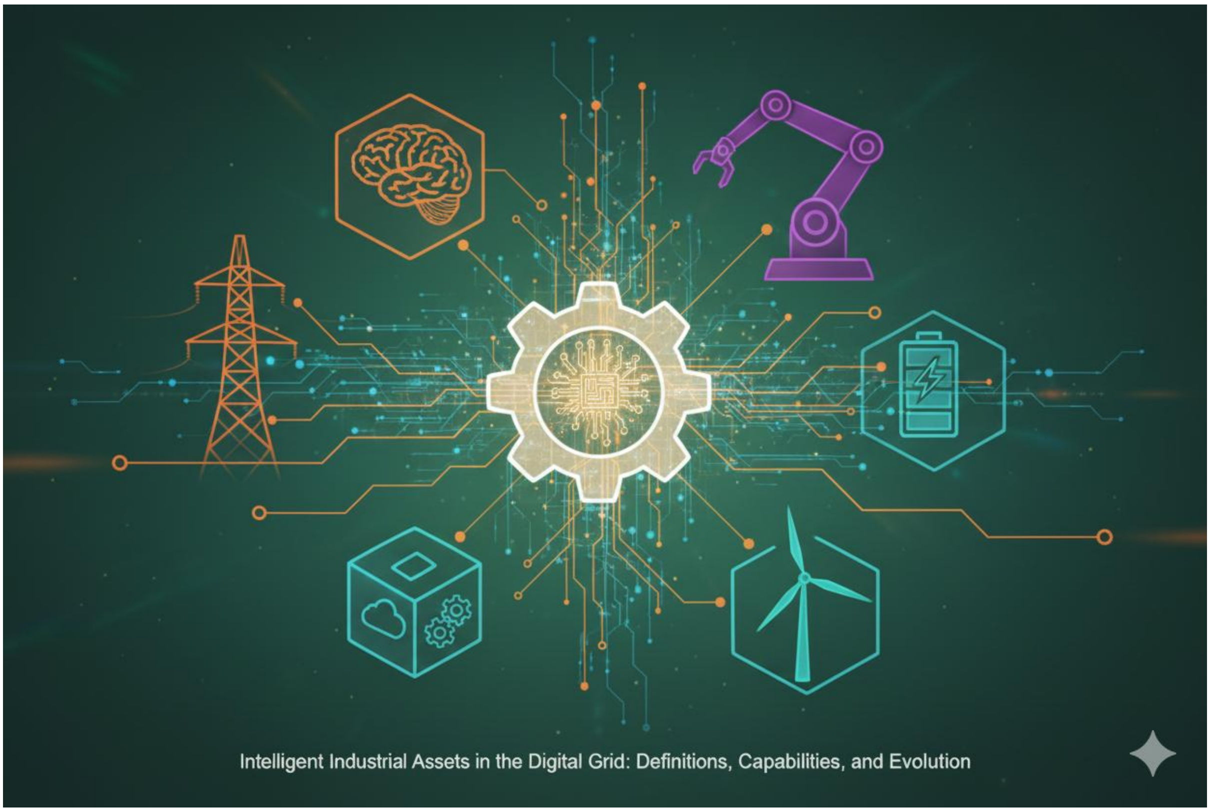

Intelligent Industrial Assets in the Digital Grid: Definitions, Capabilities, and Evolution

Abstract

The modern electrical grid is transitioning into a digital grid, hosting distributed renewable energy resources and coordinating sensing, control, computation, and analytics across the physical and digital domains. Grid assets evolve from Physical Assets to Intelligent Industrial Assets (IIAs), capable of autonomous decision-making, system-wide coordination, and multi-objective optimization. This article presents a five-stage maturity framework—Physical, Controlled, Software-Defined, Cyber-Physical System, and Intelligent Industrial Asset—clarifying key enabling concepts, including software-defined assets, digital twins, operational envelopes, smart contracts, and energy asset passports. A wind farm example illustrates the progression from isolated turbines to a coordinated IIA, highlighting capabilities such as predictive maintenance, dynamic operational management, and autonomous market participation. This framework demonstrates that IIAs provide a coherent architectural pattern for digital grids, enhancing resilience, interoperability, and operational intelligence across multiple time scales and objectives.

Introduction

The Digital Grid is a Cyber-Physical System of Systems (CPSoS)—an engineered system capable of hosting higher volumes of renewable energy while orchestrating sensing, computation, control, and analytics to interact with physical assets and humans. It operates across all the grid functional domains (generation, transmission, distribution, markets, and customers) and interfaces with other smart ecosystems (e.g., smart mobility, smart buildings). It supports safe, real-time, secure, reliable, resilient, and adaptable performance while enabling cross-sectoral value creation.

Managing rising renewable energy integration and real-time interactions among generators, storage, and customers is a major challenge. To address this, utilities are modernizing network components, accelerating the evolution of assets from simple physical devices to Intelligent Industrial Assets (IIAs).

This article presents a systematic framework that defines IIAs and traces their evolution through a five-stage maturity model, progressing the asset from a physical component to an intelligent system. It clarifies the foundational concepts—such as Software-Defined Assets, Digital Twins, Smart Contracts, and Operational Envelopes—that enable this transition. These concepts are illustrated using a wind farm example, showing how a single turbine progresses through the stages to become part of a cohesive intelligent system. The article concludes by detailing the key use cases and operational benefits of IIAs in achieving a resilient and sustainable digital grid.

Evolution of Grid Asset Types

Power system assets can be viewed in stages of digital maturity (see Table 1). Each stage incrementally enhances asset control, flexibility, and interoperability, paving the way for autonomous intelligence, with holistic integration of engineering technology (ET), operations technology (OT), and information technology (IT), enabling the intended levels of flexibility and intelligence.

Asset Type	Key Characteristics	Evolutionary Context
1- Physical Asset (Initial Stage)	Constraints, Location, Function, Condition	The base layer: the actual physical asset with its inherent characteristics, including its fixed location, fundamental function, physical constraints (e.g., maximum speed or temperature), and current state of health.
2- Controlled Asset (Enables Basic Automation)	Sensors, Controller, Network, SCADA	Extends the Physical Asset. Adds basic control and monitoring based on predefined logic.

3- Software-Defined Asset (SDA) (Enables Flexibility & Context)	Edge Compute, Remote Ops, Configurable, Digital Twin, Context	Extends the Controlled Asset. The asset's behaviour is defined by remote-managed software, enabling local optimization and directed orchestration.
4- Cyber-Physical Systems (CPS) (Enables Integration and Operational Intelligence)	Energy Asset Passport (EAP), Smart Contract, Operational Envelope, Monitored, Discoverable	Extends the Software-Defined Asset. Provides the standardized framework for system-wide interoperability, governance, and security.
5- Intelligent Industrial Assets (IIA) (Enables Autonomous and Decision Intelligence)	Decision Intelligence (Multi-Objective, AI & GenAI), Seamless Automation (Orchestration), Cyber-Physical Ingenuity (Composability)	Extends Cyber-Physical Systems. Achieves autonomous self-governance and system-wide coordination (e.g., by reconciling performance, asset health, and cost goals).

Table 1: Five-Stage Maturity Model for Digital Grid Asset Evolution

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Detailed Stage Descriptions

1. Physical Asset (Initial Stage)

The core equipment (e.g., a wind turbine's tower, transformer, or generator) with its inherent constraints, location, function, and current condition. These are the fundamental physical objects that the system is built upon.

2. Controlled Asset (Enables Basic Automation)

This stage equips the physical asset with the components necessary for basic monitoring and control. It integrates sensors (to measure parameters like temperature and vibration), controllers (such as PLCs or embedded computers), and a network that connects them to SCADA systems and operators. This system enables basic monitoring and control functions. Here, the controllers execute actions based solely on predefined, fixed logic, limiting the asset's capability to only rule-based, deterministic functions.

3. Software-Defined Asset (SDA): Enables Flexibility & Context

This stage extends controlled assets by encapsulating and virtualizing its hardware capabilities to allow remote management of its local configuration and constraints. The SDA embeds edge computing and a digital twin, enabling the asset to analyse real-time conditions locally, apply configurable software logic, and execute faster responses than a central system.

The core function of the SDA is local optimization: it dynamically adjusts its capabilities and performance across control, automation, and function to achieve higher local performance goals (e.g., adjusting power output based on real-time operational policies). Since the SDA's behavior is defined by remotely updated software, the asset becomes highly adaptable, producing rich, actionable data that supports dynamic optimization and coordination with other systems.

4. Cyber-Physical System (CPS): Enables Integration & Operational Intelligence

At this stage, the asset joins a larger Cyber-Physical System characterized by standardized digital integration for system-wide interoperability, governance, and trust. The system introduces a secure framework defined by an Operational Envelope and continuous monitoring against these safe limits (e.g., a turbine’s controller enforcing a maximum rotor speed to prevent overspeed). Furthermore, each device is assigned a secure digital identity, which is realized through an Energy Asset Passport (EAP), a concept that may require the use of Distributed Ledger Technology for tamper-proof governance, providing verifiable provenance, discoverability, and tamper-resistance. This robust framework, which enables interoperability and security, allows for the use of smart contracts (self-executing code on a ledger) to automate critical grid transactions, such as power sales or maintenance contracts.

5. Intelligent Industrial Asset (IIA): Enables Autonomous and Decision Intelligence

The Intelligent Industrial Asset (IIA) represents the highest level of asset maturity, characterized by the use of decision-oriented Artificial Intelligence (AI) for system-wide orchestration and autonomous decision-making. It leverages advanced decision intelligence through techniques such as multi-objective optimization, machine learning, and generative AI, transitioning from state monitoring to proactive self-governance and system-wide decision intelligence. IIAs predict future operational states and execute optimal autonomous control actions that resolve inherently conflicting performance objectives—for example, maximizing power generation efficiency while preserving long-term structural integrity. They also achieve system-level coordination, with clusters of assets operating cohesively within the digital grid. Building on CPS capabilities, an IIA integrates equipment and software to enable continuous learning and self-optimization, maximizing stakeholder value.

Key Concepts and Terminology

The following key concepts underpin the five-stage maturity model outlined in Table 1.

- Intelligent Industrial Assets **(IIAs):** Are assets with fully accessible and compatible datasets that support lean, automated, and end-to-end processes that simultaneously optimize operations, engineering, maintenance, planning, and economic performance for current market conditions. IIAs combine pervasive AI, machine augmentation, and unified IT/operational technology (OT) designs to maintain ongoing operational excellence while dynamically responding to changes in the external environment.

- **Software-Defined Asset (SDA):** A software-defined asset (SDA) encapsulates and virtualizes its hardware capabilities to allow remote management of its local configuration (e.g., setpoints) and constraints. This enables optimization of its capabilities, states, and performance across control, automation, function, and topology to achieve higher local performance goals. SDAs can also orchestrate with other assets and/or systems to achieve higher global performance goals without violating asset-specific decision envelopes.

- **Digital Twin:** A digital twin is a digital representation of a real-world entity or system. The implementation of a digital twin is an encapsulated software object or model that mirrors a unique physical object, process, organization, person, or other abstraction. Data from multiple digital twins can be aggregated for a composite view across a number of real-world entities, such as a power plant or a city, and their related processes. In the context of a digital grid, any asset (e.g., generator, substation, transformer, or home energy system) may have a digital twin for real-time analysis, simulation, and predictive decision intelligence.

- **Energy Asset Passport (EAP):** A secure, unique digital identity assigned to an operational asset within a Cyber-Physical System. It contains verifiable metadata about the device—such as manufacturer, specifications, compliance status, operational history, and lifecycle events—and ensures tamper-resistant provenance. EAP enables interoperability, trust, and automated management of assets across digital grids, supporting functionalities such as smart contracts, discoverability, and integration within intelligent industrial systems. This concept is also commonly referred to as a Device Passport in the general industrial context, aligning closely with the EU's Digital Product Passport (DPP) framework. The DPP is functionally defined as a structured collection of product-related data conveyed through a unique identifier. Although the high-level definition does not explicitly state "tamper-resistant provenance," the underlying legal mandate (via the Ecodesign for Sustainable Products Regulation) requires the DPP system to ensure data authentication, reliability, and integrity throughout the product's lifespan. This necessity for verifiable, unalterable historical data is what drives the requirement for tamper-resistant provenance in the EAP concept.

- **Smart Contract:** In grid operations, a smart contract is a type of blockchain record that contains externally written code and controls blockchain-based digital assets. When triggered by a specified blockchain write event, the smart contract immutably executes its code and may result in another blockchain event (based on Gartner). Smart contracts can only read from and write to the blockchain. All interactions with real-world, off-chain assets (like a wind turbine's condition) must be handled by external agents, often called oracles, that map between the off-chain data and the on-chain digital assets. This immutable, automated execution ensures transparency and enforcement without a central intermediary. For example, a predictive maintenance smart contract manages equipment health and service procurement. The workflow is: 1) Trigger: The IIA's digital twin identifies a critical component (e.g., a gearbox bearing) approaching failure, and the oracle writes this condition to the blockchain. 2) Execution: The smart contract immutably executes code to automatically initiate a warranty payment (digital asset) and issue a maintenance work order to the service provider (a transaction token). 3) Verification: The contract holds the payment in escrow. The service provider must then physically perform the repair. To ensure compliance, the payment is only released when the asset owner sends a cryptographic acceptance transaction to the blockchain, which can be conditional on the oracle confirming that the asset's post-maintenance vibration readings have returned to safe limits. This system seamlessly links asset condition, finance, and logistics.

- **Operational Envelope:** is the range of safe operating conditions for a device. It defines limits such as maximum power output, temperature, vibration, or generation profile. Modern grids increasingly use dynamic operating envelopes (instead of static ratings) for Distributed Energy Resources (DERs). That means the allowable output may change in real time based on grid conditions. In essence, this established the creation and use of dynamic operating envelopes for DER interconnections. Operational envelopes are encoded in asset controllers and smart contracts to ensure safety and reliability. For example, a static OE for a battery storage unit might be a fixed limit of 10 MW. However, its dynamic OE might be calculated in real time: on a congested feeder, the OE may restrict output to 5 MW to prevent line overload; conversely, if the battery's internal temperature exceeds a safe limit, the OE overrides all commands and limits the charge/discharge rate to 0 MW to protect the physical asset.

- **Decision Intelligence:** Is a practical discipline that advances decision-making by explicitly understanding and engineering how decisions are made and how outcomes are evaluated, managed, and improved through feedback.

  In the context of Intelligent Industrial Assets (IIAs), DI enables assets to optimize multiple objectives—such as maximizing power generation while minimizing equipment wear—at the asset (IIA) level, and to support coordinated optimization across interacting assets at the system/grid level. DI leverages multi-objective optimization, machine learning, generative AI, and digital twins to simulate "what-if" scenarios, evaluate trade-offs, and execute autonomous control. It enables assets to operate as proactive, self-optimizing, and adaptive agents within the digital grid.

- Seamless Automation / Orchestration: Coordinated automation across assets and systems. Orchestration means managing a workflow among multiple devices (e.g., dispatching three turbines to different yaw angles to reduce wake losses). It combines control, data, and AI to run complex processes end-to-end with minimal human intervention.

Wind Farm Example: An Intelligent Industrial Asset

Consider a wind farm operating in a digital grid.

1. **At the physical asset level**, each wind turbine (tower, rotor, generator) is a standalone device performing the function of converting wind into electricity. Each turbine's condition (wear, lubrication, blade pitch) and constraints (mechanical limits, location) define its base layer.
2. **Adding the controlled asset layer**, each turbine is fitted with sensors (anemometers, vibration and temperature sensors, power meters) and an embedded controller (PLC or local computer). These are connected via network (e.g., fiber or wireless) to a SCADA/DMS (Supervisory Control and Data Acquisition/Distribution Management System). The sensors continuously measure the turbine's condition and environment; the controller can actuate blade pitch, yaw orientation, and yaw brake. This enables remote monitoring (operators see turbine status) and basic control (e.g., shutting down in high winds). The farm's SCADA can issue commands to individual turbines, making them "controlled assets".
3. **At the software-defined asset layer**, each turbine hosts a digital twin and an edge compute node. The digital twin is a virtual model of the turbine's mechanical and electrical state. It receives live sensor data and simulates turbine behavior (for example, estimating internal blade loads from vibration). Operators or automated systems can run predictive analytics on the twin. The edge computer at the turbine can execute control logic and even machine learning models locally (to react faster to sudden wind gusts than a central server). In effect, the turbine becomes configurable by software. So, this asset is optimizing and modifying its capabilities to dynamically manage its local constraints – for instance, adjusting power smoothing algorithms if the grid frequency is unstable.
4. **In a cyber-physical system context**, the wind farm is fully networked and intelligent. Each turbine has a unique Energy Asset Passport (EAP) recording its identity, specifications, and perhaps maintenance history. Turbines and farm systems are discoverable on the network and continuously monitored for performance and anomalies. The farm's controller enforces an operational envelope – e.g., maximum rotor speed or power limit under certain grid conditions. These constraints can even be delivered dynamically by the grid operator. For example, if the grid is congested, the system might impose a reduced output envelope; conversely, it might allow

higher output during peak demand. Notably, regulators in some regions now require submitting a dynamic generation profile (an operating envelope) rather than a fixed limit. Smart contracts can further automate the farm’s interactions. For example, a blockchain smart contract might automatically sell electricity to the grid at certain prices or execute ancillary service agreements. It might also manage rental or maintenance contracts: if a turbine’s digital twin predicts an impending gearbox failure, a smart contract could order a parts shipment and schedule downtime. Because smart contracts are “a set of rules triggering automatic execution of transactions between peers," they enable trustless (no middleman) execution of such agreements.

5. **Finally, at the intelligent industrial asset level**, the entire farm leverages AI and orchestration. An AI-based controller might coordinate all turbines for multi-objective optimization: for example, maximizing overall energy capture while minimizing mechanical stress and noise. Predictive maintenance models (trained on historical data) can predict component lifetimes, so maintenance is scheduled just-in-time, reducing unplanned outages. The farm can also autonomously respond to grid signals: for instance, if a sudden demand spike occurs, the farm can rapidly ramp up generation within safe limits. Conversely, if storms threaten over-generation, the AI might feather blades proactively. This system continuously evaluates the outcome of its autonomous actions (e.g., measuring stress reduction after a control adjustment) and uses this feedback to refine its AI models and future optimization strategy. This level of decision intelligence enables the farm to operate almost autonomously with strategic oversight, improving performance and asset health. In summary, a wind farm constitutes an integrated Intelligent Industrial Asset (IIA). Individual turbines at the physical and controlled stages act as component units, while software-defined features—including digital twins and edge AI—provide localized intelligence. At the farm level, cyber-physical system integration and AI-driven coordination confer the characteristics of a fully intelligent industrial asset. This layered perspective highlights that modern wind farms are not merely mechanical assemblies but cyber-physical systems capable of self-optimization, autonomous decision-making, and coordinated intelligent operation within the digital grid.

Validation of IIA Integration: The ICONIC Project

The Wind Farm example illustrates the theoretical evolution to the IIA stage. A concrete, high-fidelity research blueprint is necessary to validate the seamless integration of the capabilities described. The European Union-funded ICONIC (Smart, Aware, Integrated Wind Farm Control Interacting with Digital Twins) project provides an ideal blueprint for this target state. ICONIC's entire mission is to develop and validate the hierarchical control architecture required for an IIA, specifically aiming to unify the Digital Twin, Multi-Objective

Optimization, and Cyber-Physical Orchestration into a single, cohesive system, as detailed in Table 2.

IIA Capability	ICONIC Project Objective	Demonstration of Full Integration
Software-Defined Layers and Cyber-Physical Orchestration	Develops a hierarchical, AI-based Wind Farm Control (WFC) system that serves as the overall decision intelligence layer.	The WFC system translates farm-level goals (e.g., maximizing production) into precise control setpoints for individual turbine controllers, creating a coordinated digital workflow. [See Project Objectives (CORDIS)]
Digital Twin	Develops an Integrated Digital Twin system encompassing turbine component DTs (e.g., pitch/yaw, drivetrain) and the larger wind farm flow dynamics.	The DT provides high-fidelity, real-time physical estimates necessary for the embedded control units to make an optimal trade-off between energy production and component lifetime preservation. [See Project Overview (ICONIC Website)]
Decision Intelligence and Self-Optimization	Focuses on advanced, multi-objective handling using Machine Learning (ML) and AI (Deep Reinforcement Learning).	The system autonomously balances high power generation with active load mitigation (reducing mechanical stress) to minimize the overall Levelized Cost of Energy (LCOE). [See Project Ambition (ICONIC Website)]
Seamless Automation / Feedback	Validates the integrated control loop system via extensive field tests using real operational data from an offshore wind farm (C-Power).	Aims to achieve a Technology Readiness Level (TRL) of 5, validating the entire cyber-physical control process (sensing, awareness, decision, execution) in a relevant operational environment. [See Project Overview (ICONIC Website)]

Table 2: The ICONIC Project Blueprint for Integrated IIA Control (TRL 5 Validation Target)

Illustrative Use Cases of Intelligent Industrial Assets in the Digital Grid

Following the demonstration of the Stage 5 asset (the IIA) within the wind farm context (Table 2), this section provides a functional overview of the capabilities enabled by this maturity level. Intelligent Industrial Assets (IIAs) leverage their core integrated capabilities—Decision Intelligence, Orchestration, and Composability—and their enabling technologies (including Digital Twins, Smart Contracts, and Digital Identity) to execute specific use cases across the grid. Table 3 details illustrative scenarios, mapping each IIA capability and supporting technology to its Functional Role, the Illustrative Asset associated with the use case, and the resulting operational and economic benefit derived from its completion.

No	Use Case	Capabilities/ Supporting Technologies	Functional Role	Resulting Benefit
1	**Real-Time Condition Monitoring and Fault Anticipation (e.g., Wind Turbine)**	Decision Intelligence, Digital Twins	Continuously monitor asset state and detect early signs of faults in real time, providing immediate alerts	Enhanced grid reliability and reduced unplanned outages
2	**AI-Driven Predictive Maintenance (e.g., Transformer)**	Decision Intelligence, Digital Twins	Analyse historical trends and predict component degradation to schedule proactive maintenance	Extended equipment lifespan and reduced O&M costs
3	**Multi-Turbine Farm-Level Optimization (e.g., Wind Farm)**	Decision Intelligence, Cyber-Physical Orchestration, Composability	Evaluate the performance of all turbines to identify optimal operational setpoints and coordinate outputs	Increased overall energy yield while preserving turbine longevity
4	**Dynamic Operational Envelope Enforcement for DERs (e.g., Solar Inverter/EV Charger)**	Software-Defined Features, Autonomous Control	Define operational limits and constraints for DERs dynamically based on grid conditions	Safe and scalable integration of variable renewables, mitigating risk of line overloads
5	**Automated Participation in Grid Services and Energy Markets (e.g., BESS)**	Smart Contracts, Autonomous Orchestration	Execute predefined energy trading and grid service rules autonomously	Faster, auditable, and secure market and grid interactions
6	**Transparent Asset Provenance and Cyber-Physical**	Digital Identity, Energy Asset Passports, Composability	Provide unique, verifiable asset identity for secure data exchange and	Improved traceability, data integrity, and cybersecurity

	Security (e.g., Any New Asset)		record history for auditability	across the digital grid
7	**System-Level Coordination and Self-Optimization (e.g., Virtual Power Plant)**	Decision Intelligence, Cyber-Physical Orchestration, Composability	Evaluate system-wide performance, optimize multiple objectives, and adapt strategies via feedback loops	Enhanced operational efficiency, autonomous decision-making, and system-level resilience

Table 3: Illustrative Use Cases that Demonstrate the Role and Benefits of IIA Capabilities in Digital Grids

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Conclusion

This article has examined the progressive evolution of grid assets—from physical and controlled devices to software-defined assets, cyber-physical systems, and ultimately Intelligent Industrial Assets (IIAs)—within the context of the emerging digital grid. By presenting this maturity model, the article clarified how capabilities accumulate across layers: starting with basic sensing and actuation, advancing through virtualized and programmable representations, and culminating in system-level orchestration, composability, unified datasets, and advanced decision intelligence. This structured progression demonstrates that intelligence is not an add-on but the outcome of architectural integration across operational, informational, and computational domains.

Through the wind-farm example, the article illustrated how individual turbines evolve from isolated mechanical units into components of a coordinated cyber-physical system equipped with digital twins, edge AI, and dynamic operating envelopes. At the highest maturity stage, the wind farm functions as an IIA capable of multi-objective optimization, autonomous decision making, adaptive coordination, and active participation in grid-level operations. The illustrative use cases further showed the practical implications of this transformation, including adaptive system-wide optimization, predictive maintenance, resilient operations under uncertainty, autonomous market participation, and secure data and identity management.

Overall, the analysis demonstrates that IIAs provide a coherent and future-ready architectural pattern for renewable-rich power systems. They enable grid assets to operate as composable, software-defined, cyber-physical entities that can sense, decide, coordinate, and optimize across multiple time scales and objectives. As digital grids expand and DER penetration intensifies, such intelligent asset architectures will become foundational to achieving resilience, interoperability, and autonomous grid stability. The maturity model and use-case framework presented in this article, therefore, offer both a conceptual lens and a practical guide for utilities, regulators, and technology providers as they design next-generation cyber-physical energy systems.

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