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Solar Pulse: AI Powered Multi Modal Charging Dashboard for Electric Vehicle

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Abstract - This paper presents the design and validation framework of a low-voltage multimodal electric-vehicle charging demonstrator. The system accepts energy from a photovoltaic panel, a regulated 12 V direct-current adaptor representing grid supply, and a direct-current motor operated as a generator to emulate regenerative braking. Protected source paths feed a mutually exclusive selector and a battery-compatible charge-control stage. An ESP32 acquires voltage, current, temperature, and generator-speed signals; evaluates source availability; enforces break-before-make transitions; and calculates power and accumulated energy. A desktop dashboard exchanges framed commands and telemetry through USB serial communication and displays requested and actual operating modes, trends, alarms, and session energy. The proposed validation method separates source characterization, sensor calibration, transition tests, protection tests, and communication-failure tests. The design provides a traceable educational platform for comparing renewable, grid, and recovered-energy modes while explicitly excluding direct connection to traction batteries or mains circuits without certified isolation, a battery management system, and automotive-grade protection.

Key Words: electric vehicle, multimodal charging, solar energy, regenerative braking, ESP32, PC dashboard.

1. INTRODUCTION

Electrification shifts vehicle energy management from a single fuel path to coordinated electrical conversion, storage, and recovery. A complete road vehicle operates at hazardous voltage and power, so a laboratory demonstrator is useful for teaching the same control relationships at a safer scale. The proposed platform represents three charging opportunities: photovoltaic energy, a regulated adaptor that emulates grid-derived direct current, and mechanical energy recovered through a small motor-generator during simulated braking.

The central engineering problem is not merely switching among three sources. Their voltage, current capability, availability, and dynamic behavior differ. Solar output changes with irradiance, the adaptor is comparatively stable, and the generator is intermittent and speed dependent. Directly tying such sources together can create reverse current, uncontrolled circulation, contact arcing, or misleading measurements. The design therefore assigns each source an independent conditioning and blocking path before selection.

An ESP32 provides the supervisory layer. It converts conditioned sensor signals to engineering units, evaluates limits, applies transition timing, reports the state of the power path, and records energy transferred by each mode. The personal-computer dashboard requests modes and presents data, but it does not bypass local protection. This division allows loss of the user interface or a malformed serial message to return the prototype to a defined safe state.

2. RELATED WORK

Regenerative braking uses the traction machine as a generator so that part of the vehicle's kinetic energy is returned to electrical storage rather than being dissipated entirely by friction brakes [1], [2]. The recoverable fraction depends on motor speed, converter limits, battery acceptance, road conditions, and the required braking torque. In the prototype, a driven permanent-magnet direct-current motor reproduces only the electrical generation aspect; it does not reproduce vehicle dynamics or blended-braking control.

Photovoltaic charging requires operation across changing irradiance and panel voltage. Maximum-power-point tracking is commonly used when energy yield matters, while power-path control prevents a weak input from destabilizing the battery rail [3]. The first prototype may use a regulated charge stage with explicit source-availability thresholds; an MPPT converter is identified as a future improvement rather than being assumed in the initial results.

The ESP32 analog-to-digital converter requires calibration because reference variation and attenuation settings affect voltage accuracy [4]. Oversampling and filtering reduce noise but cannot correct an unsuitable divider, poor grounding, or a sensor outside its linear range. Conductive EV charging and vehicle electrical safety are governed by standards such as IEC 61851-1 and the ISO 6469 series [5], [6]. These standards inform the safety boundary, although the demonstrator is not presented as a compliant EV charger.

3. SYSTEM ARCHITECTURE

Figure 1 organizes the prototype into energy sources, protected power interfaces, sensing and control, and the dashboard. Each input includes current limiting and reverse-current blocking. Relays or MOSFET stages implement mutually exclusive selection, followed by a battery-compatible regulator. The ESP32 observes both source-side and battery-side variables so that an enabled command can be distinguished from confirmed electrical behavior.



Fig -1: Functional architecture of the multimodal charging demonstrator.

3.1 Charging Modes

Solar mode is available when the panel exceeds the configured voltage threshold for a qualified interval and the charge controller reports a valid output. Grid mode enables the regulated 12 V adaptor through its isolated selection path. Regenerative mode becomes available when generator voltage and speed are sufficient for controlled transfer. Automatic mode applies a documented priority rule, whereas Safe mode disables every source command and retains measurement and communication.

Table -1: Operating modes and essential interlocks.

Mode	Availability condition	Controller action
Solar	Panel within limits	Enable solar path
Grid	Adaptor valid	Enable adaptor path
Regen	Generator above threshold	Enable recovery path
Auto	At least one source valid	Apply source priority
Safe	Fault, stop, or timeout	Disable all sources

3.2 Measurement and Control

Voltage dividers scale source and battery voltages below the ESP32 input limit. Current sensors are selected for the expected bidirectional or unidirectional range and are calibrated against a reference instrument. Temperature sensing monitors the battery simulator or charge stage. Generator speed can be estimated from a tachometer or pulse sensor. Raw readings are range-checked before filtering; missing or implausible samples are flagged rather than displayed as valid zero values.

Instantaneous power is calculated as $P = VI$. Energy is accumulated using $E(k) = E(k-1) + P(k)\Delta t/3600$, where Δt is the measured sampling interval in seconds and E is expressed in watt-hours. This elapsed-time formulation avoids the systematic error that appears when a nominal loop time is used during communication or processing delays.

4. IMPLEMENTATION METHODOLOGY

Implementation is divided into protected hardware, embedded firmware, serial communication, and dashboard software. Subsystems are commissioned independently at current-limited settings. The adaptor path is verified first because it provides the most stable source, followed by solar characterization and then motor-generator testing with a guarded mechanical drive. Only after polarity, blocking, scaling, and shutdown behavior are confirmed are the paths connected to the common charge stage.

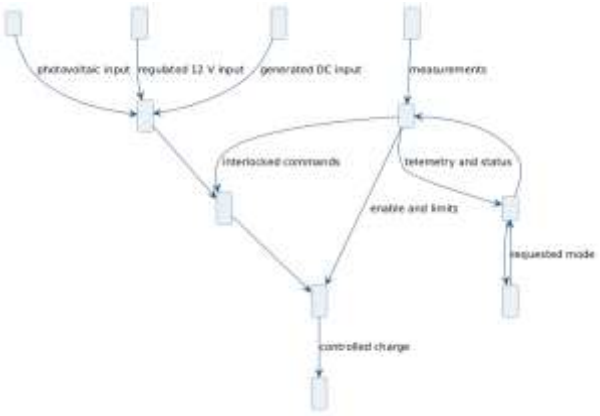


Fig -2: Verification flow from requirements to controlled charging.

4.1 Embedded State Logic

At startup, all source commands are disabled. The controller loads bounded configuration values, verifies sensor plausibility, and waits for stable source observations. A requested transition first turns off the active source, waits for the configured break interval, confirms that the common path has decayed to an acceptable condition, and then enables the new source. If feedback does not match the commanded state, the firmware latches a fault and returns to Safe mode.

The main task samples sensors and updates state at a deterministic interval. Lower-rate tasks package telemetry, integrate session energy, and process commands. Firmware watchdog supervision is complemented by hardware defaults that keep switching devices off while the ESP32 resets. Threshold hysteresis and time qualification prevent rapid source chatter near an availability boundary.

4.2 USB Serial Protocol and Dashboard

The USB serial link uses delimited frames containing a message type, sequence number, timestamp, requested mode, actual mode, measurements, validity flags, fault code, and checksum. Commands are acknowledged with the accepted state or a reason for rejection. Sequence numbers allow the dashboard to detect loss or repetition, while a heartbeat timeout allows both endpoints to display a communication fault.

The dashboard presents source-availability indicators, requested and actual modes, battery voltage and current, charge power, generator speed, temperature, trends, active alarms, and accumulated energy by source. Manual controls request Solar, Grid, Regenerative, Automatic, or Safe mode. Logged comma-separated records contain units, firmware version, calibration identifier, and test identifier so that later analysis remains tied to the configuration that produced it.

5. VALIDATION FRAMEWORK

The work is evaluated as a design and controlled prototype framework rather than as a certified automotive charger. Each test record identifies the source condition, load or battery-emulator setting, reference instruments, software versions, requested mode, actual mode, measured response, acceptance criterion, and observation. Calibration points should cover zero, mid-range, and near-maximum operating values in both increasing and decreasing directions.

Table -2: Planned verification matrix and acceptance evidence.

Test	Method	Required evidence
Sensor accuracy	Compare against meter	Error within project limit
Source isolation	Energize one source	No reverse current
Mode transition	Command each change	Break-before-make event log
Unavailable source	Remove or reduce input	Request rejected safely
Serial timeout	Disconnect USB	Local operation remains safe
Fault recovery	Inject bounded fault	Latched code and Safe mode

5.1 Result Interpretation

A successful result requires agreement among the command, switching feedback, and measured power flow. A dashboard indicator alone is insufficient evidence because it may reflect only the requested state. Similarly, a nonzero voltage does not prove useful charging unless current direction and power are consistent with transfer into the storage path. Energy comparisons must therefore state the integration interval, sensor uncertainty, and source conditions.

The expected qualitative behavior is distinct for each mode. Grid charging should provide the smallest short-term variation when the adaptor and load are regulated. Solar power should track illumination and converter operating point. Regenerative power should increase with generator speed until limited by the charge stage or load. These trends are hypotheses to be confirmed by recorded tests; numerical efficiency or energy-recovery claims should be reported only after reference measurements are available.

Uncertainty is dominated by voltage-divider tolerance, current-sensor offset and gain, ADC calibration, timing accuracy, connection resistance, and repeatability of solar illumination or generator speed. Repeated steady-state observations and transition timestamps allow the team to separate random variation from systematic bias. Any saturation, invalid sample, or protection event must remain visible in the dataset.

6. SAFETY AND LIMITATIONS

The prototype is restricted to fused, current-limited, extra-low-voltage sources. The motor-generator assembly requires guarding, secure coupling, and an emergency stop for the mechanical drive. The selected battery or emulator requires a compatible charge profile, independent overcurrent protection, reverse-polarity protection, and temperature supervision. Test leads and grounds must be arranged to avoid unintended parallel paths through the PC USB connection.

Scaling the concept to a road vehicle is a separate engineering program. It requires galvanic isolation, automotive contactors and pre-charge, isolation monitoring, electromagnetic-compatibility design, a qualified battery-management interface, thermal design, communication standards, functional-safety analysis, and regulatory certification. The present system demonstrates supervisory logic and measurement flow; it does not validate traction-battery charging.

7. CONCLUSIONS

A multimodal EV charging demonstrator can make the interaction of renewable, grid-derived, and recovered braking energy observable within one low-voltage platform. The proposed architecture separates the three inputs, uses the ESP32 for calibrated supervision and interlocking, and assigns the PC dashboard to visualization, requests, and logging. This division preserves a local safe state even when communication is absent.

The principal contribution is a traceable design and validation framework rather than an unsupported efficiency claim. Source characterization, sensor calibration, break-before-make tests, feedback confirmation, fault injection, and timestamped logging establish the evidence needed for later performance evaluation. Future work should add MPPT, synchronous regenerative conversion, battery state estimation, CAN communication, and hardware-in-the-loop testing before any higher-voltage development.

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