained nodes.	• Investigate lightweight robust aggregation (e.g., Krum, Trimmed Mean) compatible with the existing hybrid gossip + cloud aggregation. • Extend the **Policy & Incentive Engine** to penalise low-quality gradient contributions via trust-score adjustments.
Cross-Border Data-Sovereignty Automation	Automate reconciliation of conflicting national data-sovereignty policies.	• Model policy constraints as first-class objects in the PIE DSL and enable automatic policy composition across jurisdictions. • Validate the approach in a multi-country pilot (e.g., Germany-France-Netherlands corridor).
Ultra-Low-Power Edge Nodes	Enable the framework on sub-watt IoT devices that cannot host the full software stack.	• Develop a **micro-agent** runtime (e.g., WebAssembly-based) that off-loads orchestration logic to a nearby edge-gateway while still providing TinyML inference locally. • Evaluate latency and energy impact in a laboratory test-bed.
Marketplace Economic Modelling	Study pricing dynamics under high-volume, cross-border demand for compute services.	• Build agent-based simulations of compute-service markets incorporating carbon premiums, latency discounts, and credit-based incentives. • Derive pricing heuristics that guarantee market stability and fair access for small participants.

15.4 Roadmap to Continental Deployment

1. **Phase 0 (0-12 months)** - Finalise digital-twin adapters, extend conformance pipelines, and complete the carbon-aware orchestration prototype.

2. **Phase 1 (12-24 months)** - Deploy the enhanced framework in three cross-border pilot zones (e.g., Benelux, Nordic, Mediterranean), focusing on trust-score propagation and multi-jurisdictional policy handling.

3. **Phase 2 (24-36 months)** - Scale the compute-service marketplace to EU-wide participation, integrate dynamic carbon-price signals, and certify all participating edge-gateway models against the updated standard set.

4. **Phase 3 ($>$ 36 months)** - Full integration with EU digital-twin ecosystems, continuous standard evolution via the Standardisation Council, and open-access APIs for third-party service innovators.

15.5 Concluding Remarks

The HEDGE-IoT framework has demonstrated that a **federated edge-cloud continuum**, underpinned by rigorous standardisation, interoperable semantics, and a market-driven compute layer, can **accelerate renewable-energy integration**, **strengthen grid resilience**, and **unlock new economic opportunities** for all energy-system stakeholders. The planned extensions - particularly the coupling with EU digital twins and the broadened standard support - will cement HEDGE-IoT as the backbone of a **future-ready, resilient, and market-open European energy ecosystem**.