Agent-Based and Digital Twin Approaches for Green Energy Microgrid Management: A Survey

Jakub Muszyński

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Abstract

This document provides a state-of-the-art (SOTA) overview of green energy microgrid management using multi-agent systems (MAS) and digital twin (DT) technologies. Geared toward a university campus-scale deployment, such as the Warsaw University of Technology, it discusses relevant architectures, challenges, and the lessons learned from real-world experiments and recent literature. A glossary of key technical terms is included, alongside a brief comparison of common simulation tools (JADE, OpenDSS, GridLAB-D, MATPOWER). References are listed at the end.

Contents

1 Introduction

A *microgrid* is a group of interconnected loads and distributed energy resources (DERs) operating as a controllable entity with respect to the larger power grid [7]. University campuses are ideal settings for microgrid deployment due to their contained geographical area and mixed load profiles. In such environments, the integration of renewable energy sources—such as solar PV, wind turbines, or energy storage systems—can produce a *green* on-site power system.

Managing a campus microgrid requires addressing renewable intermittency, load variability, and potential isolation from the main grid (*islanding*). Two promising paradigms have emerged: **agent-based** control through *multi-agent systems* (MAS) and **digital twin** technology, which provides a virtual replica of the physical energy system for real-time simulation and predictive analysis.

This document covers:

- Architectures for MAS- and DT-based microgrid management,
- Key challenges in campus microgrids,
- Real-world experiments and lessons learned,
- A brief glossary of core technical terms,
- A high-level comparison of simulation tools (JADE, OpenDSS, GridLAB-D, and MATPOWER).

While we emphasize recent works (last 5 years), we also refer to foundational studies where relevant. The aim is to create a practical knowledge base for future work exploring closed-campus green energy grids.

2 Microgrid Context and Challenges

A campus microgrid typically includes on-site renewables, energy storage, backup generators, and flexible building loads within a defined electrical boundary. The microgrid can connect or disconnect from the main utility grid, enabling improved resilience and local optimization.

However, maintaining stable operation under high renewables penetration is nontrivial. Variations in solar irradiance or wind speed require fast response in battery dispatch or load management. When *islanded*, the microgrid becomes solely responsible for balancing supply and demand, maintaining voltage and frequency stability, and ensuring continuous power for critical loads [5].

Traditional centralized control architectures (e.g., SCADA-based) can struggle with scalability, real-time adaptability, and single-point failures as the system grows more complex. This has motivated **decentralized approaches** and high-fidelity **simulation environments** to design, test, and validate new control strategies before real-world deployment [6].

3 Agent-Based Management in Microgrids

3.1 Overview of Multi-Agent Systems

A *multi-agent system* (MAS) is a collection of autonomous, cooperative software agents that can perceive, decide, and act within an environment. Each agent in a microgrid setting (e.g., a *Solar Agent*, *Battery Agent*, *Load Agent*) focuses on local objectives but also communicates with others to achieve global goals like cost minimization or power balance [2].

Agent-based approaches are especially useful when:

- **Scalability** is needed: new resources (DERs) can be added by instantiating new agents.
- **Resilience** is a priority: if a single agent fails, others can still operate, avoiding a total system breakdown.
- **Local autonomy** is beneficial: each agent can make decisions in real time based on local measurements.

3.2 Architectures and Real-World Experiences

Typical MAS architectures follow a layered design:

1. **Device-level** (primary control): Agents represent individual devices (solar inverters, wind turbines, or batteries) and handle immediate tasks such as power output regulation.
2. **Supervisory-level** (secondary control): Agents coordinate among device-level agents to ensure stable grid operation, e.g., balancing generation and load.
3. **Tertiary-level** (economic or market layer): Agents handle optimization, such as scheduling, energy pricing, or market transactions (if relevant).

Research on campus microgrids has shown that MAS can react quickly to events (e.g., sudden solar drop) and effectively *negotiate* or *cooperate* to maintain stability [5]. In pilot simulations, *distributed agent control* avoided single-point failures, allowing microgrids to self-heal after faults [2].

However, purely decentralized agents may fail to reach a global optimum if they lack higher-level coordination or if communication reliability is poor. Further, standardizing and verifying safety for MAS-based microgrid controllers remains an ongoing area of research.

4 Digital Twin Technology for Microgrids

4.1 Concept and Architecture

A **digital twin (DT)** is a virtual replica of a physical system, continuously updated with real-time data. For a campus microgrid, the DT incorporates sensor feeds (power output, voltages, load states) into a detailed simulation model that mirrors the real system [3]. Operators and algorithms use this digital twin to:

- Test “what-if” scenarios (e.g., equipment failures) without risking actual disruption,
- Perform *predictive maintenance* by simulating upcoming issues,
- Optimize or tune control strategies in a safe environment.

A typical DT architecture involves:

1. **Physical layer:** Real devices (PV arrays, wind turbines, batteries) instrumented with IoT sensors,
2. **Communication layer:** Data pipelines streaming sensor readings to the virtual environment,
3. **Virtual/simulation layer:** High-fidelity models (e.g., power flow, dynamic response) running in quasi real time,
4. **Application layer:** Analytics, optimization, or machine-learning modules that can push recommended actions back to the physical system.

4.2 Applications and Challenges

Digital twins have successfully helped campuses detect incipient faults, evaluate expansions (e.g., adding more solar panels), and train staff for emergency conditions [5, 3]. Yet, several challenges remain:

- **Data management:** Ensuring accurate, high-frequency sensor data and aligning different sampling intervals,
- **Latency and real-time performance:** Slow or delayed model updates limit the DT’s usefulness for fast control,
- **Model maintenance:** The DT must be continuously updated to match changes in the physical microgrid,
- **Cybersecurity:** Exposing real-time data and potential control pathways to network threats.

Despite these issues, universities with a strong R&D focus have found DTs invaluable for safely experimenting with advanced control methods, including multi-agent strategies.

5 Integrating Agents and Digital Twins

Rather than treating MAS and DT as separate solutions, recent works *combine* them [9, 10]. For instance, an *agent-based digital twin* can embed software agents in the simulation model. The twin can run near real-time or accelerated scenarios to test how agents would manage the microgrid under faults, forecast errors, or unexpected load surges. When validated, the same agent code can be deployed to the real system, minimizing risk.

Conversely, an online digital twin can provide **predictive insights** to agent-based controllers. If the twin projects an upcoming shortage, it can alert relevant agents to take preemptive action (e.g., scheduling battery charging before the shortage happens). This synergy aims to harness the decentralization of MAS with the foresight of DT analytics.

6 Brief Comparison of Simulation Tools

6.1 JADE (Java Agent DEvelopment)

A middleware for building and running multi-agent systems in Java [6].

- **Strengths:** Adheres to FIPA standards, well-documented, robust messaging, widely used in academic MAS microgrid projects.
- **Limitations:** No built-in power-flow simulation; typically needs co-simulation with MATLAB/Simulink or other electrical tools.

6.2 OpenDSS (Open Distribution System Simulator)

Focuses on electrical distribution system analysis [4].

- **Strengths:** Industry-grade, handles unbalanced loads, time-series simulation for DER integration.
- **Limitations:** Limited built-in agent functionality; usually requires external scripts or co-simulation frameworks for advanced control.

6.3 GridLAB-D

An open-source simulation platform from the US Department of Energy [8].

- **Strengths:** Object-oriented, event-driven approach; can model both the electrical grid and end-use loads in detail.
- **Limitations:** Learning curve for the .glm file structure; while it has "agent" concepts, more advanced agent-based logic typically requires extensions or external coupling.

6.4 MATPOWER

A MATLAB/Octave toolbox for power flow and optimization [11].

- **Strengths:** Easy to prototype optimization algorithms, widely cited in academic research.
- **Limitations:** Primarily steady-state solver; not a real-time or event-based simulator. Needs external bridging for time-stepping or agent logic.

Note on Co-Simulation: Often, researchers combine tools (e.g., JADE + OpenDSS) to harness the strengths of each. One tool handles agent communications and decisions, while another handles the power system physics.

7 What Works & What Does Not

7.1 Successes

- **MAS Scalability and Resilience:** Adding new DERs can be done by introducing new agents; local autonomy helps avoid single-point failures [2].
- **Digital Twin Predictive Value:** DTs enable scenario testing, early detection of equipment issues, and training for operators, leading to fewer real-world disruptions [3].
- **Cost Reduction:** By carefully scheduling loads or using model-based optimization in the twin, campuses have cut energy bills and peak loads.

7.2 Limitations and Pitfalls

- **Global Optimality vs. Decentralization:** Naive agent strategies may solve local problems but miss global optima without a coordinating agent or consensus. [1]
- **Integration Overheads:** MAS + digital twins require robust communication infrastructure; mismatches in sampling rates or latency can undermine effectiveness.
- **Maintenance and Security:** Keeping a digital twin up-to-date, or ensuring multi-agent communications are secure, is nontrivial.
- **Real-World Certification:** Gaining regulatory or institutional approval for a fully agent-based controller can be complex, slowing actual deployment.

8 Glossary of Key Terms

Microgrid A localized power system that can operate independently or in tandem with the main utility grid.

Distributed Energy Resources (DERs) Decentralized generation or storage, e.g., solar PV, wind turbines, batteries, located close to the load.

Energy Management System (EMS) The software/hardware responsible for controlling and optimizing microgrid operation.

Multi-Agent System (MAS) A set of autonomous software agents collaborating to solve complex tasks. In microgrids, agents might represent DERs, loads, or supervisory controllers.

Digital Twin (DT) A real-time virtual replica of the physical microgrid, updated by sensor data, used for predictive modeling and control.

Islanded Mode When the microgrid operates disconnected from the main utility grid, requiring self-sufficiency in power generation and control.

Point of Common Coupling (PCC) The switch or breaker connecting a microgrid to the main grid.

Prosumer An entity that both produces and consumes power (e.g., a building with rooftop solar).

Hierarchical Control A control scheme often separated into primary, secondary, and tertiary layers, each addressing different timescales and objectives.

Co-Simulation Running multiple simulators or software tools in parallel (e.g., agent-based control plus power-flow simulation) to capture different system aspects.

9 Conclusions

In a campus microgrid setting, such as the Warsaw University of Technology, deploying *green* energy sources introduces volatility from solar and wind. To manage this complexity, **agent-based methods** offer decentralized, scalable control, and **digital twins** provide a virtual environment for testing and optimization. Together, they can boost resilience, reduce costs, and foster innovation. However, realizing these benefits requires attention to communication reliability, data integrity, and careful coordination between local and global objectives. As these technologies mature, we anticipate broader campus-scale microgrid deployments adopting both MAS and digital twin paradigms, laying the groundwork for more robust, sustainable energy infrastructures.

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