Optimal Participation of an EV Aggregator in Day-Ahead Energy and Reserve Markets

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Overview

Introduction

- Power systems are forever changing:
  - Minimize operating costs
  - Maintain reliable supply
  - Maximize penetration of emission-free generation

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- Electric vehicles' (EVs) batteries are poised as excellent candidates to provide services:
  - Energy arbitrage (locally or at a system level)
  - Ancillary services (different regulation intervals)
- EV Aggregation:
  - As individuals, they cannot participate in wholesale markets (*e.g.* PJM 1 MW minimum capacity)
  - Operation of EVs as an ensemble: coordinated response

EVs aggregation

- Coordination between the system operator (SO) and EV owners
  - SO seeks to minimize operating cost
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- In this framework, aggregator optimally schedules the EV fleets considering:
  - EV transportation needs (*e.g.* motion needs, range anxiety, *etc.*)
  - EV battery degradation for market participation
  - Participation into competitive energy and reserve markets

Which Markets?

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  - Expectation of energy prices and schedules EVs G2V & V2G

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- Voluntary up reserves[1]
  - Competitive reserve provider
  - Expected revenue obtained in the day-ahead (DA) as a capacity payment for being on-stand by
  - Expected revenue obtained in real-time (RT) for deployment (if called by the SO)

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- Voluntary down reserves:
  - Similar to the up reserve market
  - No deployment payment

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Aggregator's expectations

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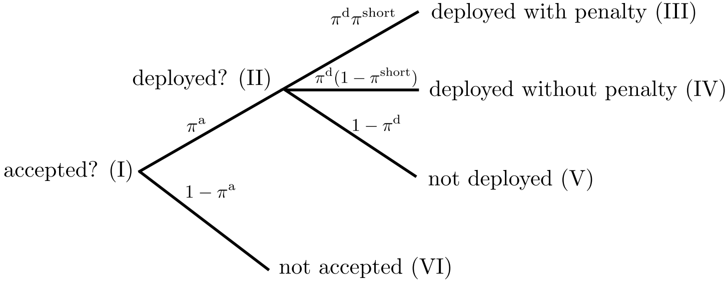
- Embed the aggregator's probability of market outcome into the decision-making process:



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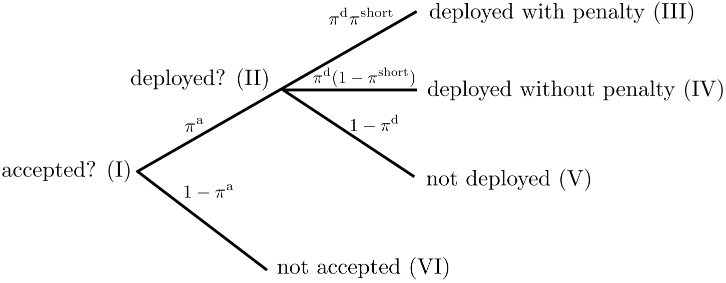

- Determine the bids/offers for the DA clearing process based on expected outcomes (including deployment in RT)

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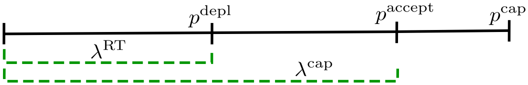
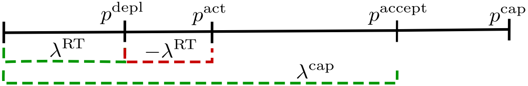


(a)



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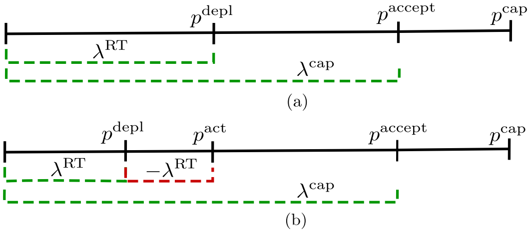
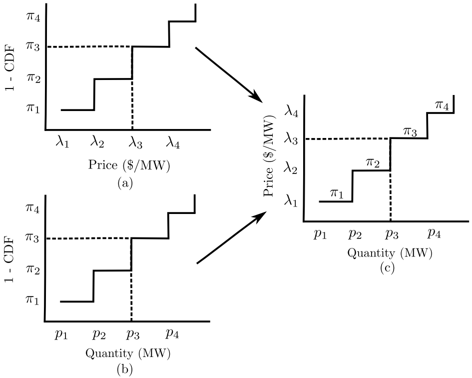


- The penalty could be adjusted to avoid over-commitments

Probabilities curves

- Use historical data from market to populate and create Probability-Quantity-Price (PQP) curves:



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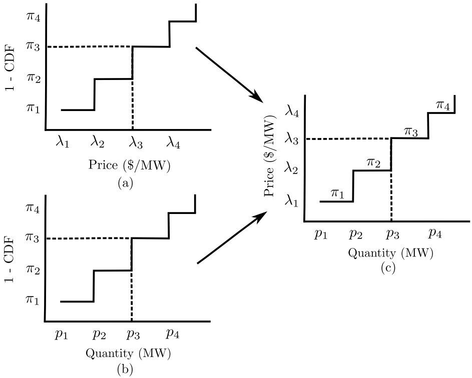
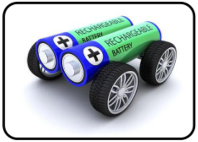


- Uses probabilities to determine bidding strategy in markets:
  - Probability of acceptance (π^a)
  - Probability of deployment (π^d)

EV participation modes



Action

Charge	Discharge

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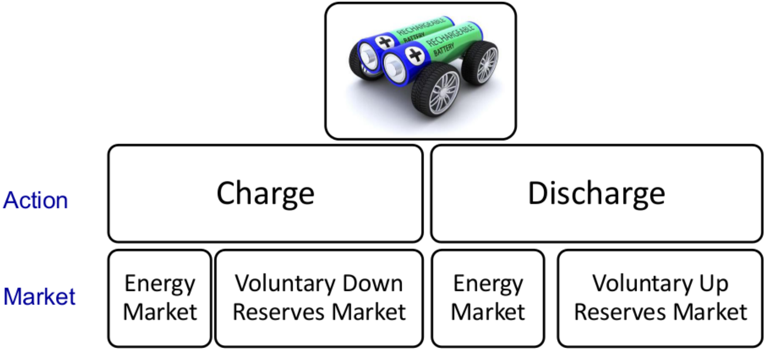

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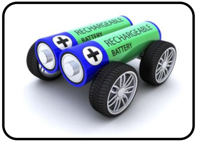

Action	Charge			Discharge		
Market	Energy Market	Voluntary Down Reserves Market		Energy Market	Voluntary Up Reserves Market	
Service	Energy Market Charge (EMCHG)	Reserve Down (REGDN)	Stop Discharge (STOPDSG)	Energy Market Discharge (EMDSG)	Reserve Up (REGUP)	Stop Charge (STOPCHG)

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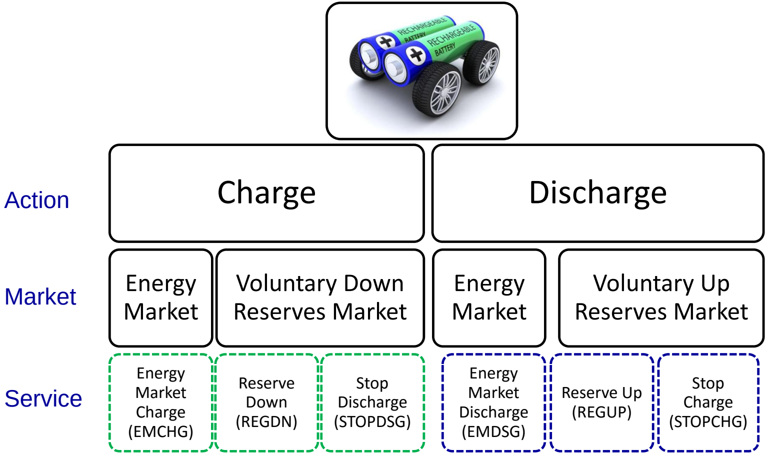

- Optimal scheduling of these services to maximize profits

Solution process

Steps:

1) Aggregator performs DA optimization to determine bids/offers in the energy and reserve markets

[2] H. Pandžić, Y. Dvorkin, Y. Wang, T. Qiu and D. S. Kirschen, "Effect of time resolution on unit commitment decisions in systems with high wind penetration," 2014 *IEEE PES General Meeting*, National Harbor, MD, 2014, pp. 1-5.

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    - Accepts bids/offers of participants to attain minimum cost
    - Determines energy and reserve clearing prices
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4) In RT, SO re-dispatches to accommodate deviations
   - Aggregator may be called upon to deploy reserves

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Aggregator's Model

- Aggregator strives to maximize their profits:

$$\max\left\{r^{\text{em}} + r^{\text{cap}} + r^{\text{depl}} - c^{\text{regup}} - c^{\text{regdn}} - c^{\text{deg}}\right\}$$

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$$r^{\mathrm{em}}=\Delta t\sum_{t\in T}\sum_{v\in V}\lambda_t^{\mathrm{DA}}\left(\eta_v^{\mathrm{dsg}}\cdot p_{t,v}^{\mathrm{emdsg}}-p_{t,v}^{\mathrm{emchg}}\right)$$

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$$r^{\text{depl}} = \pi^{\text{a}} \pi^{\text{d}} \eta^{\text{dsg}} \sum_{t \in T} \sum_{v \in V} \sum_{b \in B} \left(v_{t,b}^{\text{up}} \ \lambda_{t,b}^{\text{RT}} \right) \left(e_{t,v}^{\text{regup}} + \frac{1}{\eta^{\text{dsg}}} e_{t,v}^{\text{stopdsg}} \right)$$

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$$c^{\text{deg}} = \sum_{v\in V} C_v^{\text{bat}}\left|\frac{m_v}{100}\right|\left[\frac{\Delta t\sum_{t\in T}\left(p_{t,v}^{\text{emdsg}} + p_{t,v}^{\text{emchg}}\right) - \xi_v}{BC_v} + \frac{\sum_{t\in T}\left(\pi^{\text{a}}e_{t,v}^{\text{regup}} + \phi^{\text{a}}e_{t,v}^{\text{regdn}}\right)}{BC_v}\right]$$

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Constraints

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  - Minimum energy for motion requirements (ξ_v)
  - State-of-charge (SoC) dynamics
  - Minimum/maximum SoC (battery preservation)
  - Charging and discharging rates
  - EVs' availabilities

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Case study

- Aggregator:
  - Fleet of 1000 EVs with driving patterns from the 2009 NHTS
  - Average battery capacity (B_v) of 24 kWh
  - $0.15 \cdot B_v \leq eSoC_{t,v} \leq 0.95 \cdot B_v$ and random $eSoC_0$
  - Battery degradation characteristic from A123[6]
  - V2G & G2V $\in [0, 3.3]$ kW and $\eta_{\mathrm{R}} = 90\%$

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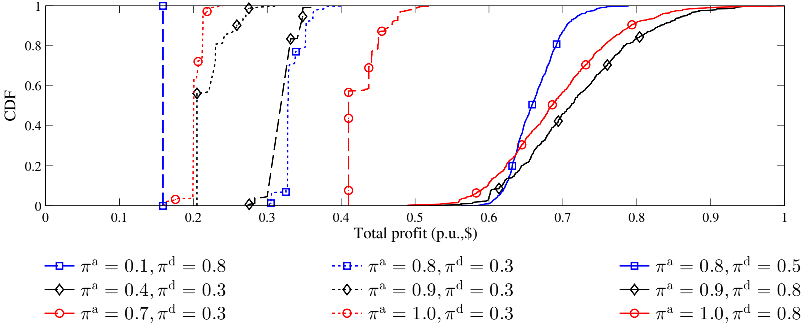
Probability of acceptance/deployment ($\pi^{\mathrm{a}}/\pi^{\mathrm{d}}$)

- Monte Carlo (MC) simulations for wind and load scenarios
- Exploration of all combinations of $\{\pi^{\mathrm{a}}, \pi^{\mathrm{d}}\}$
- Total profits for each combination are compared



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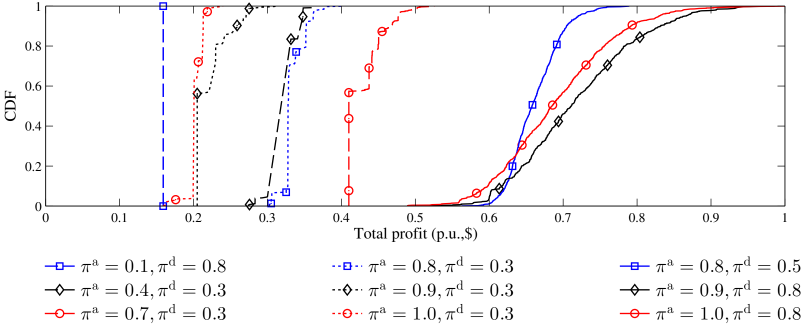
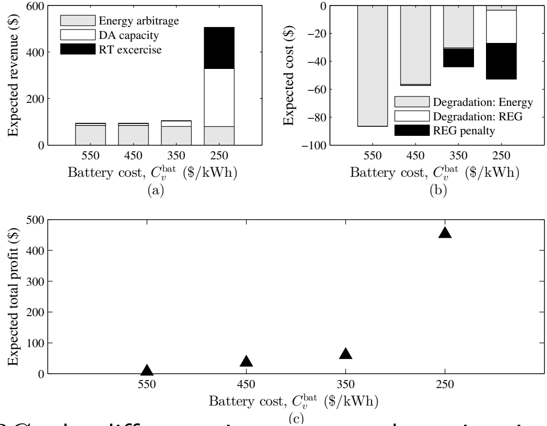


- $\pi^{\mathrm{a}} = 0.9$ and $\pi^{\mathrm{d}} = 0.8$, yield the largest profits (CDF)

Cost/Benefit analysis

- Battery cost sensitivity over {500, 450, 350, 250} \$/kWh



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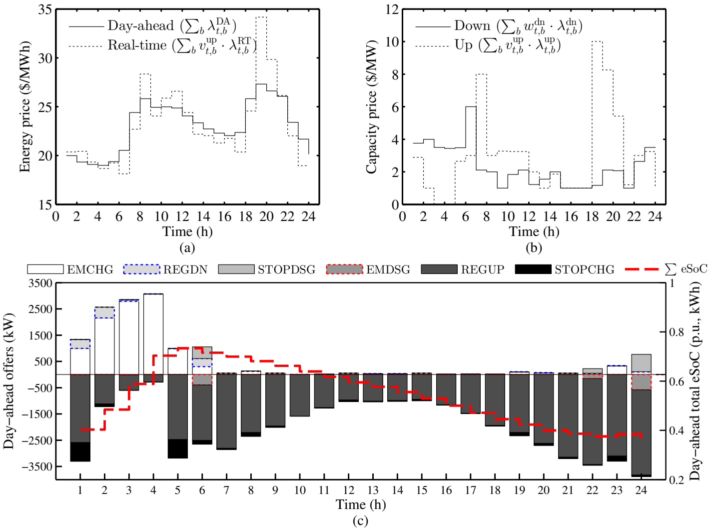
- At low BC_v the degradation costs for participation in regulation are 'affordable'

Offering strategy



Benefits to the system

- Can EV participation aid the power system?

SYSTEM OPERATOR'S COSTS

		Base	Energy Market	Regulation and Energy Market
RT	Total costs (10^6 \$)	2.436	2.435	2.433
	Standard deviation of costs(\$)	32,755	32,690	32,282
	Start-up costs (\$)	4,521	4,490	3,940
DA	Start-up costs (\$)	163,780	162,800	152,020

- With EV participation, total system costs decrease
- Decrease in the start-up costs show less cycling of conventional generation occurs in both the day-ahead and real-time

Conclusions

- Aggregators are required mediators between EV owners and SO
- Offer new streams of competitive services to the power system
- Proposed probabilistic framework for optimal participation in energy and reserve markets, influenced by:
  - Market structure (*i.e.* revenues and costs)
  - EVs' battery degradation
  - Expectations of bids/offers acceptance and deployment in the different markets
- Mutually beneficial for all players (*i.e.* SO, Aggregator, EV owners)

Conclusions

- The participation on the different markets is highly dependent on the battery cost (BC_v):
  - At high BC_v the difference in energy market prices might be attractive
  - At low BC_v the degradation costs for participation in regulation are 'affordable'
- Up reserve provision profitable due to two revenue streams: capacity and deployment
  - Arbitrage is performed between markets, i.e.
  - Energy is purchased during low-price periods
  - Then, scheduled for up reserves

Source

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  - In part also by the University of Washington's Clean Energy Institute (CEI) [url]