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# Hybrid energy storage-assisted tailoring of duck curves

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**Dear Editor,**

High renewable penetration amplifies net-load volatility, producing steep ramps and superimposed high-frequency power oscillations (hereafter referred to as 'burr', typically 0.1–2 Hz) that conventional units struggle to follow.[1-3] Accounting for load-side behavior, the net-load profile develops sharp ramps—the classic Duck Curve—with a midday solar-driven trough and a steep evening rebound in California.[4] The peak–valley spread has widened since 2015; by September 2024, the maximum three-hour ramp reached 19,441 MW. These dynamics increase reserve needs, curtailment risk, and cycling stress, underscoring the need for time-coordinated flexibility.[5] However, most existing studies describe or forecast the Duck Curve without explicitly mapping its frequency-decomposed features to multi-timescale storage sizing and division of labor.[6-9] Moreover, there is no unified, tractable framework that leverages heterogeneous storage to jointly address sub-second burr suppression and multi-hour smoothing within a single optimization.[10] We propose a hybrid energy-storage framework that maps Duck Curve dynamics to complementary time-scales: Battery Energy Storage System (BESS) for sub-second burr suppression, Heat Pump Energy Storage-Based (HPESB) for intra-hour ramps, and Adiabatic Compressed Air Energy Storage (ACAES) for multi-hour smoothing. The framework uses a frequency-aware ramp/burr separation, linearized multi-timescale capacity–dispatch co-optimization, and explicit performance targets defined by a Dynamic Ramp Identification Threshold (DRIT) and a burr energy criterion.

This work addresses a key research gap: prior studies largely optimize dispatch or single-technology hybrids without an explicit, tractable link from Duck Curve features to storage sizing and division of labor across time-scales, nor do they quantify how policy incentives shift the optimal mix. Our contributions are: (i) a unified, linearizable model that couples Duck Curve features with ACAES/HPESB/BESS sizing and dispatch; (ii) a ramp–burr decomposition that yields technology-specific references, enabling coordinated multi-band following; and (iii) simulation evidence on representative high-renewable net-load traces showing 8.6% energy envelope deviation reduction ratio, represents a 75.5% improvement compared to the BESS-only, 37.0% ramp-rate decrease, and 85% burr-energy reduction. We further demonstrate a policy-sensitivity mapping: fast frequency response credits increase the optimal BESS share, while smoothing/envelope rewards shift capacity toward ACAES/HPESB. The framework provides actionable guidance for techno-economic storage portfolios in high-renewable grids.

## THE BURR DECOMPOSITION AND RAMPING MITIGATION ON DUCK CURVE

Empirical studies confirm the prevalent manifestation of the Duck Curve phenomena in high-renewable penetration power systems, with their fluctuation magnitudes exhibiting a statistically significant positive correlation ($R^2$=0.78-0.92) with renewable capacity ratios. The characteristic diurnal peak-valley disparity inherently imposes minute-scale ramp requirements exceeding 5% nominal capacity per minute. Globally, Duck Curve-related operational inefficiencies have incurred annual economic losses equivalent to 0.17-0.35% of national GDP in major renewable-adopting countries. More critically, superimposed high-frequency power oscillations compound these impacts by inducing additional cycling stress on conventional generators. To decompose the Curve and elaborate on the ramping mitigation program, criteria have been established based on the ramping characteristics of the Duck Curve:

Ramp event criterion: DRIT is adopted as the key criterion for characterizing net-load ramping. Defined at $\Delta S/\Delta t$=5% per unit per minute (5% p.u./min), this threshold delineates operational boundaries where instantaneous slopes exceeding DRIT trigger ramp event identification requiring HESS intervention, and slope magnitudes below DRIT fall within conventional generator accommodation capabilities, deemed operationally acceptable.

Burr Criterion: Defined at a second-order derivative magnitude of $|\Delta^2S/\Delta t^2|$ = 1% per unit per second squared (1% p.u./$s^2$), this threshold delineates high-frequency 'burr' events from ramp events. Sub-second stability deviations that require immediate intervention from the fast-responding components of the HESS.

Burr and Ramp Processing Method: We first apply a time–frequency decomposition to the net-load series to obtain three bands: a low-frequency envelope, a mid-frequency ramp component, and a high-frequency "burr" component. For correlation analysis, burr severity is quantified by its envelope energy and peak deviation, and evaluated in context of the concurrent ramp by comparing the local slope to a DRIT; we also record the burr's temporal position within each ramp segment. The mitigation protocol is band-to-resource: high-frequency burrs are assigned to BESS, mid-band ramps to HPESB, and low-band envelope tracking to ACAES. Effectiveness is reported using frequency-variance reduction ($FV_{RR}$), energy-envelope deviation reduction ($EED_{RR}$), ramp-margin compliance to DRIT, and burr-reduction ratio.

Figure 1A illustrates renewable energy penetration trends over the last five years, peaking at 32.1% in 2024. While crucial for decarbonization, this growth strains grid stability through amplified net load volatility - particularly evident in California's characteristic "Duck Curve" shown in Figure 1.B. In Figure 1.C, the original curve is compared with three configurations (A: BESS; B: BESS+Flywheel; C: BESS+HPESB+ACAES): all reduce high-frequency burrs, while C tracks the daily envelope most closely with the smallest residual oscillations. Figure 1.D presents the economic radar: C bears the highest CAPEX but achieves the lowest LCOS_year and OPEX and the highest revenue; A suffers higher LCOS despite moderate CAPEX; B minimizes upfront cost but also yields the lowest revenue. Figure 1.E decomposes the dispatch of C by technology, where BESS suppresses fast burrs, HPESB handles hourly ramps, and ACAES follows the slow envelope, demonstrating the intended band-to-resource mapping.

## HYBRID ENERGY STORAGE SYSTEM

HESS, incorporating emerging ACAES, HPESB, and BESS technologies, provides bidirectional power dispatch flexibility to address Duck Curve dynamics. The ACAES and HPESB represent a functional bridge between traditional and emerging storage systems, with typically feature response times (seconds to a few minutes), capable of handling intra-hour ramps. BESS is included as the quintessential example of an emerging technology. With the sub-second response times, BESS are indispensable for managing the "burrs" and providing the instantaneous ancillary services that ACAES and HPESB are less suited for. By applying spectral decomposition to the Duck Curve, the system partitions the fluctuation within "ramp events" and "burrs" according to the frequency values. This process generates scenario-specific power demand profiles that quantify the high-frequency components, thereby defining the rapid response requirements for the HESS. This necessitates precise capacity allocation modeling, as the Power/Energy Availability Ratio (PEAR) of HESS configurations exhibits nonlinear dependence on component proportions—a critical relationship quantified in this study. We pioneer physics-constrained operational models for ACAES (efficiency: 72-78%), BESS (efficiency: 85-90%), and HPESB. A multi-objective optimization framework bridges Duck Curve characteristics with HESS design parameters, enabling Pareto-optimal solutions.

**Linearization of the storage model.** To keep the joint dispatch problem tractable while preserving Duck Curve physics, we linearize (a) grid-side constraints and tracking penalties and (b) ACAES/HPESB device maps, using

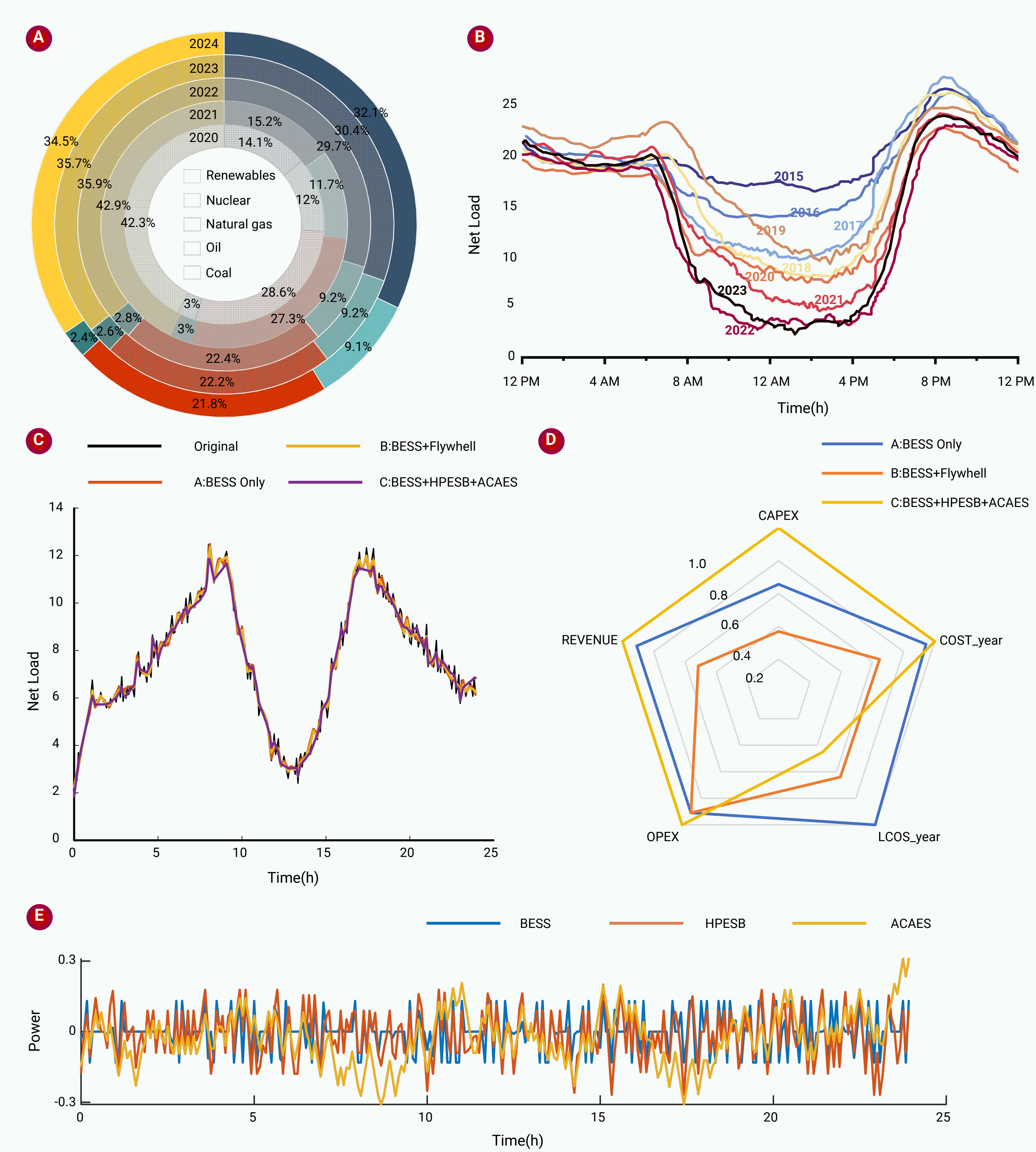


**Figure 1. Duck Curve Mitigation through Multi-Stage Energy Storage.** (A) The renewable penetration. (B) Aggravation of the Duck Curve. (C) Scenario overlay after smoothing. (D) Characteristics comparison of different HESS. (E) Per-technology dispatch under HESS.

a small-signal band/time split that routes minute-scale ramps to mid/long-duration storages and sub-second burrs to BESS. The approximation is valid only within declared operating windows—ACAES reservoir pressure 0.8–1.0 p.u., mass-flow ±20% rated, effective efficiency 72–78%; HPESB temperature lift 20–50 K, part-load 40–100%, COP linearized—and is not used outside these bounds.

**Hybrid energy storage dispatch mechanism:** We first decompose the net-load into three time-scale bands using moving-average windows: high-frequency, mid-frequency, and low-frequency. The envelope of the net-load defines the target smoothed trajectory $y_{ref}$; the storage synthesis signal $S_{ref} = S - y_{ref}$ is split by band, assigning High-frequency to the flywheel, Mid-frequency to HPESB, and Low-frequency to ACAES, with any residual allocated to BESS. A linear program then co-optimizes per-interval charge/discharge, state of energy, and minimal capacities under round-trip efficiency losses, power/energy limits, duration ratios, and ramp-rate limits. Two system-level smoothness constraints are enforced: a step-ramp bound that satisfies DRIT and an L1 bound on the second difference of y(t) that caps burr-energy around a fixed fraction of the baseline. Soft-tracking penalties tie each device to its band reference and tie y(t) to $y_{ref}$ to reduce envelope deviation, while scenario-dependent band gains and variable O&M costs bias the optimizer toward the intended role split (BESS for fast components; HPESB/ACAES for energy shifting). The result is a coordinated dispatch that jointly minimizes capacity/economic cost and tracking errors, and outputs both per-device power profiles and the grid-facing smoothed net-load y(t).

## CONCLUSIONS AND POLICY RECOMMENDATIONS

We present a unified, linearizable planning–dispatch framework that targets the Duck Curve with frequency-aware hybrid storage. Net-load variability is decomposed into complementary bands and mapped to the most suitable assets: BESS for sub-second "burrs," HPESB for intra-hour ramps, and ACAES for multi-hour envelope tracking. The framework jointly sizes capacities and schedules power using a soft-tracking, multi-band controller under explicit ramp and smoothness constraints. On high-renewable test traces, all evaluated portfolios satisfy ramping limits and achieve deep burr mitigation (≈85% cut), confirming technical feasibility. Comparative validation shows that the fully hybrid mix (BESS+HPESB+ACAES) delivers the most balanced smoothing across time scales and adheres best to the target envelope, while single- or two-technology mixes provide narrower benefits. Techno-economic assessment indicates that, despite higher upfront cost, the fully hybrid portfolio processes more energy and attains the lowest levelized cost of storage, making it the preferred option when judged on cost per delivered MWh rather than absolute profit under conservative price assumptions.

Based on Duck Curve ramping/burr characteristics and the demonstrated HESS dynamics, we recommend: 1) prioritize hybrid HESS portfolios (BESS+HPESB+ACAES) in systems with annual renewable share ≥35% or where evening ramps exceed the DRIT, with capacity configurations informed by our band-splitting optimization so that long-duration units cover the envelope and fast units are reserved for burr suppression; 2) adopt band-specific technology targets: fast band (burrs) BESS/flywheel with response ≤500 ms and 0.8–1.5 h duration; mid band (intra-hour ramps) HPESB with response ≤ 10–60 s and 2–4 h duration; low band (envelope shifting) ACAES with response ≤1–5 min and 6–12 h duration; and set performance criteria of burr-energy reduction ≥80% and ramp-tracking error ≤10%. 3) Create distinct ancillary service markets that provide higher compensation for faster and more accurate responses. Incentives for energy storage allocation are applied based on different time scales, thereby pushing capacity allocation toward the social optimum. These measures collectively address the critical need for techno-economically optimized storage solutions that match temporal and spectral requirements of modern renewable systems, ultimately supporting global decarbonization roadmaps through enhanced grid flexibility.

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## DECLARATION OF INTERESTS

The authors declare no competing interests.