Coordination of Electric Vehicle Aggregators: A Coalitional Approach

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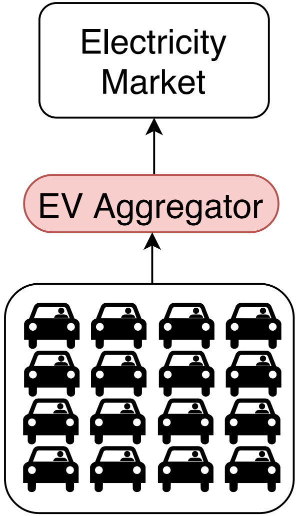
Electric vehicles (EVs) are a key technology for reducing the environmental impact of transportation

But this is not without challenges:

- Large new source of demand
- Increased prices
- Congestion problems

EV Aggregator

- Intermediary
- Buy electricity
- Control charging
- Smarter decisions



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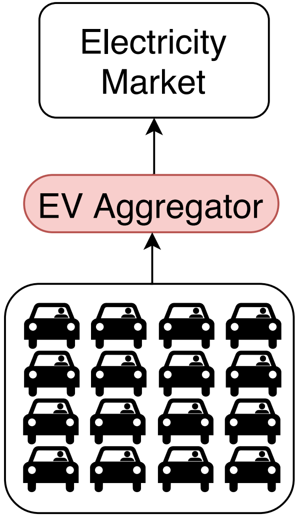

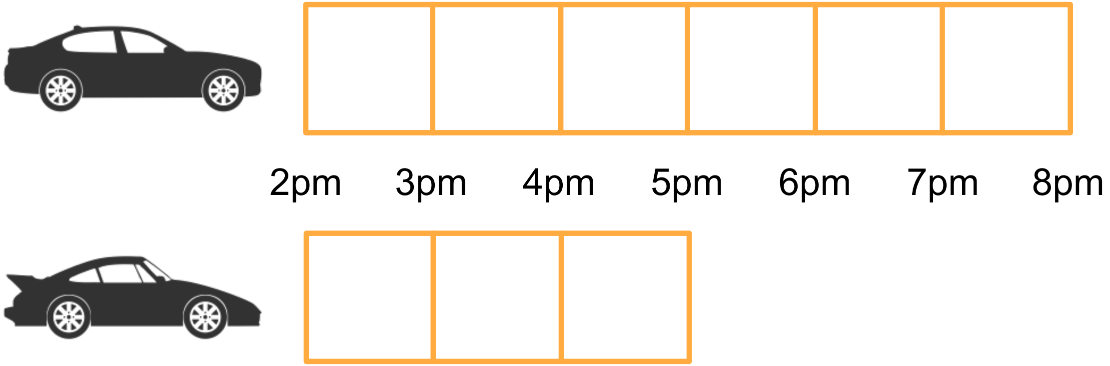

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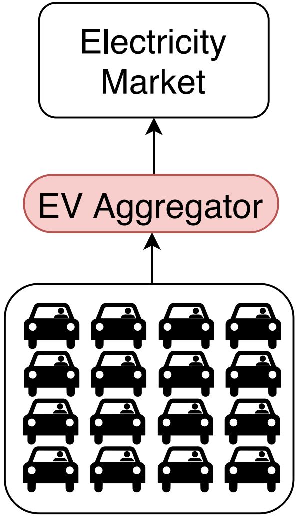

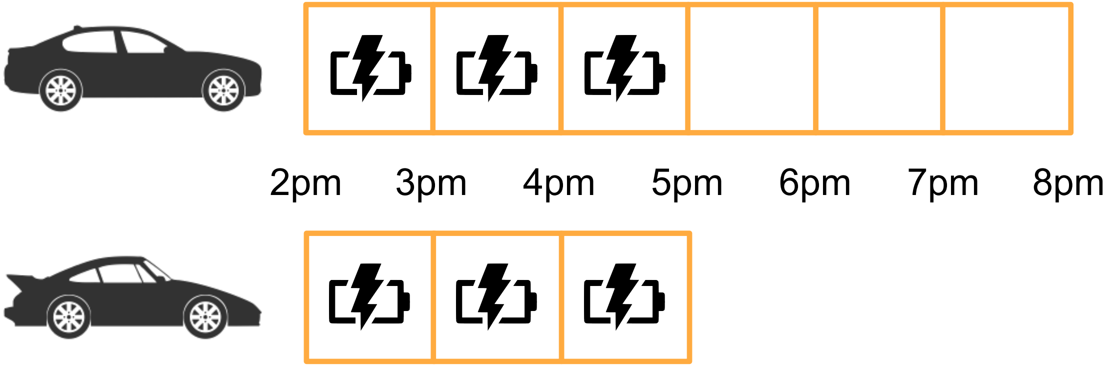

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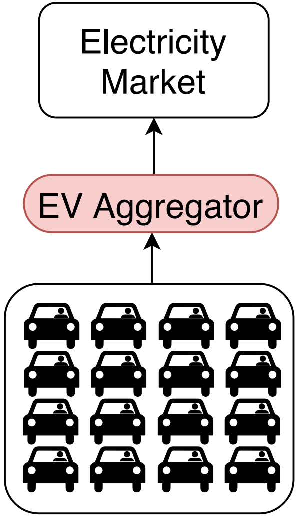
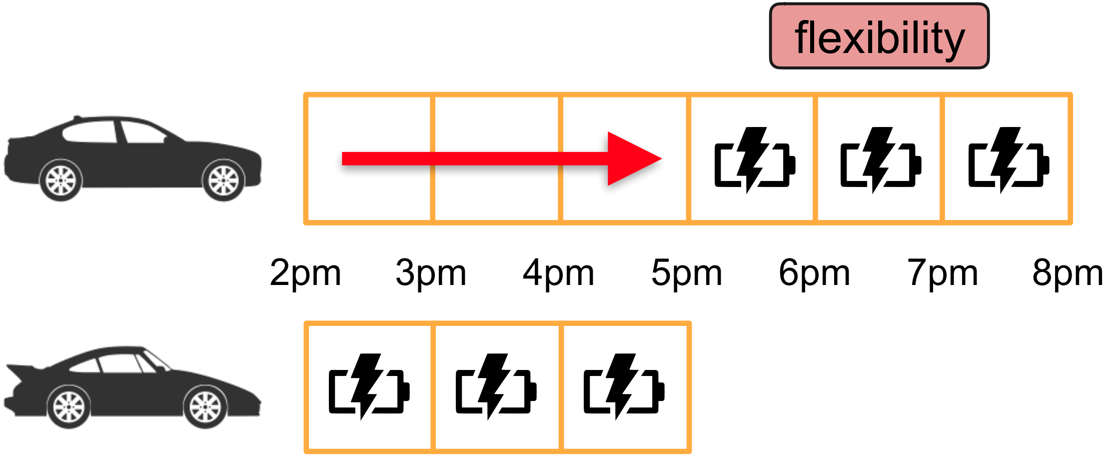
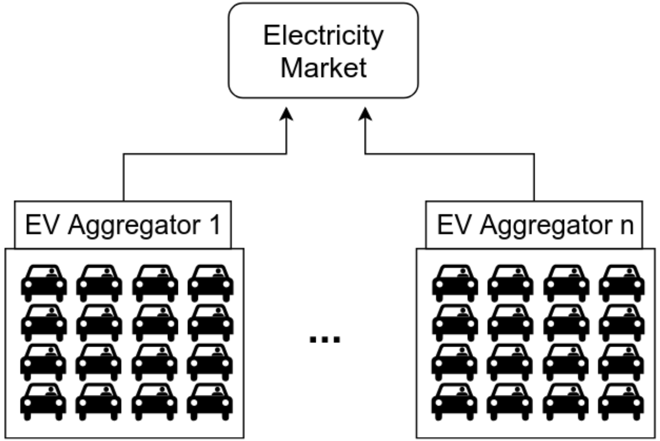




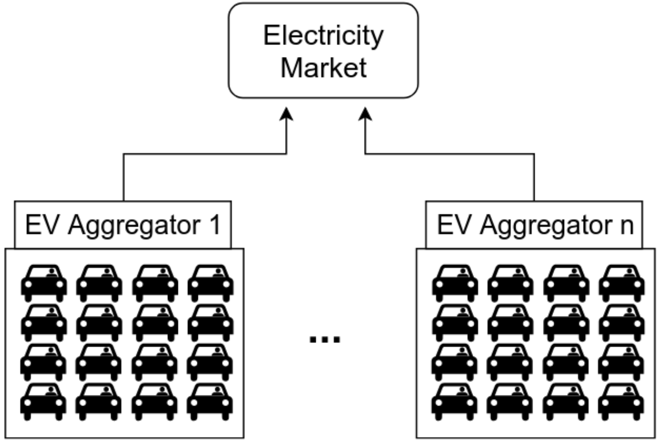
- Reduce demand peaks
- Buy cheap energy
- Reduce costs

Multiple Aggregators



- Local knowledge:
  Smart decisions within each aggregator
- No global knowledge

Multiple Aggregators



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Novel work: coalition formation
- Joint bidding
- Reduce electricity costs

- Self-interested and rational
- Buy energy in day-ahead market
  More demand → higher prices
- Cooperative game

Previous work: mechanism design
(Perez-Diaz et al., 2018)

Outline

- Day-ahead market
- Optimal bidding
- Coalition formation
- Evaluation
- Conclusions and future work

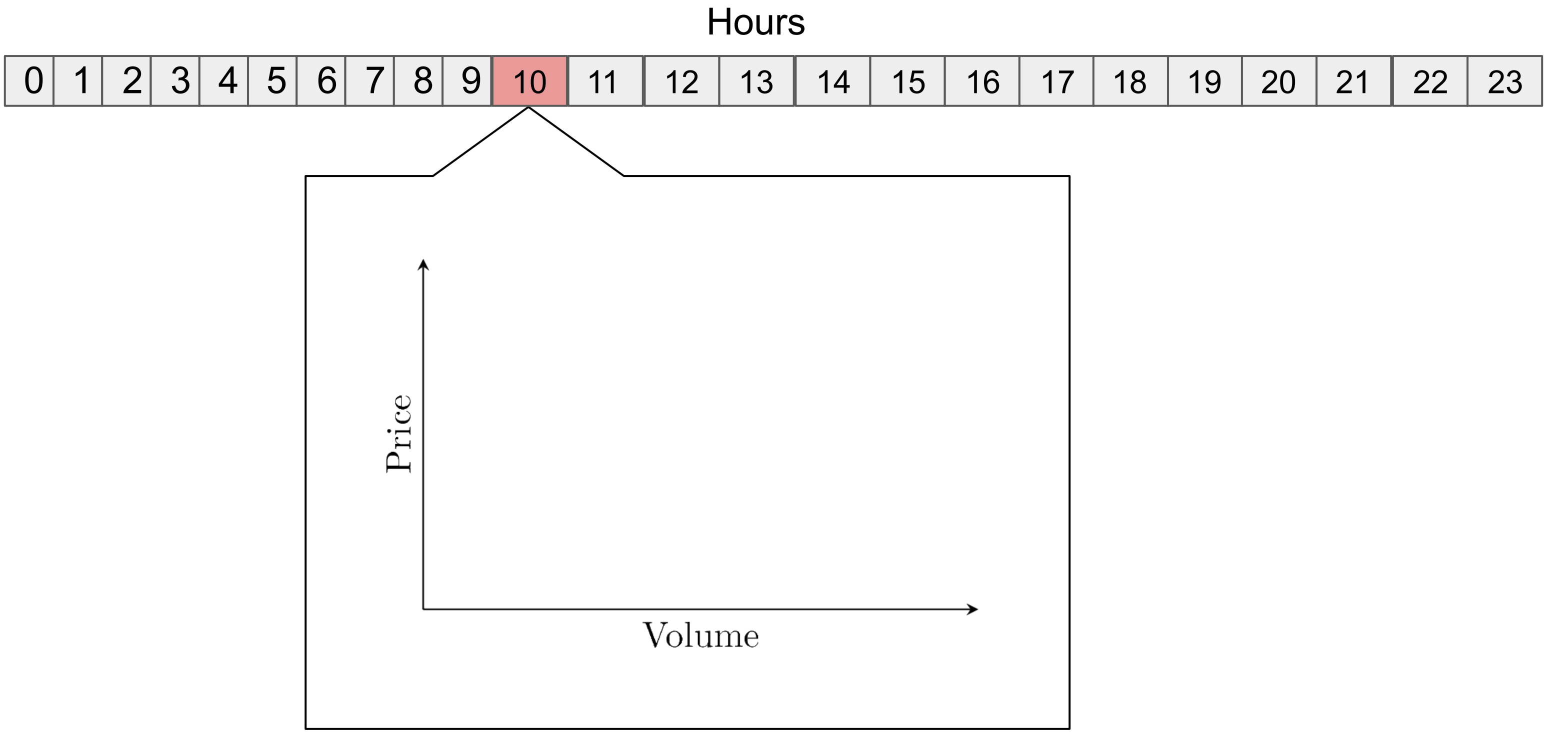
Day-Ahead Market

Hours

0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

- Run every day of the year
- Separate auction for each hour
- Futures market: one day in advance

Day-Ahead Market



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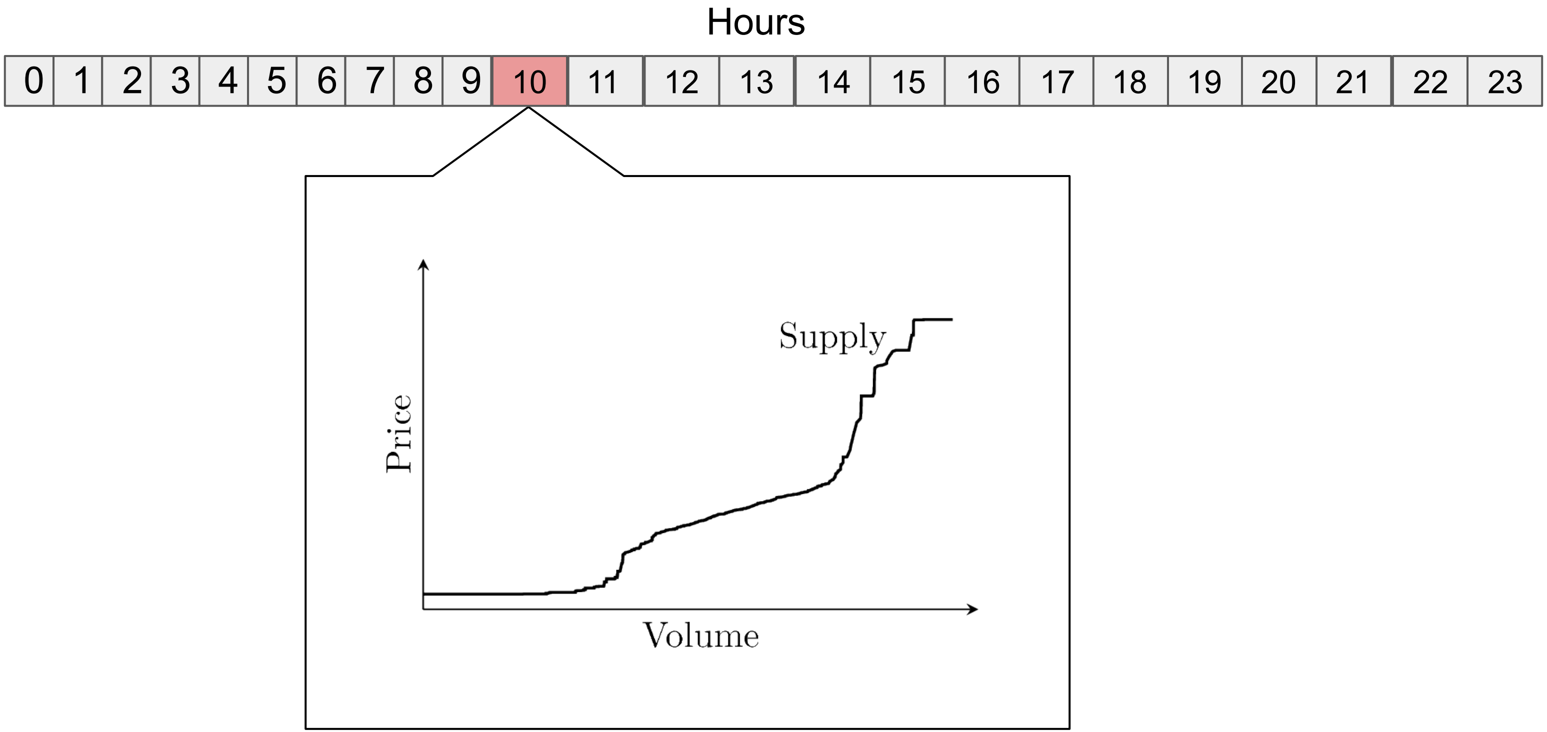

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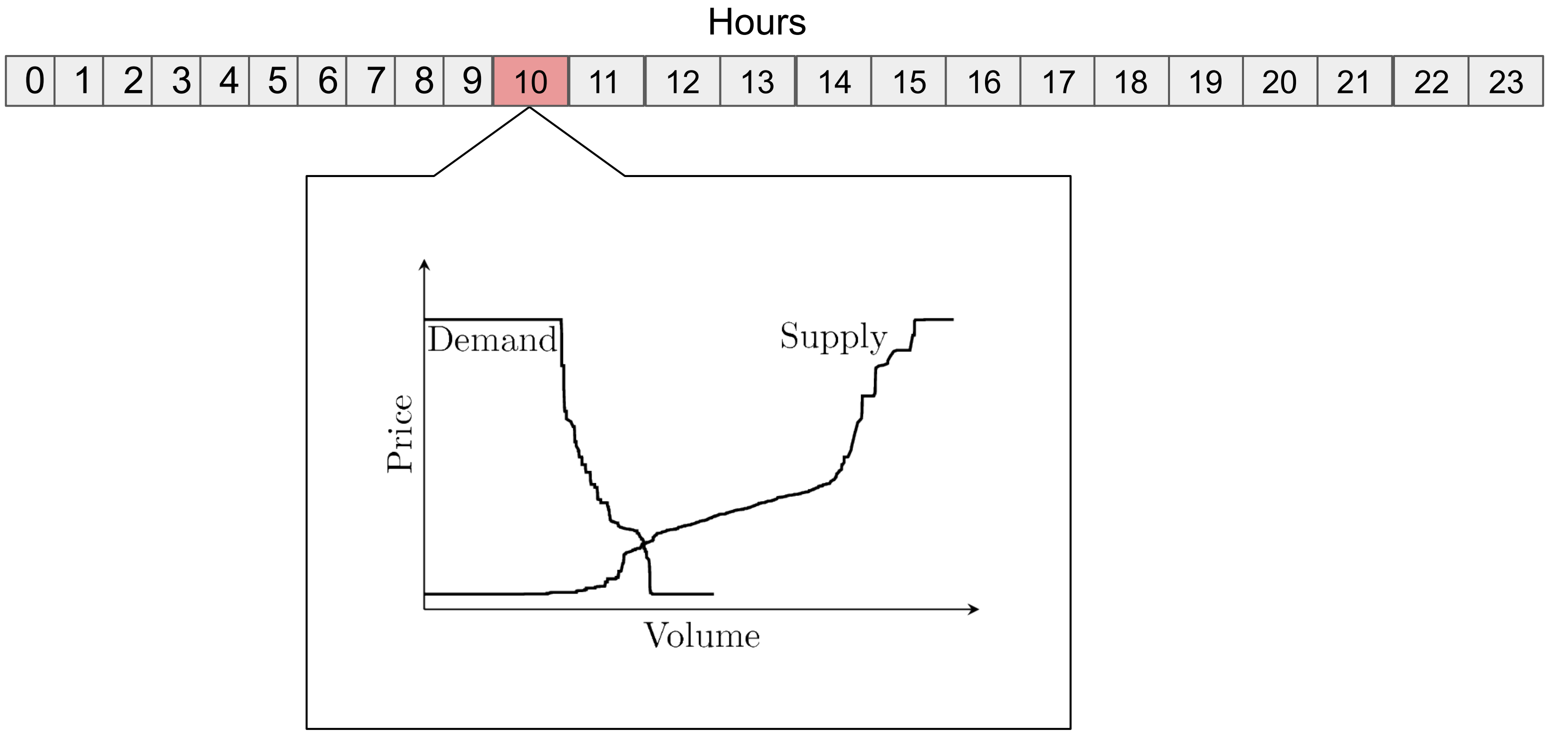

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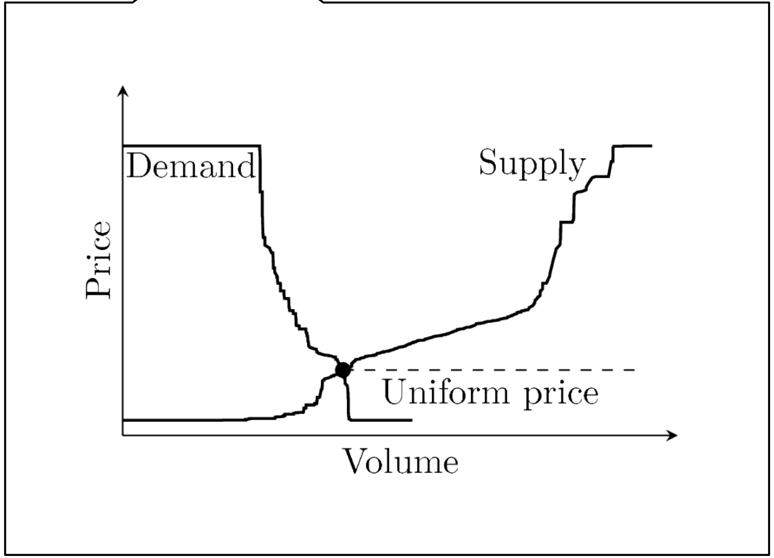

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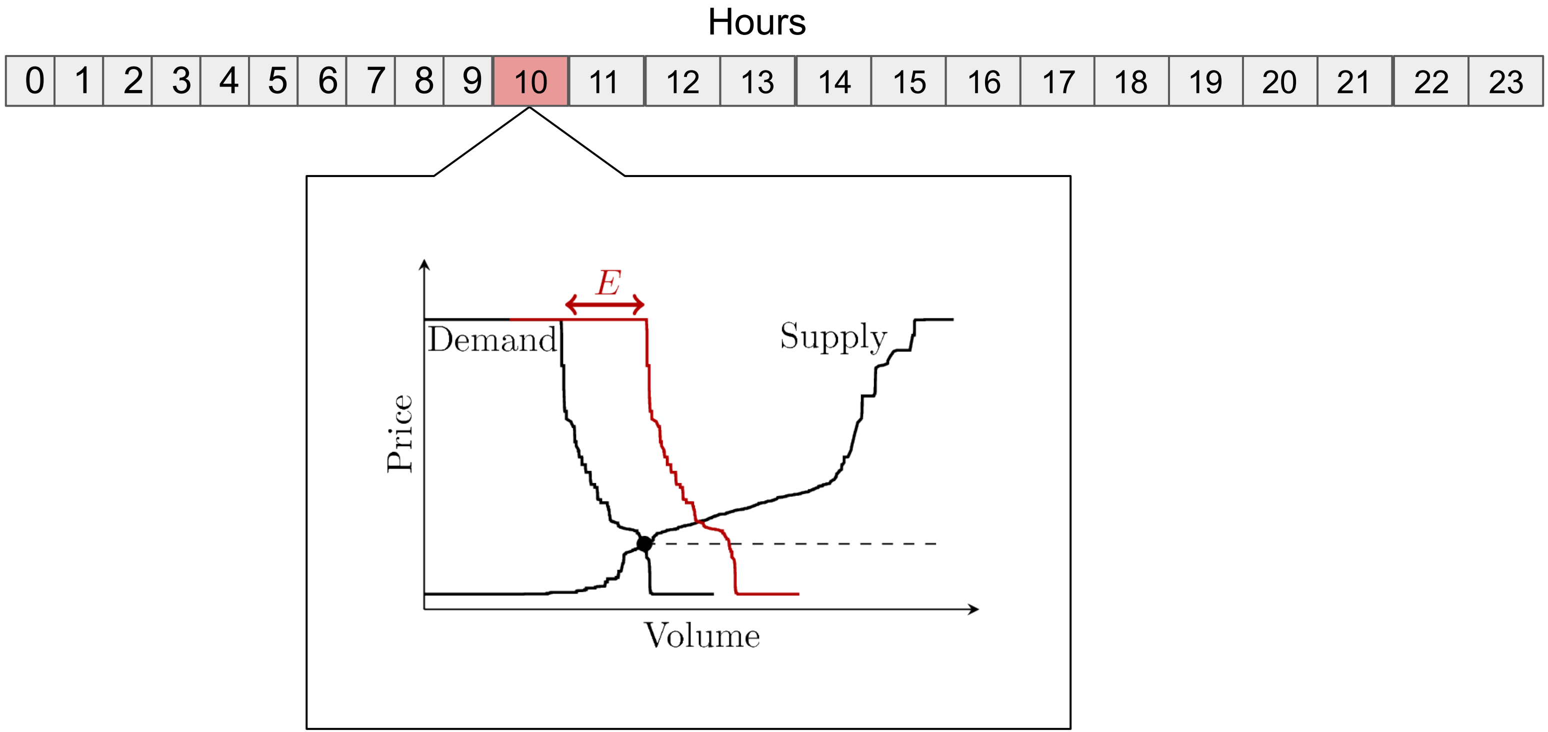

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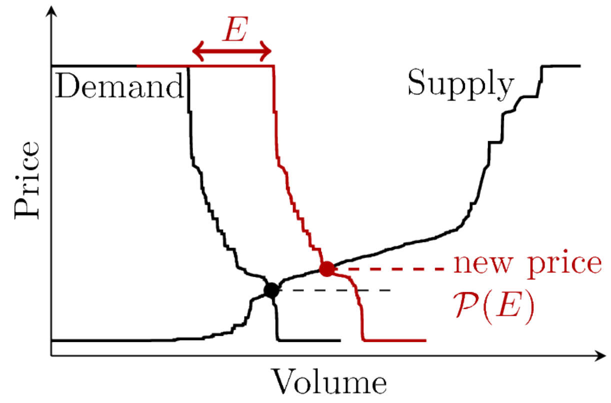
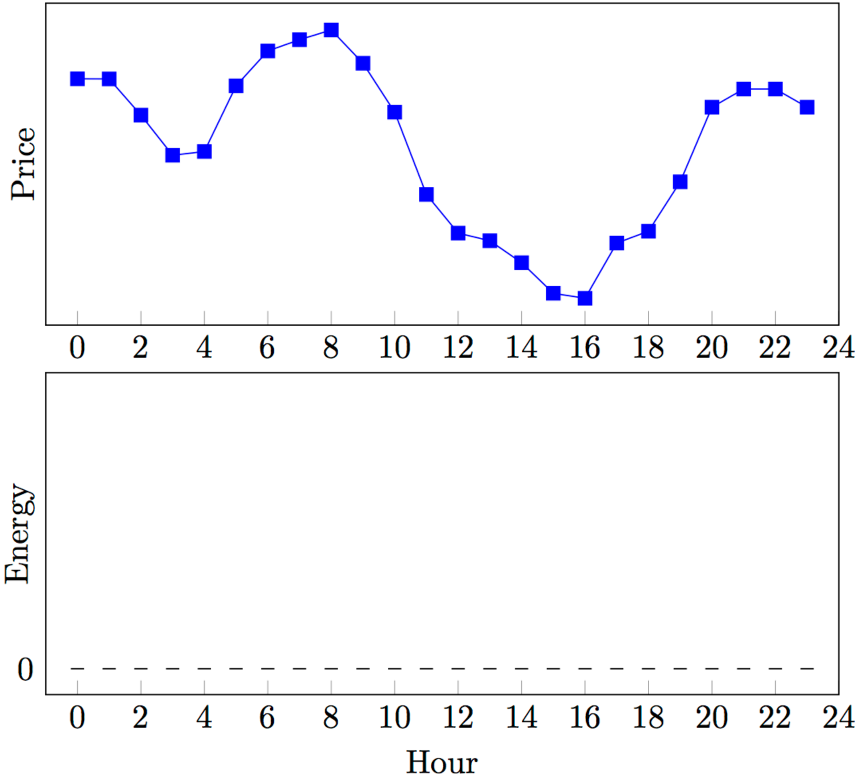


Price impact

Day-Ahead Market



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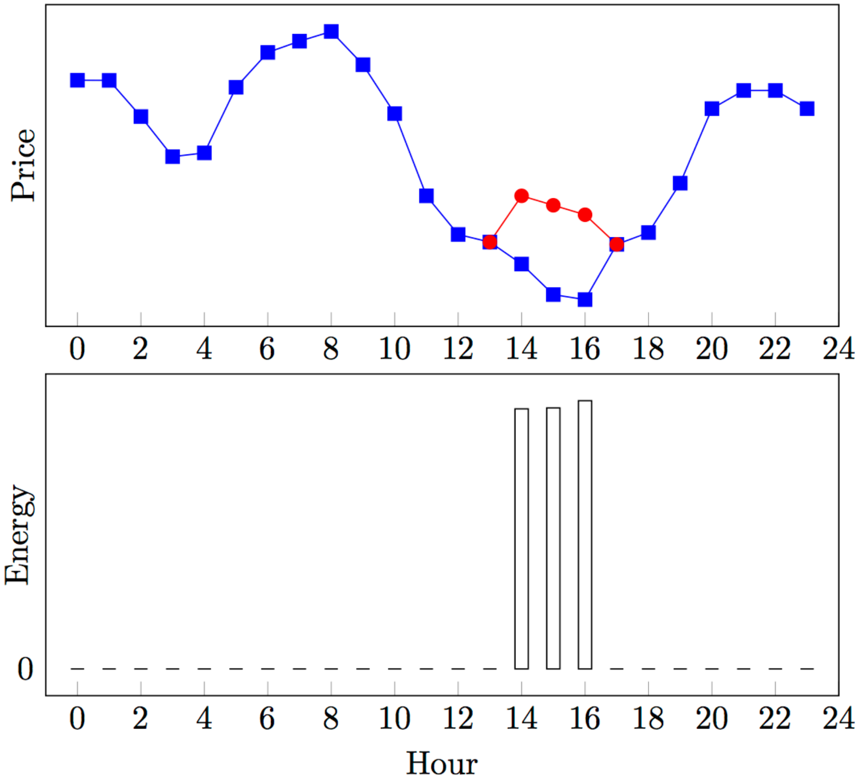

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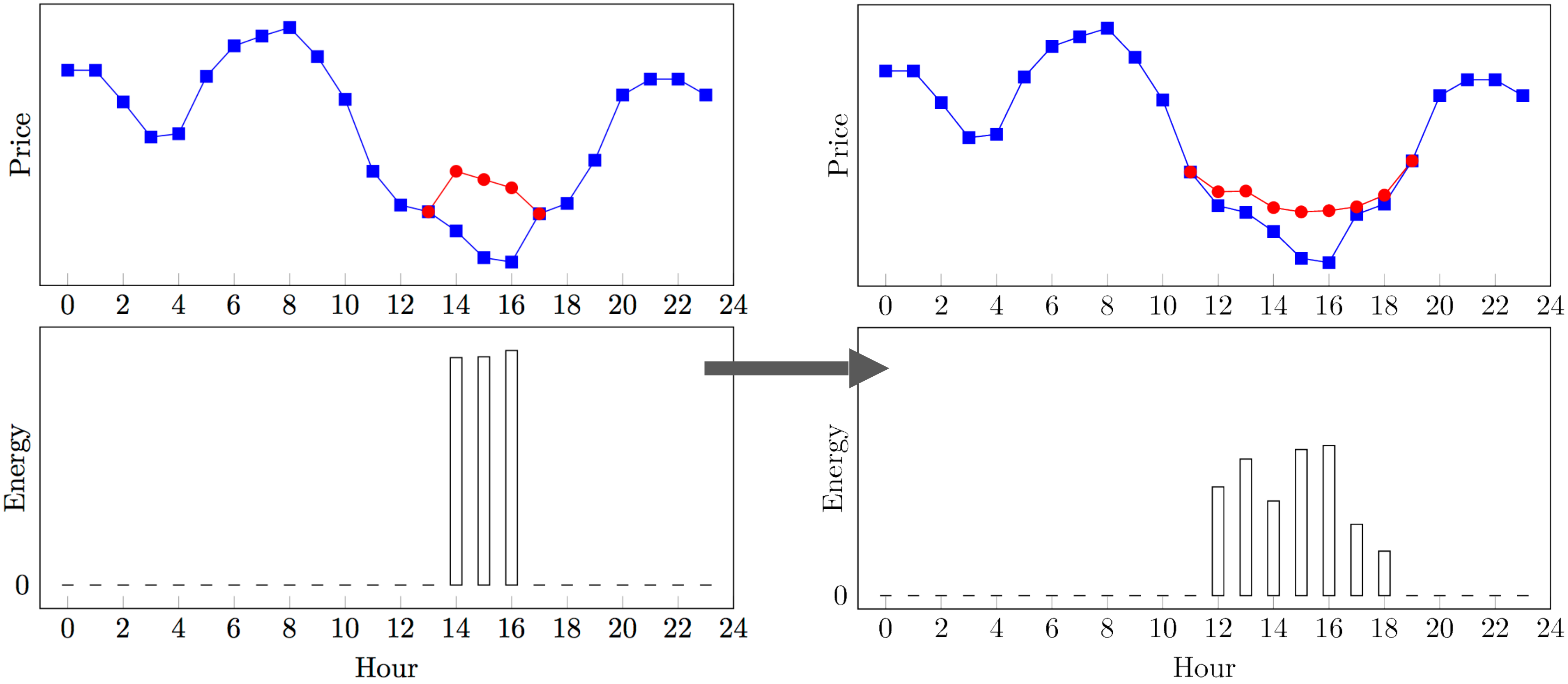

- Day-ahead market
- Optimal bidding
- Coalition formation
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Optimal Bidding

Perez-Diaz *et al.*, Applied Energy (2018)

- Aggregator needs to decide energy allocation: $\boxed{\mathbf{E} = (E_0, \ldots, E_{23})}$
  aim: minimise energy costs

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- Forecast:
  - Prices
  - Energy requirements

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- Forecast:
  - Prices
  - Energy requirements

- Find optimal allocation: $$\boxed{\mathbf{E}^* = \arg\min_{\mathbf{E}} \overbrace{\sum_{h=0}^{23} \hat{\mathcal{P}}_h(E_h) \cdot E_h}^{\text{total cost}}}$$

… while satisfying its energy requirement constraints:
make sure energy is not bought too early or too late

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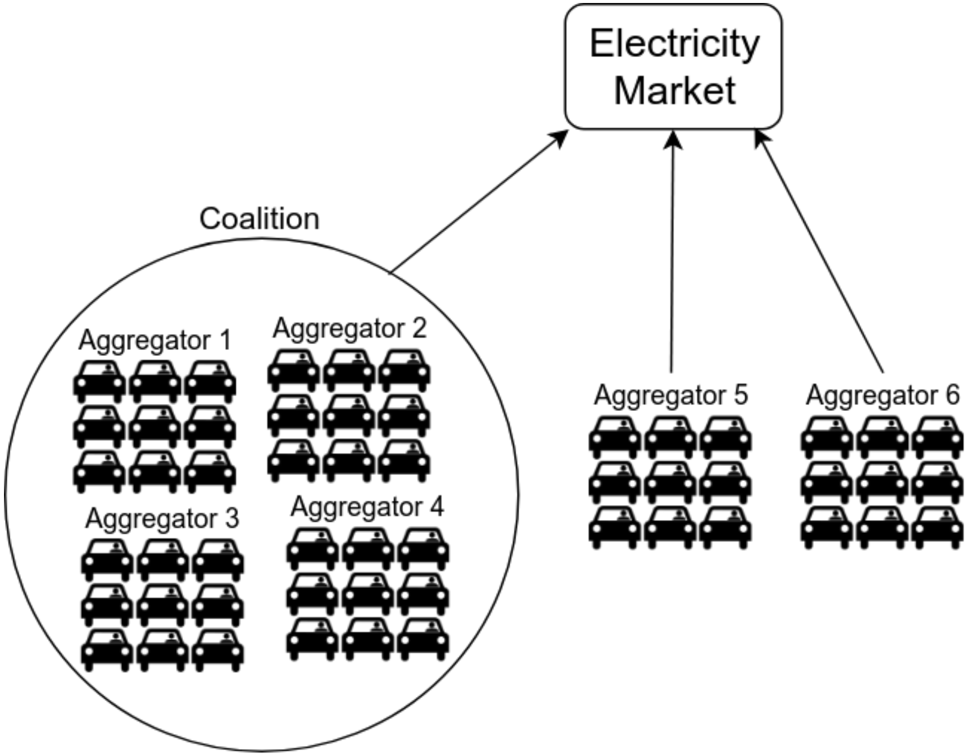
Coalition formation



Aggregators can form coalitions in order to coordinate bidding

1. Share energy requirements
2. Optimise joint bidding
3. Redistribute energy
4. Redistribute energy costs

Coalition formation

- Consider a set of EV aggregators: $N = \{1, \ldots, n\}$
- A coalition is a subset of aggregators: $C \subseteq N$
- Value function: $v(C) = -\operatorname{cost}\left(\mathbf{p}(C), \mathbf{E}(C)\right)$

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externalities

$v(C, \mathrm{CS})$

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externalities $\longrightarrow$ γ-conjecture: aggregators outside C bid individually

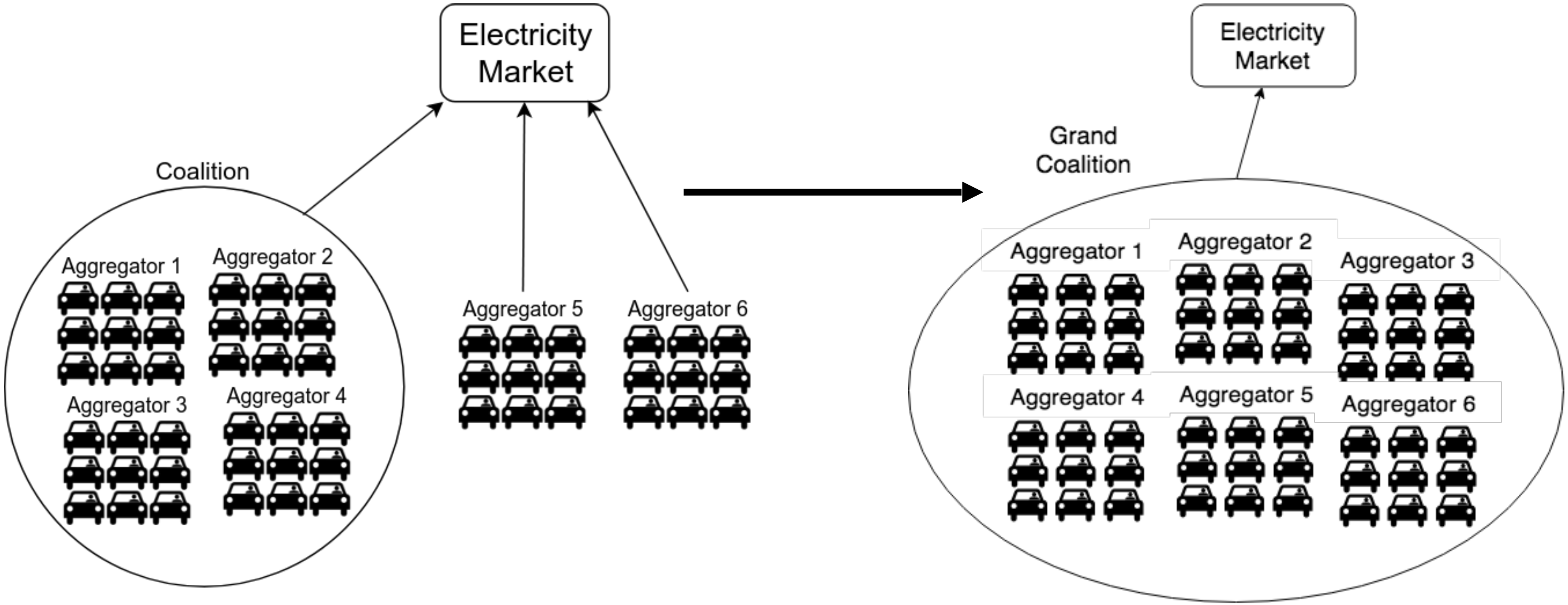
$v(C, \mathrm{CS})$

common when shared resources

(Funaki *et al.*, 1999)

Theoretical results

- The game is **super-additive** ⟶ grand coalition forms



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Find an alternative payment allocation lying in the core

Use the **least-core:** minimise worst case excess for all possible coalitions

$$e(\mathbf{x}, C) = v(C) - \sum_{i \in C} x_i$$

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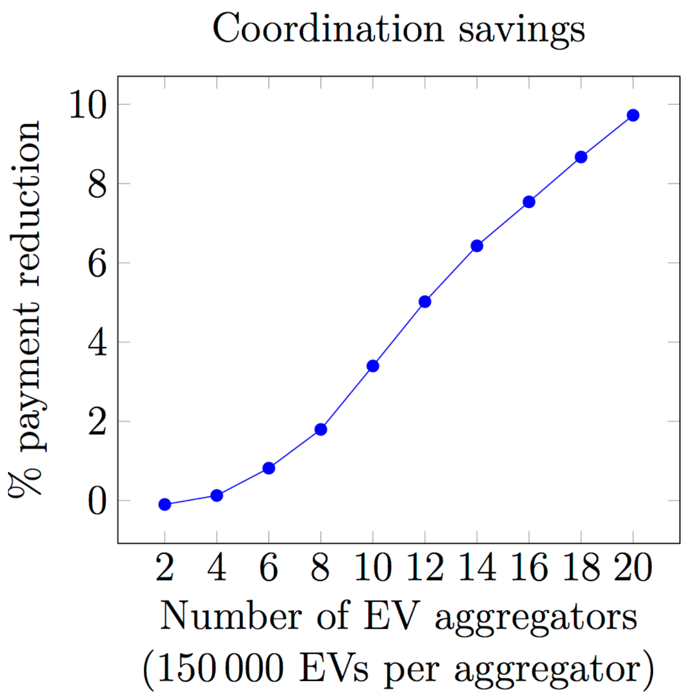
Empirical evaluation

- Real market data from Spanish day-ahead market (OMIE)
- Real driver behaviour from Spanish driver survey (MOBILIA)
- Two payment mechanisms:
  least-core and Shapley Value

Goals:
1. Evaluate the benefits of joint bidding
2. Compare the payment mechanisms

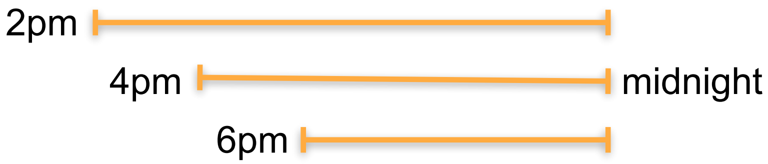
Benefits of joint bidding



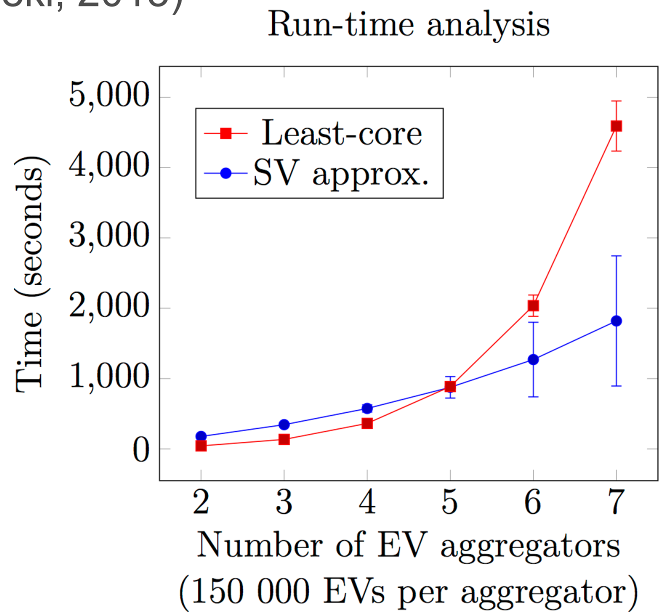
- Individual bidding vs. grand-coalition
- Savings grow with number of EVs: price impact is more important
- Up to 10% savings for 8% of EVs in the UK

Compare payments

- Least-core and approx. Shapley Value (Maleki, 2013)
- Two different scenarios (November 2016)
  1. Different size
  2. Different flexibility



- Good agreement:
  - Within 1% for the first
  - Within 3% for the second



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Conclusions

- First coalitional model of self-interested EV aggregators
- Externalities: introduce γ-conjecture
- Properties: super-additive, balanced, not convex
- Least-core payment is in the core
- Empirical evaluation:
    - Substantial savings
    - Shapley Value and least-core are close

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Future work

- Vehicle-to-grid (V2G)
- Incorporate physical network constraints

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Thanks!

Related work

- Hierarchical charging: (Qi et al., 2013), (Shao et al., 2016)
  - High level coordinator
  - Aggregators comply

- Game theoretic: (Wu *et al.*, 2016)
  - Minimise risk
  - Nash equilibrium (does not need to exist)
  - 3 Aggregators, 1000EV each

- Mechanism design: (Perez-Diaz *et al.*, 2018)
  - Similar scenario to this work
  - Derive optimisation, redistribution and VGC payments
  - No theoretical truthfulness
  - Very large numbers of aggregators and EVs

Optimisation Algorithm

Perez-Diaz et al., *Coordination and payment mechanisms for electric vehicle aggregators* (2018)

$$\min_{\{E_t\}} \sum_t \hat{\mathcal{P}}_t^{\text{convex}}(E_t) \cdot E_t$$

$$\sum_{j=0}^{t} E_j \geq \sum_{j=0}^{t} \hat{R}_j^{\text{late}}\,,\ \forall t = 0, \ldots, 23$$

$$\sum_{j=0}^{t} E_j \leq \sum_{j=0}^{t} \hat{R}_j^{\text{early}}\,,\ \forall t = 0, \ldots, 23$$

$$E_t/\Delta t \leq \hat{N}_t P_{\max}\,,\ \forall t = 0, \ldots, 23$$

Shapley Value Approximation

Maleki et al., *Bounding the Estimation Error of Sampling-based Shapley Value Approximation* (2013)

$$\mathrm{SV}_i = \sum_{C \subseteq N \setminus \{i\}} \frac{|C|!(n-|C|-1)!}{n!} \left(v(C \cup \{i\} - v(C)\right)$$

$$\mathbb{P}(|\hat{\mathrm{SV}} - \mathrm{SV}| \geq \varepsilon) \leq \delta$$

$$\delta = 0.05$$
$$\varepsilon = 0.05 \cdot \mathrm{MC}(a, N \setminus \{a\})$$

Necessary number of samples is: $m \geq \dfrac{\log(2/\delta) r^2}{2\varepsilon^2}$

where $r = \mathrm{MC}(a, N \setminus \{a\}) - \mathrm{MC}(a, \emptyset)$

Least-Core Payment

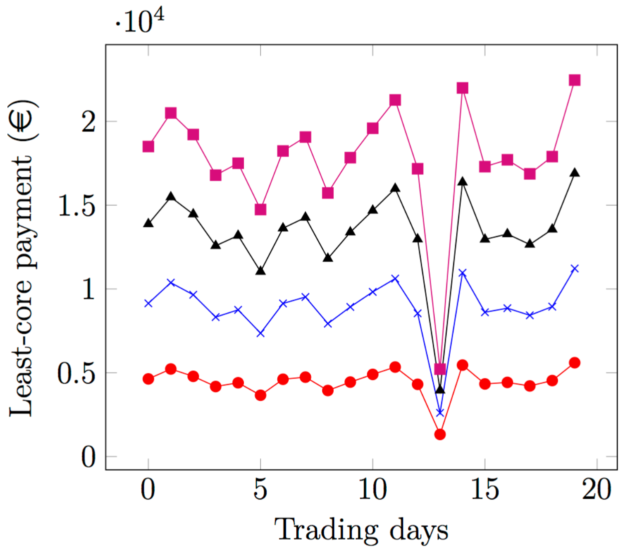
$$e^*, \mathbf{x}^* = \arg \min_{\mathbf{x} \in \mathbb{R}^n, e \in \mathbb{R}} e, \text{ s.t.}$$

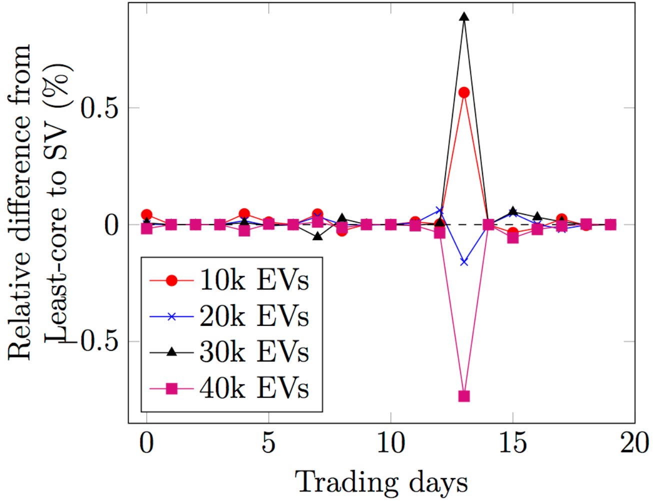
$$v(C) - \sum_{i \in C} x_i - e \leq 0, \forall C \subset N$$

$$v(N) - \sum_{i \in N} x_i = 0$$

Aggregators with different sizes

- Different sizes: 10k, 20k, 30k, 40k
- Random EV arrival (evening) and departure times (morning)





Aggregators with different flexibilities

- Common size: 150k EVs each
- Different flexibilities: