Towards a Framework for Autonomous Microgrids

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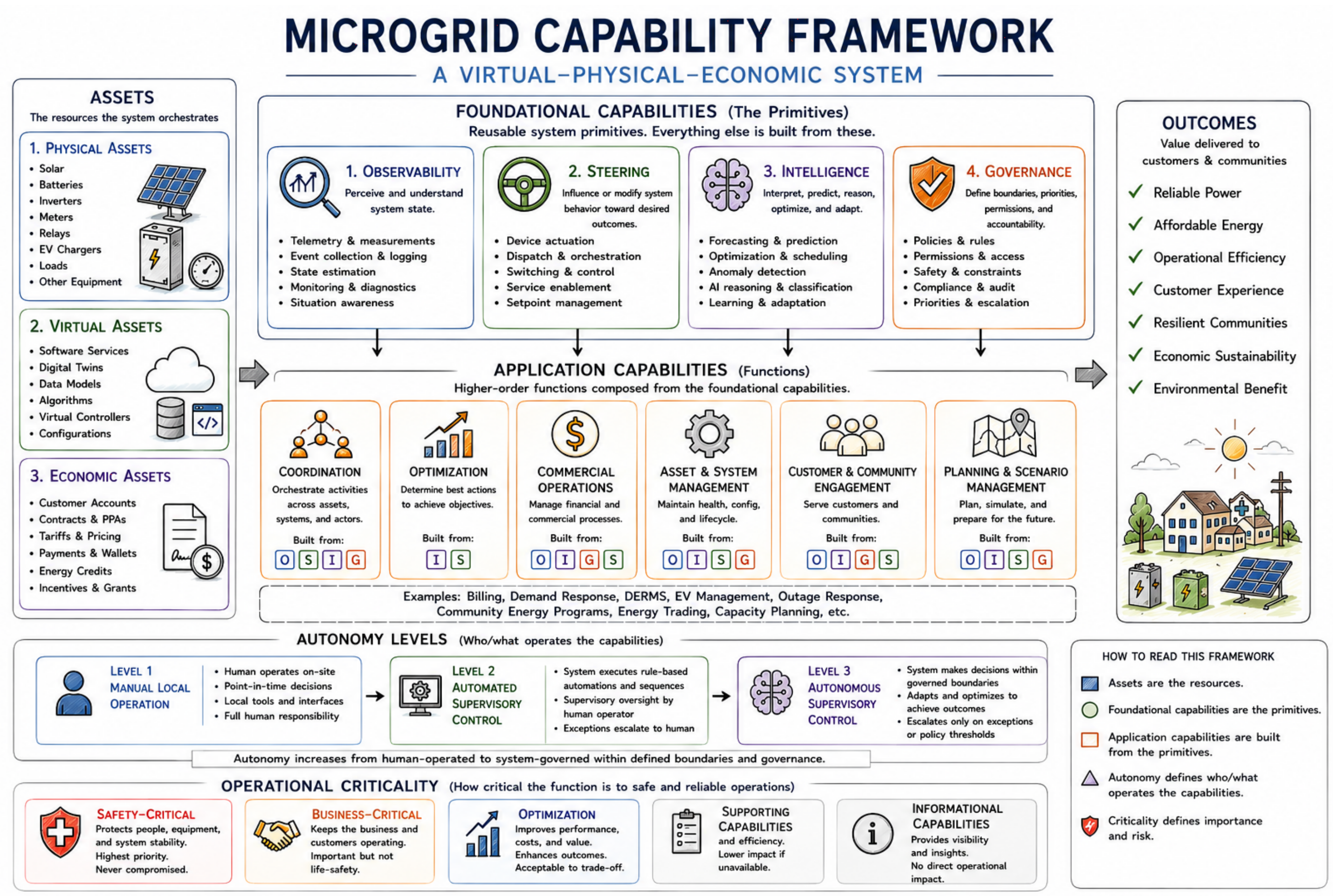
A picture with worth a thousand words



Introduction

As distributed energy resources become increasingly software-defined, microgrids are evolving from manually operated electrical systems into digitally coordinated energy platforms. This evolution creates a need for a clear framework describing the degree of operational autonomy assigned to different microgrid functions.

This document proposes a simple three-level autonomy model for microgrids inspired by concepts from industrial automation, supervisory control systems, and autonomous systems engineering.

Unlike autonomous vehicle frameworks that classify an entire vehicle into a single automation level, this framework applies autonomy levels to specific operational capabilities operating on specific assets.

For example:

- Observing smart meter consumption
- Steering battery dispatch
- Observing EV charger utilization
- Steering flexible loads
- Forecasting solar production

Each capability may operate at a different level of autonomy.

A microgrid could therefore simultaneously contain:

- Level 3 autonomous battery steering
- Level 2 remote EV charger steering
- Level 1 manual generator operation

This capability-oriented approach allows microgrids to evolve incrementally toward higher levels of operational autonomy.

Core Concepts

Assets

Assets are physical, digital, or economic components participating in the operation of the microgrid.

This framework groups assets into three primary categories.

1. Physical Assets

Physical assets are hardware systems that generate, store, distribute, consume, or protect electrical energy.

Examples include:

- Smart meters
- Battery energy storage systems (BESS)
- Solar PV inverters
- EV chargers
- Diesel generators
- Protection relays
- Flexible loads
- Distribution transformers
- Remote disconnect relays

2. Digital Assets

Digital assets are software systems, communications systems, and computational services used to monitor, coordinate, optimize, and operate the microgrid.

Examples include:

- Billing systems
- Tariff engines
- Payment systems
- Forecasting systems
- Customer identity systems
- AI orchestration systems
- SCADA platforms
- DERMS platforms
- Telemetry databases
- Mobile applications
- Notification systems

3. Economic and Contractual Assets

Economic and contractual assets represent the financial, commercial, and policy relationships governing the microgrid.

Examples include:

- Customer accounts
- Energy credits
- Tariff structures
- Power purchase agreements (PPAs)
- Service tiers
- Demand response agreements
- Payment obligations
- Credit limits
- Utility interconnection agreements

These asset categories recognize that modern microgrids are not purely electrical systems. They are virtual-physical-economic systems integrating energy infrastructure, software platforms, and operational business logic into a unified operational environment.

Foundational Capabilities

Foundational capability domains are the core operational primitives from which higher-order microgrid behaviors and applications are constructed.

Rather than treating every operational function as a separate foundational capability, this framework identifies a small set of core capabilities that can be composed together to create more advanced orchestration, optimization, commercial, and autonomous behaviors.

These foundational domains operate across physical, digital, and economic assets.

1. Observability

Observability capabilities measure, record, analyze, and communicate system state.

Observability forms the awareness layer of the microgrid.

Examples:

- Reading smart meter consumption
- Monitoring battery state of charge
- Detecting inverter faults
- Measuring feeder voltage and frequency
- Monitoring EV charging sessions
- Customer usage analytics
- Payment status monitoring
- Event logging and telemetry collection

2. Steering

Steering capabilities execute operational actions intended to guide system behavior toward desired operational outcomes.

Unlike traditional low-level control systems, steering emphasizes adaptive orchestration, policy-driven operation, and outcome-oriented system management across distributed assets.

Steering forms the action layer of the microgrid.

Examples:

- Disconnecting a load
- Dispatching battery storage
- Curtailing solar generation
- Starting a backup generator
- Setting EV charging limits
- Executing demand response actions
- Remote relay switching
- Service disconnection and reconnection

3. Intelligence

Intelligence capabilities generate predictions, recommendations, classifications, reasoning, and adaptive operational decisions.

Intelligence forms the reasoning layer of the microgrid.

Examples:

- Solar production forecasting
- Load forecasting
- Predictive maintenance
- Fault prediction
- Fraud detection
- Adaptive operational policy selection
- AI-driven energy management
- Anomaly detection
- Optimization modeling

4. Governance

Governance capabilities define and enforce operational rules, permissions, priorities, compliance requirements, and safety boundaries.

Governance forms the constitutional layer of the microgrid.

Examples:

- Access control
- Human override policies
- Safety constraints
- Regulatory compliance
- Escalation policies
- Operational audit logging
- Cybersecurity enforcement
- Service disconnection policies
- Critical load protections

Application Capabilities

Operational application domains are higher-order business and operational functions constructed from combinations of the foundational capabilities.

These applications are not themselves foundational primitives. Rather, they emerge from orchestrating observability, steering, intelligence, and governance capabilities together.

Coordination

Coordination capabilities orchestrate workflows across systems, users, assets, and operational processes.

Coordination typically combines:

- Observability
- Steering
- Governance

Examples:

- Human escalation workflows
- Multi-device orchestration
- Customer notification systems
- Utility coordination
- Maintenance scheduling
- Service provisioning workflows
- Incident response coordination

Optimization

Optimization capabilities improve operational efficiency, economics, reliability, or customer experience.

Optimization typically combines:

- Intelligence
- Steering

Examples:

- Energy arbitrage optimization
- EV charging optimization
- Demand response coordination
- Forecast-driven battery dispatch
- Load balancing
- Power quality optimization
- Asset utilization optimization

Commercial Operations

Commercial operations capabilities manage the economic and business functions of the microgrid.

Commercial operations typically combine:

- Observability
- Steering
- Intelligence
- Governance

Examples:

- Customer billing
- Tariff management
- Payment processing
- Credit management
- Revenue collection
- Energy credit accounting
- Invoice generation
- Service eligibility evaluation
- Automated service disconnection and reconnection

Automation vs Autonomy

The distinction between automation and autonomy is foundational to this framework.

Automation

Automation refers to systems that execute predefined instructions or workflows under human-defined logic.

Examples:

- Fixed battery charging schedules
- Rule-based generator startup
- Threshold-based load shedding
- Remote switching by operators
- Scheduled EV charger limits

An automated system follows instructions.

Autonomy

Autonomy refers to systems capable of independently managing operational objectives under changing conditions while operating within defined technical, economic, and safety constraints.

Examples:

- Optimizing battery dispatch based on tariffs, weather forecasts, and outage probability
- Dynamically prioritizing critical loads during constrained operation
- Coordinating EV charging across multiple users to minimize peak demand
- Predictive fault response and recovery
- Adaptive energy management based on real-time conditions

An autonomous system manages outcomes.

Levels of Operational Autonomy

This framework distinguishes between:

- Manual local operation
- Automated supervisory control
- Autonomous supervisory control

Level 1 — Manual Local Operation

At Level 1, foundational capabilities are operated directly by humans physically present at the asset location.

The asset itself provides the operational interface.

Examples:

- Reading values directly from a smart meter display
- Manually operating breakers or disconnects
- Physically starting a generator
- Local inverter configuration
- On-site battery inspection

Operational Characteristics

Question	Answer
Who monitors the system?	Human operators on-site
Who makes decisions?	Human operators on-site

Question	Answer
Who executes actions?	Human operators on-site
Who handles failures?	Human operators on-site

Characteristics

- No remote supervisory capability
- Human-driven operational awareness
- Minimal software orchestration
- Typically isolated or standalone systems

Relevant Standards

Relevant standards may include:

- IEEE 1547 for DER interconnection behavior
- IEEE 2030.7 for microgrid controller functional specification
- IEC 61850 for power system communication models

At Level 1, however, most operational authority remains local and manual.

Level 2 — Automated Supervisory Control

At Level 2, foundational capabilities are supervised remotely through software platforms and communications networks.

Humans remain responsible for operational decisions, while software automates telemetry collection, visualization, alarms, workflows, and execution of predefined control logic.

Examples:

- Remote smart meter monitoring
- SCADA-based microgrid supervision
- Rule-based battery dispatch
- Remote EV charger management
- Automated threshold alarms
- Scheduled load control

Operational Characteristics

Question	Answer
Who monitors the system?	Human operators remotely
Who makes decisions?	Human operators remotely
Who executes actions?	Automated systems under human-defined logic
Who handles failures?	Human operators with software assistance

Characteristics

- Remote visibility and control
- Centralized supervisory software
- Deterministic rule-based workflows
- Human approval remains central
- Software improves operational efficiency but does not independently manage system objectives

Relevant Standards

This level aligns closely with existing industrial automation and microgrid supervisory standards including:

- IEEE 2030.7 — Specification of Microgrid Controllers
- IEEE 2030.8 — Testing of Microgrid Controllers
- IEC 61850 — Power system communication models
- DNP3 and Modbus — Telemetry and control protocols
- OpenADR — Demand response coordination

Level 2 corresponds closely to modern SCADA and DERMS architectures.

Level 3 — Autonomous Supervisory Control

At Level 3, foundational capabilities are operated autonomously by software systems capable of independently managing operational objectives within defined technical, economic, and safety constraints.

Humans define policies, operating boundaries, escalation procedures, and override authority, but the system continuously makes operational decisions without requiring constant human supervision.

Examples:

- AI-driven battery optimization
- Autonomous load orchestration
- Dynamic outage response
- Self-optimizing EV charging coordination
- Predictive maintenance actions
- Autonomous islanding and reconnection
- Adaptive tariff-aware energy management

Operational Characteristics

Question	Answer
Who monitors the system?	Autonomous software systems with human oversight
Who makes decisions?	Autonomous systems operating within defined policies
Who executes actions?	Autonomous software systems
Who handles failures?	Autonomous systems first, humans upon escalation

Characteristics

- Goal-oriented operational behavior
- Context-aware decision making
- Forecast-driven optimization
- Dynamic adaptation to changing conditions
- Human escalation rather than continuous supervision
- Continuous optimization across multiple objectives

Key Requirements

Level 3 systems should include:

- Human override capability
- Policy enforcement mechanisms
- Audit logging
- Cybersecurity protections
- Fallback operational modes
- Confidence scoring and escalation logic
- Safety envelopes and operational constraints

Relevant Standards

Existing standards partially address autonomous operation today. Relevant references include:

- IEEE 2030.7 and 2030.8
- IEC 62351 — Power system cybersecurity
- NIST Cybersecurity Framework
- Emerging AI governance and operational safety standards

Further industry standardization may be required to fully define autonomous microgrid operation.

Operational Criticality

Not all microgrid capabilities carry the same operational importance or risk.

This framework distinguishes between different classes of operational criticality.

Safety-Critical Capabilities

Capabilities whose failure or misuse could threaten human safety, equipment safety, or grid stability.

Examples:

- Protection relay operation
- Islanding and reconnection
- Overcurrent protection
- Emergency load shedding
- Battery thermal protection
- Voltage and frequency stabilization

These capabilities typically require strict operational constraints, auditability, and human override mechanisms.

Business-Critical Capabilities

Capabilities necessary for the commercial and operational sustainability of the microgrid business.

Examples:

- Customer billing
- Payment processing
- Remote service disconnection
- Tariff enforcement
- Revenue collection
- Customer account management

These capabilities are operationally important but must remain subordinate to safety-critical protections.

Optimization Capabilities

Capabilities intended to improve efficiency, economics, customer experience, or asset utilization.

Examples:

- Energy arbitrage optimization
- EV charging optimization
- Demand response coordination
- Forecast-driven battery dispatch
- Predictive maintenance
- Customer energy recommendations

Optimization capabilities should degrade gracefully without compromising safety or core operations.

Supporting Capabilities

Capabilities that support operational continuity, efficiency, maintenance, coordination, or administrative workflows, but whose temporary failure does not immediately compromise safety or core service delivery.

Examples:

- Maintenance scheduling
- Reporting systems
- Asset inventory management
- Customer notifications
- Workforce coordination
- Historical analytics
- Non-critical integrations

Supporting capabilities improve operational effectiveness and resilience but are generally lower priority during constrained or degraded operations.

Informational Capabilities

Capabilities whose primary purpose is visibility, insights, diagnostics, learning, or reporting without direct operational authority over the system.

Examples:

- Dashboards
- Historical reporting
- Data visualization
- Energy usage insights
- Community analytics
- Educational interfaces
- Public transparency portals

Informational capabilities provide situational awareness and decision support but typically do not directly influence operational behavior.

Applying the Framework

The framework is intended to classify autonomy at the capability level rather than the whole microgrid level.

Example:

Asset	Foundational Capability Domain	Operational Function	Autonomy Level
Smart Meter	Observability	Usage telemetry	Level 2
Battery Storage	Steering	Battery dispatch	Level 3
Diesel Generator	Steering	Generator operation	Level 1
EV Chargers	Observability	Charger monitoring	Level 2
EV Chargers	Steering	Charging orchestration	Level 3
Billing System	Commercial Operations	Automated billing	Level 2
Smart Relay	Steering	Service disconnection	Level 3

This allows gradual evolution toward autonomy without requiring the entire microgrid to transition simultaneously.

Implications for a Microgrid OS

A Microgrid OS designed around this framework should:

- Treat foundational capabilities as modular services
- Support mixed autonomy levels simultaneously
- Allow policy-driven escalation to humans
- Maintain secure telemetry and control channels
- Provide auditability and operational transparency
- Support standards-based interoperability
- Maintain operational safety boundaries
- Support both edge and cloud orchestration architectures

The Microgrid OS becomes the orchestration layer coordinating assets, capabilities, policies, and autonomy levels across the energy system.

Revision #4
Created 2026-05-28 13:52:36 UTC by aaron.tushabe
Updated 2026-05-28 14:48:29 UTC by aaron.tushabe