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# Vehicle to Grid Energy Management Platform Using AI Driven Load Optimization

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Abstract - This paper presents a protected low-voltage Vehicle-to-Grid energy-management platform that combines an ESP32 controller, an 18650 lithium-ion battery pack, a current-limited bidirectional DC-DC converter and a PC-based optimization application. The ESP32 acquires battery voltage, bidirectional current, temperature and DC-bus demand, estimates State of Charge and enforces local safety limits. Framed UART communication transfers telemetry to the PC and returns a bounded CHARGE, DISCHARGE or IDLE request with a sequence number, current limit, timeout and checksum. A short-term load forecast supplies the optimizer, which seeks to reduce peak demand and unnecessary cycling while respecting energy, current, temperature and availability constraints. The proposed validation compares optimized operation with immediate charging using forecast error, peak-demand reduction, energy shifted, command latency, packet-error rate and safety interventions. The platform supports repeatable laboratory study without cloud services or direct utility-grid connection.

*Key Words: Vehicle-to-Grid, ESP32, 18650 battery, load forecasting, energy optimization, bidirectional converter.*

## 1. INTRODUCTION

Electric vehicles create a controllable electrical load and a distributed energy-storage resource. Conventional charging begins when a vehicle connects, even when local demand is high. Vehicle-to-Grid control can shift charging to low-demand periods and return stored energy during peaks. Practical scheduling must still account for uncertain demand, limited battery energy, user availability and lithium-ion safety limits.

This work proposes a laboratory demonstrator rather than a certified grid-connected charger. A protected 18650 pack represents the vehicle battery, while a low-voltage DC bus and programmable load represent local demand. The separation allows bidirectional control, fault injection and repeatable energy experiments without direct connection to utility mains.

## 2. RELATED WORK

Kempton and Tomic established methods for estimating V2G capacity, operating value and grid-support applications [1], [2]. ISO 15118-20 defines advanced vehicle-to-grid communication concepts, while IEC 61851-1 provides the broader conductive-charging context [3], [4]. These standards guide future integration, but the present prototype intentionally uses a simpler framed serial protocol for transparent laboratory testing.

Battery State of Charge estimation commonly combines coulomb counting with model- or voltage-based correction [5]. Forecasting references recommend simple baselines before adopting complex machine-learning models [6]. The proposed design follows this principle by comparing moving-average and linear-regression baselines with tree-based or compact neural models only after sufficient data become available.

## 3. PROPOSED SYSTEM

The platform separates rapid embedded protection from computationally heavier forecasting and scheduling. The ESP32 measures battery and load variables, filters noise, estimates State of Charge, evaluates protection conditions and generates converter PWM. A dedicated battery-management system, fuse and hardware cutoff remain the primary cell-protection layer. The PC records telemetry, predicts short-term demand and sends a bounded operating request.

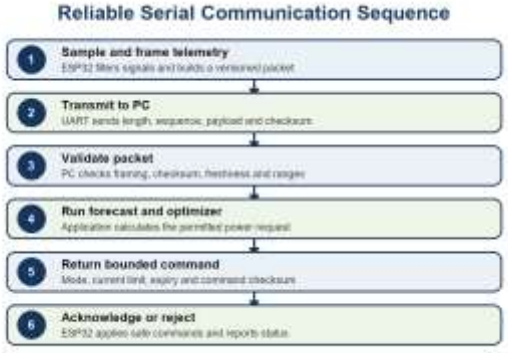



Fig -1: Proposed V2G system architecture

### 3.1 Hardware Configuration

The hardware consists of a protected 1S or 2S 18650 battery module, voltage sensing, a bidirectional current and power monitor, a temperature sensor, an ESP32 controller and a current-limited bidirectional DC-DC converter. The converter transfers energy between the battery and the emulated DC bus. Initial commissioning uses a current-limited bench supply and one protected cell before scaling the pack.

### 3.2 Serial Communication

The ESP32 sends newline-terminated telemetry containing time, voltage, current, temperature, State of Charge, load demand, fault flags and checksum. The PC returns a command containing sequence number, mode, current limit, validity period and checksum. Range checks reject corrupted fields, sequence numbers reject stale commands and a watchdog forces IDLE when communication stops.

| Packet | Representative fields |
|---|---|
| TEL | timestamp, voltage, current, temperature, SoC, load, fault, CRC |
| CMD | sequence, mode, current limit, timeout, CRC |
| ACK | sequence, accepted mode, status, CRC |

Table -1: Serial packet structure

## 4. FORECASTING AND OPTIMIZATION

At each decision interval, the PC forms a rolling history of load measurements and predicts demand for the next interval. Mean absolute error and root mean square error quantify forecast performance on unseen profiles. A moving-average or linear-regression model supplies the baseline. Random Forest, gradient boosting or a compact neural model may be evaluated only when the available dataset supports a valid training and test split.

The optimizer minimizes a weighted combination of predicted peak demand, estimated energy cost and battery cycling. Its decision variables are operating mode and requested current. Constraints enforce minimum and maximum State of Charge, converter power, current, temperature, reserve energy, user availability and command validity. The optimizer cannot override limits published and rechecked by the ESP32.

## 5. CONTROL AND SAFETY

The controller operates in CHARGE, DISCHARGE, IDLE or FAULT. CHARGE absorbs energy when predicted demand is low and State of Charge remains below its upper limit. DISCHARGE supports the DC bus during a predicted peak while maintaining reserve energy. IDLE disables active transfer during standby or after an expired command. FAULT disables PWM when a mandatory protection condition occurs.

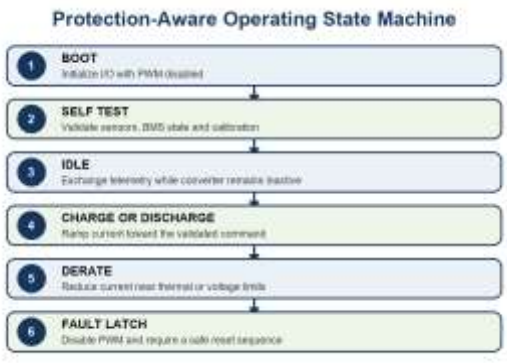



Fig -2: AI-driven energy-management flow

Firmware blocks charging or discharging for cell undervoltage or overvoltage, excessive current, excessive temperature, sensor failure, BMS trip, invalid checksum, stale sequence or communication timeout. These checks remain independent of the PC decision. Correctly rated wiring, a fuse, protected cell holders and a non-flammable test area are mandatory during experiments.

## 6. IMPLEMENTATION METHODOLOGY

Implementation proceeds from measurement calibration to open-loop converter tests, protocol verification, forecasting evaluation and closed-loop experiments. Voltage, current and temperature channels are compared with calibrated reference instruments. Charge and discharge modes are first exercised at low current. Protocol tests then inject invalid checksums, stale sequences and timeouts before the optimizer is allowed to command the power stage.

For closed-loop tests, the same load profile and initial State of Charge are used for immediate charging and optimized operation. Each run retains the raw telemetry log, command log, configuration, model version and fault record. This evidence supports reproducibility and prevents simulated or planned values from being reported as measurements.

## 7. EVALUATION PLAN

| Metric | Purpose | Evidence |
|---|---|---|
| MAE or RMSE | Forecast accuracy | Held-out load intervals |
| Peak reduction | Demand management | Baseline versus optimized load |
| Energy shifted | Scheduling effect | Integrated power measurements |
| Command latency | Control responsiveness | Timestamped packets |
| Packet-error rate | Communication reliability | CRC and sequence logs |
| Safety interventions | Protection behavior | Fault-event records |

Table -2: Planned evaluation metrics

The expected outcome is a functioning low-voltage demonstrator with observable bidirectional power flow, reliable serial control and a calibrated forecasting baseline. Quantitative conclusions will be added only after repeatable hardware tests. Until then, peak reduction and efficiency remain evaluation targets rather than measured claims.

## 8. DISCUSSION

The architecture places immediate protection near the battery and converter while allowing the PC to host models that can be changed without reflashing the embedded controller. Wired serial communication reduces networking complexity and makes packet-level faults easy to reproduce. The tradeoff is that UART does not represent a production vehicle-charging interface.

The reduced-voltage DC setup validates control logic, data handling and energy scheduling but cannot establish grid-code compliance, isolation performance or anti-islanding behavior. Scaling the system requires a renewed hazard analysis, isolated power conversion, certified protection, thermal design and an appropriate vehicle-grid communication stack.

## 9. CONCLUSION

The proposed V2G platform integrates protected battery sensing, ESP32-based local control, framed serial communication, short-term load forecasting and constrained energy optimization. Its main contribution is an auditable division of responsibility: the PC recommends an operating action, while the embedded controller decides whether the action is safe to execute. The design supports repeatable comparison of forecasting and scheduling methods without depending on cloud services or direct utility-grid connection.

Future work will complete calibrated hardware trials, compare forecasting models on unseen profiles, investigate probabilistic forecasts and model predictive control, and evaluate migration to CAN, Modbus or vehicle-charging protocols. Any hardware scale-up will retain independent protection and require new insulation, thermal and certification analysis.

## ACKNOWLEDGEMENT

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