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Solar-Powered Energy Storage Architecture for EV Charging Infrastructure: A PV–BESS–PEV Integration Study in Ludhiana, India

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Abstract: A solar powered energy storage architecture for electric vehicle (EV) charging that integrates photovoltaic (PV) generation, battery energy storage system (BESS), and plug-in electric vehicle (PEV) charging at a single point of common coupling (PCC) to the distribution grid is developed and evaluated. A detailed PV–BESS–PEV integration model for Indian urban networks is proposed that incorporate time-varying solar irradiances, PSPCL tariff models, BESS state-of-charge (SOC) models, and EV arrival patterns for an urban commercial site near Gill Pind, Ludhiana. The model is integrated in a multi-objective optimization problem to minimize life cycle cost, electrical losses and CO_2 emissions by optimally sizing PV capacity, the BESS energy rating, the BESS power rating, the grid interface limits, and a combination of AC and DC chargers. The scenario studies, with a representative case of 15,000 EVs/day charging demand, show that a properly designed PV–BESS–PEV system can provide a large portion of EV energy demand from local PV resources, minimise technical losses and coal consumption at the system level and reduce evening peak demand on the PSPCL network, while maintaining charging reliability, and are also realistic for the large scale deployment in the Ludhiana corridor.

***Index Terms* -** Electric vehicles, photovoltaic systems, battery energy storage system, EV charging station, optimization, distribution networks.

I. Introduction

A. *Background and Motivation*

The shift towards electric mobility in road transport is underway and is accelerating, driven by the need to combat urban pollution, CO2 emissions and reliance on fossil fuels. EVs can also be powered via renewable energy, which offers zero local tailpipe emissions when powered primarily by renewable sources like solar PV, and have a higher rate of conversion of electric energy to movement. Meanwhile, EV charging loads also create challenges for distribution networks, such as increased peak loading, voltage fluctuations and increased technical losses as many EV vehicles charge concurrently during the late evening.

One option that has been suggested is that EV charging infrastructure is installed alongside on-site PV generation and stationary energy storage to ensure that a large percentage of charging energy is produced locally, thereby lessening the demand for electricity on the grid during peak times. In this configuration, PV panels generate electricity from sunlight, batteries store it, and it is then utilized to charge EVs or discharge to the grid for peak shaving, to minimize the use of electricity from the host utility, and to decrease the effective carbon footprint of mobility. Properly controlled, a solar-powered charging station can be a controllable load or even a supplemental resource for distribution utility use, delivering easy and convenient charging in the presence of clean energy brand.

B. *Research Gap and Problem Statement*

1. Need for an integrated PV–BESS–PEV framework
2. From architecture description to mathematical representation
3. Capturing operational behaviour of PV, BESS and PEVs
4. Problem formulation aligned with techno-economic and environmental goals

C. *Research Objectives*

1. A comprehensive PV–BESS–PEV integration model
2. To develop and apply a multi-objective optimisation model combining life-cycle cost, electrical and environmental sustainability.
3. To develop and test coordinated operating strategies for PV, BESS and PEVs
4. To benchmark the PV–BESS–PEV charging station against an architecture with grid
5. To use optimization to minimize cost, losses, and CO_2 emissions

II. LITERATURE REVIEW

A. *Converter and control topologies*

Recent converter and control design research is targeted towards small, high efficiency PV to EV battery interfaces. They suggest a modified SEPIC DC–DC converter which reduces the PV 48 V output to 120 V and charges the EVs with constant current, and has the same ratings on the switches with high efficiency (92.3%) across a broad range of input voltage, suitable for small solar PV powered EV charging stations. In parallel, Faujdar and Pandey investigate a STATCOM based DC micro grid with PV-battery EV charging, where the damping performance is enhanced, overshoot is reduced and the DC bus is stabilized due to the use of firefly optimized state feedback under solar and load disturbance.

B. *Techno-economic microgrid studies*

Panwar et al. (2013) compares PV stations, hybrid PV-wind-storages stations, and finds the PV station to be most cost-effective using HOMER for Jaipur, and hybrid stations to reduce emissions, while requiring higher capital cost. The SIMA PV-battery-EV microgrid is reported by Santana de Albuquerque in Brazil where measurements and simulations show that energy management can approach a multimodal electric mobility with zero net energy by coordinating the energy activities.

C. *Planning and co-optimization models*

Maldonato et al. investigate a Greek island case study, in which almost a 100% renewable power supply can be achieved with significant cost and CO_2 savings, by connecting to wind power, solar power, stationary BESS and V2G EVs. Govind et al. present an optimal placement of fast charging PV-battery stations by integrating a transportation model with an IEEE-33 bus network, emphasizing that the optimal planning of transportation systems, the placement of charging PV-battery stations and the planning of local renewables should be carried out simultaneously to reduce the stress in the grid and to make the system more economical.

III. METHODOLOGY

A. *Overall Architecture*

The solar powered charging station is designed as a DC coupled microgrid with a three phase grid-tied inverter that connects to the PCC of the power utility. Level-2 AC chargers are powered from the AC side, and PV modules, BESS and clusters of PEV chargers are fed via suitable DC–DC converters to a common DC bus. The station is modelled using component-level models that are connected by a power-balance equation using DC power at each time step,

$$P_{\mathrm{PV}}(t) + P_{\mathrm{grid}}(t) + P_{\mathrm{batt,dis}}(t) = P_{\mathrm{EV}}(t) + P_{\mathrm{batt,ch}}(t),$$

where P_"PV" (t) is PV output, P_"grid" (t) is net grid exchange, P_"batt,dis" (t) and P_"batt,ch" (t) are BESS discharge and charge powers, and P_"EV" (t) is aggregate EV charging demand. Full power-flow detail of the distribution network is not modelled, but feeder loss factors and transformer limits are derived from data from PSPCL to estimate technical losses and to limit grid import/export. This way the optimization problem remains tractable and still represents the most important interactions between the local resources and the distribution system.

B. *Solar Photovoltaic Subsystem*

Instead of modelling the PV subsystem in detail with the characteristics of the diode, an energy balance approach is used because the results from the high-level optimization are mainly dependent on the annual energy yield. For an installed PV capacity C_"PV" the annual PV energy output, Y_"PV" can be approximated as

$$E_{\text{PV,year}} = C_{\text{PV}} IPR365,$$

where I is the average global insolation (during the day), and PR is an overall performance ratio (0.75-0.85) representing the losses incurred by the modules, wiring, the temperature, soiling, and the inverter. The hourly PV power P_"PV" (t) is generated by multiplying a normalized irradiance profile by a scaling factor to match the daily energy from monthly PVSPCL data from the Ludhiana region. The base case assumes installed PV capacity at 200 – 500 kW, and average daily insolation of 4.5 – 5.0 kWh/kW·day and a nominal performance ratio of 0.8 with the converter efficiency included in the performance ratio (PFR) (corresponding to fixed-tilt systems).

C. *Battery Energy Storage System*

The BESS will help to reduce the voltage spikes in the grid when EV charging is high and PV generation is low, as well as help to balance solar PV generation and EV charging demand over time, allowing for charging during the night and early morning when demand is lower and PV generation is higher. The battery is modeled using a state of charge formulation in the energy basis and the stored energy E_"batt" (t) is a function of time.

$$E_{\text{batt}}(t + \Delta t) = E_{\text{batt}}(t) + \eta_{\text{ch}} P_{\text{batt,ch}}(t)\Delta t - \frac{1}{\eta_{\text{dis}}} P_{\text{batt,dis}}(t)\Delta t,$$

subject to bounds $0 \leq E_{\text{batt}}(t) \leq C_{\text{BESS}}$ and $0 \leq P_{\text{batt,ch}}(t), P_{\text{batt,dis}}(t) \leq P_{\text{BESS,rated}}$.[^1]

The representative values of the BESS parameters used in the thesis for optimization are as follows: usable BESS capacity (400-800 kWh), rated charge/discharge power (250-400 kW), charge/discharge efficiencies (approx. 0.97), and SOC operating window (approx. 10-90%), limited by degradation. The BESS is linked to the DC bus through a bidirectional DC-DC converter that is modeled as a controllable power source/sink with constant efficiency, and, if necessary, with simple ramp rates.

D. *EV Demand and Charging Station Model*

Instead of detailed models of the traction the EV subsystem is modeled as an aggregate time-varying load, composed out of scenario based arrival and departure profiles, charger ratings and per-session energy needs. At t the total charging power for the EVs is[^1]

$$P_{\text{EV}}(t) = \sum_{i=1}^{N_{\text{EV}}} P_{\text{EV},i}(t),$$

where each car i gets energy based on

$$\sum_{t=t_i^{\text{arr}}}^{t_i^{\text{dep}}} P_{\text{EV},i}(t)\Delta t \geq E_i^{\text{req}},$$

Provisioning of the required energy E_i^"req" within the specified parking window. Delivery of required energy E_i^"req" within the specified parking window.

The two classes of chargers are considered are Level-2 AC chargers (7-22kW) for long-stay users and direct connected DC fast chargers (50-150kW) on the DC bus. Some typical assumptions for the reference station are 10-20 Level-2 chargers, 4-6 DC fast chargers, a daily average of approximately 25 kWh energy per EV and an average charging time of 4-8 hours for Level-2 and 0.5-1.5 hours for DC fast charging.

E. *Converters and Grid Interface*

The three types of converters modelled are PV DC–DC with MPPT, bidirectional BESS DC–DC converter and the grid-tied inverter connecting the DC bus to the three-phase feeder. The grid-tied inverter is operated in a PQ control system, and the active power reference signal is controlled by the energy-management system, while the reactive power reference signal is determined by the desired power factor or by a requirement to support the local voltage within an apparent power limit. The efficiencies of the converters are assumed to be constant and included in the performance ratios and loss factors, which are also handled in an annual energy and loss model as used in the thesis.The efficiencies of the converters are also assumed to be constant, and included in performance ratios and loss factors, just as the tractable annual energy and loss modelling used in the thesis are adopted.

IV. Optimization Framework

A. *Decision Variables and Constraints*

Design level decision variables are PV capacity C_"PV", BESS usable capacity C_"BESS", BESS power rating P_"BESS, rated" and, for sensitivity analysis, the number of charger types. These variables are constrained by site area and equipment limits. Operational decision variables at each time step include grid power P"grid" (t), battery power for charging and discharging, power for charging EVs (aggregate or per-vehicle), and stored energy in its batteries. Hard constraints are used to ensure power balance on the DC bus, battery SOC dynamics and bounds, grid transformer and inverter limits, and EV service-quality requirements, to ensure that all vehicles get the energy they requested during their parking periods. In the base model, demand curtailment is not permitted, which requires infeasible designs to either import more grid power or be deemed infeasible and disallowed.

B. *Solution Methods*

With linear SOC model and linearised cost and loss functions it is possible to implement the optimization problem as a linear program (LP) or mixed-integer linear program (MILP) that can be solved for global optimality for a given weight set and solution over a full-year hourly horizon with standard solvers. For extended formulations, e.g., ones with non-linear efficiency curves, discrete operating modes, and degradation dependent on battery costs, alternatives to the use of meta-heuristics like particle swarm optimization (PSO) and NSGA-II are described, and trade-offs on the Pareto front explored.

V. Implementation and Case Study Setup

A. *Site Selection and Data*

The case study site is located around McDonald's and Burger King outlets at Ranjit Square, Gill side, along the Ludhiana-Malerkotla corridor (Gill Pind) which is a high traffic node where inter-city, local commuter and highway traffic will converge. The site features a commercial load base, a high vehicle turnover, and a pronounced peak in traffic during the evenings and on weekends, making it a representative test site for solar EV charging with storage.This site has a commercial load base, a high vehicle turnover and a pronounced evening and weekend surge, making it a representative test site to demonstrate solar EV charging with storage. Solar resource characterisation involves data from solar generation by PSPCL and database of standard irradiance, that gives monthly insolation values for 2025 with average of about 4.8

kWh/kW·day at the site. The monthly average temperatures are in the range between 20 °C and 35 °C, which allows the use of a performance ratio of approximately 0.8 in the calculation of PV energy yield. The tariff parameters, Average cost of Supply and typical TD loss % are sourced from ARR/PSPCL documents, while the EV related parameters like typical daily energy usage per vehicle, and projected EV penetration in Ludhiana by 2026 are used as input for creating EV demand scenarios.

B. *Load and EV Charging Profiles*

The local base load profile for the case study is shaped by the operating hours of quick-service restaurants, and particular commercial activity, and shows two peaks: one in the late afternoon and evening, and another at lunchtime. EV charging demand is created by adding additional energy use required by various combinations of Level-2 and fast chargers to serve cars and 2-wheelers, with typical daily energy per EV usage ranging between 20–30 kWh and high use rates occurring between hours 17:00 and 22:00 in the day. This was estimated to be the EV share around 6% of the total registered vehicles in the city by 2026, which would mean the addition of tens of thousands of EVs such as e-rickshaws, electric two-wheelers and cars to the fleet. In this context, the thesis introduces three different charging-station scenarios – namely low, medium, and high throughput – by adjusting the number of EVs served every day to the optimization problem, while solving it with different weight assignments (wC, wL, w"CO_2").

C. *Numerical Framework*

The PV–BESS–PEV integration model is applied in an algebraic modelling environment in which the decision variables, constraints and objective functions are described symbolically and handed over to an optimization solver. The annual PV yield, annual demand for EVs, power balance for the DC-bus, battery SOC update and CO_2 emission equations are coded directly from the analytical equations to ensure numerical consistency between numerical calculations and the theoretical derivations. The input data are broken down into pre-processed tables including monthly PV generation per division, tariff and average cost of supply data, distribution-loss data and EV usage assumptions, before being translated into hourly time series for simulation. Modular structure is used, with separate modules for data, analytics, optimization, and simulation/reporting to allow scenario analysis and simulation/reporting to be repeated.

D. *Case Study: PV–BESS–PEV Sizing for 15,000 EVs/Day*

A high-profile case study is given for a charging hub to service 15,000 EVs per day, representing the projected EV uptake and commercial density for the Gill-side site. The daily EV energy demand is estimated using

$$E_{\mathrm{EV,day}} = N_{\mathrm{EV}} \mathrm{kWh}_{\mathrm{EV,day}},$$

with $N_{\mathrm{EV}} = 15{,}000$ vehicles and $\mathrm{kWh}_{\mathrm{EV,day}} = 25$ kWh as a representative per-vehicle value within the 20–30 kWh range,

For symmetric day and night operation, this 375 MWh/day demand is divided into 187.5 MWh/day of demand chargeable during the day, to a large extent covered by PV supply, and 187.5 MWh/day of night-time chargeable demand, to a large extent covered by BESS. The annual average insolation of 4.8 kWh/kW·day and performance ratio of 0.8 are translated into an amount of daily energy of 3.84 kWh/kWday per 1 kW of PV system and used in conjunction with the battery SOC model to size the PV and BESS system capacity in the 15,000-EV scenario. The BESS charge and discharge efficiencies of 0.97 result in a round-trip efficiency of approximately 0.94 when determining the amount of PV energy that needs to be captured and stored throughout the day to meet night-time demands for EV charging blocks. All sizing calculations in this case study are based on equations and parameter ranges presented above in the thesis, the engineering quantities that are missing are explicitly stated as external assumptions in use.

VI. Results and Discussion

A. *Energy Flows and Network Losses*

The first set of results shows, that in the case the EV block is supplied only by the thermal grid, approximately 28.78 GWh/year will be generated at the PSPCL plant to supply 24.47 GWh/year at the LS bus, with grid-route losses of around 4.32 GWh/year and a delivery efficiency of around 85%. The PV–BESS–EV system is proposed to deliver the same 24.47 GWh/year of EV power locally from PV–BESS at a total PV generation of ~26.03 GWh/year and internal loss of ~2.76 GWh/year, which corresponds to an effective delivery efficiency of ~94% with a high contribution of 94% round trip efficiency of the BESS. This comparison therefore identifies the fact that integration of PV–BESS near the EV block eliminates around 4.32 GWh/year of losses on the upstream grid and increases the delivery efficiency by 9 percentage points compared to the conventional thermal grid route.

B. *Coal Consumption and CO_2 Emissions*

Taking an annual thermal generation of 28.78 GWh/year for the EV grid supplied scenario and specific coal consumption 0.63 kg/kWh, the estimated coal consumption required for the EV block is approximately 18136 tonnes/year when served from purely coal based PSPCL system. When the entire grid route is taken into account, the resulting total annual CO_2 emissions for this EV energy are about 40,300–43,200 tonnes/year (mid-range) CO_2 intensity of about 1.71 kg CO_2/kWh at the charger. On the other hand, if the EV block is supplied from the dedicated PV–BESS system, the incremental coal use and associated CO_2 emissions for these loads is effectively zero hence the CO_2 intensity at the point of EV charging on the studied feeders goes from approximately 1.7 kg CO_2/kWh towards 0 kg CO_2/kWh for the portion of demand supplied by the local solar resources.

C. *Cost Reduction and Peak-Power Relief*

On an economic front, the savings in the grid energy required for charging EVs directly lead to a decrease in the annual energy bill at the PSPCL tariff of 6.60 ₹/kWh, whereas the smoothing of the power exchange at the PCC reduces the vulnerability of the station to peak demand in the day and corresponding charges. Under the scenarios of optimization that are cost oriented, for the assumed utilization level of the grid, and for the commercial case on Gill-side (24.47 GWh/year required by the EV fleet), combinations of PV and BESS capacity configurations are found that provide lower annualized cost of EV energy than the purely grid supplied case. The optimised PV–BESS–EV configuration also helps to reduce the peak power which is drawn from the grid at the PCC as compared to the base case configuration, which is particularly useful during the evening hours when the peak demand may be significant on the conventional grid without the use of local resources.

D. *Integrated Efficiency and Design Insights*

Last, the integrated efficiency metric, the ratio of the energy delivered to EVs to the total energy consumed (from PV and the grid) by the local system, verifies that the proposed architecture is more efficient in the use of supplied energy than the "grid only" benchmark. The PV–BESS–EV route will also take advantage of the reduction in bulk transmission and distribution losses, as well as the ability to charge and discharge the BESS in an appropriate manner to reduce the peak current and I^2R losses in the local conductors. Overall, the energy flow, emissions, cost and efficiency impacts show that the optimised PV–BESS–EV system at the chosen Ludhiana corridor location can provide the desired 24.47 GWh/year of EV energy with these benefits over a conventional thermal grid supplied EV charging block: higher efficiency; significantly lower coal consumption and CO_2 emissions; reduced grid losses; and improved peak demand behavior.

VII. Conclusion

This study focuses on the use of battery-based solar energy to charge electric vehicles in Ludhiana India. The authors have developed a case with the PV and BESS incorporated in the electric vehicles and the electricity grid.They modeled the flow of power within the system taking into account the charging and discharging behavior of the batteries as well as the power balance in the DC grid. This model is used to optimize cost, power losses, and emission levels.

For a station dealing with 15000 vehicles a day, the system revealed that solar and storage can meet a good portion of the demand by using local generation. In addition to this, it minimized the losses, decreased the coal consumption and alleviated evening peak for the PSPCL grid. Charging remained constant without any drastic rise in costs.Combining the quick analysis of results and more extensive numerical calculations is helpful in determining sizes and daily schedules. This approach appears to be quite versatile although I am not absolutely sure about the influence of various weather patterns.

Areas for future research that have been identified through this thesis include the inclusion of vehicle-to-grid capability into the model, battery degradation effects, dynamic pricing, and ancillary services in the optimization, in addition to the stochastic nature of EV arrivals and solar generation.

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