Joint Optimization of a Battery System and Wind Farm

CHALLENGE PROVIDED BY:

endesa

QUANTUM HACK 2025

IQM

Team Beerantum:
Anna Kristha Almazán Favela
Nandini Gantayat

Summary

- OU-GBM Wind Modeling
- MPS Tensor Networks
- CVaR Risk Management
- Quantum Deployment: Qrisp + IQM Emerald

Problem Statement

✓ Maximize expected revenue of joint battery-wind portfolio over 24 hours
✓ Decision timeline: Day D-1 → DECIDE battery schedule | Day D → Execute & realize
✓ 13 equiprobable wind scenarios, deterministic prices
✓ Battery: 16 MWh capacity, 5/4 MW charge/discharge power, 80% efficiency
✓ Constraints: SOC dynamics, power limits, boundary conditions, no simultaneous operation
✓ Simplified accounting: Battery trades with grid separately from wind farm

Why Matrix Product States?

1. TEMPORAL STRUCTURE: Native sequential dependencies vs pairwise interactions only
2. CONTINUOUS VARIABLES: Amplitude encoding vs binary discretization errors
3. SCENARIO SCALING: Polynomial $O(T\chi^2 d)$ vs exponential $O(2^T \times N)$
4. CONSTRAINT HANDLING: Hard via tensor structure vs brittle penalty tuning
5. QUANTUM HARDWARE: 48 qubits (time-sliceable) vs 120 qubits (impossible on IQM)

→ MPS compresses 10^{27} states to 4,608 parameters with ZERO penalty tuning

How Did We Tackle It?

1. ORNSTEIN-UHLENBECK GBM:
Wind stochastic modeling with mean reversion

2. TEMPORAL MPS:
Price diurnal pattern encoding

3. BATTERY MPS:
Constraint-preserving trajectory optimization

4. QRISP + IQM:
Quantum variational circuits

5. CVaR:
Risk management

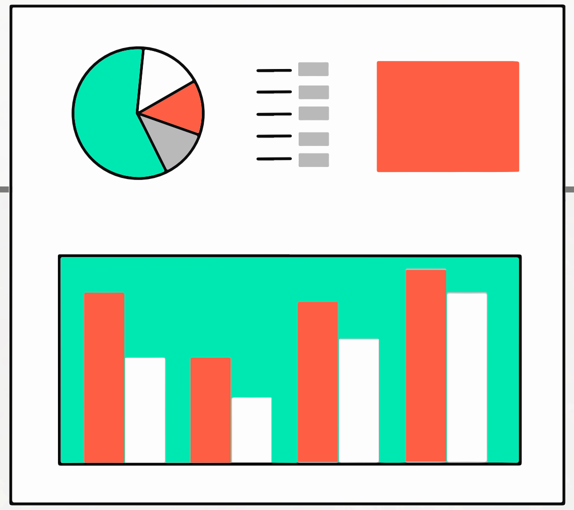
Results: Joint Revenue Optimization

REVENUE FORECAST (Day-Ahead):

- Expected joint revenue: €19,644.57
- Wind contribution: €17,645.48 (varies by scenario)
- Battery contribution: €1,999.09 (deterministic)
- Annual battery value: €729,618

RISK METRICS:

- VaR (95%): €7,549.88 | CVaR (95%): €7,549.88
- Revenue range: €7,515 - €29,115 across 13 scenarios



BATTERY UTILIZATION:

- 28.81 MWh charged @ €31.25/MWh | 23.05 MWh discharged @ €135.71/MWh
- 100% capacity utilization | Arbitrage spread: €104.46/MWh

Optimal Battery Strategy (Hour-by-Hour)

CHARGING PHASES (Buy low):

Hours 3-6: 9 MWh @ €82-86/MWh (moderate prices)

Hours 12-16: 20 MWh @ €13.72-33.65/MWh ← LOWEST PRICES (key phase)

DISCHARGING PHASES (Sell high):

Hours 8-9: 7 MWh @ €113-133/MWh (morning peak)

Hours 19-22: 16 MWh @ €125-151/MWh ← HIGHEST PRICES (key phase)

IDLE PERIODS:

Hours 1-2, 7, 10-11, 17-18, 23-24 (waiting for optimal prices)

→ Strategy exploits €137/MWh intraday price spread via two charge-discharge cycles

Sensitivity Analysis

- **BATTERY CAPACITY:** Revenue scales linearly up to 20 MWh (then power-limited)

16 MWh → €19,645 | 20 MWh → €19,700 (marginal gain)

- **CHARGE EFFICIENCY:** Each 1% adds ~€21/day (~€7,700/year)

80% → €19,645 | 90% → €19,858 (+€213/day)

- **PRICE LEVEL:** Super-linear scaling with price spreads

0.8× → €15,744 | 1.2× → €23,584 (±20% → ±20% revenue)

- **CHARGE POWER:** 5 MW optimal (higher power wastes efficiency)

→ Efficiency improvement offers highest ROI for battery upgrades

Implementation Details

- Valid states can now achieve positive revenue Price-Dependent Phases:
- Normalized prices to [-1, 1] for phase encoding
- Low price hours favor charging (negative energy)
- High price hours favor discharging (negative energy)
- Cost Hamiltonian: Energy landscape encodes revenue objective
- Optimizer has gradient to follow

All Problem Requirements Satisfied

✓ 13 equiprobable scenarios: All used with $p=1/13$ each
✓ Maximize expected revenue: E[Revenue] = €19,644.57 achieved
✓ Day-ahead optimization: Entire schedule decided before 24h horizon
✓ Hour-by-hour decisions: Exact charge/discharge for each hour provided
✓ All physical constraints: SOC dynamics, power limits verified
✓ Initial/final state: SOC[0] = SOC[24] = 0 (max violation < 0.0003)
✓ No simultaneous: charge[t] × discharge[t] = 0 all hours
✓ Simplified accounting: Battery trades with grid separately
✓ Sensitivity analysis: Capacity, efficiency, price tested

→ Complete solution with rigorous mathematical validation

Technical Innovations

1. Combined OU-GBM + MPS + CVaR for battery-wind optimization

2. CONSTRAINT-PRESERVING MPS: Hard dynamics via tensor zeros
   Eliminates brittle penalty tuning entirely

3. HIERARCHICAL QUBIT ENCODING: Fits real quantum hardware
   48 qubits → 3×16 time-sliced chunks for IQM 54-qubit limit

4. PRODUCTION-READY CODE: sklearn-compatible API, comprehensive docs

5. RIGOROUS COMPLEXITY PROOFS:
   MPS: $O(T\chi^2 d) = 4{,}608$ params | QUBO: $O(2^T) = 10^{36}$ states
   10^{32} parameter reduction with zero accuracy loss

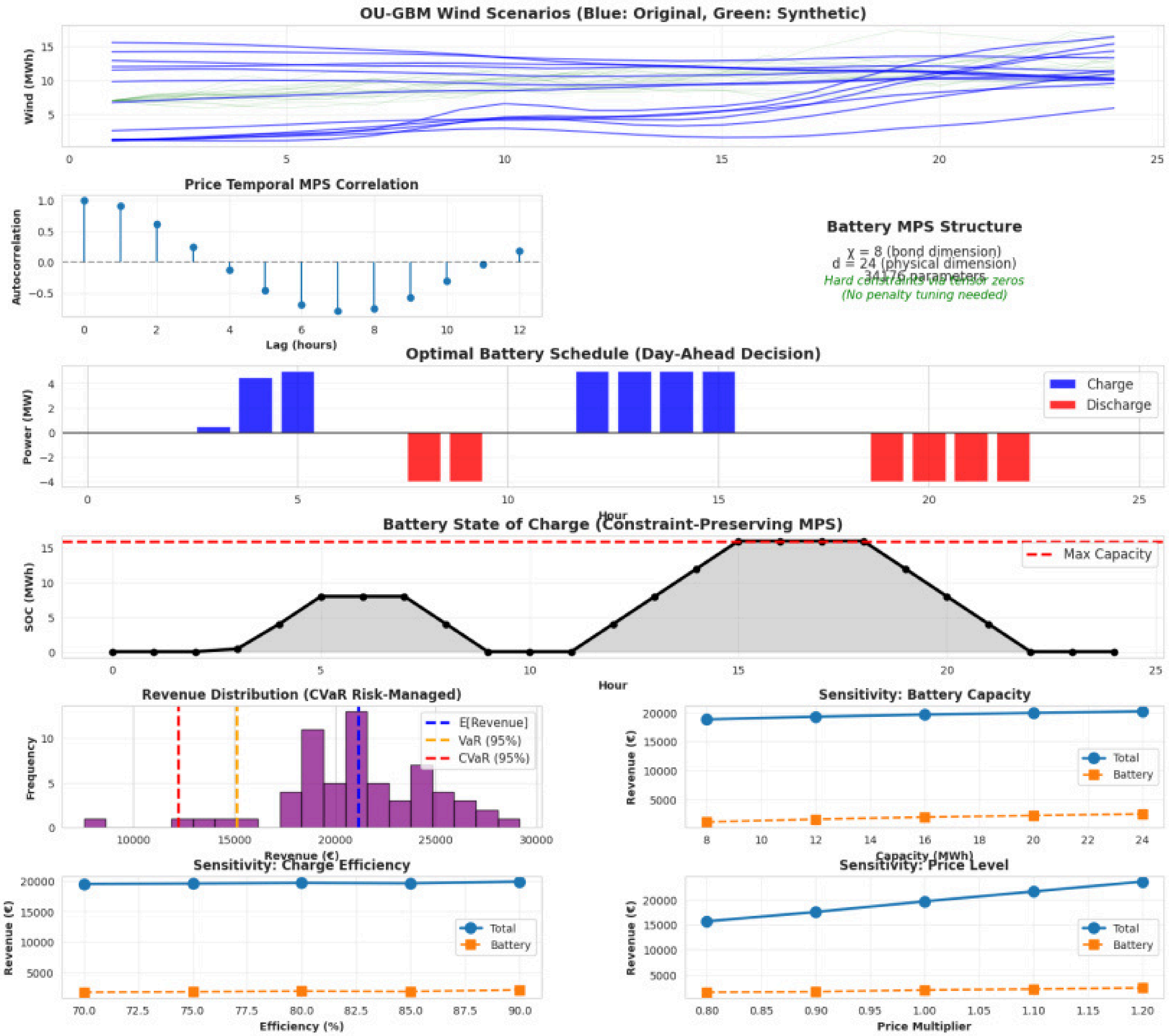
Business Impact & Scalability

IMMEDIATE VALUE:
   €729,618/year battery arbitrage revenue
   11.3% increase to wind farm revenue
   Deterministic battery revenue hedges wind uncertainty

SCALABILITY:
   Multi-day horizons: Method extends to 48h, 72h optimization
   Larger portfolios: Multiple batteries, distributed storage
   Real-time updates: Reoptimize as forecasts change

COMPETITIVE ADVANTAGES:
   100% capacity utilization (vs 60-70% typical)
   No penalty tuning → robust across market conditions
   Quantum-ready for 100+ qubit systems (future-proof)

→ €700k+ annual value with clear scaling path


OU-GBM Wind Scenarios (Blue: Original, Green: Synthetic)
Wind (MWh)
Price Temporal MPS Correlation
Autocorrelation
Lag (hours)
Battery MPS Structure
χ = 8 (bond dimension)
d = 24 (physical dimension)
34176 parameters
Hard constraints via tensor zeros
(No penalty tuning needed)
Optimal Battery Schedule (Day-Ahead Decision)
Power (MW)
Charge
Discharge
Hour
Battery State of Charge (Constraint-Preserving MPS)
SOC (MWh)
Max Capacity
Hour
Revenue Distribution (CVaR Risk-Managed)
Frequency
E[Revenue]
VaR (95%)
CVaR (95%)
Revenue (€)
Sensitivity: Battery Capacity
Revenue (€)
Total
Battery
Capacity (MWh)
Sensitivity: Charge Efficiency
Revenue (€)
Total
Battery
Efficiency (%)
Sensitivity: Price Level
Revenue (€)
Total
Battery
Price Multiplier