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DeepTech System for Intelligent Energy Coordination in Distributed Microgrids

Pre-Final Year Project Synopsis
Submitted by

ROLL	NAME
2301730191	ABHINAV KUMAR
2301730179	ROHIT RAJ
2301730152	NAMAN JOSHI
23021730141	ADITYA SUMAN

Faculty Mentor: Ms. Suman

Project Overview

Rethinking Microgrid Coordination

- **Decentralized Agentic Framework**: Transitions from a traditional central controller to a multi-agent system where microgrids act as autonomous "Prosumers," negotiating energy trades in a P2P marketplace.
- **Dual-Layer Intelligence Model**: Decouples high-level strategic reasoning from physical execution.
  - **Strategic Layer**: LLM-powered agents for market negotiation, planning and user interaction.
  - **Tactical Layer**: Event-driven MQTT Orchestrators for zero-latency safety and control.
- **Advanced Predictive Analytics**: Integrates LSTM and XGBoost forecasting for load and generation, enabling agents to proactively schedule resources instead of reacting to current states.
- **N-1 Resiliency & Safety**: Implements a mandatory 10% critical energy buffer within the low-level orchestrator to ensure immediate power availability during grid failover or "decision lag".
- **Privacy-by-Design**: **Edge Intelligence** with local Private SQLite databases, ensures granular usage data remains in the home.
- **System Impact**: Designed for collaborative communities to maximize renewable self-consumption and significantly reduce operational costs.

Specific Objectives

- **Autonomous Peer-to-Peer Trading**: To implement a decentralized marketplace where LLM-powered agents negotiate energy trades autonomously based on local surplus and community demand.
- **Dual-Layered Real-Time Control**: To develop a coordination logic that separates high-level strategic reasoning (LLMs) from sub-second physical actuation (MQTT Orchestrators).
- **N-1 Resiliency & Safety Buffer**: To enforce a mandatory 10% critical energy reserve and automated grid-failover protocols to ensure power continuity during "decision lag" or grid outages.
- **High-Accuracy Forecasting**: To achieve a 15–20% improvement in resource scheduling by integrating XGBoost/LSTM models for individual household consumption and solar generation.
- **Privacy-Preserving Edge Intelligence**: To design a data layer that keeps granular usage telemetry within local **Private SQLite databases**, sharing only high-level intents for market coordination.
- **Sustainability & Cost Optimization**: Enables sustainable microgrid system with cost optimization for every node.

Key Features

- **Agentic Strategic Reasoning**: Autonomous LLM-powered "brains" that handle high-level economic negotiation and long-term trading strategy.
- **Zero-Latency MQTT Orchestrator**: An event-driven tactical governor for sub-second hardware switching and deterministic safety enforcement.
- **Mandatory 10% Safety Buffer**: A proactive energy reserve that ensures N-1 resiliency and power continuity during "decision lag" or sudden demand spikes.
- **Privacy-Preserving Edge Data**: A hybrid storage architecture using Private SQLite (local telemetry) and **PostgreSQL** (public marketplace metadata).
- **Predictive Foresight Engine**: Integrated XGBoost and LSTM models for high-accuracy, 24-hour demand and renewable generation forecasting.
- **Autonomous Grid Failover**: Seamless, sub-millisecond transitions between P2P trading, grid connectivity, and local storage to prevent blackouts.

Project Use Cases & Scope

Target Use Cases

- **Campus Microgrid Clusters**: Hostels, academic blocks, and labs exchanging energy via LLM agents to reduce campus-wide diesel usage and grid imports.
- **Prosumer Industrial Estates**: Coordinated operation of process loads, rooftop PV, and shared battery storage to lower peak demand charges and maximize self-consumption.
- **Utility Grid Support**: Providing ancillary services like frequency support and black-start capability to the main distribution company during regional instabilities.

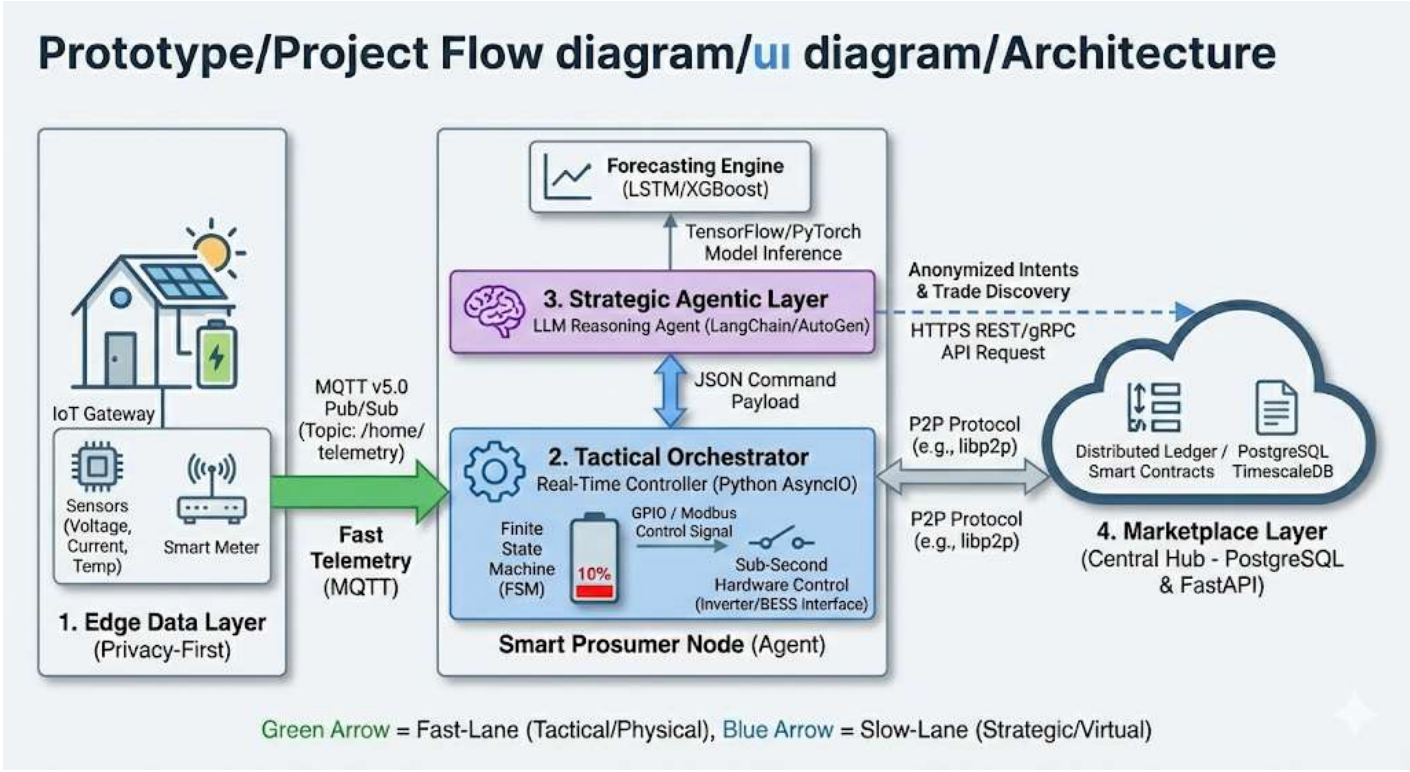
Project Scope

- **Intelligence Layer**: Developing high-level LLM agents for autonomous P2P negotiation and XGBoost/LSTM models for 24h predictive forecasting.
- **Control Layer**: Implementing a sub-second MQTT-based "Orchestrator" with a mandatory 10% safety buffer for N-1 hardware resiliency.
- **Data Layer**: Designing a hybrid privacy-centric architecture (Edge-based SQLite and centralized PostgreSQL marketplace).
- **Simulation Environment**: A functional prototype simulating 3–5 interconnected microgrid nodes (focusing on EMS software logic, not hardware fabrication).

Prototype/Project Flow diagram/Architecture

- **Edge Data Layer (Privacy-First)**: Ingests real-time telemetry (Voltage, Current, SoC) via **MQTT** into local **Private SQLite** databases. This ensures "Privacy-by-Design," as granular sensor data remains strictly at the node, preventing the exposure of household occupancy patterns to the cloud.
- **Tactical Orchestrator (Safety Governor)**: A deterministic controller that serves as the system's "Fast-Lane." It enforces the **10% critical energy buffer** and executes sub-second hardware switching. This layer ensures N-1 resiliency by managing instant grid-failover if the LLM's strategic "decision lag" exceeds physical safety windows.
- **Strategic LLM Agent (Reasoning Layer)**: Operates in the "Slow-Lane," processing **LSTM/XGBoost** forecasts and market trends. It utilizes Large Language Models to reason through complex economic trade-offs—such as battery health vs. arbitrage profit—issuing strategic directives via structured JSON commands.
- **Central Marketplace (Anonymized Hub)**: A **PostgreSQL-based** "Bulletin Board" where agents post high-level energy surplus/deficit "intents." It facilitates peer discovery and trade settlement without requiring nodes to share sensitive, raw telemetry, optimizing the community-wide energy balance.
- **Dual-Loop Feedback Synchronization**: Establishes a continuous handshake between high-level reasoning and low-level execution. The Orchestrator provides the LLM with "Safe Operating Windows," while the LLM provides the Orchestrator with "Economic Setpoints," ensuring a stable yet profitable microgrid ecosystem.

Prototype/Project Flow diagram/Architecture



Data & Resources

Data Sources

- **Kaggle Dataset**: High-resolution (15-min) load data for demand modeling.
- **Environmental Telemetry**: Real-time solar irradiance and temperature via weather APIs.

Software & Intelligence Stack

- **AI Frameworks**: PyTorch for forecasting, FSM for orchestration and LLM for reasoning.
- **Communication**: MQTT (Mosquitto) for low-latency, event-driven control signaling.
- **Hybrid Databases**: Local SQLite (Privacy-first) and Centralized PostgreSQL (Marketplace).
- **Backend Logic**: FastAPI for asynchronous P2P trade discovery and settlement.

Prototyping & Simulation

- **Power System Emulators**: Pandapower and Simulink for high-fidelity electrical modeling.
- **System Scale**: Orchestrated framework simulating a 5-10 node microgrid homes.

Methodology

Methodology & Implementation Roadmap

- **Phase 1: Edge & Data Setup**
  - Establishing the **MQTT backbone** and local **SQLite** nodes for privacy-centric telemetry.
- **Phase 2: Predictive Engine Training**
  - Developing **LSTM and XGBoost models** for high-accuracy 24h demand and solar forecasting.
- **Phase 3: Tactical Orchestrator Logic**
  - Coding the deterministic safety governor to enforce the **10% critical buffer** and failover.
- **Phase 4: Strategic Agentic Marketplace**
  - Integrating **LLM-based P2P negotiation** and a centralized **PostgreSQL** hub for trade settlement.
- **Phase 5: Simulation & KPI Validation**
  - Deploying a **3–5 node Docker cluster** to evaluate resiliency, cost savings, and renewable utilization.

Expected Results & Impact

Expected Results & Impact

- **Optimized Renewable Utilization**: Achieving **renewable self-consumption** by synchronizing agentic P2P trades with peak solar generation windows.
- **Economic Cost Reduction**: Targeted **reduction** in community energy expenditure through intelligent arbitrage and peak-shaving strategies.
- **Enhanced System Reliability**: Seamless **sub-second failover** and zero downtime during local grid outages, guaranteed by the mandatory **10% safety buffer**.
- **High-Accuracy Forecasting**: Significant improvement in predictive performance, targeting a low **Mean Absolute Percentage Error (MAPE)** for load and generation.
- **Privacy-Preserving Intelligence**: Demonstration of a **zero-leakage edge architecture**, ensuring sensitive household telemetry never leaves the local node.
- **Sustainability & Scalability**: A reduction in community carbon footprint and a proven software blueprint for autonomous, decentralized smart city energy networks.

Project Timeline

Project Timeline & Milestones

- **Month 1: System Design & Data Acquisition**
  - Literature review, architecture finalization, and preprocessing of smart meter/weather datasets.
- **Month 2: Infrastructure & Predictive Modeling**
  - Deployment of **MQTT/SQLite** backbone and training of **LSTM/XGBoost** forecasting engines.
- **Month 3: Agent Logic & Market Integration**
  - Development of the **Tactical Orchestrator** and **LLM negotiation agents** with a PostgreSQL hub.
- **Month 4: Simulation, Testing & Evaluation**
  - **3–5 node Docker simulation**, N-1 resiliency stress testing, and final KPI performance analysis.

THANK YOU