Welfare-Optimal Storage Integration in Agent-Based Electricity Market Models

Presentation ABM4Energy 2026 - Vienna

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Motivation

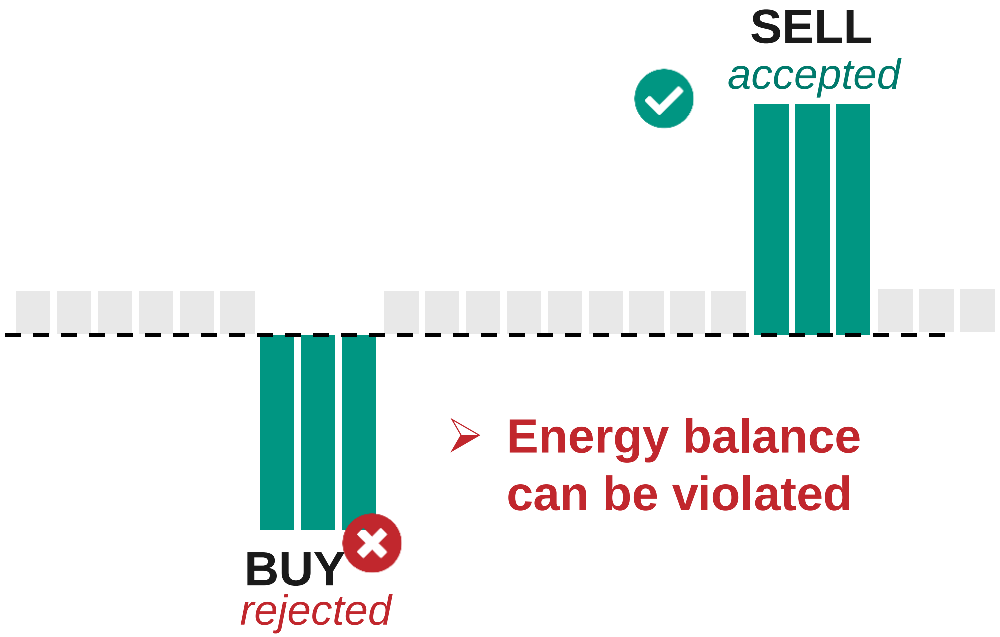
Storage has unique operational constraints

Storage plays an increasing role in electricity markets [4]

- Battery deployment, EV adoption (V2G), falling costs
- ABMs need a adequate approach to include storages [1][2][3]

ABMs typically use hourly simple bids for market clearing:

- Works well for conventional plants (no state coupling)
- **But storage has hard intertemporal constraints**
  - Becomes critical with high storage penetration
  - Price-taker to price-maker transition



➢ **Energy balance can be violated**

Research question: How can storage be integrated into ABM market clearing while preserving convexity and individual rationality?

Storage integration in ABMs

Comparison of different established ABMs

✗= No, ✓ = Yes

	AMIRIS [1]	ASSUME [2]	PowerACE [3]
DA clearing	Hourly	Hourly	Hourly
Storage agents included	✓	✓	✓
Bidding approach	Heuristic	Reinforcement Learning	Heuristic
Complex bidding formats	✗	✓*	✓**
Intertemporal coupling of clearing	✗	✗	✗

- **All three ABMs delegate storage dispatch to the agent.**
- **No ABM couple storage clearing intertemporally**

*Block bids proposed in [8] *Loop bids proposed in [7]

Welfare-Optimal Storage Integration

Modifying the market clearing to directly accommodate storage

Conventional Agents

- **Submit bids** (with mark-ups, RE-Policy, …)
- **No change to agent behavior**

Storage Assets (incl. V2G)

- **Submit no bids**
- **Technical parameters as input to clearing**

Extended Economic Dispatch Problem (24h joint)
Storage integrated directly – welfare-optimal dispatch

Bid acceptance
+ clearing prices

Storage dispatch
(welfare-optimal)

➢ **Conventional bids + optimal storage dispatch in one clearing step**

Formulation

Extended Economic Dispatch with storage constraints (24h day-ahead horizon)

Objective:

$$\min \Sigma_t \left[\Sigma_i \left(bid_{i,t} \cdot q_{i,t} \right) \right]$$

Subject to:

Energy balance: $\Sigma_i q_{i,t} + dis_t - ch_t = D_t$ Dual: λ_t

SoC dynamics: $SoC_t = SoC_{t-1} + \eta c \cdot ch_t - dis_t / \eta d$ Dual: μ_t

SoC bounds: $SoC\_min \leq SoC_t \leq SoC\_max$

Power limits: $0 \leq ch_t, dis_t \leq P\_max$

q_i,t	accepted quantity
ch_t	charge power
dis_t	discharge power
SoC_t	state of charge
D_t	demand
η_c	charge efficiency
η_d	discharge efficiency
P_max	power limit
λ_t	clearing price
μ_t	shadow price of stored energy

- **SoC dynamics couple all 24 hours → joint optimization instead of hourly clearing**
- **Linear problem**

Price Formation

Storage has no bid price – how does the model assign one?

Every primal variable has a corresponding dual constraint.

For discharging (dis_t):

$$\boldsymbol{\lambda \leq \mu / \eta_d}$$

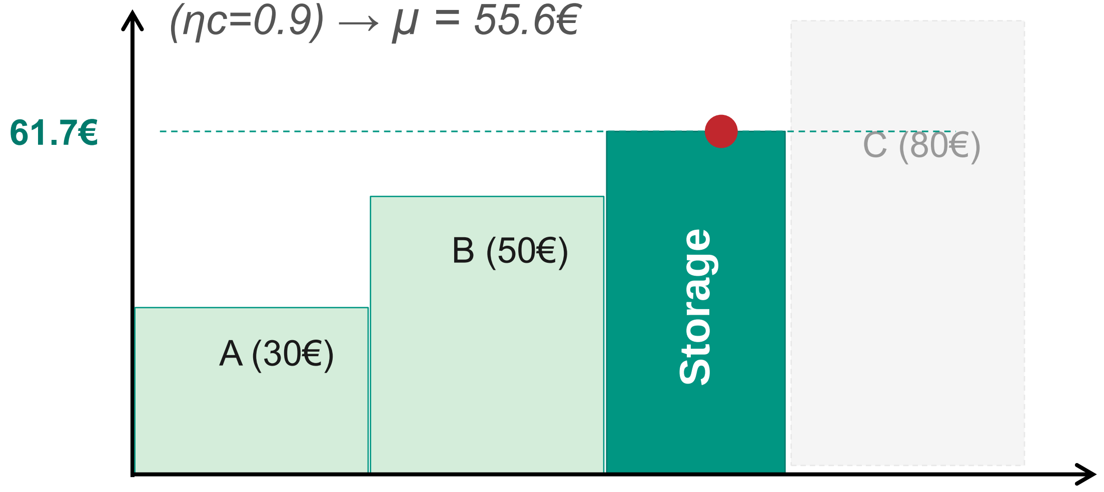
Links the value of stored energy (μ) to the MCP (λ).

Binds when dis > 0 (complementarity):

Partial:	$\lambda = \mu/\eta d$	→ Storage sets price
Full:	$\lambda = \mu/\eta d + \beta$	→ Conv. bid sets price
Idle:	$\lambda < \mu/\eta d$	→ Not dispatched

Merit order (example)

Storage charged at 50€
(ηc=0.9) → μ = 55.6€



MCP = μ/ η_d = 61.7€
Storage marginal, C not accepted

The clearing price emerges endogenously from the LP, no bid price required.
Storage enters the merit order at μ/ηd (opportunity cost).

Storage Never Loses Money

Individual rationality follows directly from duality (Slide 6)

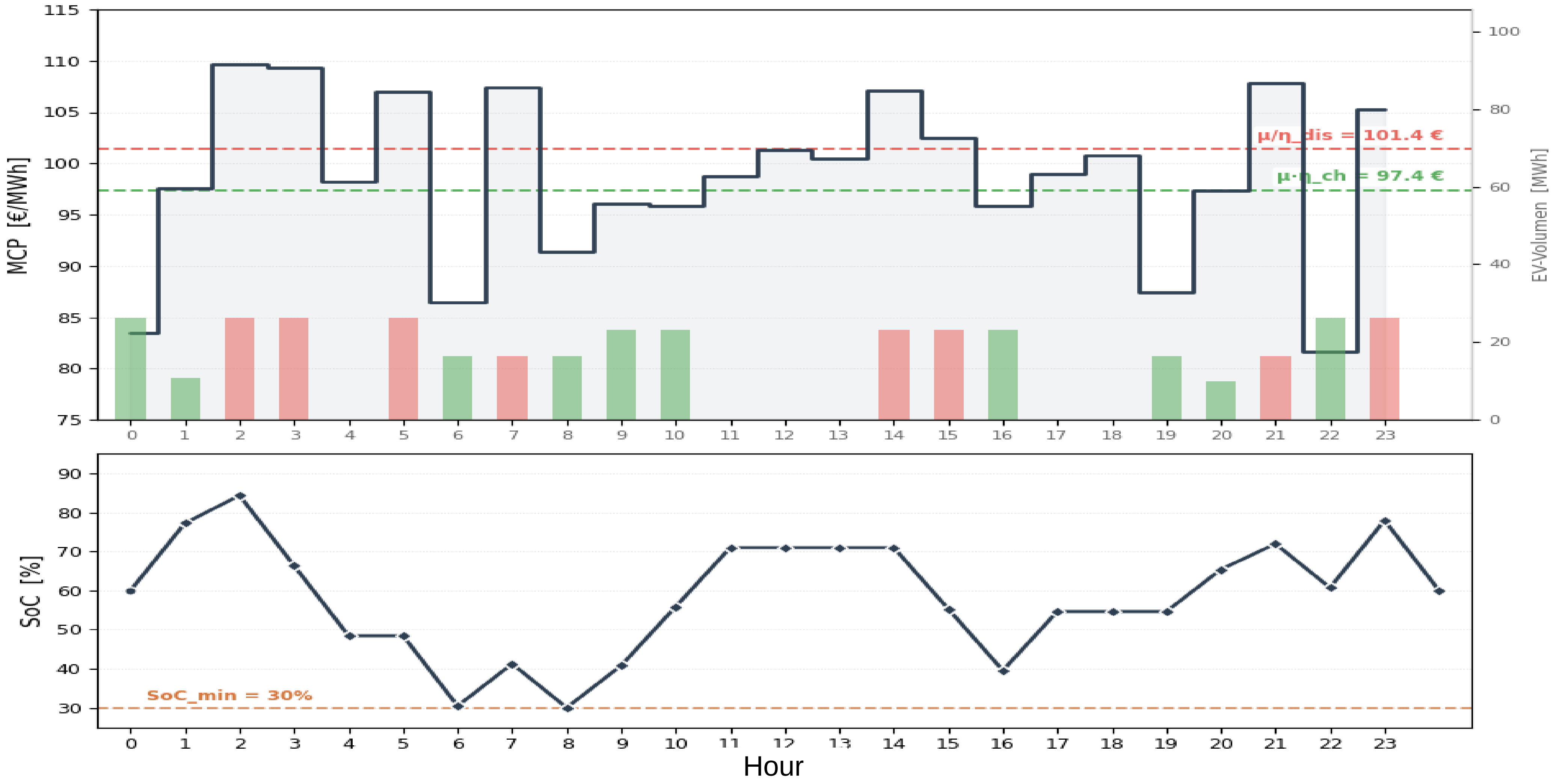
CHARGE	IDLE	DISCHARGE
Buy cheap, store energy $\lambda < \mu \cdot \eta c$	Losses eat the spread $\eta c \leq \lambda \leq \mu/\eta d$	Sell expensive, release energy $\lambda > \mu/\eta d$
Margin ≥ 0	**Margin = 0**	**Margin ≥ 0**
Low Market Price	*(λ) Market Price*	**High Market Price**

- Non-negative profit guaranteed by LP structure (not by heuristic)
- Welfare-optimal dispatch = opportunity-cost bidding strategy in a competitive market
- LP guarantees convexity → no paradoxically accepted orders (unlike block bids [5])

Convex formulation guarantees: clearing prices exist, storage profit ≥ 0, and dispatch consistent with EUPHEMIA rules [6].

Dispatch Example

Based on the test model from [7], extended with welfare-optimal clearing



Conclusion & Outlook

Key findings:

- **Simple bids break for storage** – intertemporal constraints need new approaches
- **Welfare-optimal integration**: storage submits constraints, agents bid as usual
- **LP duality assigns implicit price** – standard merit order logic applies
- **No market rule violations**; storage never loses money
- **Computational overhead manageable** (~1.7x)

Outlook:

- **Integration into PowerACE** for long-term scenarios (2025–2040)
- **Goal is to use this approach for V2G** at varying EV uptakes

Thank you for your attention!

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