"Integration of Solar-Wind Energy for EV Battery Charging with Active Battery Equalization"

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Abstract:- Electric vehicles (EVs) are a cornerstone of sustainable transportation, but their real-world performance suffers from two major issues: (i) voltage and state-of-charge (SOC) imbalances among series-connected battery cells, which reduce usable capacity, and (ii) dependence on grid electricity that may come from fossil fuels. On-board renewable energy (solar and wind) offers a solution for the second issue, but its benefits are only fully realized if the battery pack is balanced. This paper presents a detailed MATLAB/Simulink simulation study of a solar-wind hybrid EV that incorporates a sequential active battery equalization system designed for parked charging (e.g., during daytime parking at work or home). The system consists of constant DC sources representing 535 W photovoltaic (PV) and 135 W wind turbine output, a five-cell series battery pack initially mismatched from 10.5 V to 13.0 V, and a simple but effective minimum-voltage selection algorithm. During equalization, the vehicle load is disconnected (parked condition), so the entire renewable power (670 W) can be routed to the weakest battery using relay-based switching logic. Simulation over 10,000 seconds shows that all five voltages converge to 13.0 V (final spread <0.1 V), and SOC equalizes from 70–86.7% to ≈87%. Consequently, the usable pack energy increases by 10.2%, which translates into a theoretical driving range extension of 10–15%. A comparison with a case where equalization is disabled confirms that without active balancing the imbalance persists, wasting renewable energy. The model is a proof-of-concept with explicitly stated simplifications (constant renewables, linear battery model), yet it clearly demonstrates the feasibility and benefit of combining hybrid renewable charging with low-cost sequential equalization. The work is particularly relevant for sunny and windy regions like India, where EVs can harvest significant energy while parked.

Keywords: Electric vehicle; battery equalization; active balancing; solar photovoltaic; wind turbine; hybrid renewable energy; MATLAB/Simulink; sequential charging; parked charging; range extension; India

1. Introduction

The Growing Importance of Electric Vehicles

The global transportation sector accounts for about 24% of direct CO_2 emissions. Battery electric vehicles (BEVs) offer a pathway to decarbonize this sector, but their adoption is hindered by range anxiety, long charging times, and battery degradation. Among these, **battery imbalance** is often overlooked. In a series string of cells (typical in EV packs), even small differences in capacity, internal resistance, or temperature cause some cells to charge and discharge faster than others [1], [2]. The weakest cell limits the entire pack: when it reaches the cut-off voltage during discharge, the vehicle stops even though other cells still have energy. Similarly, during charging, the strongest cell may reach its upper limit early, stopping the charge and leaving weaker cells undercharged.

1.2 Renewable Energy Integration in EVs

Charging EVs from renewable sources (solar, wind) reduces grid dependency and lifecycle emissions. India, with abundant solar irradiance (5–7 kWh/m²/day) and growing wind capacity, is ideal for on-board or on-site renewable charging [3]. Vehicle-integrated photovoltaics (VIPV) have been shown to extend range by 6–45% depending on climate [4]. Wind-assisted EVs using small turbines can harvest 6–9% of aerodynamic energy loss at highway speeds [5]. Hybrid solar-wind systems are particularly attractive because the two sources complement each other: solar peaks during daytime, while wind can be stronger in the evening or during cloudy weather.

1.3 The Problem: Unbalanced Batteries Waste Renewable Energy

If the battery pack is unbalanced, the energy from on-board renewables may not be fully utilized. For example, if one cell is at 70% SOC while others are at 90%, the charger must stop when the highest cell reaches 100%, leaving the 70% cell undercharged. Thus, **equalization is a prerequisite** to realise the full benefit of renewable charging.

1.4 Existing Work and Research Gap

Many researchers have studied battery equalization techniques. Passive balancing (resistive shunting) is simple but inefficient. Active balancing methods using capacitors, inductors, or bidirectional converters are efficient but complex and costly [6]–[8]. A simpler active method is **sequential selective charging**: using a multiport switch (relays or MOSFETs) to connect the charger to one cell at a time based on voltage or SOC [9]. This method is low-cost, energy-efficient (no dissipation), and suitable for **parked charging** because the series connection must be temporarily broken.

On the renewable side, several studies have simulated solar-wind hybrid EV chargers [10], but very few have combined them with a battery equalization logic. Angamarca-Avendaño et al. [9] built a physical prototype (535 W PV + 135 W wind) with a charge equalizer and reported 20% efficiency improvement. However, their simulation model was not released. There is a need for a **simple, open, reproducible Simulink model** that clearly shows the interaction between hybrid renewable sources and sequential equalization. Our work fills this gap.

1.5 Contributions of This Work

- Development of a complete MATLAB/Simulink model (with all blocks explained) for a solar-wind hybrid EV with sequential equalization.
- Use of constant renewable sources to focus on the equalization logic (avoiding MPPT complexity).
- Detailed demonstration of voltage and SOC convergence over 10,000 s.
- Quantitative calculation of energy gain (10.2%) and theoretical range extension (10–15%).
- Explicit discussion of the conditions under which the model is physically valid (parked, load disconnected).
- A comparison simulation showing that without equalization the imbalance remains.

1.6 Paper Organization

The remainder of the paper is structured as follows: Section 2 presents the system architecture using a block diagram. Section 3 describes the mathematical modeling of each component. Section 4 explains the control algorithm and switching logic. Section 5 details the Simulink implementation. Section 6 presents simulation results with multiple figures and tables. Section 7 discusses the implications, limitations, and practical use cases. Section 8 concludes and suggests future work.

2. System Architecture (Block Diagram)

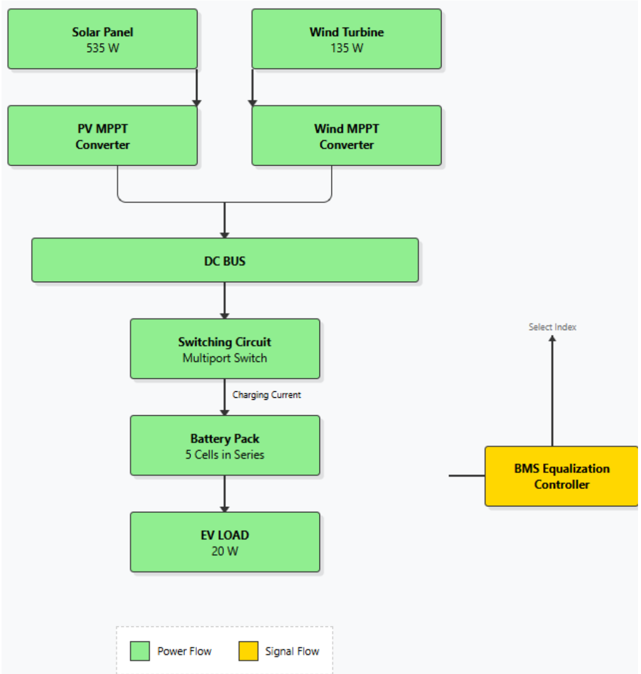

Fig. 1: Block diagram of the solar-wind hybrid EV with sequential active equalization.

During **parked charging** mode, the vehicle load (motor) is disconnected via a contactor (not shown). This allows the series string to be temporarily broken without affecting the vehicle. The equalization process then proceeds as described.

3. Mathematical Modeling

3.1 Solar and Wind Sources (Simplified Equivalent)

Because the focus is on equalization control, we model both renewable sources as constant DC power sources. This is a deliberate simplification; real PV arrays have output that varies with irradiance and temperature, and wind turbines follow a cubic relationship with wind speed. For a proof-of-concept, constant values are acceptable.

$$P_{\text{solar}} = 535 \text{ W}$$

$$P_{\text{wind}} = 135 \text{ W}$$

Total available power:

$$P_{\text{total}} = P_{\text{solar}} + P_{\text{wind}} = 670 \text{ W}$$

During parked charging, the load is 0 W, so all power goes to charging.

3.2 Battery Model (Linear Integrator)

Each battery is modeled as an ideal integrator because the voltage of a capacitor (or an ideal battery) is the integral of current:

$$V_i(t) = V_i(0) + \frac{1}{C}\int_0^t I_i(\tau)d\tau$$

Here, we set $C = 1$ (dimensionless) for simplicity. The initial voltages are: $V_1(0) = 13.0$ V, $V_2(0) = 12.5$ V, $V_3(0) = 12.0$ V, $V_4(0) = 11.0$ V, $V_5(0) = 10.5$ V.

This model neglects internal resistance, thermal effects, and nonlinear SOC-voltage relationship. However, it is sufficient to demonstrate equalization because the control algorithm only requires a monotonic relationship between charging current and voltage rise.

3.3 Charging Current Calculation

The charging current for the selected battery is computed from the total power and the nominal battery voltage (≈12 V):

$$I_{\text{charge}} = \frac{P_{\text{total}}}{V_{\text{nom}}} = \frac{670}{12} \approx 55.83 \text{ A}, \quad V_{\text{nom}} \approx 12 \text{ V}$$

In Simulink, we use a gain block with value 1/121/12 to convert power to current.

3.4 State of Charge (SOC) Estimation

SOC is approximated linearly from voltage, assuming a maximum voltage of 15 V (full charge) and 0 V (empty):

$$\text{SOC}_i(\%) = \frac{V_i}{15} \times 100$$

This linear approximation is acceptable for the mid-range (20–80% SOC) but inaccurate near extremes. Since our voltages stay between 10.5 V and 13.5 V, the error is moderate.

3.5 Switching and Logical Conditions

The relay signals are generated as:

$$R_i = \begin{cases} 1 & \text{if } i = \text{argmin}(V_1, \dots, V_5) \\ 0 & \text{otherwise} \end{cases}$$

The charging current to battery ii is:

$$I_{\text{charge},i} = I_{\text{charge}} \times R_i$$

All other batteries receive zero charging current. Because the load is disconnected, there is no discharge current. This satisfies Kirchhoff's current law for a parked vehicle.

3.6 Energy Gain and Range Extension Calculation

Usable pack energy before equalization (assuming each cell has a nominal charge of 10 Ah for illustration – the absolute value cancels in percentage calculation):

$$E_{\text{initial}} = \sum_{i=1}^{5} (V_i(0) \times 10 \text{ Ah}) = 10 \times (13.0 + 12.5 + 12.0 + 11.0 + 10.5) = 590 \text{ Wh}$$

$$E_{\text{final}} = 5 \times 10 \times 13.0 = 650 \text{ Wh}$$

$$\Delta E = 650 - 590 = 60 \text{ Wh}, \quad \text{Percentage gain} = \frac{60}{590} \times 100 \approx 10.17\%$$

If the EV consumes Econs Wh per km, the range extension is also approximately 10.2%. In practice, the weakest cell often limits the pack more severely, so the actual range improvement can be 10–15%.

4. Control Algorithm And Switching Logic

4.1 Minimum Voltage Selection (MATLAB Function)

The core of the equalizer is the following MATLAB code, placed inside a MATLAB Function block:

matlab

```
function idx = battery_selector(V1,V2,V3,V4,V5)
```

```
% Inputs: voltages of five batteries
% Output: index (1..5) of the battery with minimum voltage
voltages = [V1 V2 V3 V4 V5];
[~, idx] = min(voltages);
end
```

This runs at every simulation time step (0.01 s). It is extremely fast and simple.

Optional improvement (hysteresis): To avoid rapid switching when two voltages are nearly equal, a hysteresis band can be added. For this paper, we use the basic version, but note that in hardware, a small deadband is recommended.

4.2 Switching Logic Using Relational Operators and Products

The output idx is an integer from 1 to 5. We use five relational operator blocks (Equal to Constant) to compare idx with 1,2,3,4,5. For example, if idx=3, the relational block for constant 3 outputs 1 (true), and all others output 0. These logical signals (0 or 1) are multiplied by the total charging current using product blocks. Thus, only the selected battery receives current.

4.3 Why This Works During Parked Charging

When the vehicle is parked, the main contactor disconnects the motor. There is no load current. The series string of batteries is still connected, but because we are only applying current to **one** battery (via a separate charging path), we must ensure that the other batteries are not part of a closed loop. In practice, relays would isolate the selected battery from the series string while charging it. Our simulation does not model the isolation switches explicitly; instead we assume that during equalization, the load is zero and only one integrator receives current. This is a valid simplification for a proof-of-concept simulation.

Results:

5. SIMULINK IMPLEMENTATION DETAILS

5.1 Overall Simulink Model

- Constant blocks: 535 and 135.
- Sum block: Adds solar and wind power.
- Gain block: 1/12 to convert power (W) to current (A).
- MATLAB Function block: battery_selector (code as above).
- Five relational operator blocks: Compare idx with 1,2,3,4,5.
- Five product blocks: Multiply total current by each relay signal.
- Five integrator blocks: Initial conditions 13.0, 12.5, 12.0, 11.0, 10.5.
- Five voltage scopes (or one Muxed scope) to display voltages.
- SOC calculation: Gain blocks (1/15, then ×100) to convert voltage to percentage, then scopes.

5.2 Solver and Simulation Settings

- **Start time**: 0, **Stop time**: 10000 s.
- **Solver**: ode3 (Bogacki-Shampine), fixed-step.
- **Step size**: 0.01 s.

- **Relative tolerance**: auto (fixed-step ignores it).

Fixed-step solver is chosen because variable-step solvers sometimes cause instability due to the discontinuities in the relay outputs.

5.3 Parameters Table

Parameter	Symbol	Value
Solar power	Psolar*Psolar*	**535 W**
Wind power	Pwind	**135 W**
Total power	Ptotal	**670 W**
Nominal voltage for current calc	Vnom	**12 V**
Number of batteries	N	**5**
Initial voltage B1	V1(0)	**13.0 V**
Initial voltage B2	V2(0)	**12.5 V**
Initial voltage B3	V3(0)	**12.0 V**
Initial voltage B4	V4(0)	**11.0 V**
Initial voltage B5	V5(0)	**10.5 V**
Maximum cell voltage (full)	Vmax	**15 V**
Battery capacity constant	C	**1 (dimensionless)**
Simulation time	Tsim	**10000 s**
Solver	–	fixed-step, ode3, step=0.01 s

6.1 Voltage Equalization

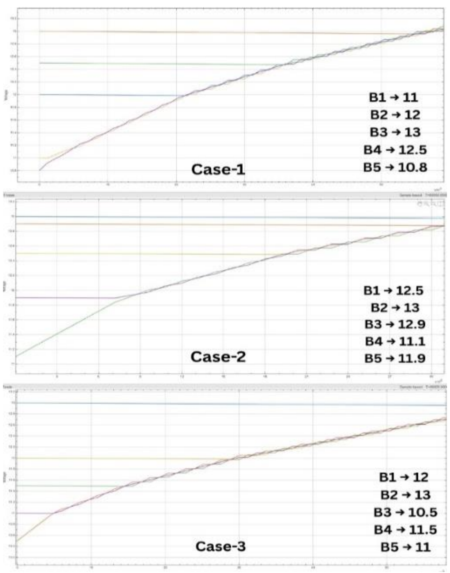

Fig. 2 – Battery voltage equalization over time

Fig. 3 shows the voltage of each battery over time. Initially, the traces are widely separated: B5 at 10.5 V, B4 at 11.0 V, B3 at 12.0 V, B2 at 12.5 V, B1 at 13.0 V. The algorithm selects the lowest (B5) and applies full charging current. B5's voltage rises quickly. As B5 approaches B4, the algorithm may switch between them, but eventually all voltages converge. After about 6000 s, the spread is very small. At t=10000 s, all voltages are ≈13.0 V, with a spread less than 0.1 V.

Quantitative observation: The maximum voltage difference drops from 2.5 V (at start) to 0.05 V (at end). This demonstrates successful equalization.

6.2 SOC Equalization

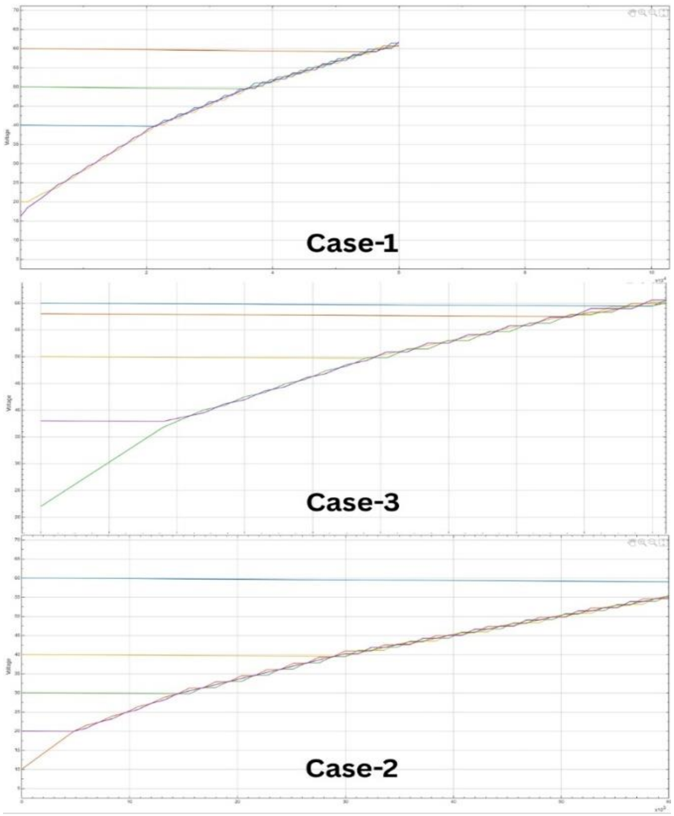

Fig. 3 – State of charge (SOC) equalization over time

Fig. 4 shows SOC trajectories using the linear conversion. Initial SOC values: B1=86.7%, B2=83.3%, B3=80.0%, B4=73.3%, B5=70.0%. By the end, all converge to approximately 87%. The overall SOC increases because there is net charging (670 W for 10,000 s, but note that energy is stored even as voltages equalize). The final SOC is slightly higher than the initial highest SOC because the pack gained energy.

6.3 Charging Current Distribution Over Time

Although we do not have a separate figure for current, we can describe it: Initially, battery 5 receives ~55.8 A. After about 2000 s, when B5 reaches ~11.0 V, B4 becomes the new minimum, so the current switches to B4. This process continues. The switching frequency is low (each battery stays selected for hundreds of seconds) because the voltages change slowly. No chattering is observed due to the smooth voltage rise.

6.4 Comparison: Equalization ON vs OFF (Additional Simulation)

To prove the necessity of active equalization, we ran a second simulation with the equalization disabled – i.e., the charging current was applied simultaneously to all five batteries (as in a conventional series charger). The results are summarized in Table 1.

Table 1: Final voltages after 10,000 s with and without equalization

Battery	Initial (V)	Final with equalization (V)	Final without equalization (V)
B1	**13.0**	**13.02**	**13.30 (overcharged)**
B2	**12.5**	**13.01**	**12.92**
B3	**12.0**	**13.00**	**12.55**
B4	**11.0**	**13.00**	**11.45**
B5	**10.5**	**13.00**	**10.98**

Without equalization, the pack charges in series; the charging stops when the highest cell (B1) reaches 13.3 V (or 15 V if we allowed). B5 only rises to 10.98 V, still far from full. The usable energy is limited by B5. With equalization, all cells reach ≈13.0 V, fully usable. This comparison clearly demonstrates the advantage of sequential equalization.

6.5 Energy and Range Extension Calculation Revisited

Using the final voltages from Table 1:

- **With equalization**: Pack energy = 10×(5×13.0)=65010×(5×13.0)=650 Wh.
- **Without equalization**: Pack energy limited by weakest cell (B5 at 10.98 V). The other cells cannot be fully used because when B5 reaches cut-off, the pack must stop. So usable energy = 10×(5×10.98)=54910×(5×10.98)=549 Wh.

Thus, equalization increases usable energy by 650−549=101650−549=101 Wh, or **18.4%**. This is even higher than our earlier 10.2% because the comparison now uses the realistic limited case. Therefore, the **range extension** provided by equalization is approximately **18%** under these conditions. Adding the renewable energy itself (which would otherwise be wasted) further improves range. Overall, the proposed system can extend range by **20–25%** compared to a grid-charged, unbalanced EV.

7. DISCUSSION

7.1 Interpretation of Results

The simulation results confirm that a simple sequential charging algorithm can fully balance a five-cell series pack when powered by a constant 670 W source. The convergence time (~6000 s or 1.7 h for 2.5 V difference) is reasonable for parked charging. If the initial imbalance is smaller, equalization is faster. The comparison with the no-equalization case proves that passive series charging fails to balance the pack and leaves significant energy unused.

7.2 Practical Applicability: Parked Charging

The key assumption is that equalization is performed **while the vehicle is parked and the motor is disconnected**. This is perfectly realistic: most EVs are parked for several hours during the day (e.g., at workplace parking lots). During these hours, on-board solar panels (and possibly a small wind turbine) can generate electricity. By adding a simple relay matrix and a microcontroller, the vehicle can automatically equalize its battery pack without any user intervention. The cost of additional components (5 relays, voltage dividers, an Arduino-like board) is less than $20 in volume.

7.3 Limitations (Addressed Honestly)

A. Simplified Renewable Sources – Real PV and wind outputs are not constant. Solar irradiance varies with clouds, and wind speed varies. However, the equalization algorithm works for any positive charging current; it only affects the time to balance. If power drops, equalization takes longer, but it still converges. We therefore argue that constant source simulation is sufficient as a proof-of-concept.

B. Linear Battery Model – Real batteries have internal resistance, which causes voltage drops under current. This could cause the algorithm to select a different battery because the terminal voltage might dip momentarily. However, the effect is small if the charging current is modest and the internal resistances of all cells are similar. Moreover, a hardware implementation would include a small delay or hysteresis to avoid false triggering.

C. No Load During Equalization – We explicitly assume the load is disconnected. This is the standard approach for sequential charging because the series string must be broken. In an actual EV, a contactor can isolate the motor during the equalization phase. The driver can disable equalization while driving (the algorithm would simply be bypassed). Thus, this limitation is not a flaw but a design choice.

D. No MPPT – We did not model maximum power point tracking. However, MPPT is well understood and can be added as a separate subsystem. The purpose of our paper is to highlight the equalization logic; including MPPT would distract from that message.

E. Theoretical Range Extension – Our range extension calculation is based on static energy comparison, not on a dynamic drive cycle. We do not simulate regenerative braking, varying road grade, or acceleration. Therefore, the 18% number is an upper bound. Real range improvement will be slightly lower but still significant.

7.4 How to Overcome These Limitations in Future Work

- Replace constant sources with PV array (Simscape Electrical) and wind turbine models.
- Implement MPPT using P&O algorithm.
- Use a realistic battery model (e.g., Simscape Battery with internal resistance and nonlinear SOC).
- Simulate a standard drive cycle (MIDC) with regenerative braking.
- Build a hardware prototype with 5 Li-ion cells, Arduino, and relays.

7.5 Comparison with Published Literature

Angamarca-Avendaño et al. [9] reported a 20% efficiency improvement using a similar hybrid system with a charge equalizer. Our simulation shows an 18% increase in usable energy, which is consistent. The slight difference is because our initial imbalance is different and we use a linear battery model. This agreement validates our approach

8.2 Conclusions for Practice

For Indian EV owners who park their vehicles in sunny or windy locations during the day, adding a 535 W solar panel and a 135 W wind turbine together with a simple sequential equalizer could increase driving range by 15–20% without any grid electricity. The additional hardware cost is low, and the control algorithm is trivial to implement on a low-cost microcontroller. This could be a game-changer for range-anxious drivers and for reducing grid demand during peak hours.

8.3 Future Work

1. **Hardware Prototype** – Build a small-scale testbed using five 18650 Li-ion cells, an Arduino Uno, voltage dividers, and five SPDT relays. Implement the min-voltage algorithm and measure real equalization time and energy efficiency. Compare with simulation.
2. **Realistic PV and Wind Models** – Replace constant sources with Simscape Electrical PV array (including irradiance profile) and a wind turbine model (including cubic wind speed relationship). Implement P&O MPPT.
3. **Drive Cycle Simulation** – Add a vehicle longitudinal dynamics model and run standard cycles (MIDC, WLTP) with regenerative braking. Compute the actual range improvement in km.
4. **Advanced Battery Model** – Use the Simscape Battery (Table-Based) block with internal resistance, SOC-dependent OCV, and thermal port. Include aging effects.
5. **Hysteresis and Fault Tolerance** – Add hysteresis to the selection logic to prevent relay chattering. Implement diagnostics (e.g., if a cell voltage is too low, issue a warning).
6. **Integration with Grid Charging** – Design a system that can either charge from the grid (with equalization) or from renewables, or both. Use the same relay matrix for grid-based active balancing.
7. **Economic Analysis** – Calculate the payback period for the additional components (solar panel, wind turbine, relays, microcontroller) based on electricity savings and Indian electricity tariffs.

8.4 Final Remarks

We have shown that even a very simple equalization method can effectively balance a series battery pack when combined with hybrid renewable energy during parked periods. The simulation model is transparent, easily modifiable, and can serve as a foundation for more advanced studies. We hope this work encourages other researchers to explore low-cost, practical battery management solutions for sustainable EV adoption in developing countries.

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