# Decentralized Integration of Solar and Storage into Wholesale Energy Markets via Mean-field Games

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# Background: DERs and the Wholesale Energy Market

## Distributed energy resources (DERs)

small-scale power generation or storage technologies, usually **behind-the-meters** (i.e., not controllable by ISOs/RTOs or utilities)

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## Benefits of the participation of DERs in the wholesale energy market

- Similar to demand response, can improve energy market efficiency and lower energy prices
- More flexibility and resilience for the grid
- Revenue to prosumers; encourage investment in renewable energy; improve sustainability

# Conceptual Models of TSO-DSO Coordination

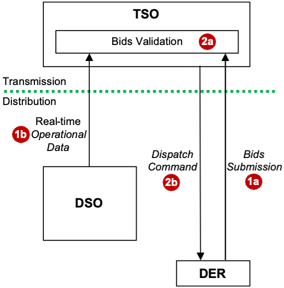


**Fig. 1.** TSO-managed model

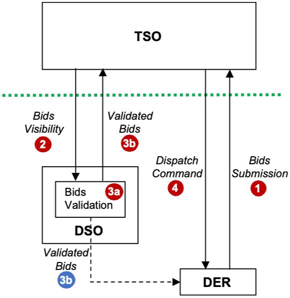


**Fig. 2.** TSO-DSO hybrid-managed model

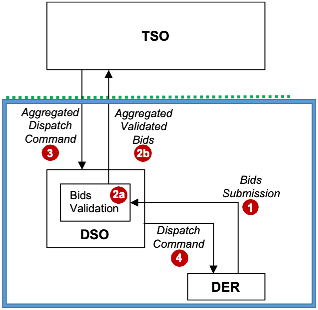


**Fig. 3.** DSO-managed model

Source: A. G. Givisez, K. Petrou and L. F. Ochoa, A Review on TSO-DSO Coordination Models and Solution Techniques. Electric Power Systems Research, 189 (2020) 106659

# Utilizing DERs: Four Approaches

- Direct load control (DER aggregation)
- DSO-operated wholesale-style market – DLMP
- Price-based control, such as real-time pricing – This work
- Peer-to-peer trading (among DERs and consumers) **over shared networks**

# Challenge and Our Goals

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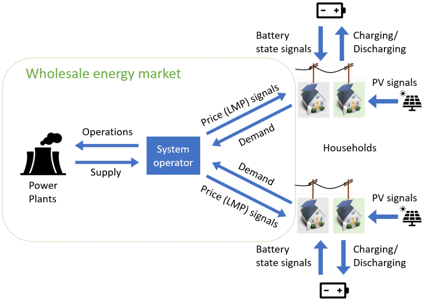
## Our Goals

- Design a control automation algorithm for prosumers (with solar and battery) to automatically make charging/discharging decisions while receiving real-time LMPs (locational marginal prices)
- Study the system-wide impact when there is a large number of autonomous agents (the mean-field approach)

# Overview of our Framework




Framework of the decentralized integration of DERs to wholesale energy markets

1. Each agent (i.e., household) holds a belief of the expectation of locational marginal price (LMP)
2. Each agent makes decisions based on their belief and local states
3. The system operator schedules the power generation from power plants by solving the economic dispatch problem
4. Each agent receives the new LMP and updates their belief

# The System Operator's Economic Dispatch Problem

$$\min_{\mathbf{p}} \quad \sum_{i=1}^{M} C_i(p_{t,h}^i) \quad (\text{– minimize total production cost})$$

$$\text{s.t.} \quad \sum_{i=1}^{M}\sum_{k=1}^{N_i} d_{t,h}^{i,k} = \sum_{i=1}^{M} p_{t,h}^i \quad (\text{– supply/demand balance; dual variable -}LMP_h)$$

$$-\,\overline{\mathrm{F}}_l \leq \sum_{i=1}^{M} \mathrm{G}_{l,i}(p_{t,h}^i - \sum_{k=1}^{N_i} d_{t,h}^{i,k}) \leq \overline{\mathrm{F}}_l, \quad (\text{– transmision constraints})$$

$$\forall l \in \{1, ..., L\}$$

$$0 \leq p_{t,h}^i \leq \overline{\mathrm{p}}_i, \quad \forall i \in \{1, ..., M\}, \quad (\text{– generation capacity constraints})$$

# Agents (Prosumers): Key Assumptions

- Each agent has a PV panel and energy storage, and a type index $\theta \in \Theta$, where $\Theta$ is a finite set and agents within the same type are homogeneous.
- Each type has an infinite number of agents.
- The power consumption and generation pattern for the same agent are stationary on different days.
- The charging/discharging efficiency of the energy storage:

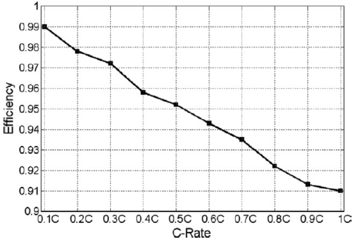



Figure: Charging efficiency w.r.t. battery capacity (Amoroso and Cappuccino (2012)

# Problem Formulation: the Agent's Side

Markov decision problem (MDP) from single agent's perspective (the agent index is omitted):

- Price belief $LMP_h \in \mathcal{R}^+$: the agent holds a belief of the expectation of LMP in the agent's area for hour $h \in \{1, ..., 24\}$.
- State $e_{t,h} \in [0, 1]$: the battery state (ratio to the maximum capacity) in the $h$-th hour on day $t$.
- Net power demand $q_{t,h} \in \mathcal{R}$: demand less renewable energy supply, which is a random variable.
- Action $a_{t,h} \in [-1, 1]$: energy charged(+)/discharged(-) to the battery (ratio to the maximum capacity).

# Problem Formulation

MDP from a single agent's perspective (cont'd):

- State transition:

$$e_{t,h} = \begin{cases} \max\{\min\{e_{t-1,H} + a_{t-1,H}, 1\}, 0\}, & \text{if } \; h = 1; \\ \max\{\min\{e_{t,h-1} + a_{t,h-1}, 1\}, 0\}, & \text{otherwise,} \end{cases} \tag{1}$$

- Reward $r_{t,h} \in \mathcal{R}$: cost of charging ($a > 0$) or profit of discharging energy (and sell to wholesale; $a < 0$) at the price belief of $LMP_h$ (including the charging and discharging loss):

$$r_{t,h} = -LMP_h \cdot \left( q_{t,h} + \eta(a_{t,h})\overline{e} \cdot \min\{a_{t,h}, 0\} + \frac{\overline{e} \cdot \max\{a_{t,h}, 0\}}{\eta(a_{t,h})} \right),$$

where

$\eta(\cdot)$ : the charging/discharging efficiency function,

$\overline{e}$ : battery capacity.

# Problem Formulation

MDP from a single agent's perspective (cont'd):

- Objective: the objective for the agent is to maximize its long-term payoff under the price belief $(LMP_1, ..., LMP_{24})$:

$$\sup_{\pi} \mathbb{E}_{\pi} \Big[ \sum_{t=0}^{\infty} \sum_{h=1}^{24} \beta^{24+h} r_{t,h} \Big], \tag{2}$$

where $\pi$ is a policy for the MDP and $\beta \in (0, 1)$ is the discount factor.

$\longrightarrow$ Problem (2) can be solved by a dynamic programming approach.

# Problem Formulation: Interaction Between the System and a Single Agent

- Mean-field equilibrium (informal definition):

  If in the mean-field game formulation of the wholesale market:

  1. each agent holds a belief of the population state-action profile (i.e., market bid distribution or expectation of LMP),
  2. given that belief, each agent of type $\theta \in \Theta$ adopts the optimal policy $\pi_\theta$ that solves the problem (2),
  3. and the actual population profile (i.e., actual market bid distribution or LMP) is the same as their belief after each agent takes the optimal action,

  then the pair (population profile, optimal policy $\{\pi_\theta\}_{\theta\in\Theta}$) is called a mean-field equilibrium.

# Mean-Field Equilibrium Analysis: Existence of MFE

## Proposition

*The expectation of LMP is continuous with the state-action-type population profile w.r.t. a weak topology.*

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**Proposition**

*The optimal stationary strategy is single-valued and is a continuous function w.r.t (battery state, population profile).*

**Theorem**

*Suppose each agent in the system belongs to a type $\theta \in \Theta$, where $\Theta$ is a finite set. Agents within the same type are homogeneous. Each agent's type is fixed throughout the horizon. Then there* exists a mean-field equilibrium *for the mean-field game formulation of the wholesale market.*

Outline of proof:

- prove the continuity of the MFE operator (mapping from the current population state-action profile to the one in the next step)
- use Schauder-Tychonoff Fixed Point Theorem

# Case Study: Key Configurations

- Test case: IEEE-14 bus test case
- Agent types: prosumers and pure consumers on each bus
- Number of agents: 3,000 for each type on each bus (different buses have different types)
- Daily shape: average hourly net demand (for prosumers) and gross load data (for pure consumers) from California Independent System Operator (CAISO)
- Power plants: one at each bus with a cubic cost function (so a quadratic marginal cost function to mimic a supply stack of different power plants)
- Simulation length: 100 days

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- Simulation length: 100 days
- Demand/supply shock: each of the peak (6, 7, and 8 p.m.) and off-peak (0, 1, and 2 a.m.) hours has a probability of 0.03 to suffer a demand/supply shock respectively, which means a 20% increase in base load/DER supply.

# Proposed (heuristic) algorithm: Update of the Belief

The strategy for each agent to update the belief (the agent index is omitted):

1. Start with a random belief $\widehat{LMP} = (\widehat{LMP}_1, \cdots, \widehat{LMP}_{24}) \in \mathcal{R}^{+24}$;

2. After receiving the actual LMP of its area for hour $h$ on Day $t$, update the belief of LMP for hour $h$ by:

$$\widehat{LMP}_h = \widehat{LMP}_h - (t+1)^{-1}(\widehat{LMP}_h - LMP_{t,h}),$$

where $LMP_{t,h}$ is the actual LMP of its area for hour $h$ on Day $t$.

# Numerical Results

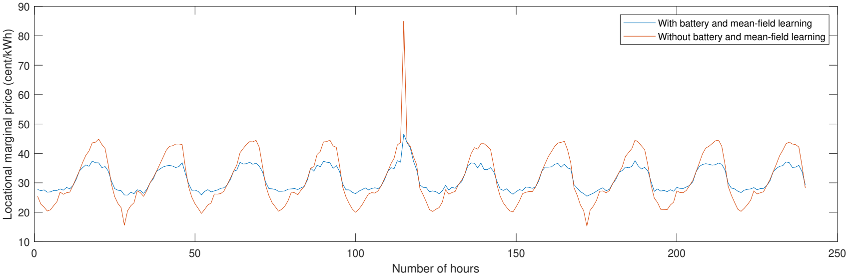


Figure: Hourly LMP of Bus 3 at the end of simulation. x: hour; y: LMP(cent/kWh)

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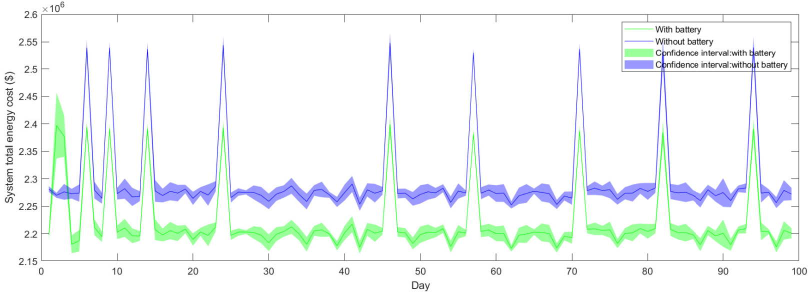


Figure: Daily system total energy cost over the simulation. x: day; y: daily system cost($)

# Numerical Results

- The wholesale market achieves a steady state under our decentralized DER integration framework
- DER supply aligns better with the overall system's demand pattern after the decentralized learning of each prosumer's strategy
- Both the consumer/prosumer and power system can benefit, even with exogenous demand or supply shocks

# Thank you!

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