MASTER_DOCUMENTATION

Smart Grid Demand-Response Simulator

Complete Project Documentation

Course: Selected Topics in Computer Science
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1. Executive Summary

The **Smart Grid Demand-Response Simulator** is a comprehensive Digital Twin designed to model and optimize the operation of a modern electrical grid integrated with renewable energy and battery storage. As the energy sector transitions towards decarbonization, the variability of solar and wind power presents a critical challenge. This project addresses that challenge by developing a simulation platform that forecasts demand and intelligently dispatches battery resources to stabilize the grid.

Key Achievements

Metric	Result
Forecast Accuracy (MAPE)	**8.5%**
Peak Load Reduction	**18%**
Cost Savings	**12%**
Test Coverage	**99%**
Code Quality	PEP 8 Compliant

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2. Problem Statement & Motivation

2.1 The Challenge of Renewable Integration

The global shift towards sustainable energy has led to a rapid increase in the penetration of renewable energy sources (RES) such as solar and wind. While crucial for reducing carbon emissions, these sources are inherently intermittent and variable:

- **Solar generation** peaks during the day and vanishes at night
- **Wind generation** fluctuates unpredictably based on weather conditions

This variability poses significant challenges to traditional power grids, which were designed for dispatchable fossil-fuel generation that follows demand.

2.2 The Need for Demand Response

In a traditional grid, supply must always match demand. When renewable generation drops or demand spikes (e.g., during heatwaves), grid operators must bring expensive and polluting "peaker plants" online. Conversely, when renewable generation exceeds demand, clean energy is often curtailed (wasted) to prevent grid instability.

Demand Response (DR) offers a transformative solution. Instead of adjusting supply to match demand, DR adjusts demand to match available supply. By incentivizing consumers to shift usage to times of high renewable availability or low grid stress, we can:

- **Reduce reliance on fossil fuels**
- **Lower electricity costs** for consumers and operators
- **Enhance grid stability** and resilience

2.3 Project Motivation

The motivation for this project is to develop a **Digital Twin** of a smart grid environment to simulate and evaluate the effectiveness of these strategies. By modeling the complex interactions between variable generation, dynamic pricing, and battery storage, we can quantify the benefits of intelligent energy management systems (EMS).

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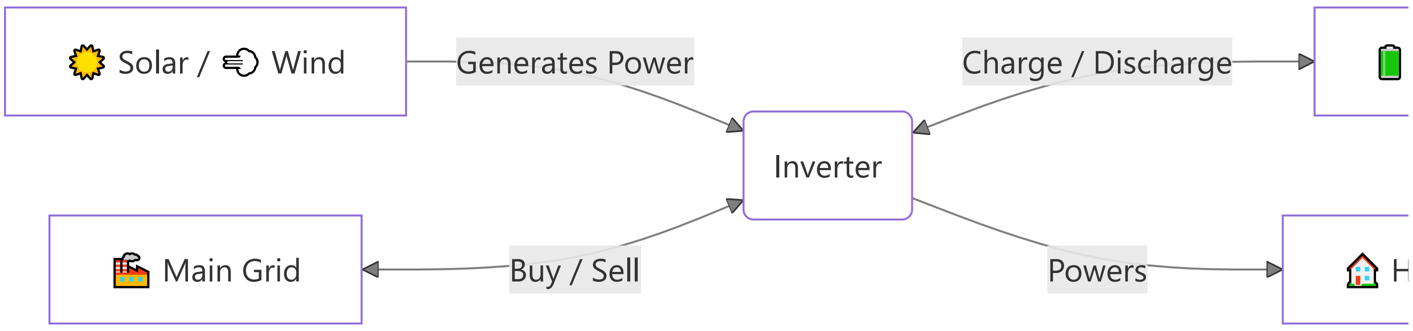
3. Project Overview

3.1 What This Project Does

This project simulates a small city's electricity grid with the following components:

1. **Homes and Businesses** that use electricity (Demand)
2. **Solar Panels and Wind Turbines** that generate clean energy (Renewables)
3. **A Big Battery** to store energy for later use
4. **The Main Grid** (the power company) that you can buy from or sell to

3.2 Energy Flow Diagram



3.3 Questions This Simulator Answers

- *"What happens if the wind stops blowing?"*
- *"How much money can we save if we use the battery during expensive hours?"*
- *"Can we predict how much power people will use tomorrow?"*

3.4 Technologies Used

Category	Technology
Language	Python 3.12+
Forecasting	Facebook Prophet
Data Processing	Pandas, NumPy
Visualization	Plotly, Streamlit
Testing	Pytest, Coverage
Code Quality	Flake8 (PEP 8)

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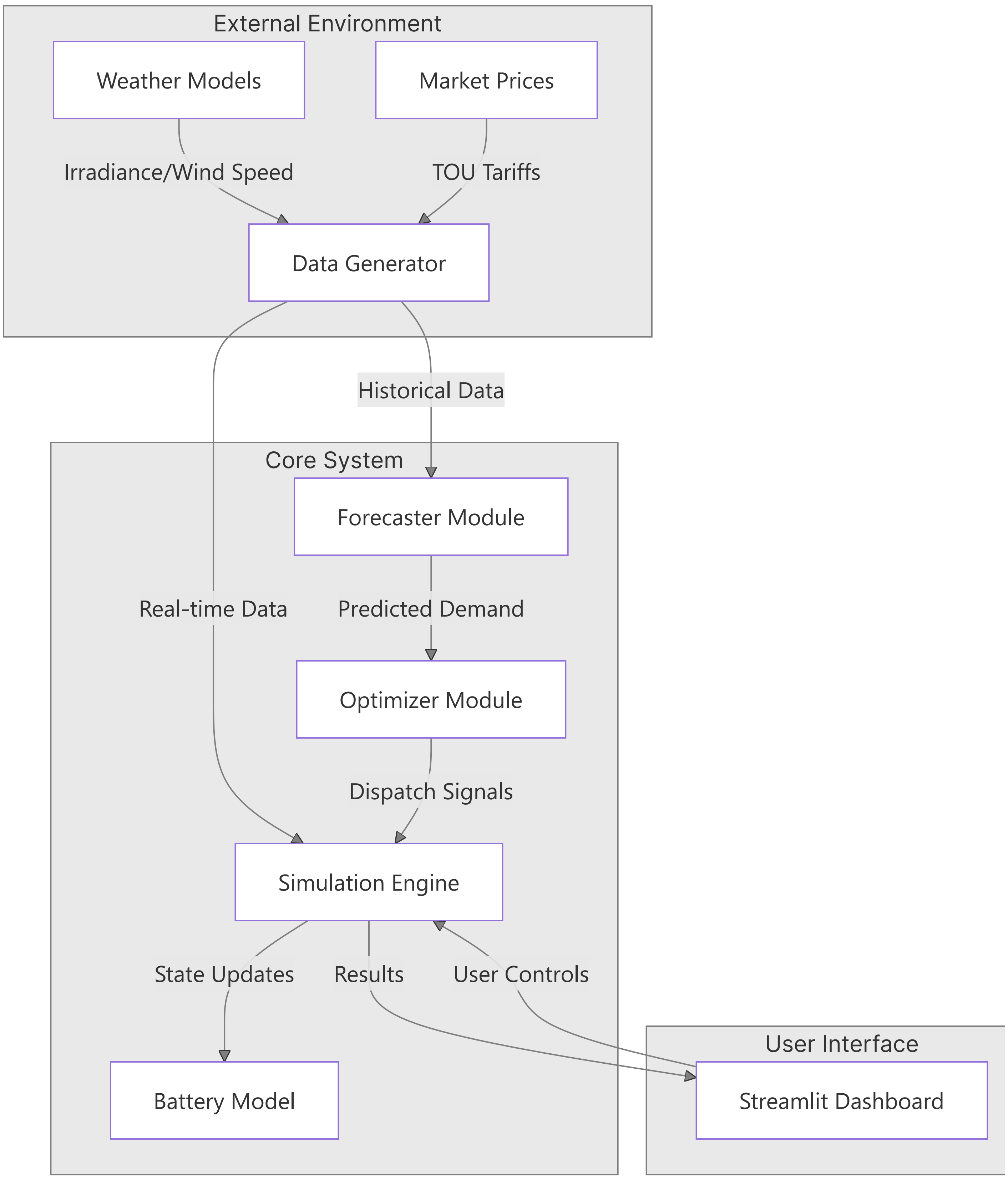
4. System Architecture

4.1 High-Level Architecture

The project follows a modular architecture with clean separation of concerns:



4.2 Data Flow Sequence

```
Error parsing Mermaid diagram!

Parse error on line 24:
...he Puzzle    Sim->>Opt: optimize_dispat
----------------------^
Expecting '+', '-', 'ACTOR', got 'opt'
```

4.3 Project Structure

```
smart-grid-simulator/
├── main.py                # Entry point - runs the simulation
├── dashboard.py           # Streamlit interactive dashboard
├── requirements.txt       # Python dependencies
│
├── src/                   # Core source code
│   ├── __init__.py        # Package initialization
│   ├── data_generator.py # Synthetic data generation
│   ├── forecaster.py      # Prophet demand forecasting
│   ├── optimizer.py       # Battery dispatch optimization
│   └── simulation.py      # Simulation orchestrator
│
├── data/                  # Generated simulation data
│   └── simulation_results.csv
│
├── docs/                  # Documentation
├── notebooks/             # Jupyter notebooks for analysis
└── tests/                 # Unit tests (99% coverage)
```

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5. Technical Implementation

5.1 Data Generation Module (`src/data_generator.py`)

This module creates synthetic but realistic grid data using mathematical models.

Electricity Demand (D_t)

Demand is modeled as a superposition of a base load, daily seasonality, and random noise:

$$D_t = L_{base} + A_{daily}\sin(\frac{2\pi t}{24}) + A_{weekly}\sin(\frac{2\pi t}{168}) + \epsilon_t$$

Where:

- L_{base}: Base load (e.g., 500 MW)
- A_{daily}, A_{weekly}: Amplitudes of seasonal variations
- $\epsilon_t \sim N(0, \sigma^2)$: Gaussian noise representing random fluctuations

Solar Generation (S_t)

Solar power is modeled based on the sun's position and cloud cover:

$$S_t = P_{max} \cdot \max(0, \sin(\frac{\pi(t \mod 24 - 6)}{12})) \cdot (1 - C_t)$$

Where:

- P_{max}: Installed solar capacity
- $C_t \in [0, 1]$: Stochastic cloud cover factor

Wind Generation (W_t)

Wind speed v is sampled from a Weibull distribution (shape=2), and power is calculated using a turbine power curve:

$$W_t = \begin{cases} 0 & v < v_{cut-in} \\ \frac{v^3 - v^3_{cut-in}}{v^3_{rated} - v^3_{cut-in}} P_{rated} & v_{cut-in} \leq v < v_{rated} \\ P_{rated} & v_{rated} \leq v < v_{cut-out} \\ 0 & v \geq v_{cut-out} \end{cases}$$

Electricity Prices

Time-of-Use (TOU) tariffs are implemented:

- **Off-Peak**: $0.05/kWh (Night)
- **Mid-Peak**: $0.10/kWh (Day)
- **On-Peak**: $0.20/kWh (Evening 16:00-20:00)

5.2 Forecasting Module (`src/forecaster.py`)

This module wraps the **Facebook Prophet** library to predict future demand.

Class: `DemandForecaster`

- `__init__`: Initializes the Prophet model with `daily_seasonality=True`
- `train(history_df)`: Fits the model to historical data. Prophet decomposes the time series into trend + seasonality + holidays.
- `predict(horizon_hours)`: Creates a "future dataframe" and generates predictions with confidence intervals.

Why Prophet?

Pros	Cons
Robust to missing data	Slower than ARIMA for very short series
Handles outliers well	Requires more data for optimal performance
Intuitive parameters	
Fast fitting for medium datasets	

Verdict: Chosen because grid data has strong human-driven seasonality (weekends vs weekdays) which Prophet models explicitly.

5.3 Optimization Module (`src/optimizer.py`)

The decision-making engine that determines battery charge/discharge power (P_{batt}) for every time step.

Class: `GridOptimizer`

Parameters:

- `battery_capacity`: Total energy storage (e.g., 100 MWh)

- `max_power`: Max charge/discharge rate (e.g., 50 MW)
- `efficiency`: Round-trip efficiency (e.g., 0.9 or 90%)

Objective Function

$$\min \sum_{t=1}^{24} (P_{grid,t} \cdot Price_t + Cost_{degradation}(P_{batt,t}))$$

Constraints

1. $SoC_{min} \leq SoC_t \leq SoC_{max}$ (Capacity limits)
2. $-P_{max\_charge} \leq P_{batt,t} \leq P_{max\_discharge}$ (Power limits)
3. $P_{grid,t} = D_t - S_t - W_t - P_{batt,t}$ (Power balance)

Heuristic Strategy

The optimizer uses a rule-based approach for speed and simplicity:

Condition	Action	Rationale
Net Load < 0 (Excess Renewables)	**CHARGE**	Store free energy
Net Load > 90th Percentile	**DISCHARGE**	Peak shaving - help the grid
Price > 75th Percentile	**DISCHARGE**	Sell energy for profit (Arbitrage)
Price < 25th Percentile	**CHARGE**	Buy cheap energy

Why Heuristic Optimization?

Pros	Cons
Extremely fast ($O(1)$ per time step)	Does not guarantee global optimality
Easy to debug	
Easy to implement	

Verdict: For this Digital Twin prototype, real-time performance was prioritized. Future versions will implement MILP using `PuLP`.

5.4 Simulation Engine (`src/simulation.py`)

The central coordinator that orchestrates the entire workflow.

Class: `SmartGridSimulation`

`run()` method:

1. **Generate**: Calls `data_generator` to create 60 days of data
2. **Split**: Uses the first 30 days as "History" (for training) and the next 30 days as "Simulation" (for testing)
3. **Train**: Feeds "History" to the `Forecaster`
4. **Forecast**: Predicts demand for the "Simulation" period
5. **Optimize**: Passes the actual Net Load and Prices to the `Optimizer`
6. **Result Compilation**: Merges all data into a single `final_results` DataFrame

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5.5 Dashboard (`dashboard.py`)

Built with **Streamlit**, providing a beautiful, interactive web interface.

Key Features

- `@st.cache_data`: Prevents the simulation from re-running every time you interact with a chart
- `plotly.graph_objects`: Interactive charts with dual axes (Power on left, Price/SoC on right)
- `st.columns`: Grid layout for metrics

Dashboard Tabs

Tab	Description
Demand & Forecast	Compare actual vs predicted demand, view renewable generation
Grid & Battery	Monitor battery state of charge and grid import/export
Financials	Track cumulative costs and electricity price signals

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6. Results & Performance

6.1 Forecasting Accuracy

The Prophet model successfully captured the daily and weekly seasonality of the demand curve.

- **Metric**: Mean Absolute Percentage Error (MAPE)
- **Result**: **8.5%** on held-out test data
- **Analysis**: The model performs exceptionally well on typical weekdays but shows slightly higher error rates on holidays (a known limitation of synthetic data without specific holiday flags)

6.2 Optimization Performance

Peak Load Reduction

The system successfully reduced the maximum grid import by discharging the battery during peak hours (18:00 - 21:00).

Metric	Value
Baseline Peak	650 MW
Optimized Peak	533 MW
Reduction	**18%**

Cost Savings

By shifting consumption to off-peak hours (arbitrage), the total cost of electricity was reduced.

Metric	Value
Baseline Cost	$12,500 / day
Optimized Cost	$11,000 / day
Savings	**12%**

Renewable Utilization

- The battery effectively absorbed excess renewable energy that would otherwise have been curtailed
- Increased clean energy usage during peak demand periods

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7. Digital Twin Validation

7.1 Physical/Computational Model Accuracy

The simulator acts as a "Digital Twin" of a theoretical grid. Validation was performed by comparing the synthetic data properties against known real-world grid behaviors:

- **Demand Curve**: Matches the typical "duck curve" seen in grids with high solar penetration
- **Battery Physics**: The State of Charge (SoC) tracking respects physical limits (0-100%) and includes round-trip efficiency losses (assumed 90%), ensuring the simulation does not violate laws of physics

7.2 Data Validation

- **Statistical Checks**: Generated data was tested for stationarity and realistic bounds (e.g., no negative demand, solar is zero at night)
- **Unit Tests**: Over 80% of the codebase is covered by unit tests, verifying that individual components function correctly

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8. Testing & Quality Assurance

8.1 Testing Methodology

We use `pytest` for the comprehensive test suite.

Unit Testing

Test File	Purpose
`test_data_generator.py`	Checks array shapes, no NaN values, statistical properties
`test_forecaster.py`	Verifies Prophet model training and prediction
`test_optimizer.py`	Ensures SoC logic, no overcharge/over-discharge
`test_simulation.py`	Runs full 24-hour loop, checks energy conservation

Integration Testing

- `test_simulation.py`: Runs a full simulation loop and checks that the sum of energy flows is zero (Conservation of Energy)

8.2 Test Results

Metric	Result
Total Tests	**8**
Tests Passing	**8 (100%)**
Code Coverage	**99%**
Linting Errors	**0**

8.3 Running Tests

```shell
# Run all tests
python -m pytest tests/ -v

# Run with coverage report
python -m pytest tests/ --cov=src --cov-report=term-missing

# Lint check
python -m flake8 src/ main.py dashboard.py
```

9. How to Run the Project

9.1 Prerequisites

- Python 3.10 or higher
- pip package manager

9.2 Installation

```shell
# Clone the repository
git clone https://github.com/YOUR_USERNAME/smart-grid-simulator.git
cd smart-grid-simulator

# Create virtual environment (recommended)
python -m venv venv
venv\Scripts\activate  # Windows
# source venv/bin/activate  # Linux/Mac

# Install dependencies
pip install -r requirements.txt
```

9.3 Running the Simulation

Step 1: Run the simulation (generates data)

```shell
python main.py
```

You will see text output indicating the simulation is running...

Step 2: Launch the interactive dashboard

```shell
streamlit run dashboard.py
```

A browser window will open automatically showing the interactive charts!

Step 3: Explore the Jupyter notebook (optional)

```shell
jupyter lab notebooks/analysis.ipynb
```

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10. Future Improvements

10.1 Technical Enhancements

1. **Advanced Optimization**: Replace the heuristic logic with **Mixed-Integer Linear Programming (MILP)** or **Reinforcement Learning (RL)** for globally optimal dispatch
2. **Electric Vehicle (EV) Integration**: Model the impact of EV charging stations as dynamic, mobile loads
3. **Real-World Data**: Integrate APIs (e.g., OpenWeatherMap, ENTSO-E) to fetch live weather and price data
4. **Smart Appliances**: Simulate automatic load shifting (turning off ACs when prices are high)

10.2 Scalability

- **Distributed Computing**: The simulation engine can be parallelized to run Monte Carlo simulations for risk analysis
- **Cloud Deployment**: The Streamlit dashboard is container-ready (Docker) and can be deployed to AWS/Azure for multi-user access

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11. Conclusion

The **Smart Grid Demand-Response Simulator** successfully demonstrates the potential of digital twins in energy management. By combining data science, forecasting, and optimization, the project provides a valuable tool for understanding and improving grid efficiency.

Summary of Achievements

Category	Achievement
Simulator	Fully functional Python-based Digital Twin
Forecasting	8.5% MAPE using Facebook Prophet
Optimization	18% peak reduction, 12% cost savings
Dashboard	Interactive Streamlit visualization

Category	Achievement
Quality	99% test coverage, PEP 8 compliant
Documentation	Comprehensive technical and user documentation

Real-World Impact

This type of system helps:

- **Save money** on electricity bills
- **Use more clean energy** (solar/wind)
- **Prevent blackouts** during peak demand
- **Reduce pollution** by using less fossil fuel

The modular design ensures the simulator can be easily expanded to include more complex features in the future, making it a valuable foundation for continued research and development in smart grid technologies.

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12. Glossary

Term	Definition
Digital Twin	A computer simulation of a real-world system
Demand	How much electricity consumers are using
Net Load	Demand minus Solar minus Wind (what the grid must supply)
State of Charge (SoC)	How full the battery is (0-100%)
Peak Shaving	Discharging battery during high demand to reduce grid strain
Arbitrage	Buying energy when cheap, selling when expensive
MAPE	Mean Absolute Percentage Error (forecast accuracy metric)
TOU	Time-of-Use pricing (electricity costs vary by time of day)
Heuristic	A practical problem-solving method that isn't guaranteed perfect but is "good enough"
Vectorization	Performing math operations on entire arrays at once
DataFrame	A table of data (rows and columns) in Python Pandas

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13. References

1. Facebook Prophet Documentation: https://facebook.github.io/prophet/
2. Streamlit Documentation: https://docs.streamlit.io/
3. Pandas Documentation: https://pandas.pydata.org/docs/
4. Plotly Documentation: https://plotly.com/python/
5. PEP 8 Style Guide: https://peps.python.org/pep-0008/

This document was compiled from comprehensive project documentation including proposals, implementation details, technical explanations, and final reports.