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Design and Analysis of a Solar-Powered EV Charging Microgrid with Battery Storage

Vivek Arvindbhai Raval[1], Deepak Dev[2]

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Abstract – *Electrical Vehicle (EV) fast charging station integrating a solar photovoltaic (PV) Generation with Battery Energy Storage System (BESS) present a promising solution to supply clean electrical energy, overcome peak power demand and improve operational economics. We present an optimal design, engineering and techno-Commercially analysis of a solar + BESS powered EV Fast Charging station suitable for India Urban and Semi – Urban Environments.*

Key Words: **Electrical Vehicle (EV) fast is charging station, solar photovoltaic (PV) Plant, Battery Energy Storage System (BESS).**

1. INTRODUCTION

Integrating solar plants and Battery Energy Storage Systems (BESS) into fast EV charging stations in India is a pivotal strategy to address grid constraints, enhance sustainability, and improve economic viability. This integrated approach enables a more resilient and efficient e-mobility ecosystem.

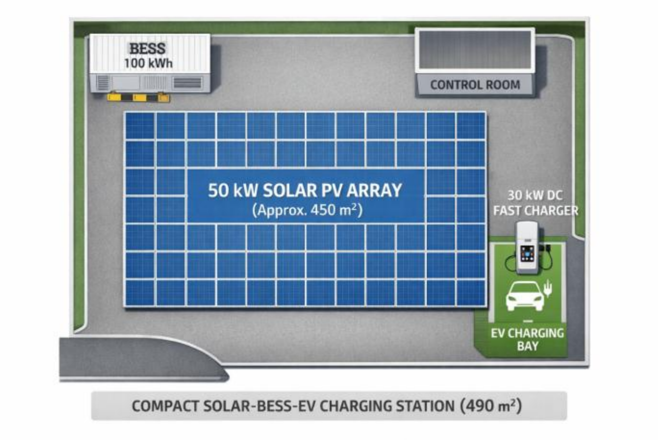

Figure 1: Block diagram of Compact Solar Bess-EV Charging Station

1.1 Grid Independence and Stability:

Fast charging demands high power instantly, which can strain the local grid and cause instability (e.g., voltage fluctuations). BESS acts as a buffer, storing energy and delivering it rapidly to EVs, thus reducing sudden peak loads on the main grid infrastructure.

1.2 Optimal Use of Renewable Energy:

Solar power is intermittent. BESS stores excess solar energy generated during peak sunlight hours and makes it available for use during the night, cloudy periods, or peak EV charging times. This maximizes the consumption of clean, renewable energy, making EV charging truly "green" and aligning with India's climate objectives.

1.3 Cost Optimization and Peak Shaving:

By storing cheaper solar or off-peak grid electricity, charging station operators can avoid drawing power from the grid during expensive peak-rate periods (time-of-use tariffs). This "peak shaving" significantly lowers operational costs, which can be passed on to consumers as more cost-effective charging rates.

1.4 Energy Resilience and Backup Power:

In areas with an unreliable grid or frequent power outages, BESS provides a reliable emergency power source, ensuring uninterrupted charging services. This is especially crucial for highway stations or critical fleet operations.

1.5 Enabling Deployment in Remote Areas:

Off-grid solar-BESS configurations allow for the establishment of fast-charging stations in remote or rural areas where grid connectivity is limited or costly to upgrade, promoting wider EV adoption across India.

1.6 Improved Power Quality:

Advanced control systems within the integrated setup can provide power factor correction and harmonics filtering, ensuring a stable and clean power supply that protects sensitive EV charging equipment and the grid itself.

2. Technical and Operational Aspects:

2.1 Solar PV System: Sized to maximize energy generation based on site-specific solar irradiance and demand profiles. It uses inverters with Maximum Power Point Tracking (MPPT) capability to optimize energy capture.

2.2 Battery Energy Storage System (BESS): The battery (commonly Lithium Iron Phosphate (LFP) for safety and durability) is integrated to store excess solar energy and provide power during peak demand or low solar generation.

2.3 Power Conversion System (PCS): A crucial bidirectional converter that manages the flow of energy between the AC grid, DC solar panels, DC battery storage, and DC fast chargers. It performs DC-to-AC and AC-to-DC conversion efficiently.

2.4 EV Fast Chargers: These are DC fast chargers, with power ratings typically ranging from 50kW upwards, designed to rapidly charge high-voltage EVs.

2.5 Smart Energy Management Systems (EMS): Intelligent software and control algorithms are essential for managing the flow of power among the solar plant, BESS, the grid, and the EVs. EMS optimizes charging schedules based on solar availability, battery state of charge (SOC), and real-time electricity prices.

2.6 Main Low-Voltage Panel: The central connection point for all components and the grid connection.

3. Step-by-Step Working Principle

3.1 Solar Energy Generation (DC Power): Photovoltaic (PV) panels convert sunlight directly into Direct Current (DC) electricity. An MPPT (Maximum Power Point Tracking) controller is typically used to optimize the power output from the panels based on current weather conditions.

3.2 Power Conversion (DC to AC/DC):

1. The generated DC power needs conditioning. A Power Conversion System (PCS), essentially a sophisticated bidirectional inverter, manages this process.
2. For use within the station's DC infrastructure (e.g., charging the battery or directly powering DC fast chargers), the DC power is routed appropriately.
3. If excess energy is to be sent to the AC utility grid, the PCS converts DC power to AC power.

3.3 Energy Storage and Management (BESS & EMS):

1. The BESS stores excess energy that is not immediately used by EVs during peak solar hours.
2. The EMS, which acts as the central brain, dynamically decides where power should flow based on a set of rules and real-time data (e.g., time of day, electricity prices, EV demand, Battery State of Charge).
3. When EV charging demand is low and solar production is high, the EMS directs power to the BESS or back to the grid for potential revenue (energy arbitrage).

3.4 Fast Charging Operation:

1. When an EV plugs in, the charger communicates with the vehicle's Battery Management System (BMS) to determine its charging needs (voltage, current, State of Charge).
2. The EMS ensures the required high power for fast charging is met instantly by prioritizing energy from the BESS and the grid simultaneously, thereby achieving "peak shaving" and preventing demand spikes on the main grid.
3. The high-power DC is then delivered directly to the EV's battery.

3.5 Grid Interaction and Resilience:

1. The system can draw power from the grid during off-peak hours when electricity is cheaper to charge the BESS.
2. In the event of a grid outage, the BESS provides immediate backup power, ensuring uninterrupted service for critical charging operations (microgrid functionality)

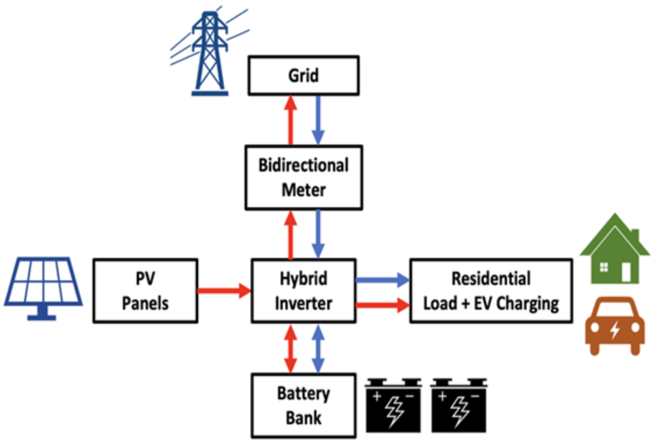

Figure 2: Operating modes of the solar PV–BESS integrated EV charging system

3.6 Operational Modes

1 Solar Direct Mode: Solar power directly charges EVs or the BESS when available.
2 Peak Shaving Mode: BESS discharges stored energy to supplement solar and grid power during high-demand periods, avoiding expensive peak tariffs.
3 Grid Charging Mode: BESS is charged from the grid during off-peak, low-cost hours.
4 Backup Mode: BESS provides power to the station in case of a grid failure, ensuring resilience.
5 Grid Export Mode: If allowed by regulations and the BESS is full, surplus solar energy can be exported to the grid for credit.

4. Technical Functionality & Control

The technical operation relies on sophisticated management and control systems:

Peak Shaving and Demand Control: The BESS supplies power during high-demand periods to prevent the station's total consumption from exceeding the contracted grid limit, thus avoiding penalties and reducing infrastructure upgrade costs.

Energy Arbitrage: The EMS charges the BESS with cheaper, off-peak grid electricity or solar energy and discharges it during expensive peak-rate periods to minimize operational expenses.

Power Quality Management: The BESS and PCS help maintain grid stability by providing voltage regulation, power factor correction, and filtering harmonic distortions caused by fast chargers.

Power Balance and Control Algorithms: The system operates on power balance equations, where the BESS fills the gap between the power demanded by EV chargers and the power available from the grid and solar PV at any given time

$$P_{BESS(t)} = P_{load(t)} - P_{grid(t)}$$

Operational Resilience: The BESS provides reliable backup power, ensuring uninterrupted service even if the main grid experiences an outage.

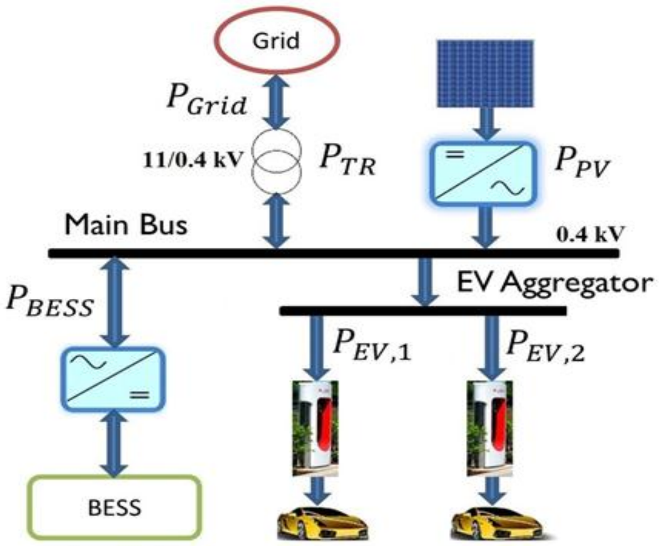

Figure 3: Power flow and control strategy of the solar + BESS EV charging micro grid

4. Key Mathematical Equations and Graphs for Solar + BESS EV Charging

5.1 Essential Mathematical Equations

I. **PV Generation Equation**
The PV output is calculated using irradiance and performance ratio:
P_PV(t) = P_rated × G(t) × PR
Where:
- P_rated = PV system peak capacity
- G(t) = Irradiance (normalized)
- PR = Performance Ratio

II. **Battery SOC Equation**
The battery State of Charge is updated each time-step as:
SOC(t+Δt) = SOC(t) + (η_ch × P_ch − P_dis / η_dis) × Δt / E_batt
This models charging, discharging, and loss factors.

III. **Power Balance Equation**
The EV charging station follows this power balance:
P_load = P_PV→load + P_BESS→load + P_grid
This ensures all power supplied equals demand.

IV. **Peak Shaving Constraint**

To protect the grid and reduce demand charges:
P_Grid(t) ≤ P_Threshold
Battery discharges when load exceeds this threshold.

5.2 Key Graphs with Short Explanations

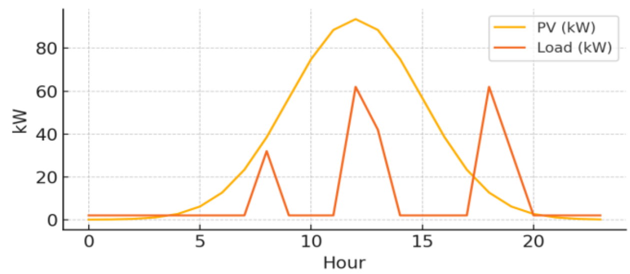

Chart 1: Solar PV output and EV charging load profile

This graph compares hourly PV generation with EV charging demand. Peaks in load correspond to fast-charging events. PV supports midday charging, while evening charging requires battery or grid.

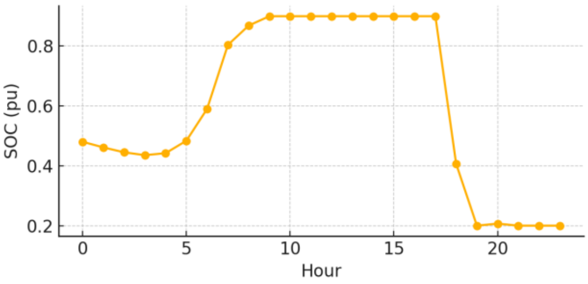

Chart 2: Battery state of charge (SOC) variation over a typical day

The SOC curve shows battery charging during high PV generation and discharging in the evening to support charging while limiting the grid draw.

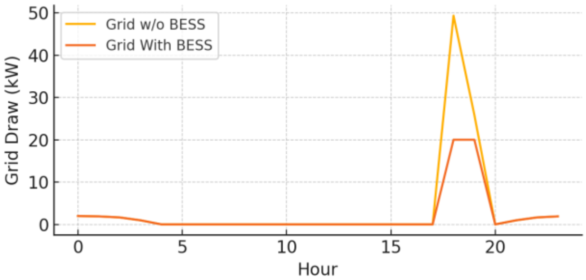

Chart 3: Grid power draw comparison with and without BESS

This plot shows how the battery dramatically reduces maximum grid draw. Without BESS, grid demand spikes up to 49 kW; with BESS, it is limited to the threshold of 20 kW (peak shaving).

6. System Description (Realistic India-Based Site)

Table 1: System Specifications (Realistic India-Based Site)

Solar Capacity	50 kW
Battery	100 kWh (usable ≈ 85 kWh)
EV Charger	30 kW DC Fast Charger
Grid Limit	25 kW (Common LT Connection)

Table 2 Real-Time Operation (HOUR–BY–HOUR)

9 AM – 12 PM (Morning Solar Building Up)	
Solar Generation	20 KW – 30 KW
EV Charging load:	10 KW – 15 KW
Result	• Extra solar (5–20 kW) → charges battery • Battery SOC increases from 40% → 70%

12 PM – 3 PM (Peak Sun Hours)	
Solar Generation	45 KW – 50 KW
EV Charging load:	30 KW
Result	• Solar directly powers EV charger (30 kW) • Extra solar (15–20 kW) → battery charges faster • Battery SOC increases to 100% (full) • Grid use: 0 kW

6 PM – 9 PM (Evening Peak Period — Real Problem Time)	
Solar Generation	0 KW
EV Charging load	30 KW
Grid limit	25 KW
Result	• Grid supplies: 25 kW • Battery supplies: 5 kW • EV charger receives full 30 kW • Battery SOC drops from 100% → 70%

Table 3 Cloudy / Rainy Day Real Example

9 AM – 6 PM (Solar generation drops drastically)	
Solar Generation	5 KW – 10 KW
EV Charging load	30 KW
Grid limit	25 KW
Result	• Grid supplies: 25 kW • Battery supplies: 5 kW • EV charger receives full 30 kW • Battery SOC drops from 100% → 70%

6.1 Daily Energy Summary (REAL VALUES)

Table 4: Daily Energy Summary

Component	Daily Contribution
Solar (50 kW)	180–200 kWh/day
Battery (100 kWh)	1 full cycle/day
Grid	60–80 kWh/day
Results	Solar + battery supply 70–75% energy Grid supplies only 25–30%

6.2 Financial Benefit (Approx. India Values)

Table 5: Financial Benefit Analysis (India Values)

Component	Daily Contribution
Without Solar + Battery	**250–260 kWh/day grid use**
Cost	**₹2,250 per day**
With Solar + Battery	**Only 60–80 kWh/day grid use**
Cost	**₹540–720 per day**
Daily Saving	**₹1,500–1,700 saved per day**
Yearly Saving	**₹5.5–6.0 lakh saved per year**

7. Safety Considerations

1) **Electrical Safety:-** Fast chargers (30–350 kW), high-voltage batteries, and solar inverters create complex electrical environments.

- Proper earthing/grounding in line with CEA regulations
- Surge protection devices (SPD) for DC and AC sides
- Arc-fault detection (especially in large solar DC runs)
- Isolators and DC disconnects for emergency shutdown
- Short-circuit protection in BESS and charger circuits
- Proper cable sizing & thermal protection

2) **Battery Energy Storage Safety: -** BESS is the most sensitive component due to fire risk.

- Battery Management System (BMS) with:
  Cell balancing, Over-charge/over-discharge protection,
  Thermal runaway detection
- Fire detection and suppression systems
  Aerosol-based fire suppression, Novec, FM200, or Equivalent agents
- Thermal management:
  Air-cooled or liquid-cooled systems
- Hazardous gas ventilation
  Especially for LFP/NMC chemistries
- Compliance with standards like:
  IEC 62619 (battery safety)
  IEC 62933 (BESS systems)
  CEA safety guidelines in India

3) **Solar Plant Safety**

- Anti-islanding protection
- String monitoring for early fault detection
- Proper insulation and cable routing to avoid hotspots
- Use of MC4-certified connectors to prevent thermal incidents
- Periodic cleaning + maintenance (especially in dusty Indian environments)

4) **EV Charger Safety**

- Overcurrent and overvoltage protection
- Liquid-cooled charging cables for 200–500 A output
- Automatic emergency stop (E-Stop button)
- Real-time monitoring of connector temperature
- IP55–IP65 weatherproof enclosures
- Ground fault detection (RCD protection)

5) **Fire & Thermal Safety**

- Fire zones clearly separated (solar, BESS, charger area)
- Thermal cameras for early fire detection
- Fire extinguishers rated for electrical & lithium fires
- 24/7 remote monitoring + SCADA alarms

6) **Regulatory & Compliance Requirements (India)**

- CEA (Central Electricity Authority) safety rules
- IEC standards for solar, BESS, and EV chargers
- BIS requirements for charger and battery equipment
- DISCOM interconnection rules
- Fire NOC for BESS installations

CONCLUSIONS

This research paper presented the design, operational analysis, and techno-economic evaluation of a **solar-powered EV fast-charging microgrid integrated with a Battery Energy Storage System (BESS)**, specifically tailored for Indian urban and semi-urban conditions. The study demonstrates that combining solar PV with BESS effectively addresses the major challenges associated with fast EV charging, including high peak demand, grid constraints, energy cost volatility, and supply reliability.

Through detailed system modeling, operational modes, mathematical formulations, and real-time hour-by-hour analysis, it is shown that the proposed solar-BESS microgrid significantly reduces grid dependency while ensuring uninterrupted high-power charging. Peak shaving and energy arbitrage strategies implemented via a smart Energy Management System (EMS) successfully limit grid draw within contracted limits, prevent demand penalties, and enhance overall grid stability. The battery system plays a critical role in buffering intermittent solar generation and supplying instant power during peak charging periods and grid outages.

The India-based case study confirms that a properly sized **50 kW solar PV system with a 100 kWh BESS** can supply approximately **70–75% of the daily energy demand** of a DC fast-charging station, reducing grid consumption by nearly **70%.** The financial analysis highlights substantial operational cost savings of **5.5–6.0 lakh per year**, demonstrating strong economic feasibility alongside environmental benefits.

Additionally, the paper emphasizes essential safety, regulatory, and compliance considerations aligned with **CEA,**

IEC, BIS, IESA and DISCOM guidelines, reinforcing the practical deploy ability of such systems in real-world conditions. The proposed architecture also enables deployment in remote or weak-grid areas, supporting India's broader objectives of EV adoption, renewable integration, and energy resilience.

Although the proposed solar-powered EV charging microgrid with BESS is technically feasible, the technology is still under active research and development. Ongoing advancements in battery chemistry, power electronics, and energy management systems are expected to improve performance and reliability. With declining battery costs, large-scale manufacturing, and supportive policies, this technology is projected to become significantly more cost-effective and widely deployable in the near future.

In conclusion, solar-powered EV charging microgrids with integrated BESS represent a **technically robust, economically viable, and environmentally sustainable solution** for future EV infrastructure in India. The findings of this study can serve as a reference framework for policymakers, charging infrastructure developers, utilities, and researchers aiming to scale fast-charging networks while minimizing grid impact and maximizing renewable energy utilization.

BIOGRAPHIES

Vivek Arvindbhai Raval
Qualification: M.Tech in EPS
(Electrical Power System)
Designation: Assistant Manager

Deepak Dev
Qualification: B.Tech in EE
(Electrical Engineering)
Designation: Sr. Engineer