Minor Project Synopsis Report

DeepTech System for Intelligent Energy Coordination in Distributed Microgrids

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ABSTRACT

The global shift toward decentralized energy requires a move away from static, rule-based control toward autonomous, intelligent coordination. Existing microgrid implementations often suffer from localized inefficiencies—such as solar curtailment and battery mismanagement—due to a lack of inter-microgrid communication. This project presents a **DeepTech System for Intelligent Energy Coordination** utilizing a decentralized **Multi-Agent System (MAS)** architecture that transforms passive households into active "Prosumers."

Unlike traditional centralized models, this system deploys independent **LLM-powered agents** for each household. These agents utilize high-level reasoning to navigate complex peer-to-peer (P2P) energy markets, negotiating trades based on real-time sensor data, weather forecasts, and dynamic pricing. To bridge the gap between AI reasoning and physical safety, each home features a low-level, **event-driven orchestrator**. This orchestrator operates with near-zero latency via **MQTT**, enforcing a **10% critical energy buffer** and managing instant failovers to the main grid or local generators during supply deficits.

The project implements a hybrid data strategy: **Private SQLite** databases ensure local telemetry privacy, while a **PostgreSQL-based Central Marketplace** facilitates global indexing of energy surplus and demand. By moving the decision-making "to the edge," the system maximizes renewable self-consumption and enhances N-1 grid resiliency. Evaluation through high-fidelity simulations demonstrates that this agentic approach significantly reduces operational costs and carbon footprints compared to conventional, isolated microgrid control strategies.

Keywords: *Decentralized Multi-Agent Systems, LLM Agents, P2P Energy Trading, Real-Time Orchestration, Microgrid Resilience, Distributed Energy Resources (DER), Edge Intelligence.*

1. INTRODUCTION

The global energy sector is undergoing a paradigm shift from centralized generation to distributed, renewable-based systems. Traditional power grids, designed for unidirectional flow from massive power plants to passive consumers, are proving inadequate for the modern "Prosumer" era. Modern infrastructure increasingly features residential societies, commercial complexes, and industrial parks that generate, store, and manage their own electricity through localized networks known as **Microgrids**.

A microgrid is a localized group of interconnected loads and distributed energy resources (DERs) with clearly defined electrical boundaries that can operate in grid-connected or islanded modes. While the technology for generation (Solar PV) and storage (Lithium-ion batteries) has matured, the **coordination intelligence** governing these systems remains primitive.

Current State of Microgrid Operations

Today’s microgrids typically operate as isolated silos using static, rule-based logic. These systems rely on hard-coded thresholds such as:

- "If Battery State-of-Charge (SoC) < 20%, switch to Grid."
- "If Solar Generation > Demand, charge Battery."

These binary, "if-else" rules are inherently limited. They are non-predictive, non-adaptive, and—most critically—incapable of cross-border negotiation. In a neighborhood where one building has a solar surplus and another has a deficit, current systems fail to facilitate a trade, leading to wasted renewable energy and unnecessary grid costs.

The DeepTech Solution: Decentralized Agentic Coordination

This project proposes a transition from static control to **Autonomous Agentic Coordination**. In our architecture, every microgrid is managed by a dual-layered intelligence system:

1. **The Strategic Layer (LLM Agent):** A Large Language Model-based agent that performs high-level economic reasoning. It monitors local demand forecasts and

"negotiates" with neighboring agents on a distributed marketplace to optimize energy costs.

2. **The Tactical Layer (Event-Driven Orchestrator):** A low-level, near-zero latency controller that interfaces directly with sensors and actuators. It ensures physical safety, maintains a **10% critical energy buffer**, and manages sub-second transitions between peer-to-peer (P2P) trading, grid connectivity, and local generation.

By decoupling strategic negotiation from real-time physical execution, the system achieves a level of resilience and economic efficiency impossible with traditional centralized or rule-based models. This decentralized approach ensures privacy by keeping granular data within local **Private Databases** while only sharing high-level "Limit Orders" with the central microgrid marketplace.

2. MOTIVATION

The project is driven by the need to bridge the gap between advanced renewable hardware and reactive, siloed control software through the following factors:

2.1 Overcoming Siloed Intelligence

Current microgrids operate in isolation, leading to a "Tragedy of the Commons" where local solar energy is wasted while neighbors import expensive grid power. We aim to demonstrate that **Multi-Agent Systems (MAS)** can transform these silos into a cooperative ecosystem using LLM-driven negotiation for complex economic balancing.

2.2 Empowering the Prosumer Economy

Traditional markets treat users as passive consumers. This project motivates the transition to "Prosumers"—active participants generating revenue from surplus energy. Automated P2P marketplaces ensure community-wide cost reduction without requiring constant human intervention.

2.3 Real-Time Resilience and Islanding

Centralized grids remain fragile. We are motivated to prove that a microgrid with a zero-latency orchestrator and a **10% critical buffer** can maintain essential loads autonomously during grid failures, ensuring high-reliability "Islanded" operation.

2.4 Privacy-Preserving Decentralization

Standard smart grids compromise user privacy by centralizing granular usage data. Our architecture prioritizes **Edge Intelligence**, keeping sensitive telemetry in local Private SQLite databases and sharing only high-level trading "intents" via a central marketplace.

2.5 Technical Innovation in AI/ML

- **LLM Reasoning** for strategic economic decision-making.
- **Time-Series Forecasting** (XGBoost/LSTM) for consumption/generation.
- **Event-Driven MQTT** for real-time, low-latency control.

3. LITERATURE REVIEW

The evolution of microgrid management spans three generations: traditional control, predictive models, and decentralized agentic coordination.

3.1 Traditional and Rule-Based Control

Legacy microgrid control relies on "Droop Control" and static thresholds (Guerrero et al., 2011). While robust, these rule-based systems are "myopic," failing to anticipate weather shifts or demand spikes, which leads to inefficient energy allocation and excessive diesel reliance.

3.2 Machine Learning for Forecasting

To solve static limitations, researchers utilize RNNs and LSTM networks for high-accuracy demand and solar forecasting (Hossain et al., 2020). However, most current studies treat these forecasts as passive data rather than integrating them into active, real-time negotiation frameworks.

3.3 Multi-Agent Systems (MAS) and P2P Trading

Peer-to-Peer (P2P) trading enables microgrids to act as rational economic actors (Zhou et al., 2018). While Game Theory provides a mathematical basis for these markets, traditional MAS often lack the flexibility to process non-numerical constraints like user preferences or complex regulatory logic.

3.4 Emerging Frontier: Agentic LLMs

The latest frontier involves Large Language Models (LLMs) acting as autonomous "Reasoning Agents." LLMs excel at "Zero-Shot" coordination by interpreting natural language constraints and economic trade-offs (Zhang et al., 2024). This project bridges the gap between high-level LLM reasoning and low-level physical safety—a critical intersection missing in current literature.

4. GAP ANALYSIS

Despite the extensive research in microgrid management, several critical gaps exist between academic theory and practical, resilient implementation. This project addresses the following primary gaps:

4.1 Reasoning Gap: Rule-Based vs. Agentic Logic

Most existing microgrid controllers rely on static, "if-then" thresholds. These systems lack the cognitive flexibility to handle multi-variable scenarios, such as weighing long-term battery degradation against short-term energy arbitrage opportunities. There is a clear gap in utilizing **Natural Language Reasoning (LLMs)** to handle these strategic, non-linear economic decisions.

4.2 Latency Gap: High-Level Planning vs. Real-Time Execution

Current "intelligent" systems often suffer from "Decision Lag." If a centralized AI takes several seconds to process a trade, local voltage stability may already be compromised. Existing literature fails to provide a robust framework that decouples **High-Level Strategic Reasoning** (which is slow) from **Low-Level Deterministic Orchestration** (which is sub-second), a gap this project bridges with its dual-layered MQTT architecture.

4.3 Privacy Gap: Centralized Data vs. Edge Intelligence

Smart grid research typically assumes a centralized data-sharing model, where granular consumption patterns are sent to a single server. This creates significant privacy and security risks. There is a noticeable gap in implementing **Decentralized Data Architectures**—like our Hybrid Private SQLite model—that allow for community coordination without exposing individual household habits to a central authority.

4.4 Resilience Gap: Reactive vs. Proactive Buffering

Standard microgrid protocols are reactive; they switch to the grid only *after* a deficit occurs. Academic solutions often ignore the physical necessity of an "immediate response buffer." This project addresses the gap by implementing a **10% Mandatory Energy Buffer** and proactive grid-failover logic, ensuring N-1 resiliency during the "decision window" of the AI agent.

4.5 Integration Gap: Academic Theory vs. Deployable Prototypes

Many research papers focus on complex mathematical optimization (e.g., Mixed-Integer Linear Programming) that is difficult to deploy on standard IoT hardware. This project fills the gap by providing a **Practical DeepTech Stack** (Python, MQTT, FastAPI) that integrates forecasting, reasoning, and execution into a modular, plug-and-play architecture.

5. PROBLEM STATEMENT

Distributed microgrids are critical for sustainable energy, yet their current implementations face fundamental limitations that prevent them from operating as a cohesive, resilient ecosystem. This project addresses the following primary problems:

5.1 Static and Non-Adaptive Control Logic

Existing microgrids rely on hard-coded "if-then" thresholds that cannot adapt to changing environmental or economic conditions. Without predictive intelligence, batteries are often charged when demand is low and remain empty when demand peaks. Furthermore, the lack of inter-microgrid visibility prevents surplus energy from being shared with neighboring nodes, resulting in high grid imports and suboptimal resource allocation.

5.2 Significant Renewable Energy Wastage

A critical mismatch exists between the peak of solar generation (midday) and the peak of household demand (evening). Without intelligent, coordinated trading, excess solar energy is curtailed (wasted) once local batteries reach capacity. In typical residential settings, several megawatt-hours of clean energy are lost daily because no mechanism exists to identify and export surplus to neighbors in need.

5.3 High Decision Latency and "Control Lag"

Integrating AI into power systems introduces "Decision Lag"—the time required for a model to process data and return a strategy. In energy networks, even a few seconds of delay during a demand spike can lead to voltage instability or localized blackouts. Current systems lack a mechanism to bridge the gap between slow high-level reasoning and sub-second physical actuation.

5.4 Privacy Vulnerabilities in Centralized Grids

Modern smart grid architectures often require homes to transmit granular, second-by-second consumption data to a central authority for coordination. This exposes sensitive household habits and creates a single point of failure. There is a lack of decentralized frameworks that allow for community-level coordination while keeping granular sensor data strictly local and private.

5.5 Poor Resilience and Lack of Proactive Buffering

Microgrids often lack the intelligence to "pre-stage" reserves for anticipated outages. Current failover strategies are reactive; they wait for a deficit to occur before switching to backup sources. Without a proactive energy buffer and autonomous islanding capabilities, microgrids remain vulnerable to cascading failures and unnecessary power cutoffs during grid instability.

6. OBJECTIVES

The primary objective of this project is to design and prototype a decentralized, agent-based coordination system that enables autonomous energy trading and resilient microgrid management. The specific objectives are as follows:

1. **Architecture Design:** To design a multi-agent system (MAS) architecture where each home acts as an autonomous "Prosumer" agent, decoupling high-level strategic reasoning from low-level physical execution.
2. **Edge Data Layer Development:** To implement a localized data acquisition system using **Private SQLite databases** for each home to store granular sensor telemetry (load, solar generation, battery SoC) while maintaining user privacy.
3. **Predictive Modeling:** To develop and train machine learning models (e.g., XGBoost or LSTM) for accurate short-term forecasting of individual household consumption and local renewable generation.
4. **Strategic LLM Agent Integration:** To integrate a Large Language Model (LLM) as a strategic reasoning agent capable of interpreting market data and forecasts to negotiate Peer-to-Peer (P2P) energy trades via a central marketplace.
5. **Real-Time Orchestration:** To build an event-driven **Low-Level Orchestrator** using MQTT that enforces a mandatory **10% energy buffer**, manages instant grid-failover, and executes trade commands with near-zero latency.
6. **Decentralized Marketplace Implementation:** To develop a central "Bulletin Board" marketplace using **PostgreSQL** that allows agents to post and discover energy buy/sell orders without compromising private telemetry.
7. **System Evaluation:** To evaluate the system’s performance through high-fidelity simulations, measuring its impact on renewable energy self-consumption, reduction in grid dependency, and N-1 resilience during simulated outages.

7. TOOLS / PLATFORM USED

The project leverages a specialized DeepTech stack designed to handle high-level AI reasoning, real-time messaging, and decentralized data management.

7.1 Programming Languages and Core Frameworks

- **Python 3.11+**: The primary language for building the multi-agent system, forecasting models, and orchestration logic.
- **Asynchronous I/O (Asyncio)**: Utilized within Python to manage non-blocking concurrent operations, essential for handling simultaneous MQTT streams and API calls.

7.2 Intelligence and Forecasting Layer

- **LLM API (Gemini 2.5 Flash)**: Functions as the "Strategic Brain" for each home agent, utilizing structured JSON output mode for autonomous economic negotiation.
- **XGBoost / Scikit-learn**: Used for developing local time-series forecasting models to predict household energy consumption and solar generation.

7.3 Communication and Messaging (The Nervous System)

- **MQTT (Eclipse Mosquitto)**: An ultra-lightweight messaging protocol used for real-time, event-driven communication between home sensors, the orchestrator, and the marketplace.

7.4 Data Management (Hybrid Architecture)

- **SQLite**: A lightweight, serverless database used as the **Private Data Layer** for each household to store granular, sensitive sensor telemetry locally.
- **PostgreSQL with TimescaleDB**: The **Central Marketplace Layer** used to store the public order book, trade history, and system-wide performance metrics.

7.5 API and Integration Layer

- **FastAPI**: A high-performance web framework used to build the Marketplace API and facilitate communication between the agents and the central database.

8. METHODOLOGY

The methodology for this DeepTech system is structured to move beyond traditional centralized control toward a decentralized Multi-Agent System (MAS). The approach is divided into seven distinct phases, focusing on the synergy between high-level reasoning and real-time physical orchestration.

8.1 Decentralized Multi-Agent System (MAS) Design

The core of the methodology involves designing a hierarchical agentic architecture for each household node. This is split into two specialized layers:

- **The Strategic Layer (LLM):** An asynchronous agent that utilizes LLM APIs to process historical trends and marketplace data to formulate long-term economic strategies.
- **The Tactical Layer (Orchestrator):** A deterministic, Python-based controller that executes MQTT commands, enforces the 10% safety buffer, and manages sub-second hardware failovers. By decoupling these layers, the system ensures that high-level "reasoning" (which is computationally intensive and has higher latency) never compromises low-level "safety" (which must be instantaneous).

8.2 Data Acquisition and Edge Privacy

To ensure data sovereignty, each node implements an **Edge Data Strategy**:

- **Sensor Ingestion:** Local energy sensors (simulated or IoT-based) publish raw telemetry (Wattage, Voltage, SoC) to an MQTT broker.
- **Private Storage:** A local Python script subscribes to these streams and persists the data into a **Private SQLite Database**. This ensures that granular consumption habits never leave the home's local network.
- **Market Summarization:** Only high-level, anonymized metadata (e.g., "Home_ID_102 has 2kW surplus available") is extracted and sent to the central PostgreSQL Marketplace.

8.3 Predictive Modeling (The Senses)

The system utilizes supervised machine learning to give each agent "foresight":

- **Load Forecasting:** Training XGBoost or LSTM models on local consumption data to predict demand spikes over a 24-hour horizon.
- **Generation Forecasting:** Integrating weather API data with historical PV (Solar) performance to estimate future renewable availability.
- **Uncertainty Quantization:** The output of these models includes a confidence score, allowing the LLM agent to make "risk-aware" decisions (e.g., "I won't sell my energy because there is a 40% chance of a demand spike in an hour").

8.4 The Agentic Reasoning Loop

Every 10–15 minutes (or upon a significant event), the Home Agent initiates a reasoning cycle:

1. **State-to-Prompt Synthesis:** The orchestrator converts current sensor data, market rates, and forecasts into a structured natural language prompt.
2. **LLM Inference:** The LLM API evaluates the prompt to determine the optimal strategy—balancing cost reduction, battery health, and grid independence.
3. **JSON Command Generation:** The LLM outputs a strictly formatted JSON command (e.g., `{"action": "BUY", "target": "Peer_B", "amount": "1.5kWh"}`).

8.5 Event-Driven Orchestration and Safety Buffer

The low-level orchestrator acts as a "Physical Safety Governor." It manages the **Fast-Lane** of the system:

- **Continuous Buffer Maintenance:** The orchestrator continuously monitors the Battery State-of-Charge (SoC). If the SoC hits the mandatory **10% threshold**, it instantly blocks further discharges and initiates a grid-failover, regardless of what the LLM instructs.
- **MQTT Handshaking:** For P2P trades, the orchestrator performs a direct "Handshake" with the neighboring orchestrator to confirm energy availability before opening the (simulated) circuit.
- **Latency Mitigation:** By maintaining the current system state in RAM, the orchestrator achieves near-zero latency for emergency switching.

8.6 P2P Marketplace and Order Book Integration

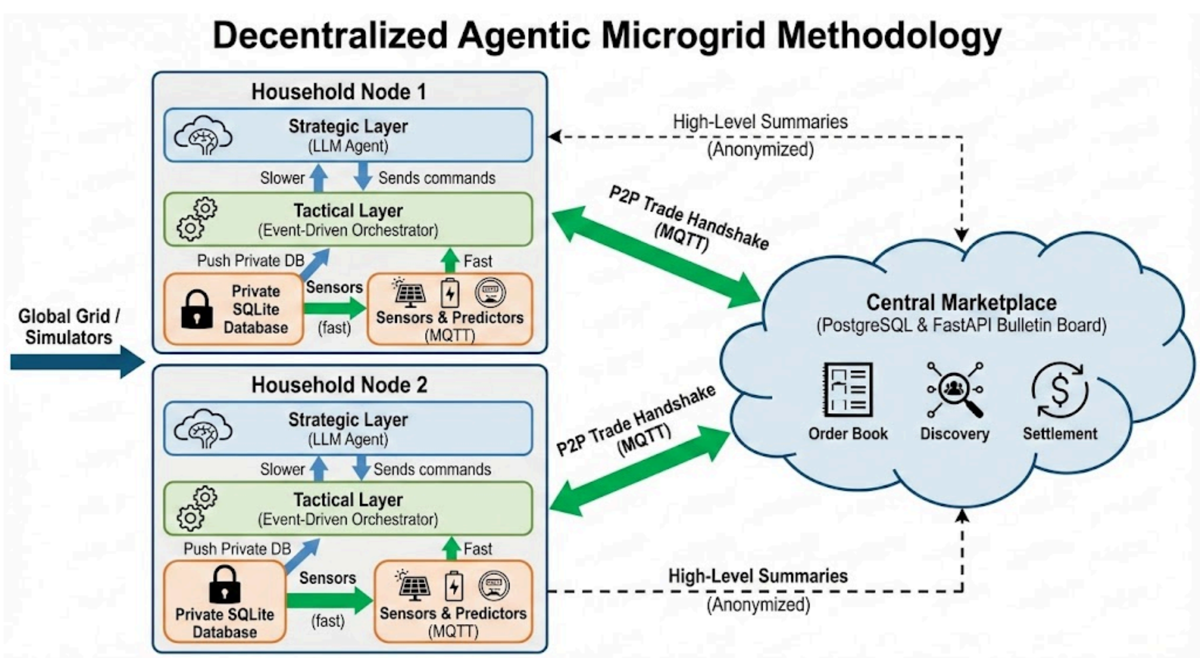
A central Marketplace API (built with FastAPI and PostgreSQL) serves as the "Bulletin Board":

- **Order Placement:** Agents with a surplus post "Limit Orders" defining the amount and price.
- **Discovery:** Searching for the best local deal based on price and physical proximity.
- **Settlement:** Once a trade is confirmed via MQTT, the marketplace records the transaction for virtual billing and system-wide usage metrics.

8.7 Simulation and Evaluation Metrics

The prototype will be evaluated using high-fidelity simulations with the following criteria:

- **Renewable Self-Consumption:** Measuring the percentage of solar energy used locally vs. curtailed.
- **N-1 Resilience:** Testing the system's ability to maintain power to critical loads during a simulated total grid failure.
- **Control Latency:** Analyzing the time delay between a demand spike and a corrective switching action.



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