SmartGrid: A Technical Report on Quantum Energy Optimization

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Contents

Report Section Overview

This document provides a comprehensive technical overview of the SmartGrid-QUBO solution, intended for technical evaluators.

- **Section 1 (Detailed Technology Description)** provides an in-depth, expansive explanation of the QUBO formulation, moving beyond the simple pitch deck narrative to explain the complex mechanisms and mathematical background of the solution.
- **Section 2 (Technology Readiness Level Assessment)** clearly states the current TRL of the technology, provides detailed justification for this assigned level based on experimental (simulated) results, and outlines the necessary future steps for advancement.
- **Section 3 (Minimum Viable Product Technical Validation)** provides the technical specifications for the MVP, details the experimental setup (the "Greedy" vs. "Global" comparison) that confirms the MVP successfully validates the technology, and explains the methodology for future feedback collection.
- **Section 4 (Intellectual Property Status)** details the current status of the IP (the formulation), analyzes potential risks, and outlines a clear strategy for defending against competitors.

1 Detailed Technology Description and Methodology

1.1 The Problem: The Energy Trilemma

The core challenge of "Demand Response" is not a single problem, but a trilemma—a set of three, competing pressures.

- **For Consumers:** Electricity is expensive and bills are unpredictable, penalizing users for using energy during peak times.
- **For The Grid:** "Peaky" demand stresses the entire system, risking blackouts and forcing the use of expensive, high-emission 'peaker' plants.
- **For The Planet:** Clean solar and wind energy is generated when demand is low and this potential is lost, even as we burn fossil fuels hours later.

The grid is fundamentally unbalanced. A simple 'if-then' rule, or a "greedy" algorithm, cannot solve this; it merely moves the peak. This is a complex, multi-objective optimization problem that demands a powerful, holistic approach.

1.2 The Data Foundation and Problem Space

Our first step was to digitize the problem, creating a high-resolution digital twin of a home's energy environment for a 24-hour period. Using the `smart_grid_dataset_2024.csv`, we extracted three "Given" vectors across 96 time steps (one for every 15 minutes):

- **Baseline Load (B_t):** The home's existing, non-negotiable power consumption.
- **Energy Price (C_t):** The volatile 15-minute cost from the utility.
- **Renewable Generation (R_t):** The on-site 'free' energy from solar and wind.

With the battlefield set, we defined our "Problem Space"—the controllable appliances. These are not simple variables; they have unique, real-world constraints (e.g., EV charger requires a 4-hour block, but only overnight). This combination creates a massive, interacting search space of 2^{101} possibilities, as there are 101 total valid start times across all three appliances.

1.3 The QUBO Formulation: The "Digital Brain"

To solve this, we speak the native language of quantum annealers: **QUBO (Quadratic Unconstrained Binary Optimization)**. Our goal is to build a single, massive cost function, $E(x)$, representing a vast energy landscape where the lowest valley is the cheapest, most stable, and valid schedule.

The objective function is a weighted sum of three competing goals, where $x_i \in \{0, 1\}$ is a binary variable representing an appliance's start time:

$$\min E(x) = A \cdot H_{\text{cost}} + B \cdot H_{\text{peak}} + C \cdot H_{\text{constraint}}$$

This equation is built in three layers:

1. $H_{\textbf{cost}}$ **(Term A):** A simple **linear** term. It assigns a dollar cost to each of the 101 'on' switches (x_i). This term is linear because the cost of one appliance does not depend on another.
$$H_{\text{cost}} = \sum_i (\text{CostOfRun}_i) \cdot x_i$$
2. $H_{\textbf{constraint}}$ **(Term C):** Our **quadratic** 'Service Guarantee'. It creates penalties *between start times of the same appliance*. For any given appliance j, this term enforces that exactly one start time is chosen:
$$H_{\text{constraint}} = \sum_{j \in \text{appliances}} \left(\sum_{i \in \text{starts}_j} x_i - 1 \right)^2$$
Expanding this creates the $x_i x_k$ quadratic terms that penalize picking two different start times (i and k) for the same appliance.
3. $H_{\textbf{peak}}$ **(Term B):** The core innovation. This **quadratic** term makes our model 'grid-aware' by creating penalties *between different appliances*. It penalizes the square of the total net load at every time step t:
$$H_{\text{peak}} = \sum_{t=1}^{96} (B_t + L_{\text{deferrable}}(t) - R_t)^2$$
Where $L_{\text{deferrable}}(t)$ is the sum of all deferrable appliance loads at time t. When expanded, this term $L_{\text{deferrable}}(t)^2$ creates the $x_i x_j$ quadratic interactions that add a cost for *any* two appliances (i and j) that happen to be 'ON' at the *same time step t*.

This formulation resulted in a complex model with **101 linear terms** and **2,327 quadratic interaction terms**.

2 Technology Readiness Level (TRL) Assessment

2.1 Current TRL: TRL 4 (Lab Validation)

We assess the SmartGrid-QUBO technology at **TRL 4: Technology validated in a lab (simulated) environment.**

2.1.1 Justification for TRL 4

- **TRL 3 (Proof-of-Concept) was met:** We established the analytical proof-of-concept by formulating the problem as a three-part QUBO and demonstrating its mathematical soundness.
- **TRL 4 (Validation) has been achieved:** We successfully built and executed this QUBO model in a simulated environment (the Python notebook). This simulation used real-world data from the `smart_grid_dataset_2024.csv`. The model's performance was not just asserted; it was experimentally validated against a baseline "Greedy" algorithm, proving its 73% superiority in peak-load reduction. The hyperparameter sweep further validated the model's robustness and confirmed our design choices.

2.2 Future Steps for Advancement

The development path to a market-ready product is clear.

- **To TRL 5 (Validated in Relevant Environment):** The next step is to move from a static CSV to a dynamic environment. This involves deploying the model on a cloud server and feeding it a *live* data stream (e.g., from a utility's price API and a home's smart meter).
- **To TRL 6 (Demonstrated in Relevant Environment):** We will connect the TRL 5 prototype to an actual hardware-in-the-loop (HIL) simulation, where the model's output (e.g., "turn on EV charger") triggers a physical smart plug in a controlled, relevant environment (a test home).
- **To TRL 7 (System Prototype Demo):** The final step before commercialization is to run a pilot program with several dozen homes, demonstrating the system's performance and stability in a real-world operational environment.

3 Minimum Viable Product (MVP) Technical Validation

3.1 MVP Technical Specifications

The current MVP is the "Global QUBO" model, implemented as a complete software solution. It is "barely working, but it's working" in that it successfully solves the core trilemma.

- **Input:** A 96-step time-series dataset (as 3 NumPy arrays for B_t, C_t, R_t) and a set of appliance definitions (power, duration, constraints).
- **Core Logic:** The Python-based system that constructs the 2,300+ term QUBO matrix based on the $H_{\text{cost}}, H_{\text{peak}}, H_{\text{constraint}}$ formulation.
- **Solver:** A D-Wave `SimulatedAnnealingSampler` ('neal').
- **Output:** A 101-bit binary vector representing the single, optimal, "one-hot" schedule.

3.2 Experimental Setup and Validation

The MVP's core claim is that its "grid-aware" H_{peak} term makes it superior to simple schedulers. We designed a direct experiment to validate this.

- **The Control (The "Greedy" Model):** We created a "control" model by completely removing the H_{peak} term (Term B). This made the appliances "selfish," optimizing only for cost.
- **The Experiment (The "Global" Model):** This is our MVP, which includes the H_{peak} term, forcing the appliances to "coordinate."
- **The Result (The "Smoking Gun"):** The "Greedy" model created a massive, 11.63 kW peak load by stacking all appliances. Our "Global" MVP *prevented* this, holding the line at 3.18 kW.

This experiment provided a clear, numerical validation: our MVP's core technology is **73% more effective** at the primary goal (peak reduction) than the naive alternative.

3.3 Customer Feedback Methodology

Initial feedback will be collected to "tailor the product to customer needs."

- **Phase 1 (Simulated Bills):** We will recruit a test group of 100 smart-home owners. We will use their real, historical utility data to run our model. We will then present them with two simulated bills: "What your bill *was*" and "What your bill *would have been* with our scheduler." We will use surveys to gauge their price sensitivity and the value they place on stability.
- **Phase 2 (A/B Testing):** In our TRL 6-7 pilot, we will A/B test different (A, B, C) "personalities" (e.g., a "Max Savings" mode vs. a "Grid-Friendly" mode) to determine which features drive user adoption and satisfaction.

4 Intellectual Property (IP) Status and Defense

4.1 Current IP Status

The core Intellectual Property of this solution is not the code, but the *formulation itself*.

- **Type:** Trade Secret / Proprietary Formulation.
- **Description:** The specific mathematical formulation of the H_{peak} term and its interaction with the $H_{\text{constraint}}$ term. A key piece of IP is also the *data-driven proof* of the optimal hyperparameter ratios (e.g., $B = 3.0, C = 100,000$).

- **Patents:** A provisional patent application for the "Multi-Objective QUBO Formulation for Energy Demand Response" is in the drafting and review stage. Filing this patent will secure our place on the market, even if a competitor tries to "fast follow."

4.2 IP Risk Analysis and Defense Strategy

- **Risk:** A competitor (e.g., a major utility or smart-home company) is "faster to release" a simple, "greedy" scheduler that only optimizes for cost.
- **Defense:** Our defense strategy is not to be *first*, but to be *demonstrably better*. Our IP is the "secret sauce" that makes our solution 73% more effective at peak reduction.
- **Strategy:** By patenting the *formulation*, we allow competitors to release inferior, "greedy" products. We will then enter the market with clear, data-driven proof (our 73% improvement) that their solution is flawed and our "Grid-Aware" model is the only one that truly solves the problem. The patent will secure our right to sue competitors who attempt to replicate our H_{peak} formulation.