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Carbon-Aware Dispatch of PV-Storage Distribution Networks with Demand Response and AC Loss Feedback

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Abstract: A 24-hour carbon-aware dispatch model is developed for photovoltaic (PV) generation, battery storage, and demand response in distribution networks. The mixed-integer linear program minimizes electricity procurement, storage operation, demand-response compensation, PV curtailment, and carbon costs. Dispatch schedules are checked using hourly AC power flow on the IEEE 33-bus feeder, and calculated network losses are fed back into the power balance. Five scenarios distinguish storage operation, fixed and time-varying carbon emission factors, and flexible demand. Loss updates converge within four iterations in every scenario. Relative to a fixed emission factor, the time-varying factor reduces carbon emissions by 0.37% and grid purchases during high-carbon hours by 2.40%. Compared with the PV-only baseline, coordinated PV-storage-demand operation lowers total cost by 4.52%, carbon emissions by 1.74%, and peak-to-valley load spread by 6.87%, while PV utilization increases by 3.56 percentage points. These results demonstrate the value of time-resolved carbon signals and loss-consistent performance accounting under the specified case-study assumptions.

Keywords: Carbon-aware dispatch; photovoltaic generation; battery storage; demand response; time-varying emission factor; distribution network; network loss correction

1. INTRODUCTION

High photovoltaic (PV) penetration creates a mismatch between daytime generation and evening electricity demand. Battery energy storage systems (BESS) and demand response (DR) can shift energy use, but dispatch based only on time-of-use prices neglects the changing emissions intensity of purchased electricity. Recent studies have investigated PV-rich feeder scheduling and flexible energy resources [1–3], whereas carbon-aware demand coordination has received increasing attention [4–9].

Moreover, an aggregated mixed-integer dispatch may neglect feeder losses, causing inconsistent grid-purchase and carbon accounting when evaluated with an AC network model. We therefore combine time-varying carbon factors, mutually exclusive flexible-load actions, and iterative AC loss feedback. The aim is to compare five dispatch cases under consistent carbon-accounting rules, not to claim globally AC-optimal scheduling.

2. DISPATCH MODEL

2.1 Objective and Operating Variables

A one-day horizon is divided into 24 intervals of 1 h. Decisions include grid purchases, PV utilization and curtailment, battery charging/discharging, and load shifting or reduction. Reverse power flow to the upstream grid is excluded. The optimization minimizes total operating cost:

$$min\ F\ = C_g + C_s + C_d + C_p + C_c \tag{1}$$

In (1), Cg, Cs, Cd, Cp and Cc are the grid-purchase, storage, demand-response, PV-curtailment and carbon costs. Grid purchases use hourly tariffs λt; the carbon term uses emission factors γt and the carbon price. Other terms apply the indicated unit penalties, and κ = 1000 converts MW·h to kW·h.

2.2 Flexible Resources and Constraints

Battery state of charge (SOC) evolves as follows:

$$\mathrm{SOC}_t = \mathrm{SOC}_{t-1} + \frac{\eta_{\mathrm{ch}} P_{\mathrm{ch},t} \Delta t}{E_{\mathrm{ESS}}} - \frac{P_{\mathrm{dis},t} \Delta t}{\eta_{\mathrm{dis}} E_{\mathrm{ESS}}} \tag{2}$$

Charging and discharging are nonnegative and mutually exclusive, each limited to 0.5 MW. SOC remains between 0.20 and 0.90 and returns to its initial value of 0.50; charging and discharging efficiencies are both 0.95. With P_in,t, P_out,t and P_cut,t representing shifted-in, shifted-out and curtailed load, respectively, the net demand is

$$P_{\mathrm{L},t} = P^0_{\mathrm{L},t} + P_{\mathrm{in},t} - P_{\mathrm{out},t} - P_{\mathrm{cut},t} \tag{3}$$

Shifted-in and shifted-out energy are balanced over 24 h. Binary indicators forbid simultaneous shifting-in, shifting-out or shedding in one interval; individual hourly limits are 10%, 10% and 5% of flexible baseline demand. Total shifted and curtailed energy is limited to 0.45 and 0.20 MW·h, respectively.

2.3 Carbon Signals and AC Loss Feedback

Hourly carbon emissions are evaluated as

$$E_{\mathrm{C}} = \kappa \sum_{t=1}^{T} \gamma_t P_{\mathrm{g},t} \Delta t \tag{4}$$

An initial mixed-integer linear program is solved without losses. Each resulting schedule is mapped to the IEEE 33-bus system for hourly forward/backward-sweep AC power-flow calculations [10, 11]. Calculated losses are added to the next dispatch round:

$$P_{\mathrm{g},t} + P_{\mathrm{PV},t} + P_{\mathrm{dis},t} = P_{\mathrm{L},t} + P_{\mathrm{ch},t} + P^{(k-1)}_{\mathrm{loss},t} \tag{5}$$

The dispatch is updated until the maximum hourly change in calculated loss is at most 10^{-4} MW (or 20 iterations). The feeder checks use 0.95–1.05 p.u. voltage limits, a 5.0 MW import limit, and an equivalent on-load tap changer with 0.00625 p.u. steps over 1.0000–1.0500 p.u. All calculations were implemented with

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MATLAB R2024a, YALMIP, and intlinprog [12]. The procedure provides loss-consistent accounting but is not a fully network-constrained AC optimal-power-flow method.

3. CASE STUDY AND RESULTS

3.1 System Setup

The IEEE 33-bus benchmark has a base active/reactive demand of 3.715 MW/2.300 Mvar. PV capacity totals 3.5 MW at buses 6, 18 and 30 (1.2, 0.8 and 1.5 MW). A 1.0 MW·h BESS is connected at bus 14; buses 18, 25 and 30 form the DR pool. Charging/discharging efficiencies are 95%, with initial and terminal SOC both 0.50. The illustrative daily demand is 2.10–3.72 MW; PV generation peaks at 3.50 MW at hour 13. Prices range from 0.38 to 1.05 CNY/kW·h, and carbon factors from 0.40 to 0.80 kg/kW·h (daily mean: 0.6175). The daily load, PV, tariff and carbon-factor profiles are illustrative case-study assumptions rather than measured operating data.

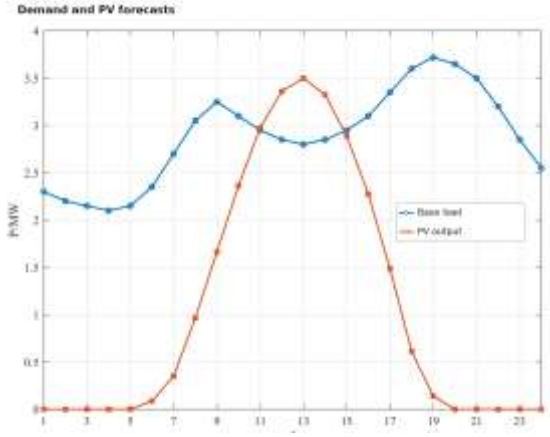


Figure 1. Illustrative daily base demand and PV forecasts.

The storage, load-shifting, load-shedding and PV-curtailment penalties are respectively 0.05, 0.10, 0.60 and 0.30 CNY/kW·h; the carbon penalty is 0.08 CNY/kg. Five cases are compared: S1, PV only; S2, PV+BESS; S3, S2 with a fixed carbon factor; S4, S2 with time-varying carbon factors; and S5, S4 with DR. All scenarios undergo the same loss-feedback procedure.

3.2 Five-Scenario Comparison

Table 1. Operating results for the five dispatch scenarios.

Case	Total cost (CNY)	Emissions (kg)	PV utilization (%)	Peak–valley spread (MW)
S1	34451.36	32525.93	94.31	1.6200
S2	33335.47	32300.40	97.19	1.6200
S3	33335.47	32300.40	97.19	1.6200
S4	33302.75	32180.31	97.19	1.6200
S5	32892.75	31959.14	97.86	1.5088

For fair comparison, every row in Table 1 is evaluated using the identical time-varying carbon-factor profile and carbon price; the fixed factor in S3 is used only to produce its schedule. Compared with S3, S4 lowers total emissions by 0.37% and high-carbon-hour grid imports by 2.40%, while the maximum normalized branch loading decreases from 90.30% to 86.44%. S3 and S2 produce identical schedules because the fixed carbon signal provides no temporal incentive under these inputs.

Relative to S1, S5 reduces combined cost by 4.52%, emissions by 1.74%, and peak-to-valley net-load spread by 6.87%; PV use rises by 3.56 percentage points. The shifted-in and shifted-out energies are each 0.4500 MW·h, and load shedding totals 0.1739 MW·h. AC verification places all cases within the prescribed voltage interval; the S5 voltage range is 0.9504–1.0416 p.u. Branch-loading percentages are calculated against the same assumed 5.0 MVA reference, not verified conductor thermal ratings.

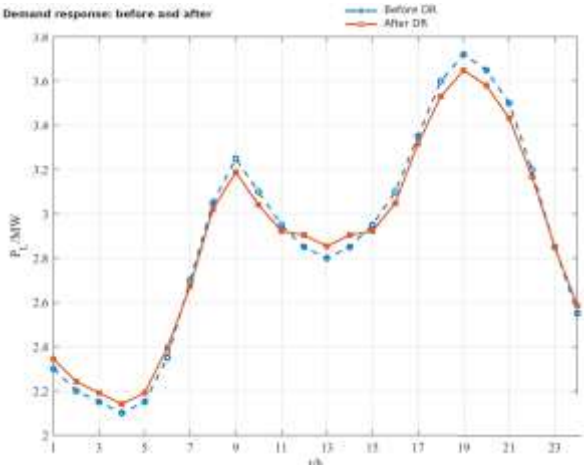


Figure 2. Load profiles before and after demand response (S5).

3.3 Loss Feedback and Sensitivity

For S5, the first AC check of the loss-free schedule yields 2.1283 MW·h of daily feeder losses. After iteration, computed losses are 2.1372 MW·h. Import cost rises from 28,613.13 to 29,879.89 CNY (+4.43%), total cost from 31,575.63 to 32,892.75 CNY (+4.17%), and reported emissions from 30,677.10 to 31,959.14 kg (+4.18%) when losses are included in dispatch accounting. All five cases reach the 10^{-4} MW loss-change tolerance within four iterations.

Sensitivity is assessed using $\gamma t(\alpha) = \bar{\gamma} + \alpha[\gamma t^{0} - \bar{\gamma}]$, where γt^{0} is the original carbon profile and $\bar{\gamma}$ is its daily mean. With $\alpha = 0$, 0.5, 1.0, 1.5, and 2.0, carbon reductions relative to the respective fixed-factor schedules are 0, 0.22%, 0.37%, 0.51%, and 0.63%. The high-carbon-hour purchase reduction is 2.40% for $\alpha \geq 0.5$ because the selected storage switching pattern remains unchanged over the tested range. High-carbon hours refer to hour 1 and hours 19–24 in the original profile.

4. CONCLUSION

In the IEEE 33-bus tests, time-varying carbon factors lower emissions, while coordinated storage and demand response improve cost, PV utilization and load smoothing. AC loss feedback improves accounting consistency. The deterministic, sequential framework is not an AC optimal-power-flow solution; uncertainty, network constraints and tap-operation penalties remain for future work.

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