# Decentralised Coordination of Electric Vehicle Aggregators

*Alvaro Perez-Diaz*
University of Southampton

*Enrico Gerding*
University of Southampton

*Frank McGroarty*
University of Southampton

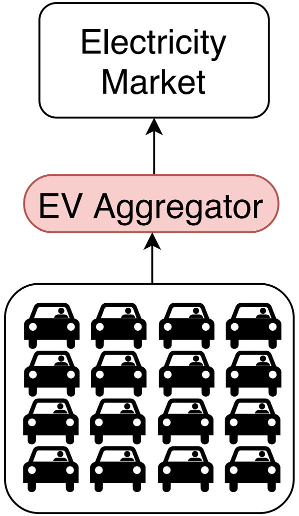
# Electric vehicles (EVs) are a key technology for reducing the environmental impact of transportation


But this is not without challenges:

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

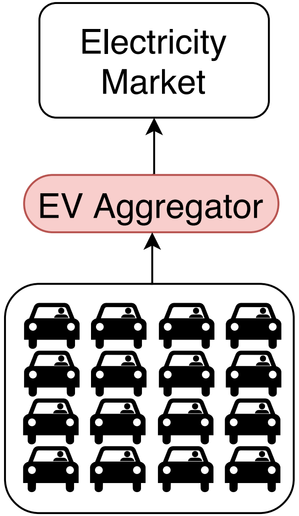
# EV Aggregator

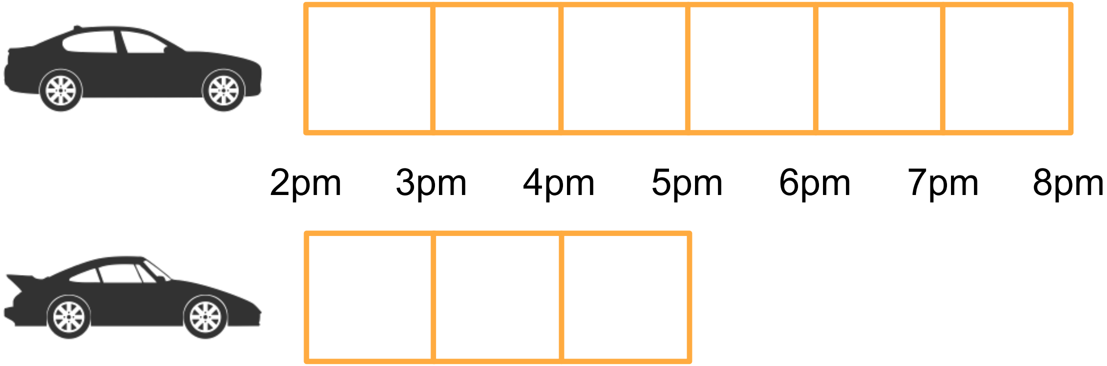
- Intermediary
- Buy electricity
- Control charging
- Smarter decisions



# EV Aggregator

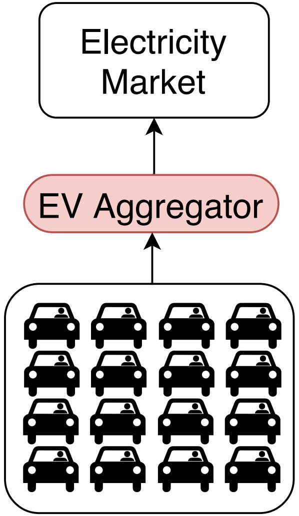
- Intermediary
- Buy electricity
- Control charging
- Smarter decisions

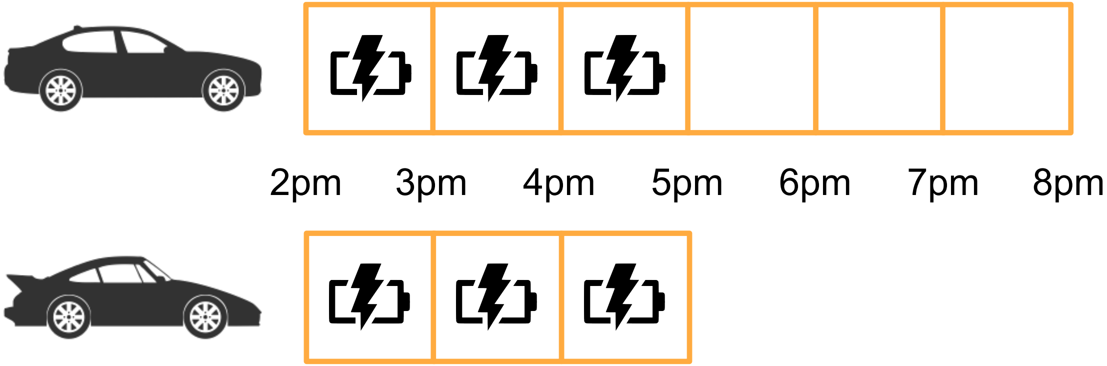


# EV Aggregator

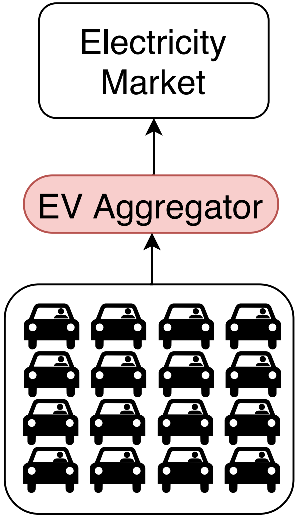
- Intermediary
- Buy electricity
- Control charging
- Smarter decisions

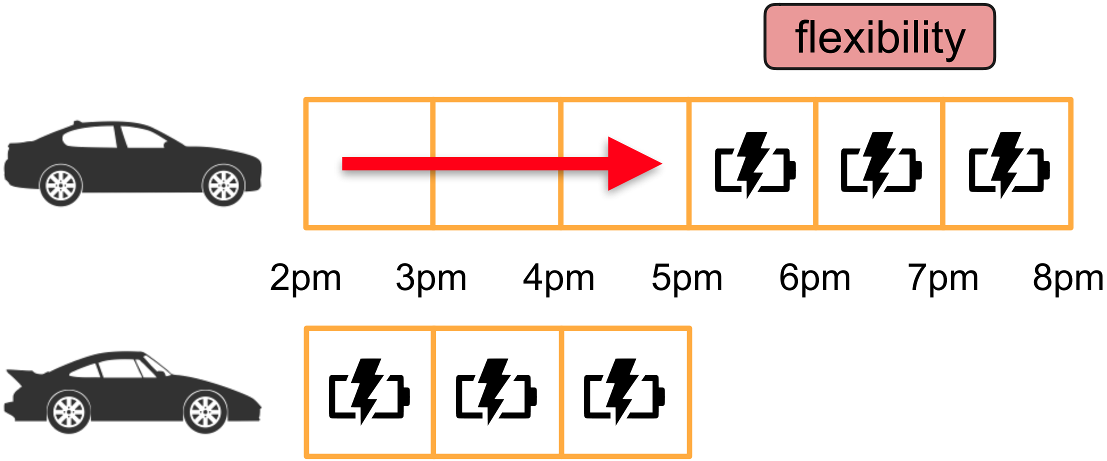


# EV Aggregator

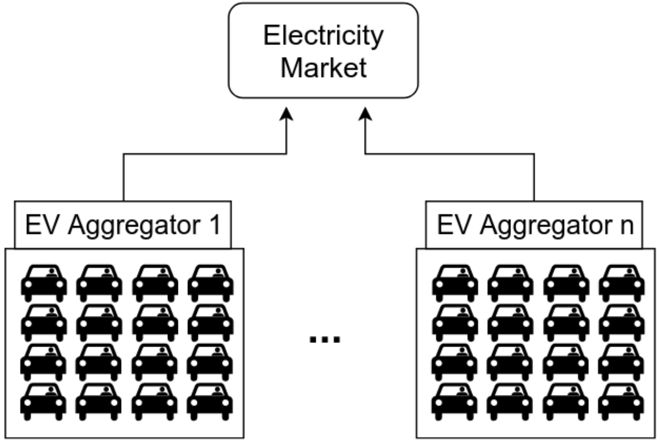
- Intermediary
- Buy electricity
- Control charging
- Smarter decisions



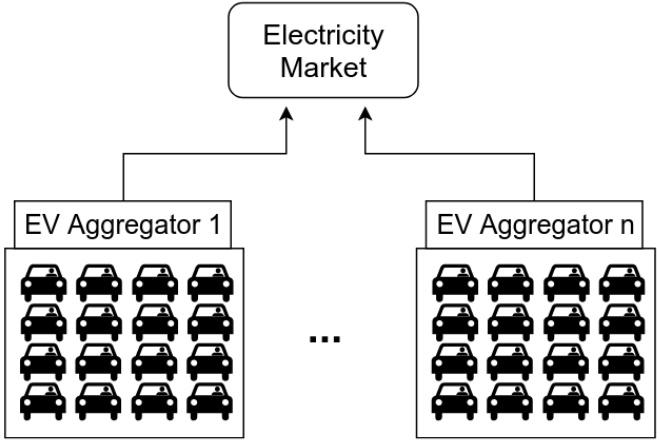

- Reduce demand peaks
- Buy cheap energy
- Reduce costs

# Multiple Aggregators




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

# Multiple Aggregators

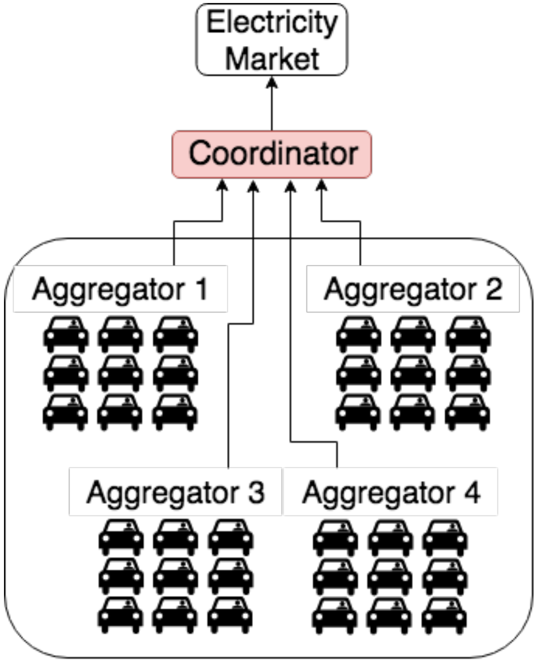



- Local knowledge:
  Smart decisions within each aggregator
- No global knowledge

Enable inter-aggregator coordination to produce joint bidding and reduce electricity costs

- Self-interested and rational
- Buy energy in day-ahead market
- More demand $\longrightarrow$ higher prices

# Joint bidding




Centralised approaches:

- Mechanism design

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

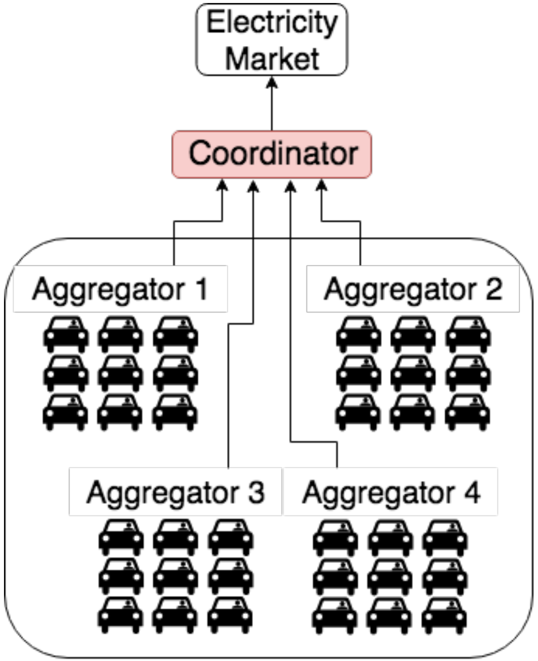
- Cooperative game theory

(Perez-Diaz et al., AAMAS 2018)

Framework:

1. Report requirements to coordinator
2. Coordinator performs global bidding
3. Redistribute purchased energy
4. Redistribute energy costs

# Joint bidding




Centralised approaches:

- Mechanism design

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

- Cooperative game theory

(Perez-Diaz et al., AAMAS 2018)

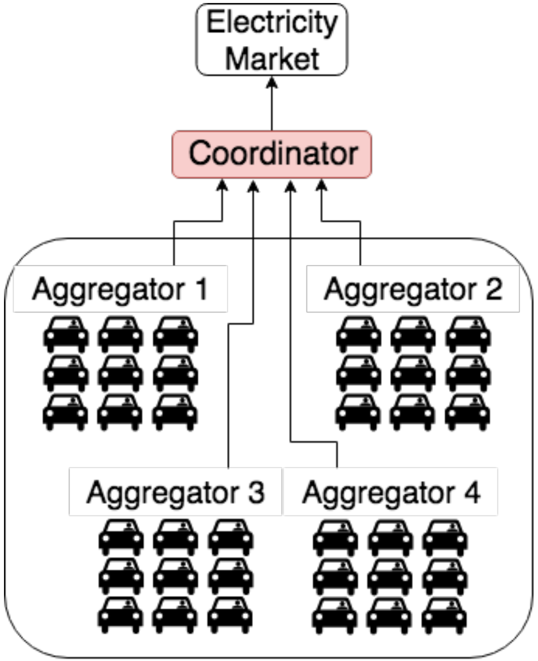
Framework:

Privacy

1. Report requirements to coordinator
2. Coordinator performs global bidding
3. Redistribute purchased energy
4. Redistribute energy costs

Black-box

# Joint bidding




Centralised approaches:

- Mechanism design

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

- Cooperative game theory

(Perez-Diaz et al., AAMAS 2018)

Framework:

Privacy
1. Report requirements to coordinator
2. Coordinator performs global bidding

Black-box
3. Redistribute purchased energy
4. Redistribute energy costs

Novel work: decentralised coordination
- Preserve privacy
- Transparent coordination step

# Outline

- Day-ahead market
- Individual bidding
- Decentralised joint bidding
- Evaluation
- Conclusions and future work

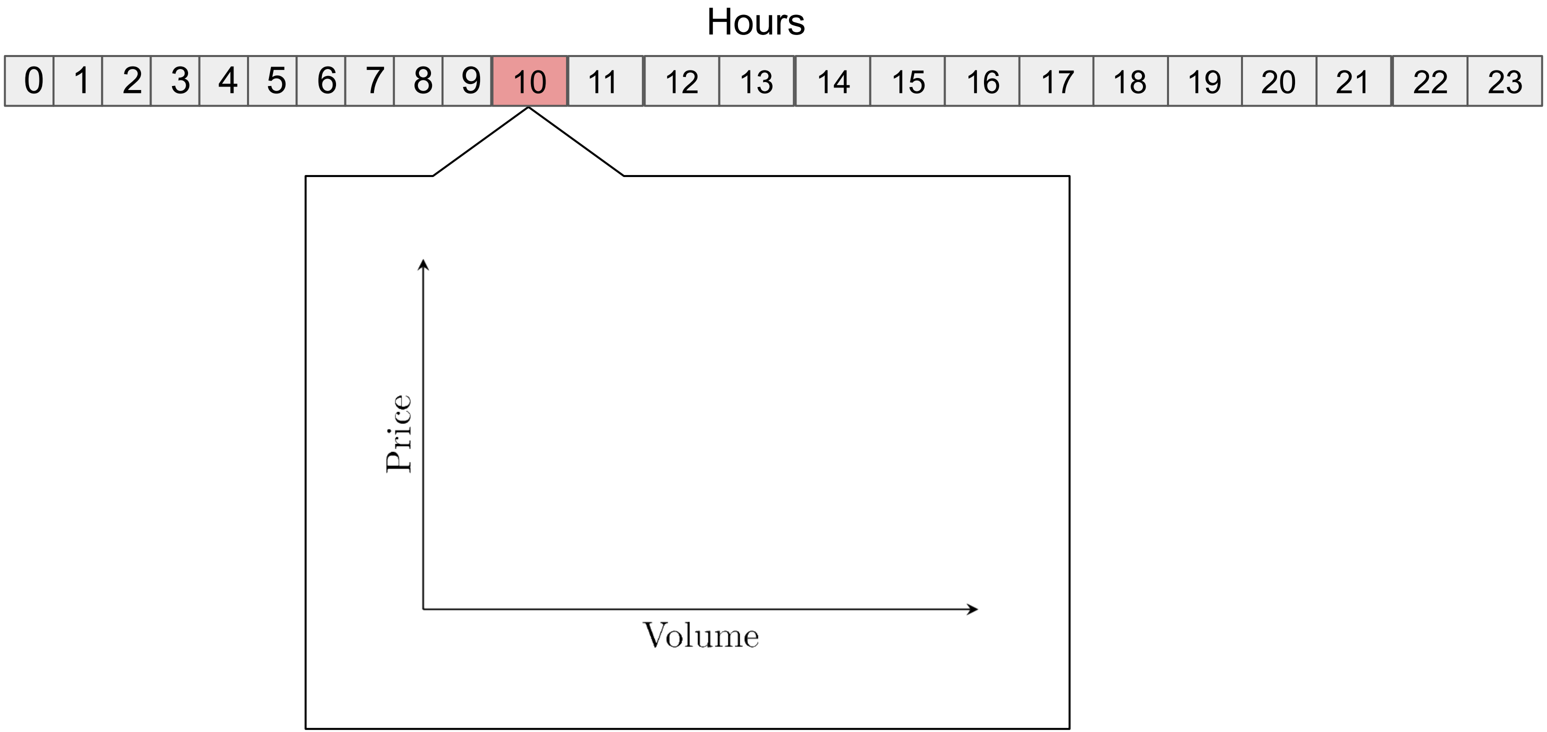
# Day-Ahead Market

Hours

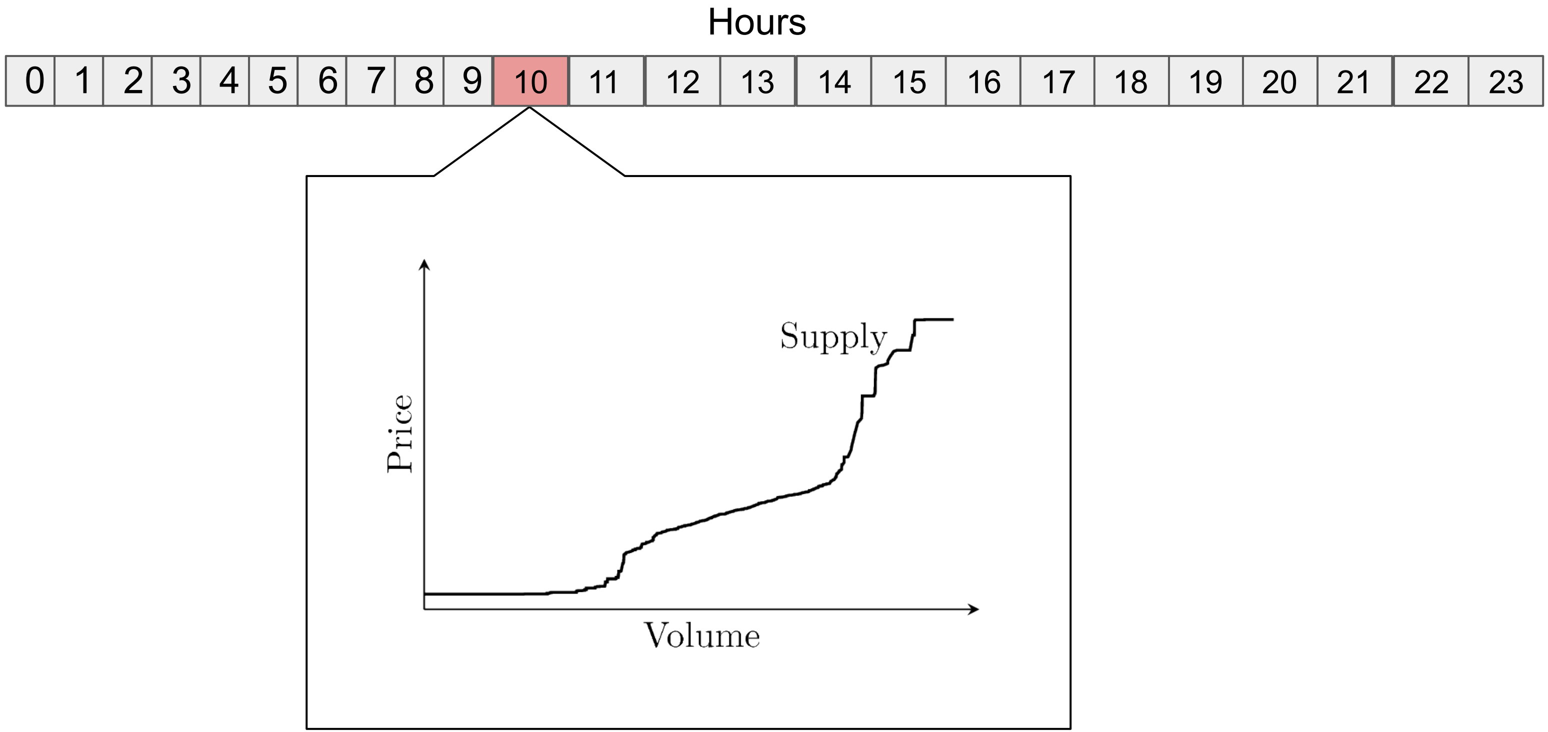
| | | | | | | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 |

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

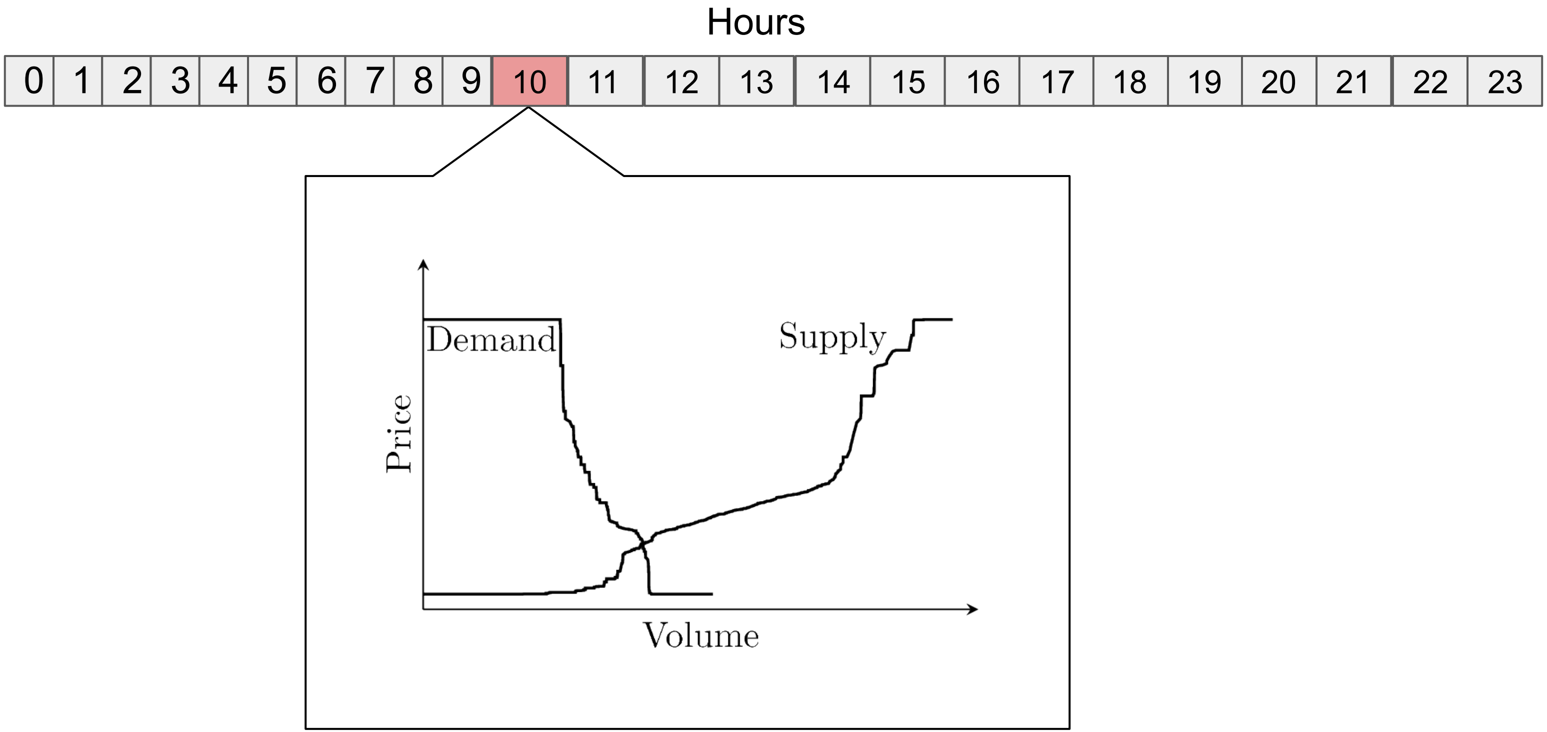
# Day-Ahead Market



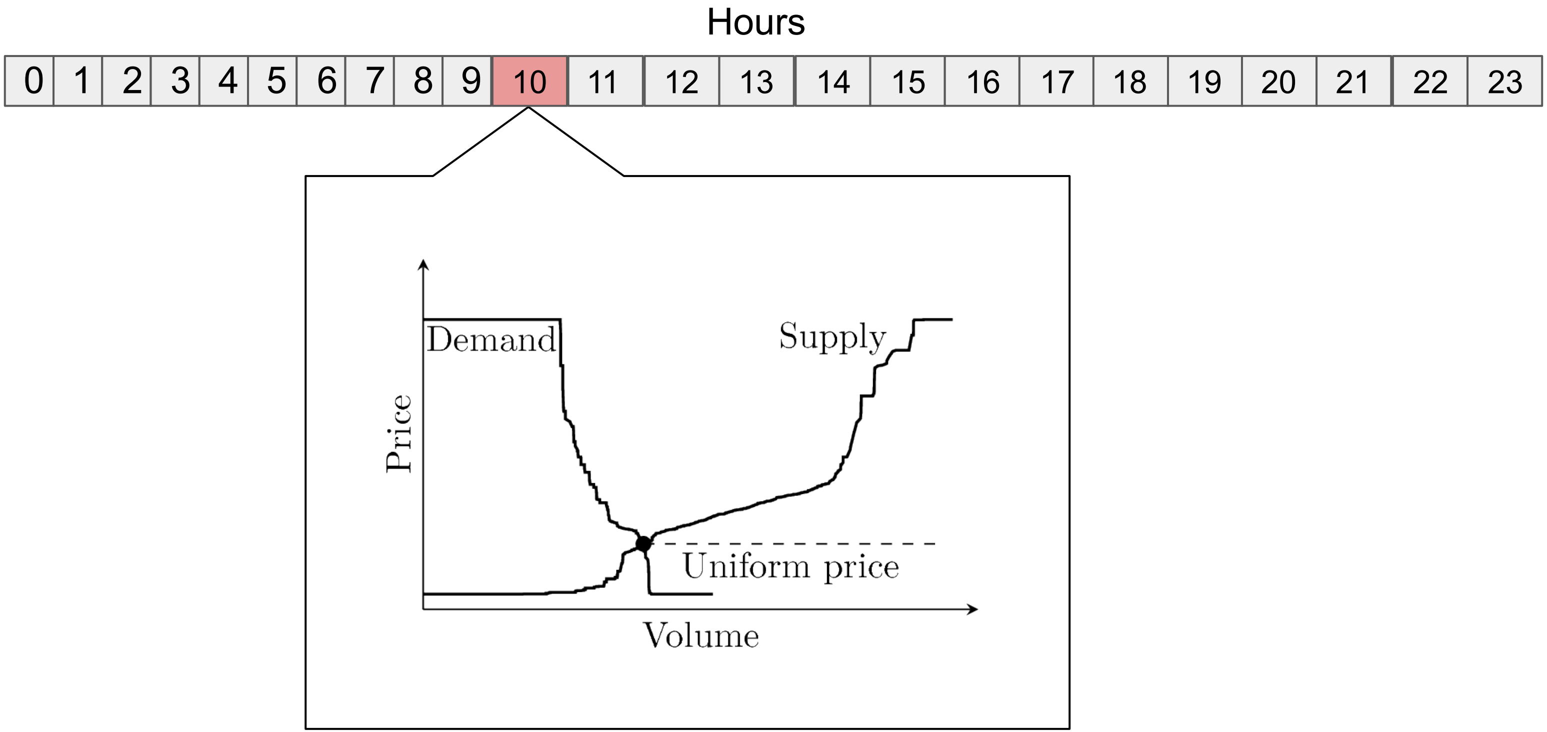
# Day-Ahead Market



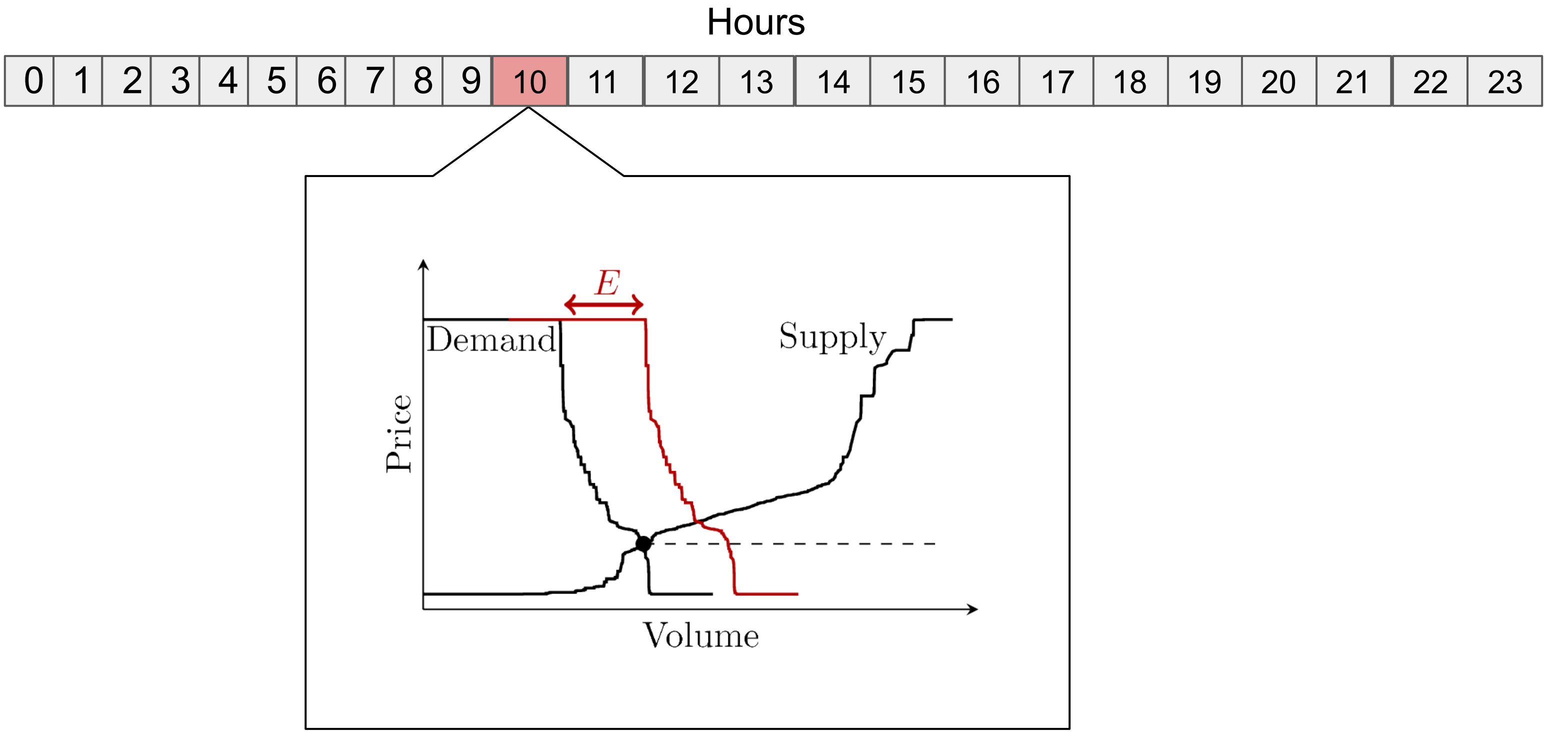
# Day-Ahead Market



# Day-Ahead Market



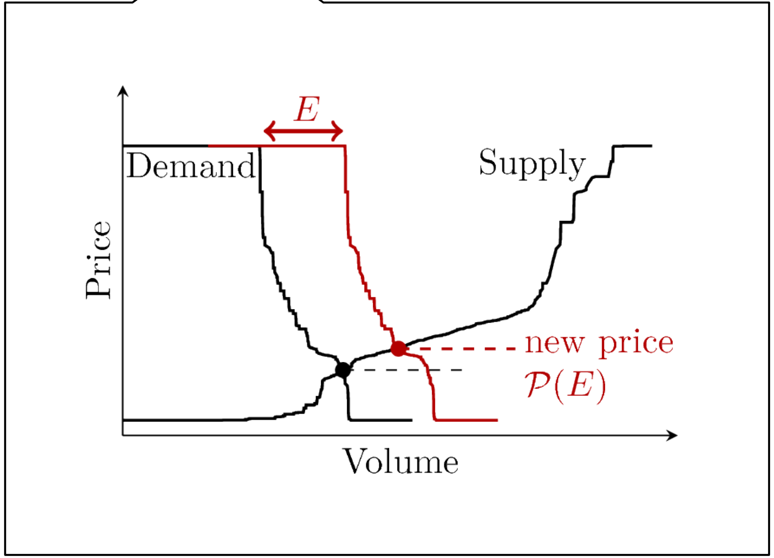
# Day-Ahead Market



# Day-Ahead Market

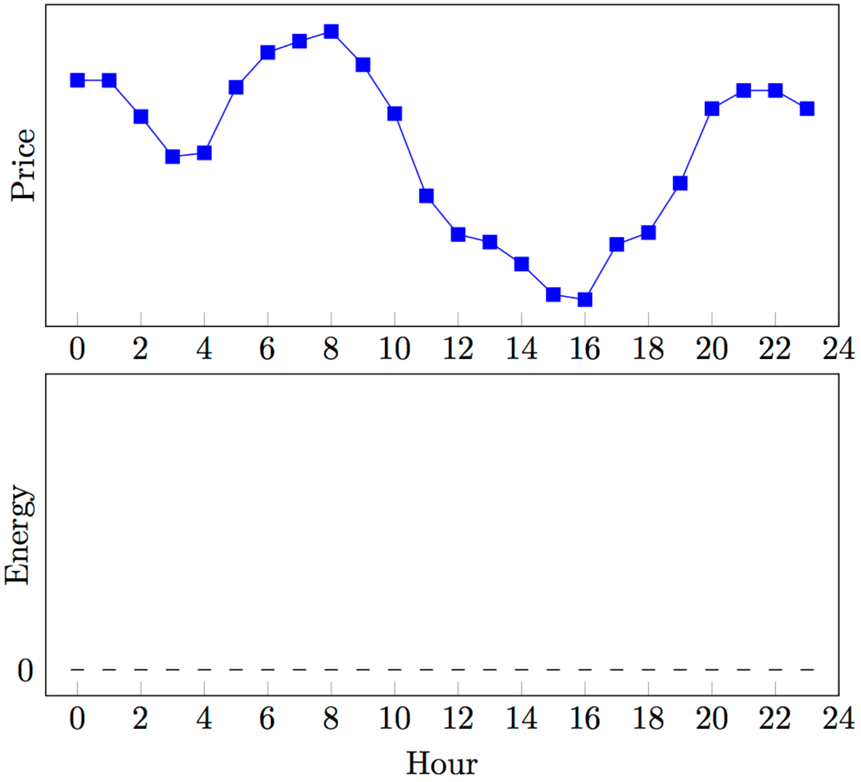
Hours

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

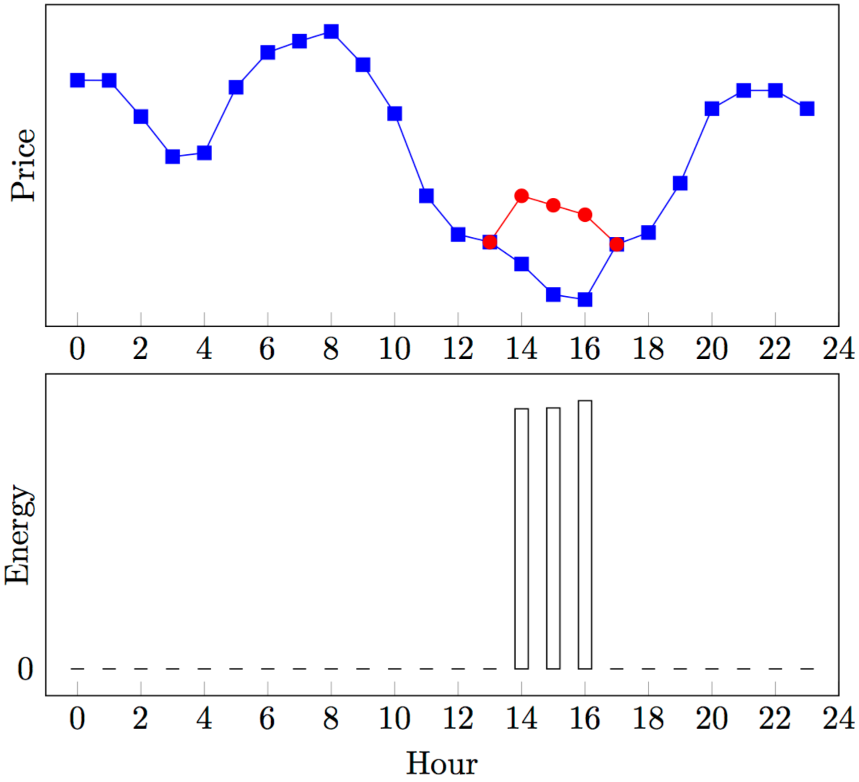



Price impact

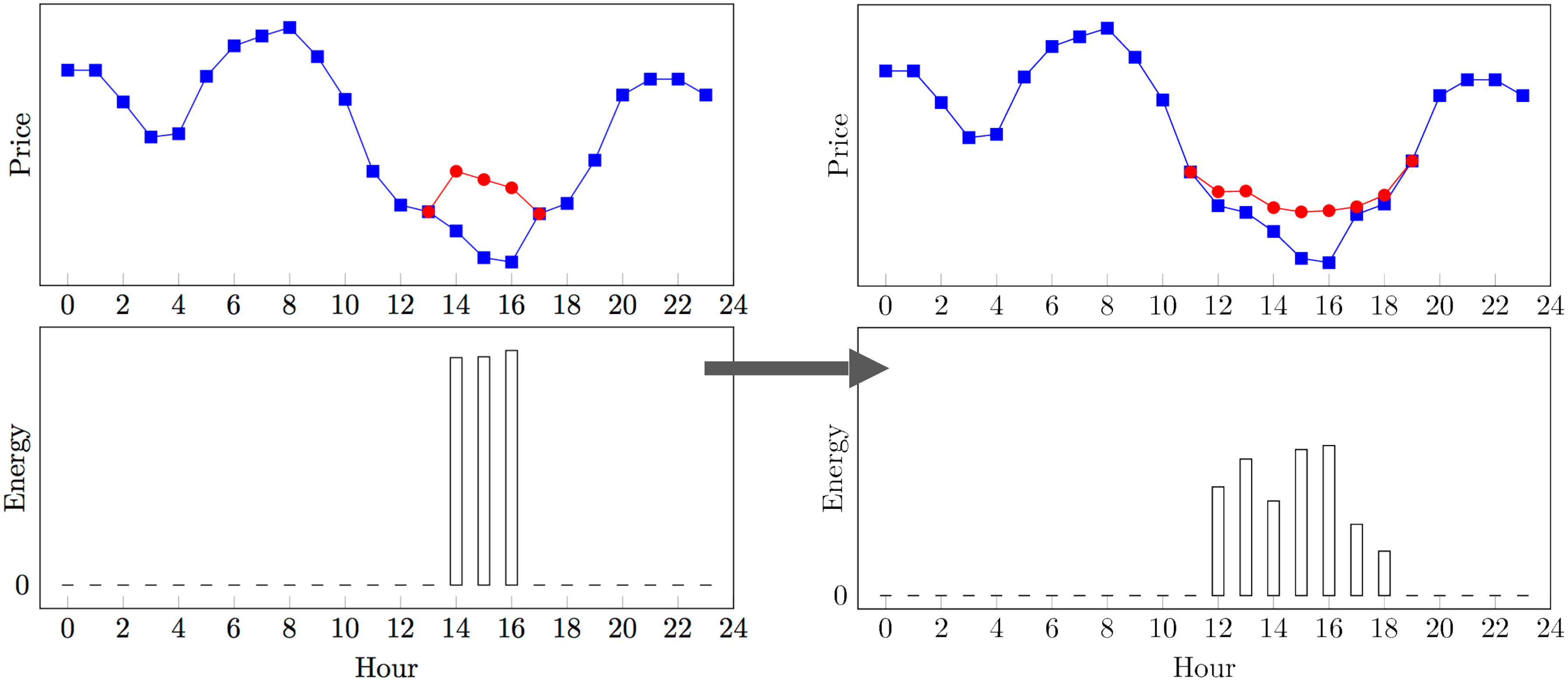
# Day-Ahead Market



# Day-Ahead Market



# Day-Ahead Market



- Day-ahead market
- Individual bidding
- Decentralised joint bidding
- Evaluation
- Conclusions and future work

# Individual optimal bidding

Perez-Diaz *et al.*, Applied Energy, 2018
Perez-Diaz *et al.*, AAMAS 2018

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

# Individual optimal bidding

Perez-Diaz *et al.*, Applied Energy, 2018
Perez-Diaz *et al.*, AAMAS 2018

- Aggregator needs to decide energy allocation: $\boxed{\mathbf{E} = (E_0, \ldots, E_{23})}$
- Forecast:
  - Prices
  - Energy requirements

# Individual optimal bidding

Perez-Diaz *et al.*, Applied Energy, 2018
Perez-Diaz *et al.*, AAMAS 2018

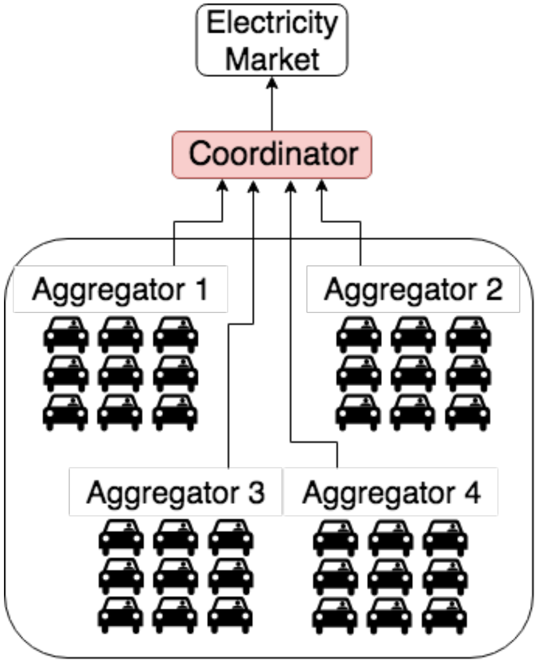
- Aggregator needs to decide energy allocation: $\boxed{\mathbf{E} = (E_0, \ldots, E_{23})}$
- Forecast:
  - Prices
  - Energy requirements
- Find optimal allocation: $$\boxed{\mathbf{E}^* = \arg\ \min_{\mathbf{E}} \overbrace{\sum_{h=0}^{23} \hat{\mathcal{P}}_h(E_h) \cdot E_h}^{\text{total cost}}}$$

… while satisfying energy requirement constraints:

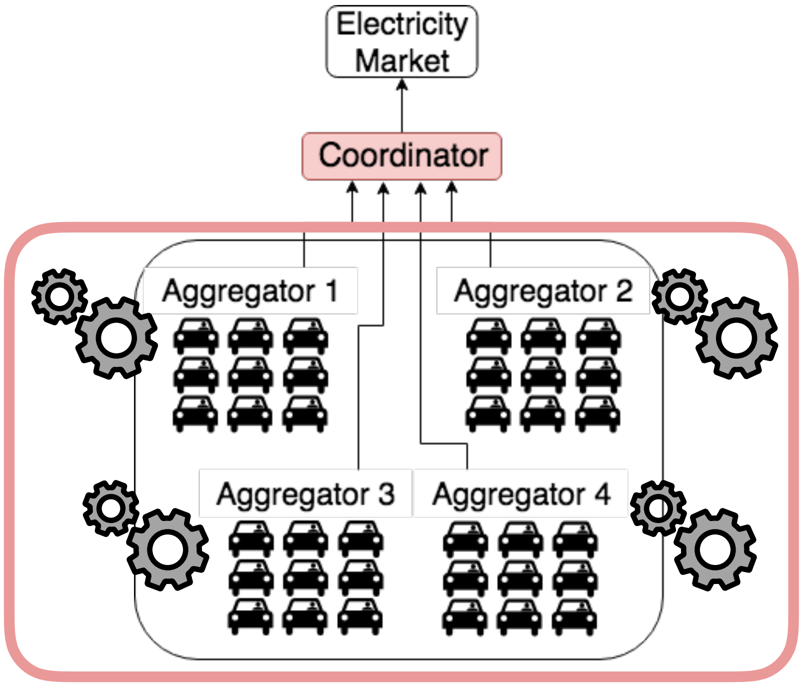
make sure energy is not bought too early or too late

- Day-ahead market
- Individual bidding
- Decentralised joint bidding
- Evaluation
- Conclusions and future work

# Decentralised joint bidding

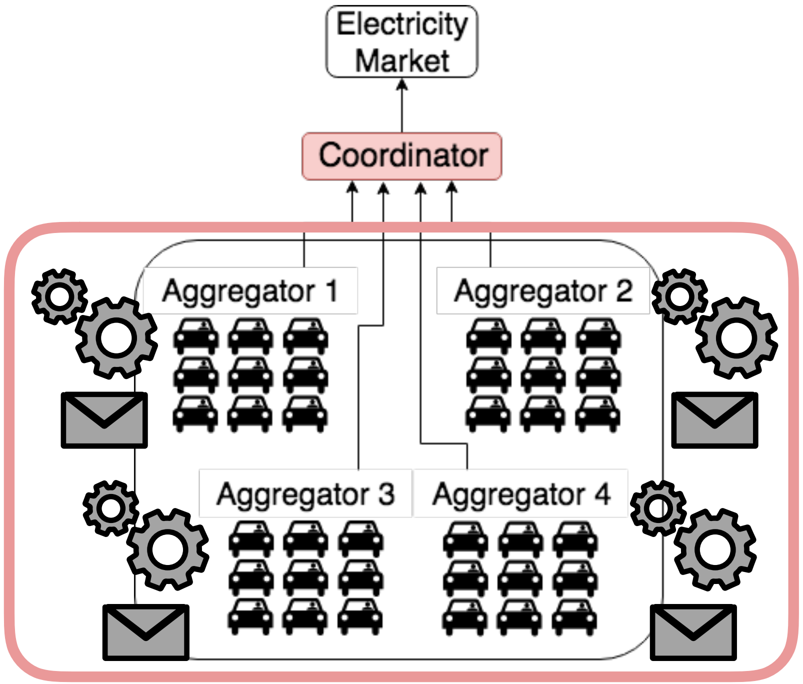


# Decentralised joint bidding




computation: privacy preserving

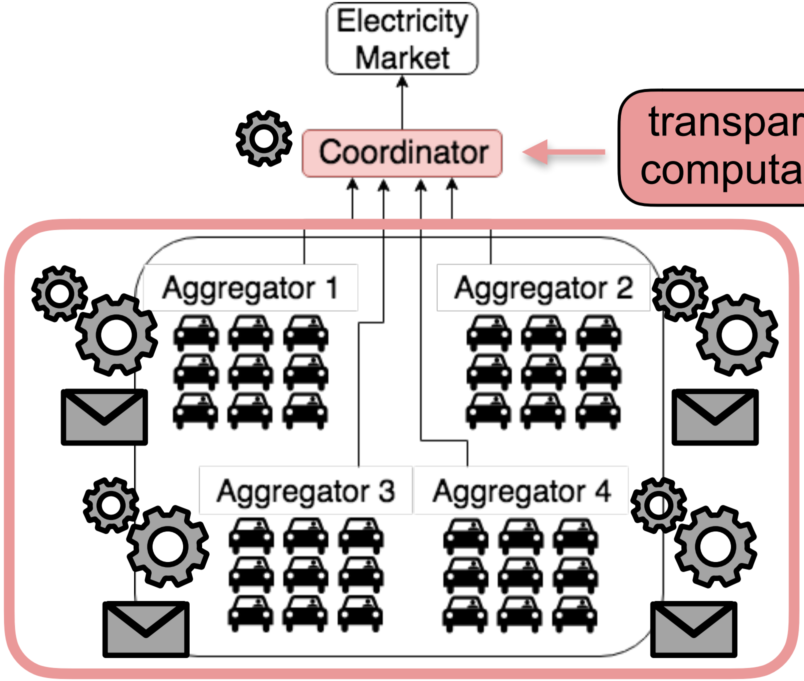
# Decentralised joint bidding




computation: privacy preserving

message the coordinator

# Decentralised joint bidding

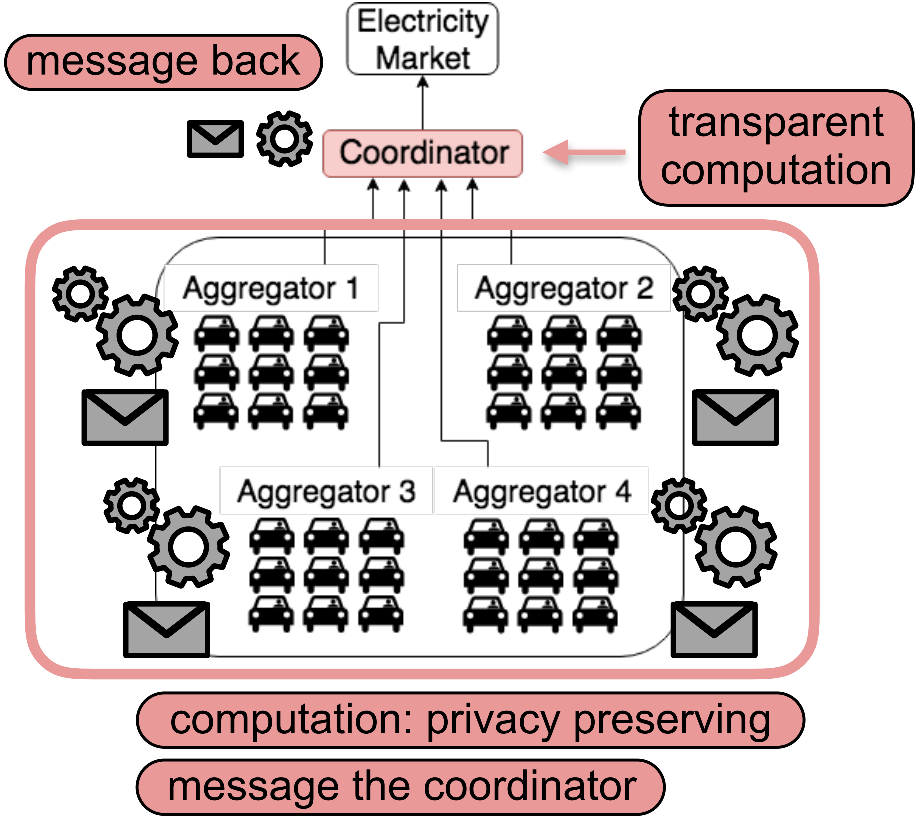



transparent computation

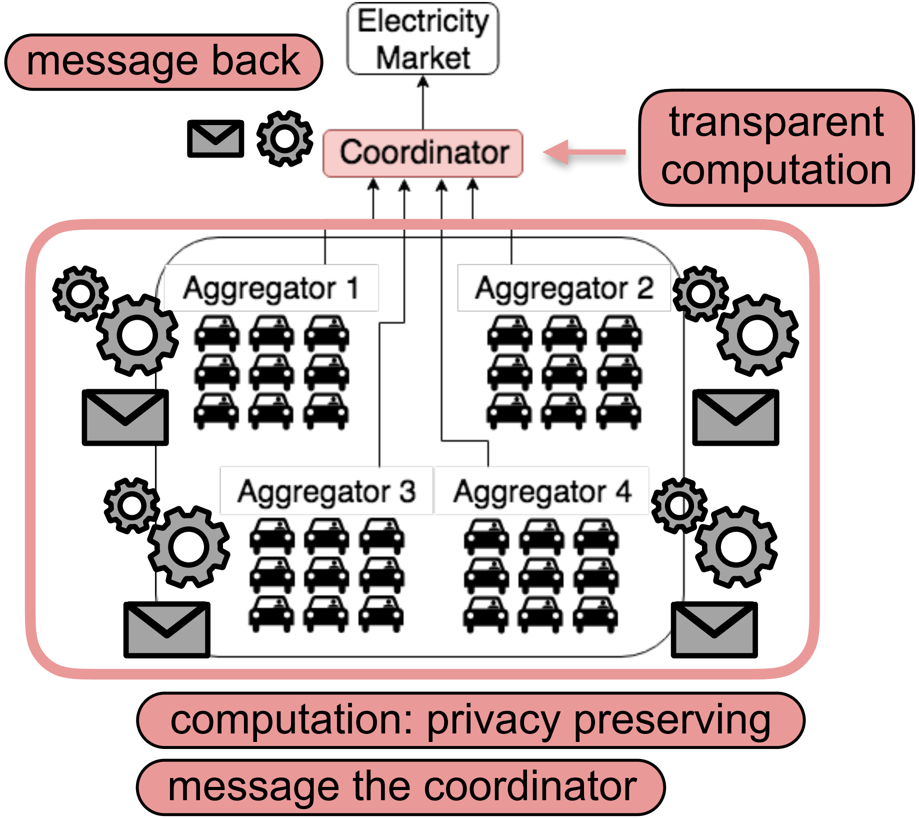
computation: privacy preserving

message the coordinator

# Decentralised joint bidding



# Decentralised joint bidding




**Alternating Direction Method of Multipliers (ADMM)**

- Iterative, decentralised
- Good convergence
- Very popular

(Boyd *et al.*, 2010)

# Decentralised algorithm

- Decision variables: $\vec{E} = \left(\vec{E}_1, \ldots, \vec{E}_N\right)$

24-dimensional vectors:
energy allocation for each aggregator

# Decentralised algorithm

- Decision variables: $\vec{E} = \left(\vec{E}_1, \ldots, \vec{E}_N\right)$

24-dimensional vectors:
energy allocation for each aggregator

- Optimisation problem:

$$\min_{\vec{E}} \mathrm{Cost}(\vec{E})$$

# Decentralised algorithm

24-dimensional vectors:
energy allocation for each aggregator

- Decision variables: $\vec{E} = \left(\vec{E}_1, \ldots, \vec{E}_N\right)$
- Optimisation problem:

$$\min_{\vec{E}} \mathrm{Cost}(\vec{E}) = \min_{\vec{E}} \sum_{i=1}^{N} \mathrm{Cost}_i(\vec{E})$$

Distribute the problem
among $N$ aggregators

# Decentralised algorithm

24-dimensional vectors:
energy allocation for each aggregator

- Decision variables: $\vec{E} = \left(\vec{E}_1, \ldots, \vec{E}_N\right)$

- Optimisation problem:

Variables are not separable

$$\min_{\vec{E}} \mathrm{Cost}(\vec{E}) = \min_{\vec{E}} \sum_{i=1}^{N} \mathrm{Cost}_i(\vec{E})$$

Distribute the problem
among $N$ aggregators

# Decentralised algorithm

24-dimensional vectors:
energy allocation for each aggregator

- Decision variables: $\vec{E} = \left(\vec{E}_1, \ldots, \vec{E}_N\right)$

Variables are not separable

- Optimisation problem:

$$\min_{\vec{E}} \mathrm{Cost}(\vec{E}) = \min_{\vec{E}} \sum_{i=1}^{N} \mathrm{Cost}_i(\vec{E})$$

Distribute the problem
among $N$ aggregators

global variable consensus

Introduce local variables: $\vec{E}^i$

and global variable: $\vec{E}$

$$\text{subject to: } \vec{E}^i - \vec{E} = 0, \; i = 1, \ldots, N$$

# Decentralised algorithm

Iterative algorithm:

1. Each aggregator solves local problem:

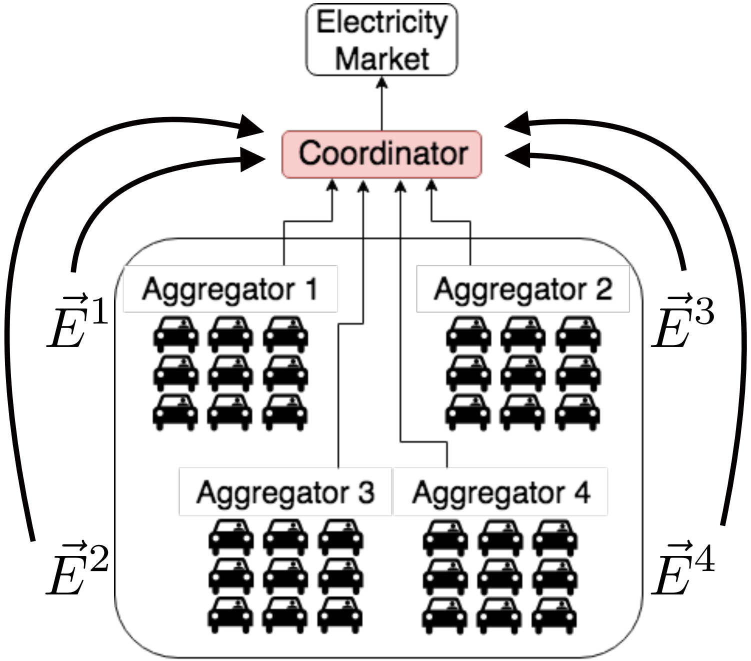
$$\vec{E}^i = \min\left( \boxed{\text{Reduce own cost with personal constraints}} + \rho \boxed{\text{Be close to tentative global solution}} \right)$$

2. Coordinator collects all solutions, averages $\longrightarrow$ tentative global solution
3. Report tentative global solution to all aggregators

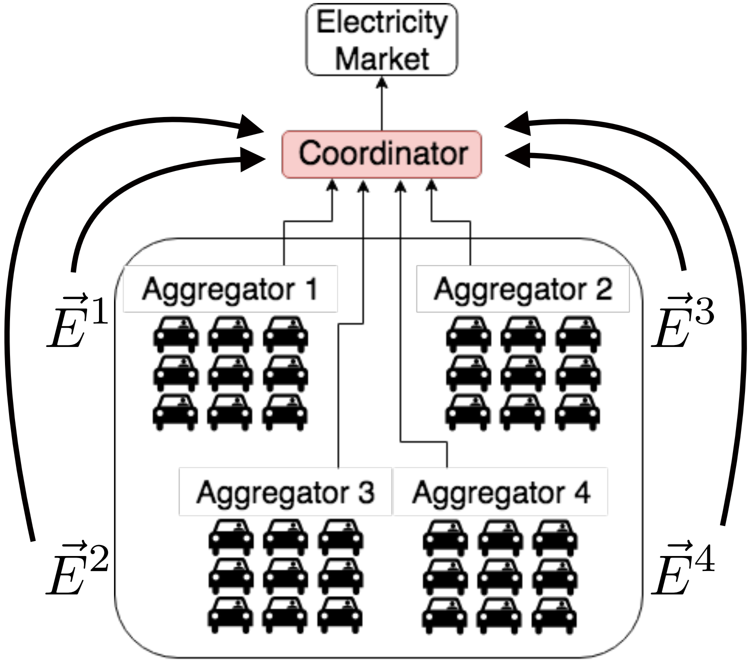
**Theoretical convergence to centralised optimal solution**

(Boyd *et al.*, 2010)

# Coordination step



# Coordination step




Coordinator performs an *average* of the proposed local solutions

↓

very cheap computation

↓

well suited for implementation on blockchain: smart contract

(Baroche *et al.*, 2018)
(Horta *et al.*, 2017)
(Munsing *et al.*, 2017)

↓

transparent, trust-less

Juliette,
PowerLedger,
WePower

- Day-ahead market
- Individual bidding
- Decentralised joint bidding
- Evaluation
- Conclusions and future work

# Empirical evaluation

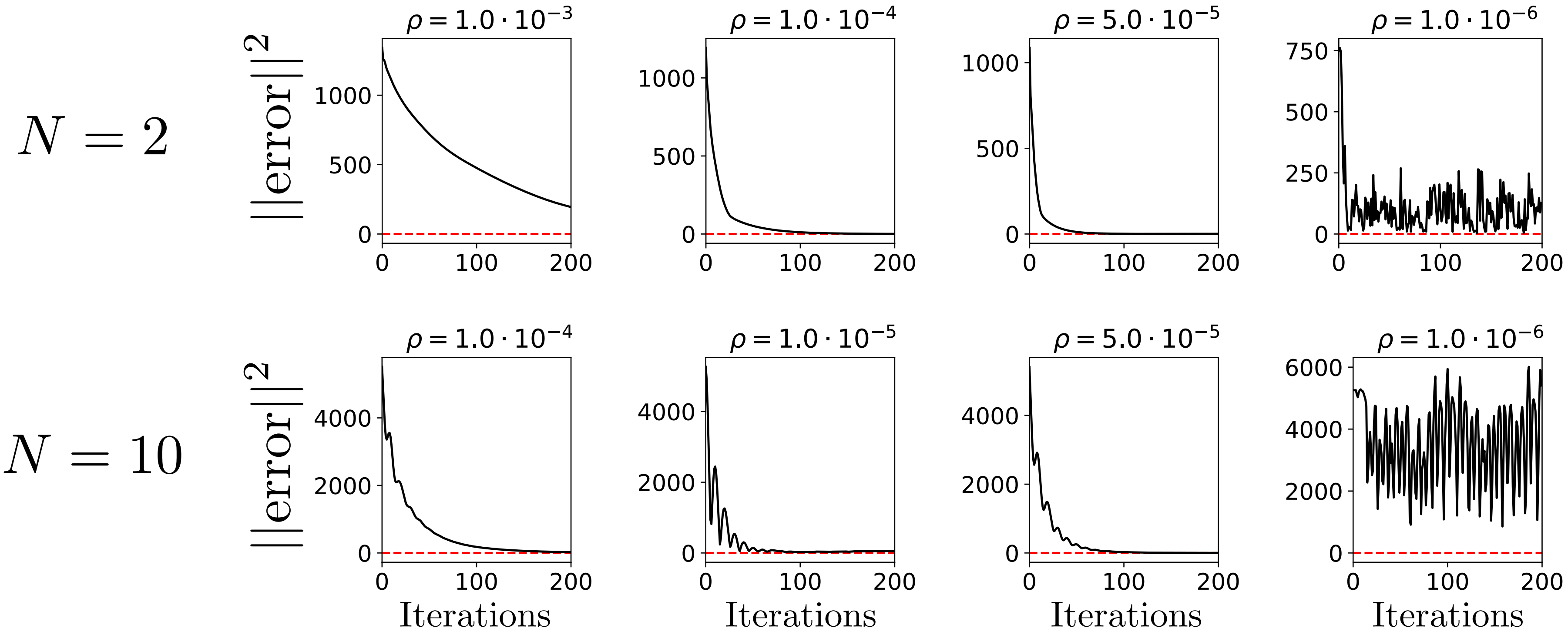
- Night time scenario: EVs arrive in the evening, leave in the morning
- Real market data from Spanish day-ahead market (OMIE)
- Real driver behaviour from survey (MOBILIA)

Goal: study the convergence of the proposed decentralised algorithm

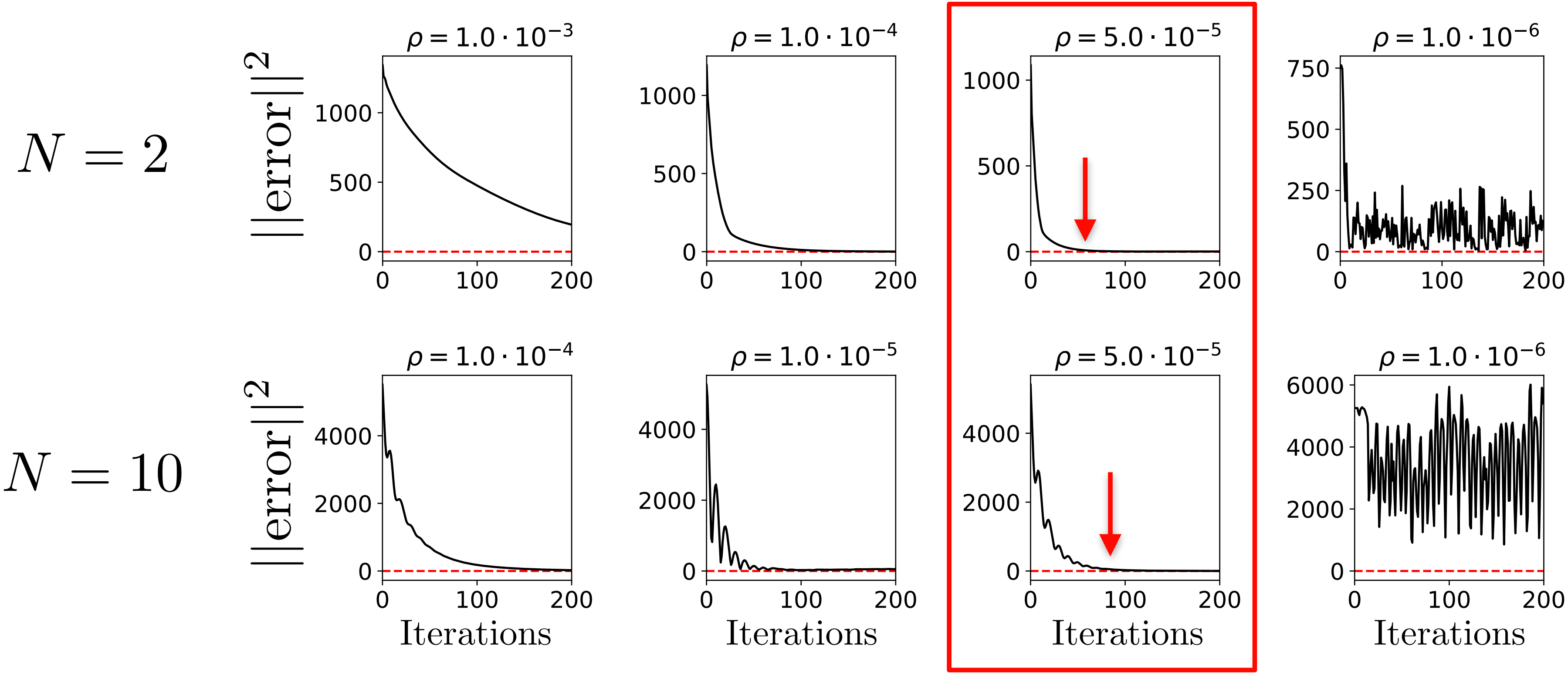
↓

compare with the centralised optimal solution

# Convergence analysis



# Convergence analysis



- Day-ahead market
- Individual bidding
- Decentralised joint bidding
- Evaluation
- Conclusions and future work

# Conclusions

- Novel decentralised coordination algorithm for EV aggregators
- Address privacy and transparency
- Use ADMM and global variable consensus
- Coordination step on blockchain
- Empirical evaluation: convergence, scalability

# Conclusions

- Novel decentralised coordination algorithm for EV aggregators
- Address privacy and transparency
- Use ADMM and global variable consensus
- Coordination step on blockchain
- Empirical evaluation: convergence, scalability

# Future work

- Larger problem sizes
- Blockchain implementation
- Study strategic manipulation

# Conclusions

- Novel decentralised coordination algorithm for EV aggregators
- Address privacy and transparency
- Use ADMM and global variable consensus
- Coordination step on blockchain
- Empirical evaluation: convergence, scalability

# Future work

- Larger problem sizes
- Blockchain implementation
- Study strategic manipulation

Thanks!

# Related work: multi-aggregator

- Hierarchical charging: (Qi et al., 2013), (Shao et al., 2016)
  - High level coordinator
  - Aggregators cooperate
- 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.*, Applied Energy, 2018)
  - Derive optimisation, redistribution and VGC payments
  - No theoretical truthfulness
  - Very large numbers of aggregators and EVs
- Coop game theory: (Perez-Diaz *et al.*, AAMAS 2018)
  - Coalitional game
  - Very large numbers of aggregators and EVs

# Centralised Optimisation Algorithm

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

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

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

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

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

# Decentralised Optimisation Algorithm

$$\vec{E}^{(i)}_{[k+1]} = \arg\min_{\vec{E}'} \left( f_i(\vec{E}') + \vec{\xi}^{(i),T}_{[k]} \left( \vec{E}' - \vec{E}_{[k]} \right) + \frac{\rho}{2} ||\vec{E}' - \vec{E}_{[k]}||^2_2 \right)$$

$$\vec{E}_{[k+1]} = \frac{1}{n} \sum_{i=1}^{n} \left( \vec{E}^{(i)}_{[k+1]} + \frac{1}{\rho} \vec{\xi}^{(i)}_{[k]} \right)$$

$$\vec{\xi}^{(i)}_{[k+1]} = \vec{\xi}^{(i)}_{[k]} + \rho \left( \vec{E}^{(i)}_{[k+1]} - \vec{E}_{[k+1]} \right)$$

$$f_i\left(\vec{E}^{(i)}\right) = \begin{cases} \sum_{t=0}^{23} \left[ E_t^{(i),i} \cdot \hat{\mathcal{P}}_t \left( \sum_{j=1}^{n} E_t^{(i),j} \right) \right], & \text{if local } i \text{ constraints are met by } \vec{E}^{(i),i} \\ \infty, & \text{otherwise} \end{cases}$$