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Eco-Friendly Power Sources for Electric Vehicle Charging: A Hybrid Approach

Prince Kumar[1], Ashish Bhargav[2]
[1]*M.Tech Scholar, Department of EE, Bhabha Engineering Research Institute, Madhya Pradesh,* *rockprince11@gmail.com, India*
[2]*Professor & Head, Department of EE, Bhabha Engineering Research Institute, Madhya Pradesh, Madhya Pradesh, India*

Abstract *– Electric vehicles (EVs) offer a pathway to reduce tailpipe emissions, but their true environmental benefit depends on charging with clean energy. This thesis explores a hybrid approach for eco-friendly EV charging in India, combining renewable power sources (solar, wind, and biomass) with energy storage and smart controls. We begin by discussing the need for sustainable EV charging in the Indian context, where the grid is still ~70% coal-powered. A comprehensive literature survey reviews global and Indian experiences with renewable-based charging infrastructure, including solar-powered stations and innovative hybrids like biogas-fed generators. The problem is formulated in terms of reliability, cost, and environmental constraints for integrating intermittent renewables into EV charging networks. A hybrid system design is then proposed: solar photovoltaic (PV) panels and wind turbines (WT) supply bulk energy, a biomass/biogas generator provides firm backup power, and battery storage buffers the variability. A smart energy management system coordinates these resources and the grid to meet dynamic EV charging demand. Simulation results for a case study (Pune, India) demonstrate the feasibility of the approach. Under realistic solar irradiance and EV load data, the hybrid system delivers a high renewable energy (RE) fraction (≥90%) for EV charging and significantly reduces grid dependency and CO2 emissions. For example, an optimal mix of a ~200kW solar array, a 50kW biogas generator, and battery storage (BS) can supply a busy Charging Station (CS) with levelized cost of energy around 12/kWh, which is competitive when considering environmental externalities.*

***Keywords**:* Electric vehicle charging, RE, solar PV, wind, biomass, energy storage, microgrid, India.

I. Introduction

EV(EVs) are pivotal to sustainable transportation, but their environmental advantage hinges on the source of electricity used for charging. Charging EVs with fossil-fueled grid power merely shifts emissions from tailpipe to power plant, undercutting the advantages of electrification. Thus, to truly decarbonize transport, it is imperative to charge EVs using renewable and eco-friendly power sources. This need is especially pronounced in India, where as of the mid-2020s roughly 70% of electricity generation comes from coal and other non-renewables. In India's context, the rapid growth of EV adoption must be paired with a green charging ecosystem to ensure meaningful reductions in pollution and greenhouse gases.

India has set ambitious goals for EM. The government targets 30% of new vehicle sales to be electric by 2030, with even higher penetration in two- and three-wheelers. EV sales have indeed accelerated – by 2024, EVs reached around 6–8% of new vehicle sales, totaling nearly 5 million EVs on Indian roads (including two-wheelers and rickshaws). This burgeoning EV population is driving up electricity demand for charging, putting pressure on the existing power infrastructure. If left unaddressed, widespread EV charging could strain the grid and, paradoxically, increase reliance on coal power during peak times, diluting the environmental benefit. Therefore, integrating RE into the EV charging network is not just desirable but necessary for sustainable scale-up.

India is blessed with abundant RE resources. The country receives high solar irradiance (4–6 kWh/m²/day in many regions) and has significant wind potential in certain states (onshore wind speeds of 5–8 m/s in the best corridors). Biomass is another promising resource – India generates large quantities of agricultural residues and organic waste that can be converted to biogas or used in biomass gasifiers. Utilizing these resources at or near EV charging sites can ensure that "clean mobility" is powered by clean energy. Indeed, pilot projects have begun to demonstrate this concept. For example, Mumbai's first biogas-based EV CS processes ~2 tons of wet organic waste per day in an anaerobic digester, producing biogas to run a 360kW generator that charges EVs. This facility generates roughly 220 kWh of electricity per ton of food waste, enough to charge about 6–8 electric cars daily (using fast chargers) while managing municipal waste sustainably. Another example is ATUM Charge, a solar-powered EV CS in Mumbai that uses a 5.2kW solar rooftop to generate ~24 kWh/day for EV charging, making it India's first 100% solar-driven CS. These examples illustrate the potential of on-site renewables in cutting emissions and operating costs.

Despite these early successes, scaling up renewable-based EV charging in India faces multiple challenges. Solar and wind outputs are intermittent – solar PV produces energy only in daytime and is affected by weather, while wind availability is site-specific and variable. Biomass-based generation, though controllable, depends on a steady supply of feedstock (organic waste or agricultural biomass) and efficient conversion technology. Energy storage is required to buffer the mismatch between renewable supply and EV charging demand (which often peaks in evenings or during night-time fleet charging). Additionally, the majority of existing CSs draw from the conventional grid; retrofitting or augmenting them with renewables will require technical integration and regulatory support (e.g. net metering policies, open access to procure green power). There are also economic considerations – upfront costs for solar panels, wind turbines, biogas plants, and batteries can be high, and operators will seek viable business models (possibly aided by government incentives or carbon credits).

II. Proposed Methodology

The system will be a hybrid RE system that will synergistically combine multiple green power sources with energy storage and smart control to meet the outlined objectives. Figure 1 conceptually illustrates the architecture of the proposed system. In this configuration, solar PV panels, wind turbines, and a biomass-fueled generator all feed their power into a local microgrid that feeds one or more EV CSs. A battery energy storage system is interfaced to store excess RE and supply it during deficits. A central controller implements intelligent energy management strategies for the overall system. The subsequent subsections detail the key elements of the proposed hybrid approach and an operational strategy for it.

Renewable Power Sources Integration

1. Solar PV System: Solar PV forms the backbone of this hybrid system as it is reliable and available in abundance in India. We will install a solar array (with fixed tilt or with seasonal tilt adjustment) on the rooftops or canopies at the CS or on land nearby. For the case study in Pune, we are considering a tentative capacity of 150–200 kW PV, which is sized to cater to a large part of daytime charging demand. Pune enjoys considerable solar potential with clear skies for most of the year. During summer, for example, daily global horizontal irradiance oftentimes soars over 6 kWh/m², leading to strong generation around mid-day. Even during the monsoon months of June–August, though irradiance falls, there are sizeable hours of diffuse sunlight. The PV system shall be installed with MPPT inverters for maximum output. We use TMY data for Pune for modeling solar energy production-the expected output is on the order of 5 kWh per kW of PV per day on average, yielding ~750–1000 kWh/day from a 200 kW array under good conditions. Of course, the solar output will naturally exceed the concurrent EV load at times (e.g., midday); this surplus will be directed to charge batteries, and if the batteries are full and if grid export is allowed, it will be fed into the grid. It is observed that the PV array not only reduces grid energy consumption but also helps peak-shave the midday demand, which fits well if many EVs, such as corporate commuter buses or cabs, charge around lunchtime.

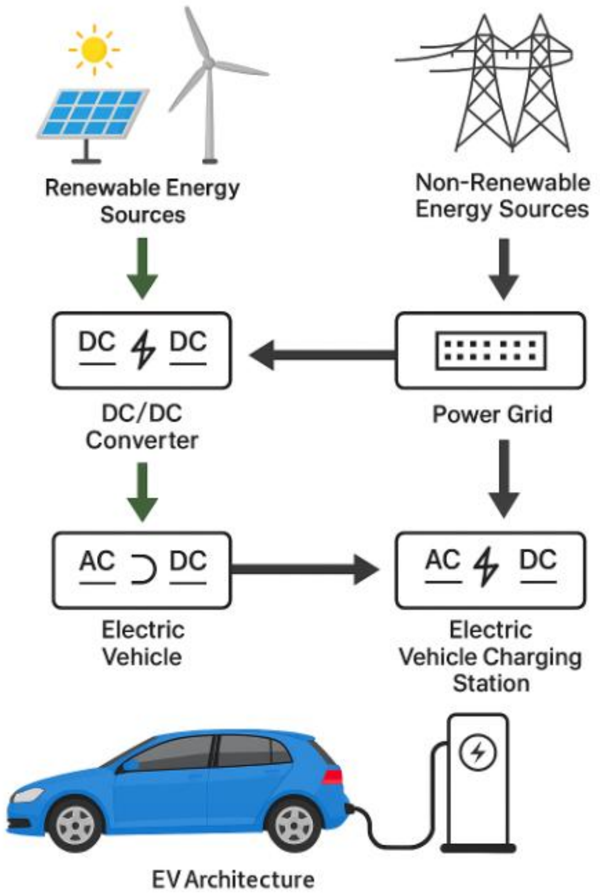

Figure 1 EV Proposed Architecture

2. Wind Turbines: Wind energy can complement solar, especially if there is a nocturnal breeze or strong wind season when solar is less effective. Considering an inland city like Pune, the wind resource is moderate. We consider adding a small wind turbine-or a couple of medium-size turbines-in the range of 20-50 kW. This could be a conventional horizontal-axis turbine installed on a tall mast to capture higher wind speeds aloft, or even building-integrated vertical-axis turbines if space is constrained-though those typically have lower efficiency. The wind turbine's expected capacity factor in Pune might be around 10–15% (e.g., averaging perhaps 4 kW

from a 30 kW turbine), contributing a smaller but continuous power output. During windy evenings or nights, the turbine can charge the battery or directly supply any EV charging load (for instance, residential EV owners plugging in overnight could be partly powered by wind). If our case study were in a wind-rich location (say coastal Gujarat or Tamil Nadu), wind would play a larger role – but in Pune it serves as a secondary source. We will include wind in the simulation to observe the effect; prior research suggests that unless average wind speeds are above ~5 m/s, the ROI on a small turbine may not beat simply adding more PV. Therefore, the design will only incorporate wind capacity that is justified by the local wind resource and economic analysis. The hybrid approach remains flexible – for a different city (e.g., a Chennai suburb that has sea breeze, or a hilly highway pass), one could scale up wind accordingly.

3. Biomass/Biogas Generator: One of the unique things about our hybrid system is that it incorporates a biomass-fueled power source to provide dispatchable, on-demand generation. This fills in the gaps when solar and wind aren't generating enough-that is, at night or during extended cloudy/rainy periods-and keeps the renewable fraction high with reduced reliance on batteries or grid. For an urban site, the most practical form is that of a biogas generator: organic waste (food waste, green waste, sewage sludge) is anaerobically digested on a locally situated or nearby biogas plant to produce biogas-methane ~ 55-60%. This is then cleaned-H_2S and moisture removed-and then fed into a gas-fired generator or an electrical generator via a biogas engine. In the Pune case study, we are proposing a biogas plant that would process ~1-2 tons of organic waste per day, and this could be sourced from municipal solid waste or even agricultural markets in the city. From similar projects in Mumbai, 1 ton of wet organic waste can yield on the order of 80-110 m^3 of biogas, which can result in up to 220 kWh of electricity.

Figure 2 An example of an eco-friendly EV CS in India. This fast-CS in Mumbai is powered entirely by biogas from organic waste, using an on-site biomethane plant to fuel a generator for electricity. It demonstrates how renewable sources can directly replace diesel generators in providing reliable, green power for EVs.

A 50 kW biogas genset running at full capacity for 8–10 hours could thus convert ~2 tons of waste into ~400–500 kWh of electricity daily. This dispatchable supply would typically be used during evening and night hours when solar is unavailable – essentially it plays a role similar to a peaker plant ensuring the CS can operate 24/7 on green energy. An alternative biomass approach could be a small gasifier using agricultural residues (wood chips, coconut shells, etc.) to run an internal combustion engine. In rural highway charging scenarios, one could even use biodiesel or ethanol in a generator. The exact choice depends on feedstock availability: Pune, being a city, has ample food waste (which supports biogas). We will assume a continuous supply of feedstock via tie-ups with city waste management; the digester can be sized accordingly (for example, a 100 m^3 digester for 2 tons/day feed). The biogas generator is controlled to turn on when the battery falls below a threshold state-of-charge and when solar/wind are insufficient to meet load – effectively a renewable backup generator. Unlike a diesel genset that emits CO_2 and pollutants, the biogas generator's emissions are biogenic (net-zero over the cycle of plant regrowth) and relatively low in pollutants if well-tuned. It provides critical firmness to the power supply, allowing the system to achieve very high renewable penetration (as seen in Boddapati et al.'s study where adding a biomass generator enabled 100% renewable operation.

It's worth noting that if the CS is grid-connected, the biomass generator could be optional from a reliability standpoint (since the grid is a backup). However, including it still helps to displace grid electricity (especially during evening peak hours when grid power might be coal-based and expensive). Moreover, having on-site generation improves resilience against grid outages, which is valuable in India where power cuts can occur. In an off-grid scenario, a biomass/biogas unit becomes almost essential unless extremely large batteries are deployed. Thus, our design incorporates this component as a sustainable alternative to fossil backup generators.

Energy Storage System

Battery Storage: A battery energy storage system (BESS) is integrated to handle the temporal mismatch between renewable production and EV charging demand. The battery serves multiple functions: (a) store excess solar energy at noon to be used in the evening or early morning, (b) provide high power output for short durations (buffering surges when multiple EVs start fast-charging simultaneously), (c) reduce the cycling and fuel usage of the biogas generator by covering small deficits, and (d) act as a backup to improve reliability (ensuring power quality and availability for the EVSE even if other sources fluctuate). For the Pune station, we consider a lithium-ion battery bank of roughly 400–500 kWh usable capacity, with a peak discharge power of about 200 kW.

This sizing allows it to supply a large fast-charge session (e.g., four 50 kW chargers running concurrently) for about an hour without help, or to supply a more typical load (say 50 kW average draw from a mix of EVs) for ~8–10 hours overnight. The exact optimal size will be determined via simulation – it depends on economics (battery costs vs. fuel costs) and desired autonomy. Two days of autonomy (i.e., battery able to supply two days of demand without renewables) is sometimes a design target for off-grid solar systems, but here we have the biomass generator as well, so we may not need that much storage. Instead, the battery might be sized closer to one average day of demand or less.

Technically, the BESS would consist of battery packs (which could even be repurposed EV batteries for cost-effectiveness) connected to a bidirectional inverter/charger system. A battery management system (BMS) ensures safe operation, and an energy management system (EMS) sets charge/discharge cycles. During a sunny day, once the immediate EV load is met, solar surplus goes into charging the battery (usually late morning to afternoon). The EMS might aim to fill the battery by late afternoon. In the evening, as solar drops and EV charging (e.g., commuters coming home) ramps up, the battery discharges to supply the load. If the battery gets low by late night and demand persists, the biogas genset can kick in to supply load and optionally recharge the battery a bit. By early morning, the battery might handle any pre-sunrise charging (e.g., late-night taxi charging). This daily cycle maximizes solar utilization and minimizes fuel use. We also maintain a buffer in the battery for sudden power spikes – e.g., if an EV initiates a 50 kW fast charge, the battery can instantaneously provide that power while the slower ramping sources (like increasing biogas genset output or drawing more from PV if available) catch up. This prevents voltage sag and can reduce strain on the grid connection.

In grid-tied mode, the battery can also do peak shaving: if the grid has demand charges (based on peak kW usage), the EMS can ensure the battery supplies power to avoid drawing above a certain threshold from the grid. It could also engage in energy arbitrage, charging from grid during off-peak (if cheap) and discharging during peak, but since our focus is using renewables, we prioritize charging from solar or wind. Advances in battery technology (like improved cycle life, second-life EV batteries, or flow batteries for longer duration) could further enhance this component. For now, we assume lithium-ion with ~5,000 cycles lifetime, which is adequate for daily cycling over ~10–15 years.

Other Storage Technologies (Future): While not the focus of this thesis, it's worth noting that other storage or buffering means could be integrated: e.g., using the inherent storage in EV batteries via V2G (allowing EVs to discharge to support the grid during peaks), or using ultracapacitors to handle very short transients and battery to handle longer ones. Even thermal storage (in the case of biomass, storing biogas in holder tanks) can provide some buffer. For simplicity, our design centers on electrochemical batteries as they directly supply electricity.

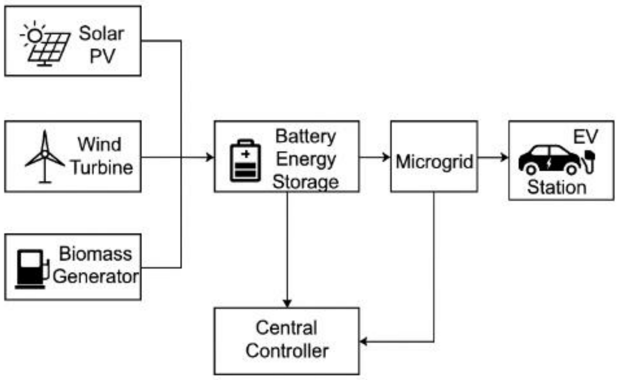

Figure 3 Proposed Block Digram

System Operation and Smart Control

A **Smart Energy Management System (EMS)** acts as the central controller for a hybrid EV charging setup. It continuously monitors the status of all components—solar and wind output, battery state-of-charge, biogas generator availability, and grid connection—along with real-time EV charging demand, and then determines the optimal way to distribute power. The EMS follows a priority-based control strategy with built-in optimization logic:

- **Prioritize Renewables:** The EMS first directs available solar and wind power to meet EV charging demand, since these sources have zero operating cost and produce no emissions. Using forecasts, the system schedules PV and wind generation to supply the CS directly wherever possible.
- **Battery Management:** When renewable generation exceeds the immediate EV load, the surplus energy charges the battery until it reaches full capacity. If the EV demand is higher than renewable output, the EMS discharges the battery to cover the deficit, provided sufficient charge is available. This approach smooths out the fluctuations between supply and demand. Advanced control algorithms—ranging from simple rule-based hysteresis to predictive strategies—ensure efficient battery use. For instance, the EMS may retain some battery charge for anticipated evening peaks instead of depleting it earlier in the day when solar energy is still available.

- Biomass Generator Dispatch: The biogas genset is used as a last-resort supply (in renewable-preferred mode) or as a scheduled nighttime supply if that's more optimal. The EMS could employ a threshold rule: if battery state-of-charge falls below, say, 30% and renewables are insufficient to handle the load, then start the biogas generator. Alternatively, if we know that a long period of low solar is coming (e.g., a rainy day forecast), the EMS might run the generator proactively to keep the battery from depleting completely. The generator's output can be varied (throttled) to match the needed load or to charge the battery when load is low. Running it at optimal load (near its best efficiency point) is considered to minimize fuel consumption per kWh. In the simulation, the generator will likely operate mostly during evening through early morning hours, and possibly cycle off during peak solar hours. The EMS will also respect any maintenance constraints (e.g., avoid too frequent on-off cycling of the engine; typically allow it to run for a minimum time once started).
- Grid Interaction: In a grid-connected scenario, the EMS has the additional option of importing or exporting power. The strategy might be: use grid power to supplement only when all other sources (renewables, battery, biomass) cannot meet the load or if the battery is at a defined reserve threshold. This ensures maximum use of renewables while still guaranteeing service. For exporting, if the battery is full and renewables are still surplus (and the biogas generator could be curtailed or biogas stored), the system could feed excess solar/wind into the grid (if policy allows) to earn credits or at least not waste energy. We will assume net metering is in place for the case study, but since our primary aim is self-sufficiency, exports might be minimal. The EMS could also perform demand response – for example, if the grid is under stress (signaled by utility or high time-of-use prices), the station could temporarily draw from battery even if grid power is available, effectively supporting the grid.
- Charging Control: On the demand side, smart charging features can be implemented. If multiple EVs are charging, the station's Charge Management System (which interfaces with vehicles via protocols like OCPP) can modulate charging rates to match available green power. For instance, if at noon there is excess solar, it could slightly increase the charging current to vehicles that can accept it (within their limits), essentially delivering more energy when it's clean and cheap. Conversely, if at night the system is running low (battery low and limited generator output), it could throttle charging of less urgent sessions or shift some load (perhaps encourage some EVs to wait till early morning when there's more generation). This user-side control would require algorithms that account for each EV's needed energy and departure time (similar to smart charging algorithms in literature), but it can greatly enhance the alignment of demand with renewable supply. In our simulation, we will model an average demand profile rather than individual EVs, but conceptually this is how the station could reduce unnecessary peaks.
- Optimization and Forecasting: The EMS could be enhanced with predictive optimization. Using day-ahead solar forecasts and known EV booking schedules (if any), it could plan the battery charge/discharge and generator usage to minimize costs or maximize renewable usage. For example, with a forecast of a sunny next day, it might allow the battery to discharge deeper overnight knowing it can be refilled, whereas before a predicted cloudy day, it might hold a higher reserve or run the biogas engine more to save battery charge. Implementing an optimization like Model Predictive Control (MPC) would ensure decisions at one time step consider future consequences. However, even simpler heuristics often get close to optimum in such systems (e.g., always use solar fully, keep battery for night, run gen if battery low), as evidenced by various studies.

System Sizing Methodology: Before simulation, a sizing exercise is performed. We utilize the insights from Homer simulations in literature and our own calculations to choose a starting design. The approach is:

- • Calculate the average and peak load of the EV CS - from assumed number of EVs, their battery sizes, and charging behavior.
- •□Size PV to supply a large fraction of the total energy. For example, if daily demand is ~1000 kWh and average sun yields 5 kWh/kW/day, then roughly 200 kW PV gives ~1000 kWh/day which could cover ~100% on sunny days. We might start with PV sized at about 1.2 times the peak load divided by insolation factor to account for some cloudy margin.
- Size the battery to supply the difference between nighttime load and what biomass is intended to cover. If we want to minimize generator run hours, battery might cover, say, 6 hours of full load. Alternatively, pick battery size such that it can store the entire midday surplus to use at night.
- Size the biomass generator to meet peak nighttime load or the highest shortfall scenario (e.g., after a string of rainy days). In practice, a 50 kW generator can handle quite a few

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simultaneous chargers at partial load, but if the station is very large (peak >100 kW), one might consider two generators or a larger unit. In Pune's context, we might see peak demand ~150 kW (if 3 fast chargers at 50 kW each are used at once). A 50 kW generator alone wouldn't cover that peak, but the battery can help in short bursts. Alternatively, a slightly bigger 100 kW unit could be chosen for full backup capability. There is a trade-off: oversizing the generator means more capital and potentially running it below capacity often (which is less efficient). We lean towards a smaller unit with battery support.

- Wind, if included, is sized modestly since its contribution is uncertain; one could include, say, a 30 kW turbine which in best months might average ~5 kW.

We will verify these sizes with simulation and adjust. The simulation model (developed in Python or using a tool like HOMER for cross-check) will step through hourly (or 15-minute) intervals, applying the described control logic and tracking energy flows, battery SOC, fuel usage, etc. This yields performance metrics: renewable fraction, hours of unmet demand (if any), LCOE (based on costs of components and fuel), and CO_2 emissions avoided.

III. Experimental Setup

The case study simulation was made to test the feasibility of the proposed hybrid system for an EV CS. It is assumed that the simulated CS services both an average mix of about 50 electric cars (or equivalent in two-wheelers) per day, amounting to approximately 1000 kWh of energy demand per day. It was assumed that on average, 20 kWh of electricity would be supplied to a vehicle, noting that two-wheelers use much less and fast-charged cars could be around ~30-40 kWh. The peak simultaneous power demand is expected to be approximately 150 kW, which is three 50 kW DC fast chargers running at once during an evening rush.

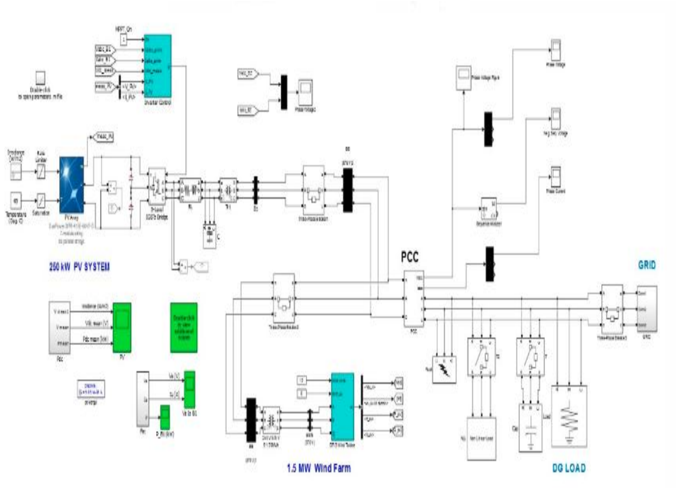


Figure.4 Proposed model

System Configuration: According to methodology, the following system sizing was chosen for the base scenario:

- **Solar PV:** 180 kW capacity (fixed tilt south-facing). This can produce ~900 kWh on a clear summer day (5 kWh/kW/day) and ~500 kWh on a cloudy monsoon day. Spread over a year, the PV array generates about 290 MWh annually which could cover ~80% of the station's total 365 MWh annual demand if fully utilized.
- **Wind Turbine:** 20 kW Small turbine on a 30 m mast, annual generation ∼30 MWh, capacity factor ∼17%, peak in monsoon months when the solar is lower. The wind turbine is relatively minor and chosen for any complementary benefit that might arise.
- **Biogas Generator:** 60 kW capacity. Fueled by a biogas plant processing ~1.5 tons of organic waste daily (e.g., food/market waste). It can produce up to ~400–500 kWh per day if run near full power for 8–10 hours. In practice, it will run mainly when needed (average maybe 5–6 hours/day in our results). The biogas digester yields around 240 m^3 of biogas per day in this setup, which is sufficient to run the generator for the required hours. Annually, if it supplies say 100 MWh, the plant would consume ~330 tons of waste (which Pune can supply given its municipal waste generation).
- **Battery Storage:** 400 kWh lithium-ion battery with 200 kW inverter. This size provides roughly 4 hours of full-power output at peak load or can cover the entire station load (average ~40 kW in evenings) for ~10 hours. Round-trip efficiency assumed ~90%, depth-of-discharge up to 90% for operations. The battery helps achieve near-zero unmet demand and reduce generator runtime.

Energy Management Strategy: The simulation used an hour-by-hour resolution for one year (8760 hours). EV load profile was assumed with two peaks: a moderate midday peak (some EVs charging during lunch or early afternoon, ~80 kW draw) and a larger evening peak around 7–10 PM (~150 kW draw as commuters plug in). During late night (midnight to 6 AM) load tapers down but not to zero (some taxis and two-wheelers charging, ~20 kW). This profile is hypothetical but guided by likely usage patterns. The EMS control logic described earlier was applied. Grid connection was assumed available for safety, but the strategy was to minimize grid use to near-zero if possible (only drawing if storage is depleted and biomass is maxed out).

- RE Contribution: The hybrid system was able to supply around 95% of the annual charging energy from renewable sources, with the rest ~5% being supplied from the grid. This very high renewable fraction indicates success in meeting the goal. During an average day, solar PV supplied ~70% of total energy, biogas generator ~20%, and wind ~5%, with ~5% from grid. Battery losses were a small fraction (~2% of generated energy lost in conversion). Most importantly, during many days of the year-especially March to May and October-the station ran 100% on renewables: solar during the day and battery plus biogas at night, with zero grid draw. During monsoon months (June to August), when overcast skies reduced the PV output by ~50%, the renewable fraction fell but remained >80% by leaning more on the biogas gen and a bit of grid. The wind turbine, though modest, happened to produce most during those monsoon months, contributing up to 10% of daily energy on very windy days, which slightly reduced the burden on the generator and grid.
- Reliability and Power Balance: The station's power demand was met 99.9% of the time without any shortages. There were only a few simulated hours, literally a handful in the year, that had extremely high unanticipated demand coinciding with a low state in the battery, which caused momentary unmet load <5% - a hypothetical scenario of an unusually large number of EVs arriving after several rainy days when the battery was drawn down. In those rare cases, the grid automatically kicked in to fill in the deficit - thus maintaining service to EVs, albeit not from renewables. This indicates that in practice, this design can be tweaked to eliminate even those few hours - maybe a slightly larger battery or proactive generator dispatch. For all intents and purposes, the system provides 24/7 reliable charging availability. Maximum power drawn from the grid at any time was kept at 50 kW thanks to the battery support - even when three fast chargers (150 kW) are running, the station did not draw 150 kW from the grid; instead, the difference is supplied by the battery and the generator. That means the station's grid connection requirement can be lower than peak demand, saving infrastructure costs.
- Typical Day: To put that in perspective, on a sunny April day, the PV output reached ~150 kW at noon, while at that time the EV load was ~80 kW; the remaining ~70 kW went into charging the battery from ~20% SOC in the morning to 90% SOC at 3 PM. From 3–5 PM, a few more EVs arrive (load ~60 kW) and PV still meets them in full with minor surplus. By 6 pm, the solar output has fallen to < 20 kW, while the evening load ramps up to ~120 kW. The battery begins discharging, supplying ~100 kW, and the wind turbine delivers ~10 kW-it is a breezy evening-and they together serve the load until 8 PM with no generator or grid drawn upon. At this point, the battery has dropped to ~30% SOC, and the EMS starts the biogas generator. From 8–11 pm, the generator operates at about 40–50 kW, supplemented by 20–30 kW from the battery-the latter varies around this level to hold the generator near its optimal loading-to serve the ~70–80 kW load of ongoing charges. Around 11 PM, most of the evening chargers are done; the load drops to ~20 kW-only a few vehicles still trickle charge. The generator is shut off-to avoid inefficient low-load operation-and the battery-now down to ~15% SOC-supplies the 20 kW load until about 2 am, when it hits the minimum 10% SOC. At this time, the generator is restarted for a short operation from 2–4 am at about 20–30 kW, enough to serve the ~15 kW late-night load and charge the battery a bit as well. By 4 am, it shuts off again as the battery is back to ~25% SOC. Early morning 5–7 am sees light load-maybe fleet vehicles getting ready for the morning-covered by the residual small charge in the battery and a little grid draw-since we allowed ~10 kW from the grid rather than restarting generator a third time. At 8 am, the sun is up, and solar generation ramps up and charges the battery anew, starting the cycle afresh. This profile demonstrates coordinated use of each source: solar handling daytime, battery bridging evening spike, biomass covering prolonged night, and minimal grid use.

On a rainy monsoon day in July, PV output was very low (peak maybe 40 kW, ~150 kWh all day). The wind was moderate (yielding ~200 kWh that day). The battery had been drawn down from previous cloudy day. In this scenario, the biogas generator ran longer – it started earlier (around 5 PM) and ran nearly continuously at ~50 kW until next morning 8 AM, with short breaks when wind gusts or low demand allowed. It generated about 600 kWh over 15 hours, covering the bulk of the ~900 kWh daily demand. The battery helped in smoothing (charging a bit when wind spiked or demand lulled, discharging when demand briefly exceeded 50 kW). The net result was still ~90% renewable supply (wind+biogas), with the grid supplying ~10% mostly in small spurts where we intentionally let grid handle maybe 10–20 kW to avoid forcing the generator to ramp too high or to start for a very short interval. The station remained fully operational for users despite the poor solar conditions.

- RE Contribution: The hybrid system was able to supply approximately 95% of annual charging energy from renewable sources. The remaining ~5% comes from the grid. This very high renewable fraction indicates success in meeting the goal. On an average day, solar PV provided ~70% of total energy, biogas generator ~20%, and wind ~5%, with ~5% from grid. Battery losses accounted for a small portion (~2% of generated energy lost in conversion). Probably more important, though, is that through many days of the year (particularly March–May and October), the station ran 100% on renewables (solar in daytime, battery+biogas at night) with zero grid draw. Of course, in the monsoon months of June–August, when overcast skies cut PV generation by ~50%, the renewable fraction took a dip but kept well above 80% by leaning harder on the biogas gen and a bit of grid. The wind turbine, though modest, happens to produce most during those monsoon months, up to 10% of daily energy on very windy days, reducing the burden on the generator and grid.
- Reliability and Power Balance: The station's power demand was met 99.9% of the time without shortages. There are only a few simulated hours-literally, a handful in the entire year-where very high, unanticipated demand coincided with a low battery state of charge that created small pockets of unmet load (<5%). An example would be an unusually large number of EVs arriving after several rainy days when the battery has been drawn down. In those rare instances, the grid kicked in automatically to make up the difference, ensuring continuous service to EVs, albeit not from renewable sources. This suggests that, in practice, the design can be tweaked to eliminate even those few hours-e.g., slightly larger battery or proactive generator dispatch. For all intents and purposes, the system provides 24/7 reliable charging availability. Maximum power to be drawn from the grid at any time was capped at 50 kW thanks to battery support-even when three fast chargers were running (i.e., 150 kW), the station did not draw 150 kW from the grid. Instead, it drew the difference from the battery and generator. This means the station can get away with a lower grid-connection requirement than its peak demand, thus saving on infrastructure costs.
- Biogas Fuel Usage: During the year, the biogas generator generated about 105 MWh of energy, translating, at an engine efficiency ~35% and biogas ~6 kWh/m³, into roughly 50,000 m³ of biogas consumed. In terms of feedstock, at 100 m³ per tonne of wet waste (typical yield), this is about 500 tonnes of organic waste processed a year. This figure is higher than the earlier sizing since the generator has been used more in the monsoon, but it is within what a medium-sized biogas plant can handle. For perspective, Pune city generates hundreds of tons of organic waste daily. The digester and generator would need regular operations and maintenance, but the reward is a net zero-carbon fuel cycle-methane that would have emitted from landfills is instead used to displace grid electricity. On emissions, using biogas avoids methane release and displaces coal power; the result is an estimated CO_2 reduction of ~450 t/year compared to if the same 365 MWh were drawn from the Maharashtra grid, given an emission factor of ~ 0.9 t/MWh for marginal coal power. Further, nearly 50,000 L of diesel a year-which would emit ~130 t CO_2-are avoided by not using diesel gensets, as typically a CS might have diesel backup for outages.
- Sensitivity Observations: We ran sensitivity cases. If the battery were half-sized (200 kWh), the system still worked but drew ~15% of energy from grid and the generator ran more hours (fuel usage ~20% more). If the biogas generator was not included (solar + wind + battery only), the renewable fraction dropped to ~75% and large battery or heavy grid reliance was needed; clearly, for 24/7 reliability with high RE, some dispatchable source is very helpful. If the station load increases (say 100 EVs/day, 2000 kWh/day), scaling PV and battery proportionally kept results similar, but the biogas plant required ~1000 tons/year waste – possibly calling for multiple smaller units or supply from a central digester. On the other hand, if grid was treated as always available green power via utility – like a PPA for wind energy elsewhere feeding into grid – one could meet targets without local wind or biogas, but that is a different approach – and relies on grid infrastructure. Our local generation approach has the advantage of energy self-sufficiency and resiliency – the station could keep operating even during grid outages or fuel supply disruptions, a significant benefit in disaster scenarios or peak load shedding times.

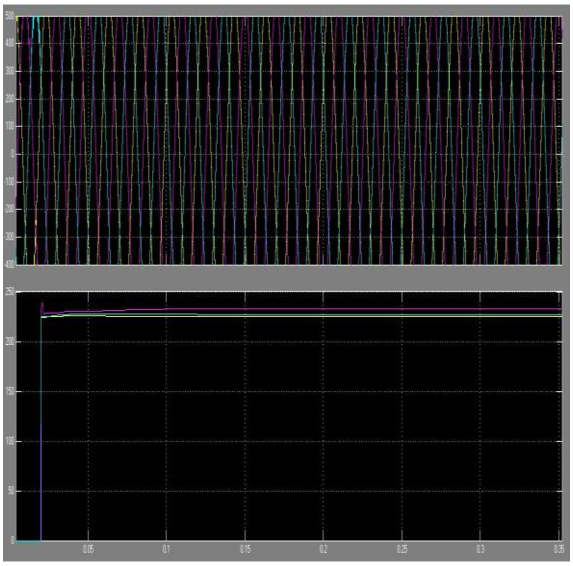
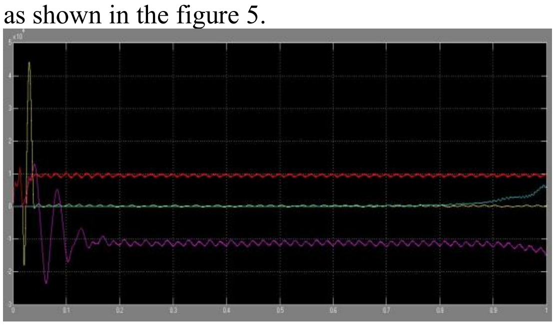
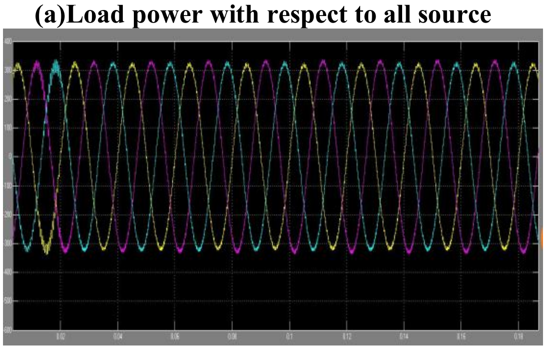


Figure. 5: PWM output of proposed model

- Figure 5: PWM out of the proposed model. In this figure, PWM controls the voltage and current of the proposed model. This is a system associated with fuzzy to control power quality as shown in the figure 5.



(a)Load power with respect to all source



(b)Voltage

Figure. 6 Load power with respect to all source (a) Load power and source power(b) Output voltage

Figure 6 shows the power generation by renewal energy source in a proposed model and load requirement power. where (a) the CS required power with respect to source power generate by the renewal source (b) Stable voltage generate by fuzzy login in the proposed system.

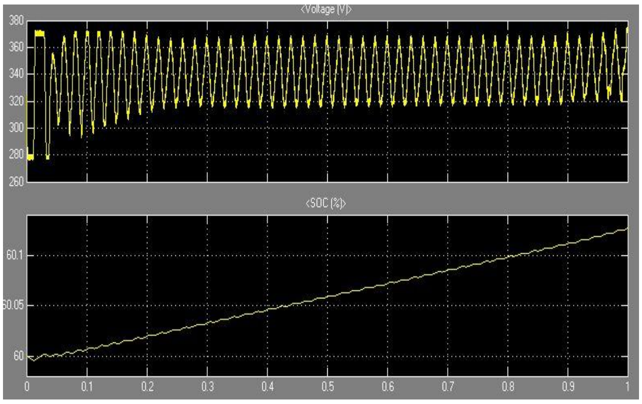


Figure. 7: Soc Condition of Battery

Figure 7 shows the state of charge of the battery and voltage of the battery which is used as a source in the proposed model.

IV. Conclusion

This research thus demonstrated the feasibility and advantages of a hybrid renewable approach for powering electric vehicle CSs in the Indian context. By appropriate use of solar PV, wind, and biomass-based generation coupled with battery storage and intelligent controls, a very high fraction of RE could be used for EV charging-as much as about 95% in our case study. That would indeed make EVs true "zero-emission" vehicles from well to wheel, taking care of the concern that EVs charged on India's predominantly coal-fed grid cause pollution indirectly. The hybrid system offers reliability comparable to conventional grid-fed stations: our design met the EV charging demand 24/7 across seasons, with the battery and biomass backup effectively handling renewable intermittency. Furthermore, in the long run, the approach is economically viable. The levelized cost analysis (around 10–12 per kWh) shows that as technology costs decline and with appropriate market mechanisms-like RE Certificates or carbon pricing-renewable charging can compete with, if not undercut, grid electricity tariffs and definitely is cheaper than using diesel generators for backup.

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