Algorithmic Game Theory applications: Electricity Markets

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Structure

- Electricity markets
- Dual variables as prices
- Problems with incentive compatibility
- High RES penetration and new markets
- An application of VCG
- Research threads
- Capacity mechanisms

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Electricity as a commodity

- Auction framework

Items: Electricity Demand
Players: Generators
Objective: Maximize SW → serve demand at the minimum generation cost

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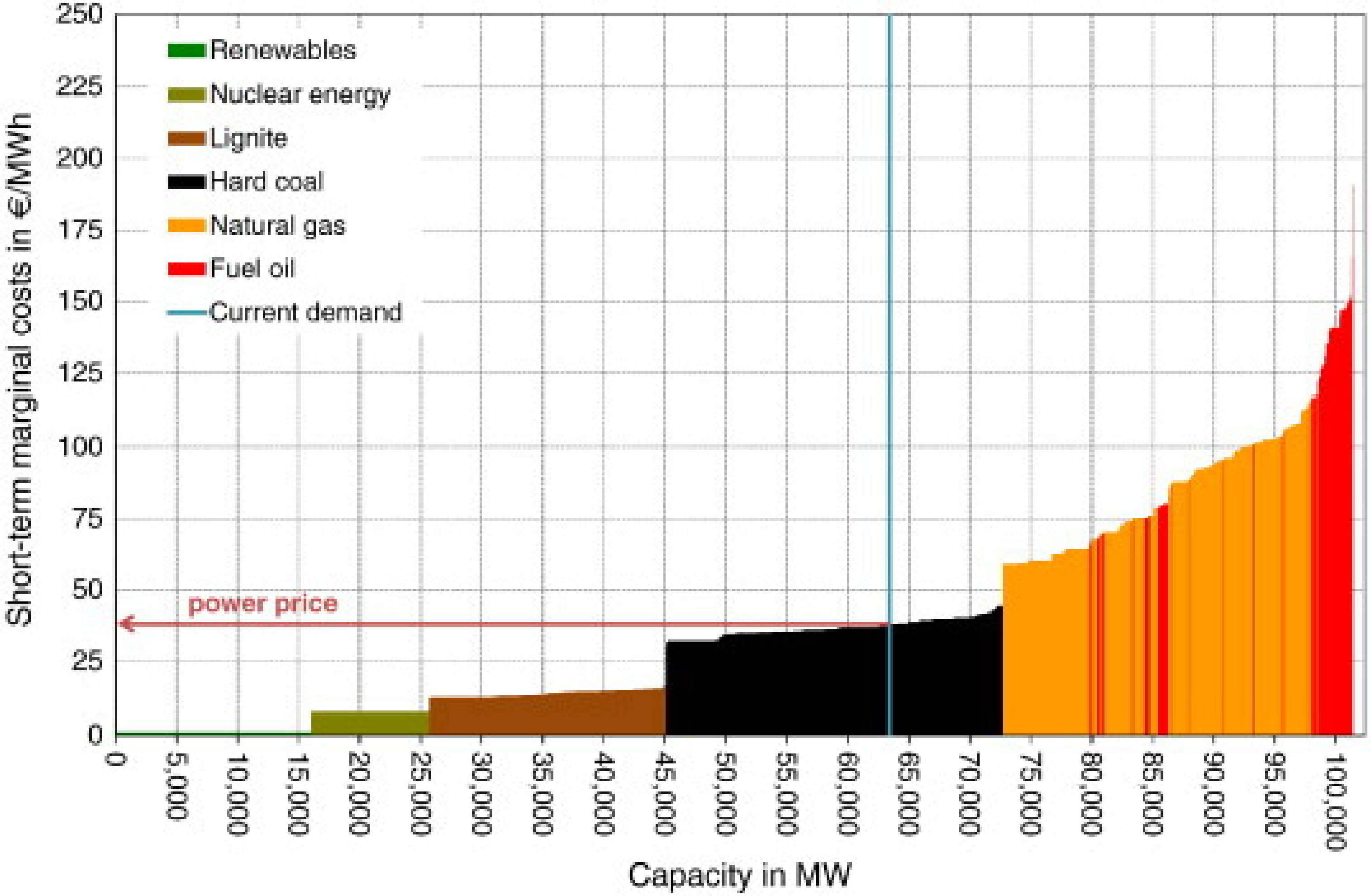
Supply-Demand Equilibrium

- Merit order list



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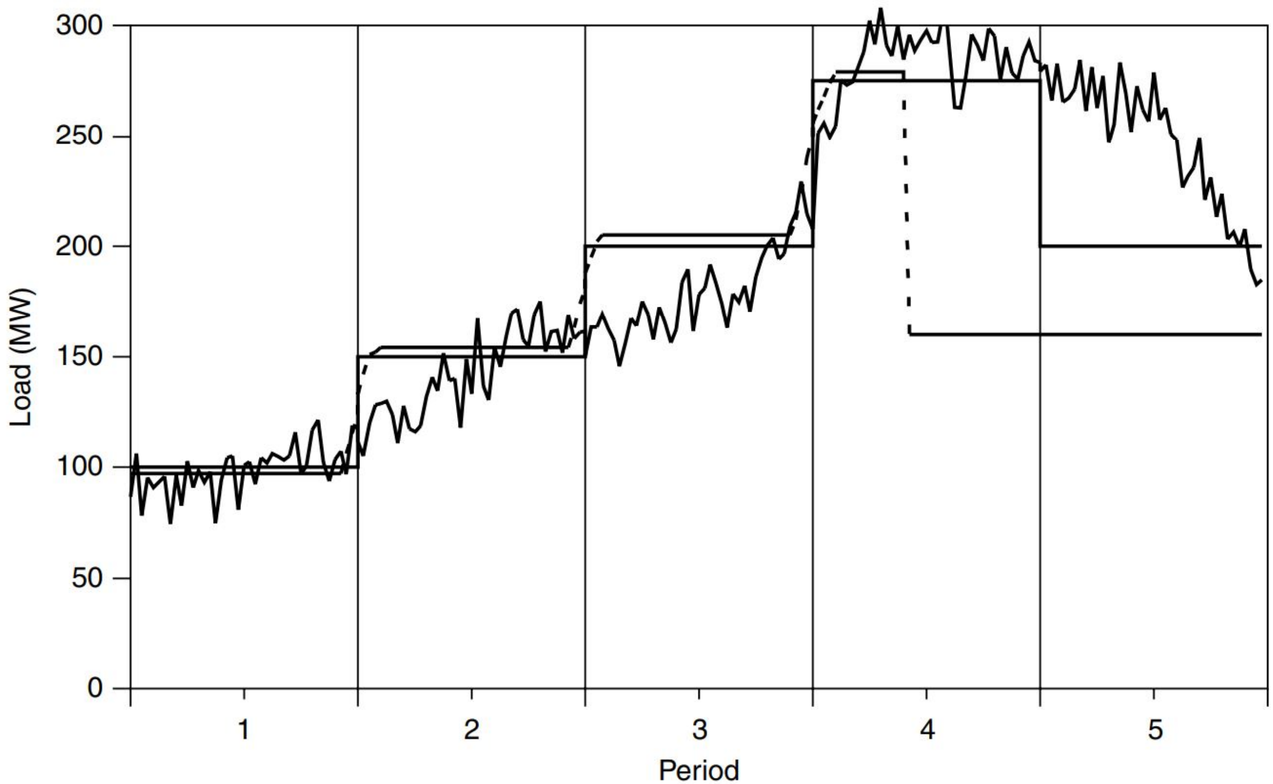
Specialties of electricity

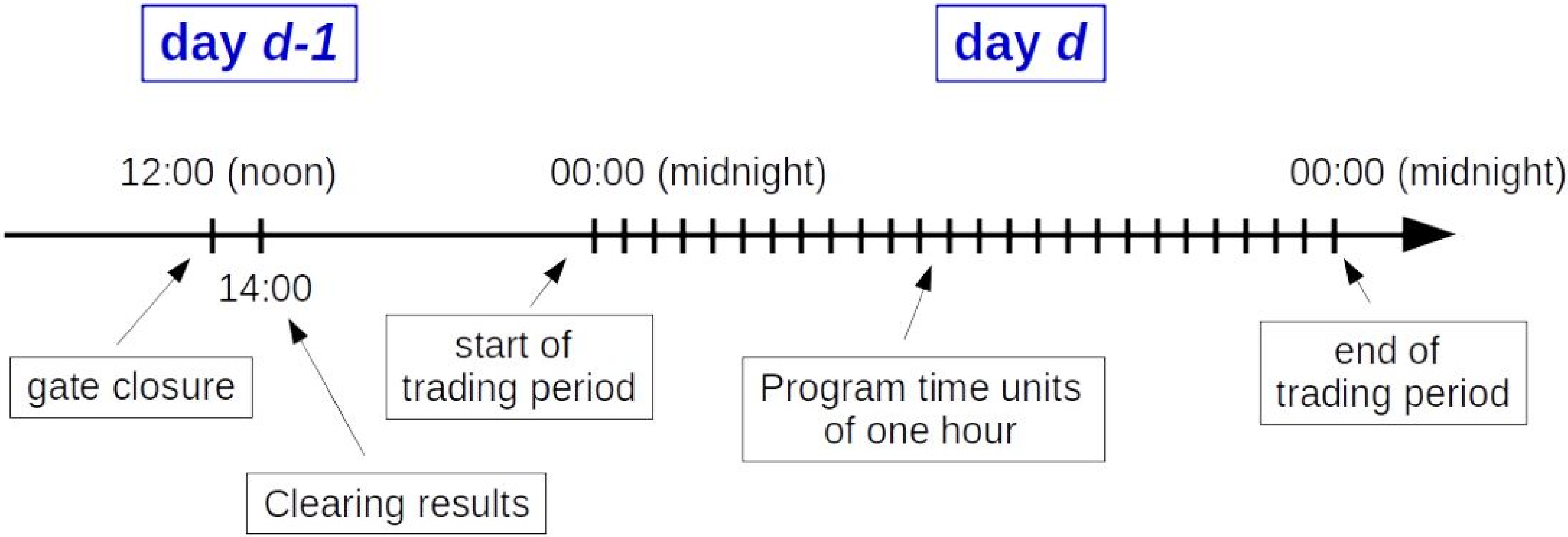
- Generation and Consumption must be balanced in real-time
- Cannot be stored economically
- Operates on a physical network

Security of supply

- Demand forecasts on different timescales
  - capacity mechanisms
  - day-ahead energy market
  - balancing market and ancillary services



The day-ahead market



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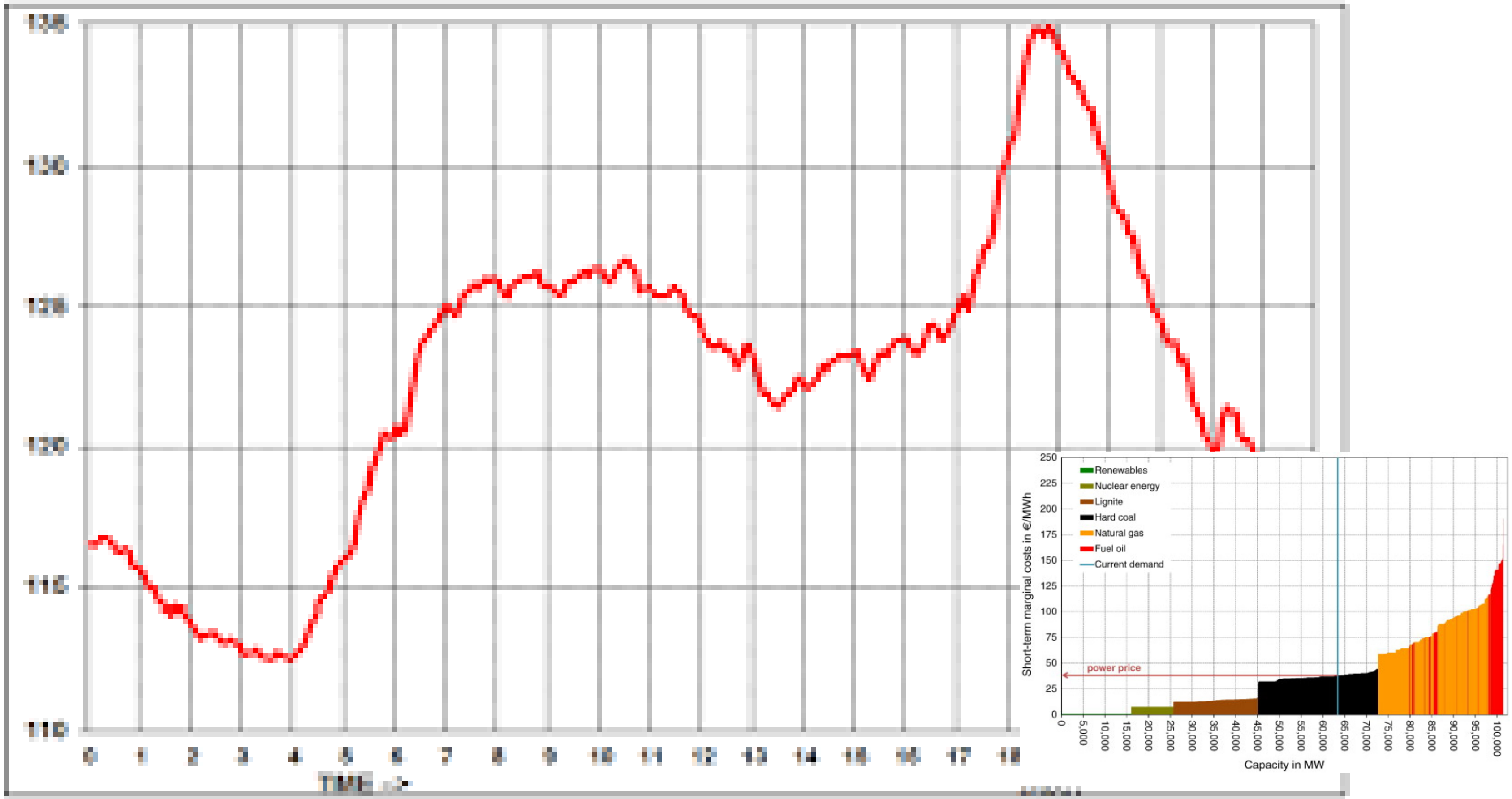

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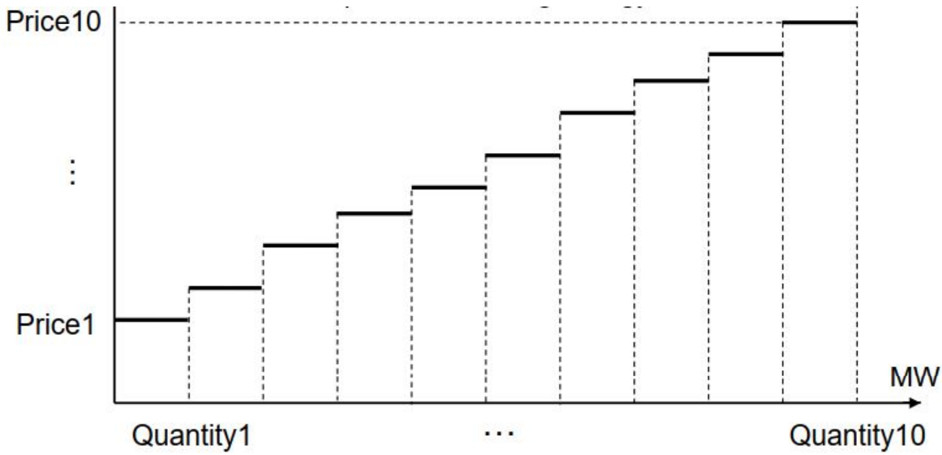
Bids/Offers

Inputs:

- All offers in the market are formulated in terms of a *quantity* P and a *price* λ
- On the *supply* side (N_G supply offers):
  - set of offers: $\mathcal{L}_G = \{G_j,\ j = 1, \ldots, N_G\}$
  - maximum quantity for offer G_j: P_j^G
  - price for offer G_j: λ_j^G
- On the *demand* side (N_D demand offers):
  - set of offers: $\mathcal{L}_D = \{D_i,\ i = 1, \ldots, N_D\}$
  - maximum quantity for offer D_i: P_i^D
  - price for offer D_i: λ_i^D

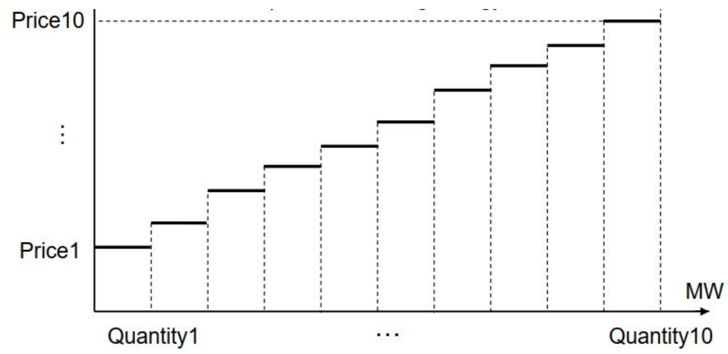


Optimal Bidding Problem: Approximate the Actual Costs

Decision variables:

- *Generation* schedule: $\mathbf{y}^G = [y_j^G, \ldots, y_{N_G}^G]^\top$, $0 \leq y_j^G \leq P_j^G$
- *Consumption* schedule: $\mathbf{y}^D = [y_1^D, \ldots, y_{N_D}^D]^\top$, $0 \leq y_i^D \leq P_i^D$

SW optimization



$$\max_{\mathbf{y}^G,\mathbf{y}^D} \quad \sum_{i=1}^{N_D} \lambda_i^D y_i^D - \sum_{j=1}^{N_G} \lambda_j^G y_j^G$$

$$\text{subject to} \quad \sum_{j=1}^{N_G} y_j^G - \sum_{i=1}^{N_D} y_i^D = 0$$

$$0 \leq y_i^D \leq P_i^D, \; i = 1, \ldots, N_D$$

$$0 \leq y_j^G \leq P_j^G, \; j = 1, \ldots, N_G$$

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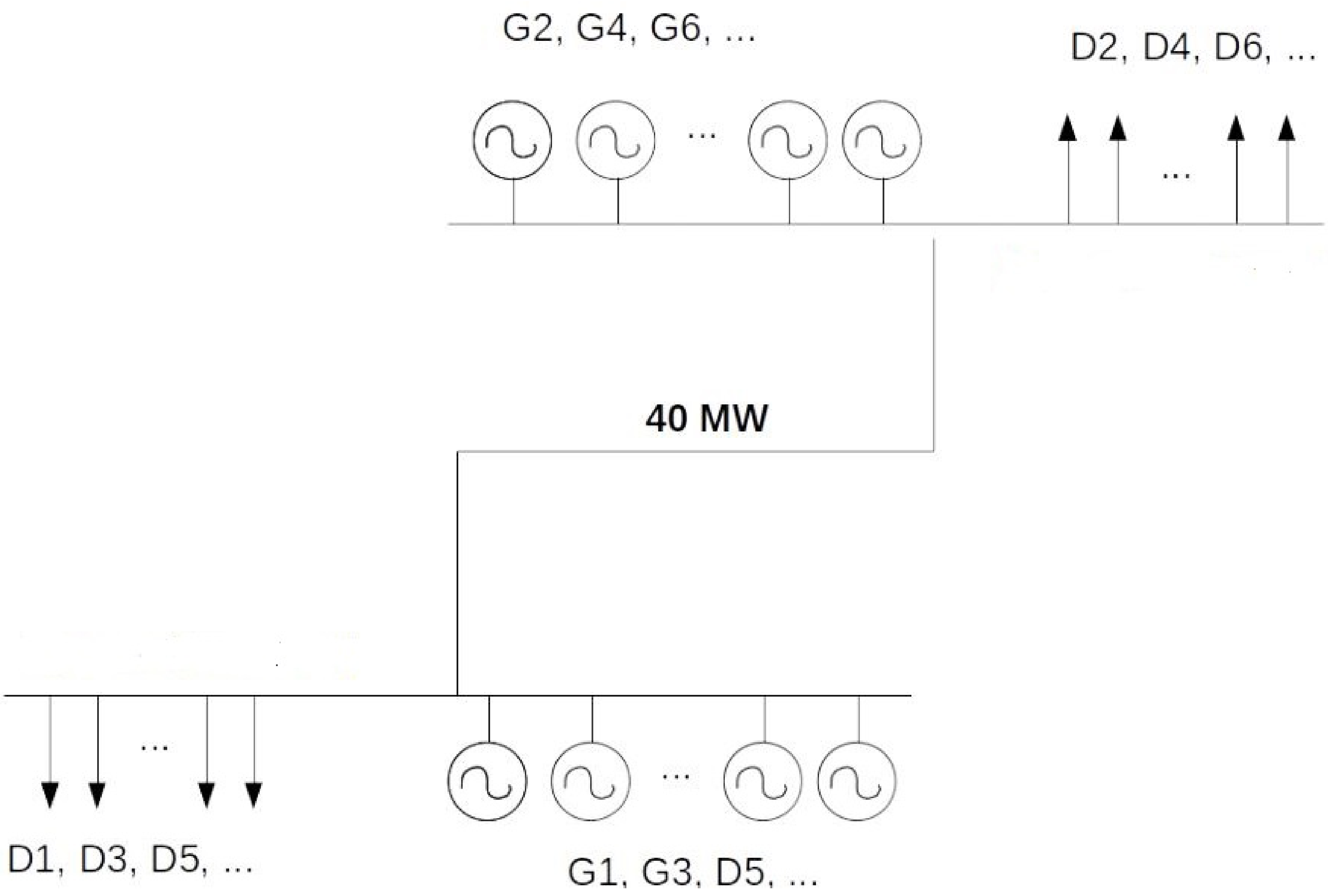
Line capacities and zones



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Nodal prices

$$\max_{\{y_i^D\},\{y_i^G\}} \quad \sum_i \lambda_i^D y_i^D - \sum_j \lambda_j^G y_j^G$$

subject to

$$\sum_i y_i^{D,West} - \sum_j y_j^{G,West} = B\Delta\delta \ : \ \lambda^{S,West}$$

$$\sum_i y_i^{D,East} - \sum_j y_j^{G,East} = -B\Delta\delta \ : \ \lambda^{S,East}$$

$$0 \le y_i^D \le P_i^D, \ i = 1, \ldots, N_D$$

$$0 \le y_j^G \le P_j^G, \ j = 1, \ldots, N_G$$

$$-40 \le B\Delta\delta \le 40$$

B is the absolute value of susceptance (physical constant) of the interconnection

$\Delta\delta$ is the difference of voltage angles between the 2 buses

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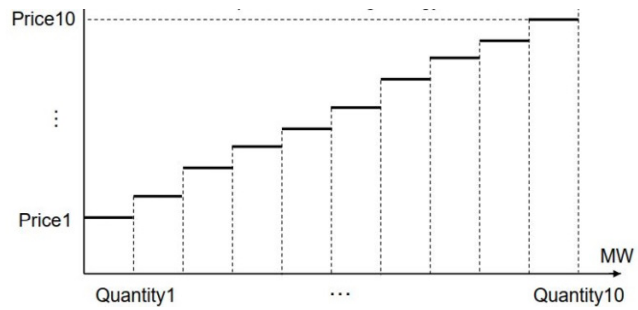
Price Manipulation



Optimal Bidding Problem:
Approximate the Actual Costs

- Why not VCG?
  - Price signals
  - Collusion
  - …
  - <u>Not</u> necessarily incentive compatible

- Market monitoring
- Promote market liberalization so that, hopefully, the market gets closer to perfect competition

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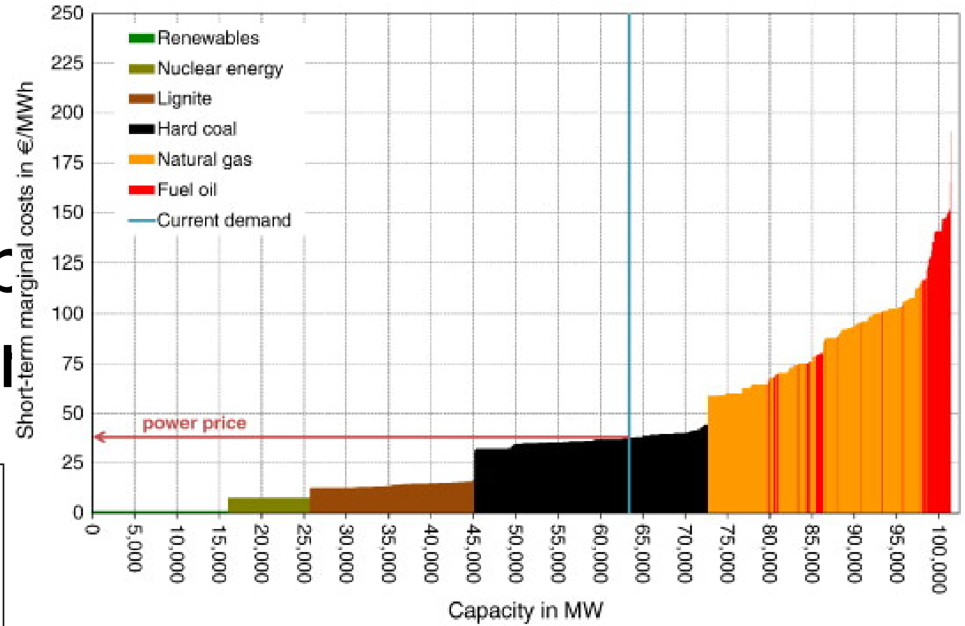
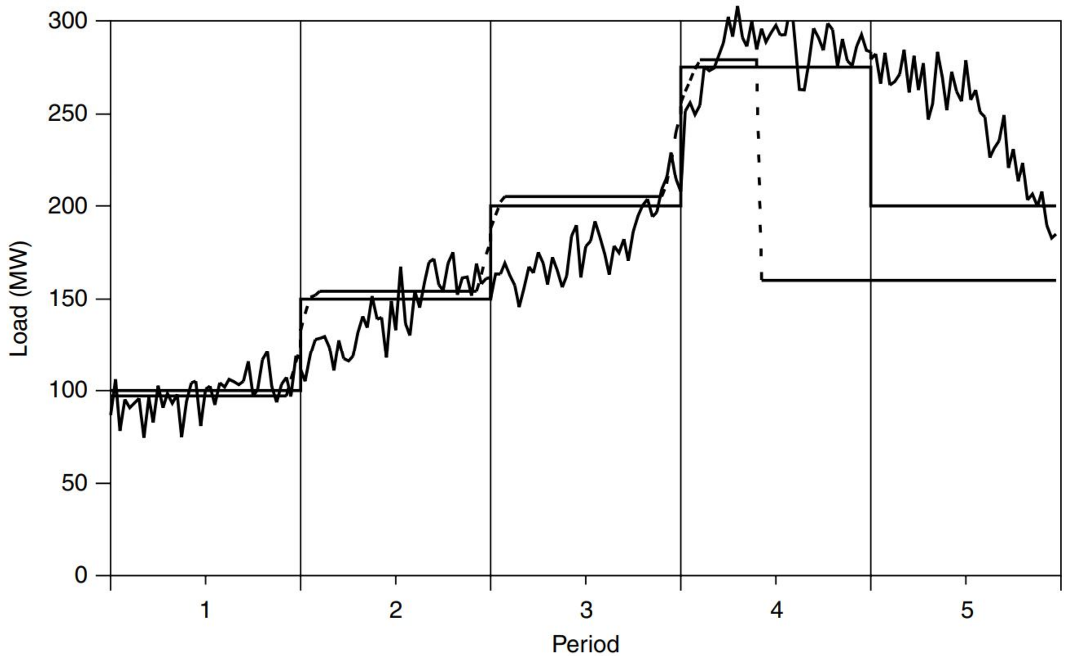
Strategic behavior

- Strategic behavior across markets (day-ahead and balancing)
- Activity rules
- Difficult to distinguish b
behavior and actual unin





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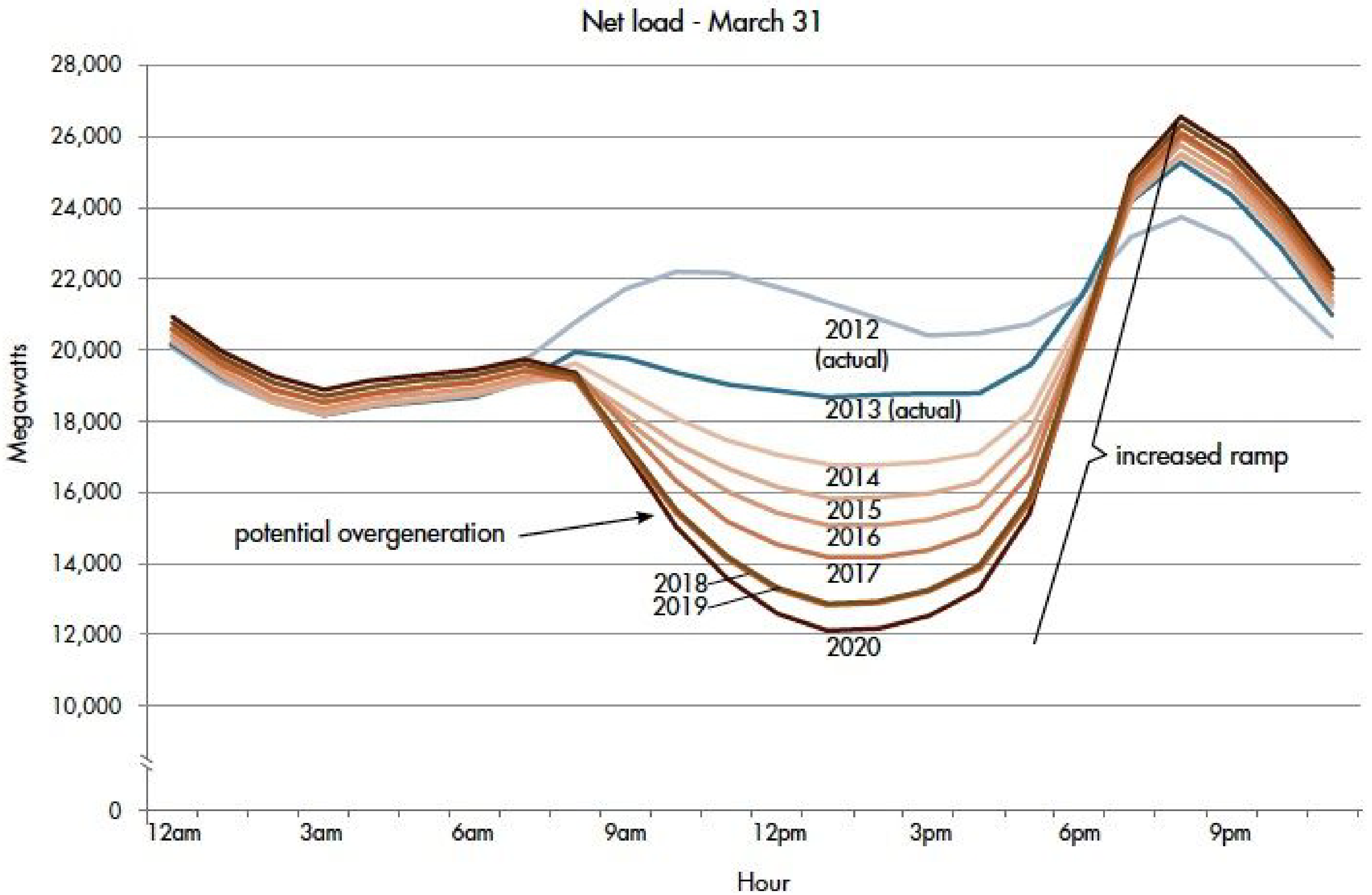
High RES penetration



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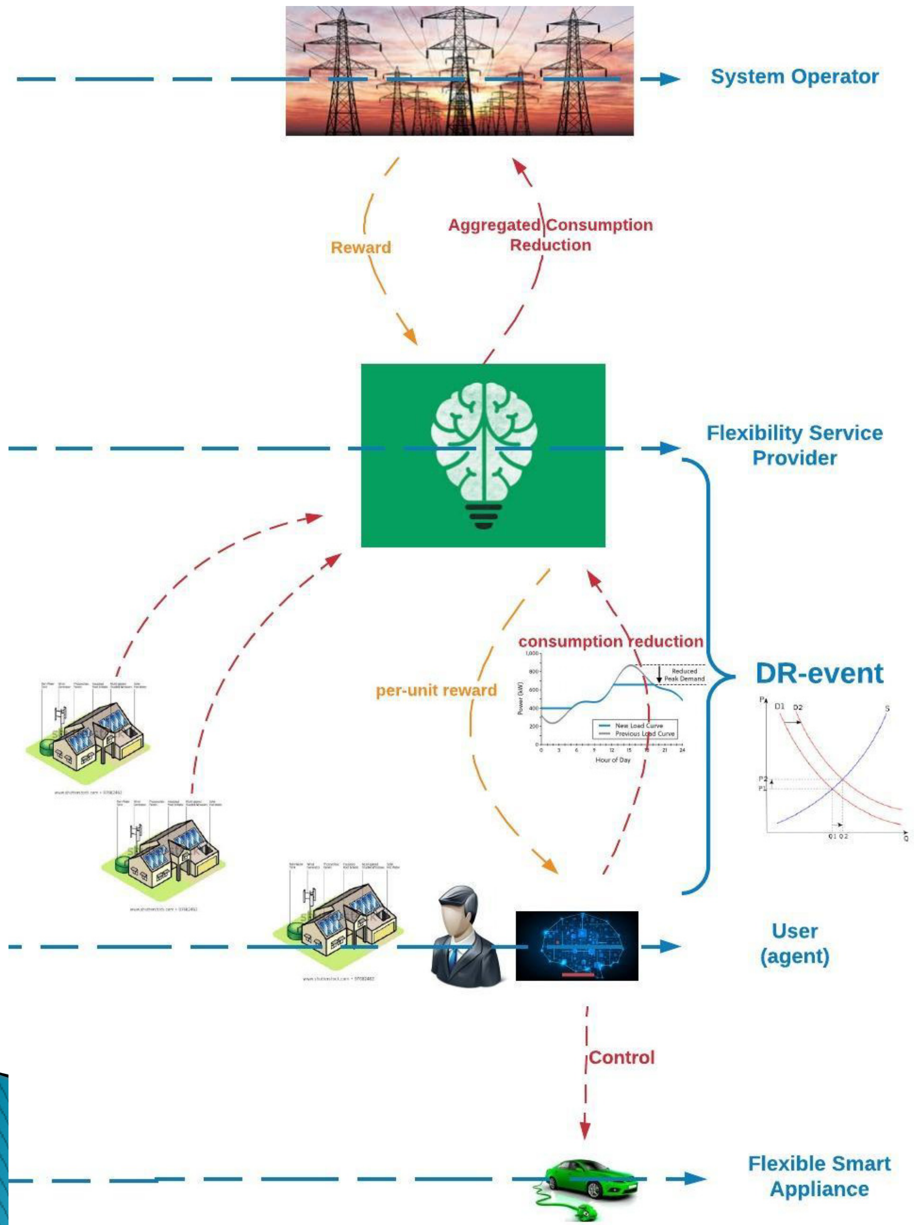
Demand Side Flexibility



- Focus on demand flexibility
- Smart meters, flexible assets (electric vehicles, storage, smart devices)
- Too many variables --> Aggregation
- Flexibility markets

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Intelligent agents and valuation functions

$$C_j^t = C_j^{t-1} + ins_j(C_{env}^t - C_j^{t-1}) + con_j x_j^{t-1}$$

$$U(x, \omega) =$$

$$\begin{cases} 0, & \left|C_j^t - C_{j,sp}^t\right| \leq tol_j \\ \sum_{t \in [arr_i, dep_i]} \omega_j \cdot \left(C_j^t - C_{j,sp}^t\right)^2, & \left|C_j^t - C_{j,sp}^t\right| > tol_j \end{cases}$$

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Research issues

- Market design

$$\max_{\{y_i^D\},\{y_i^G\}} \quad \sum_i \lambda_i^D y_i^D - \sum_j \lambda_j^G y_j^G$$

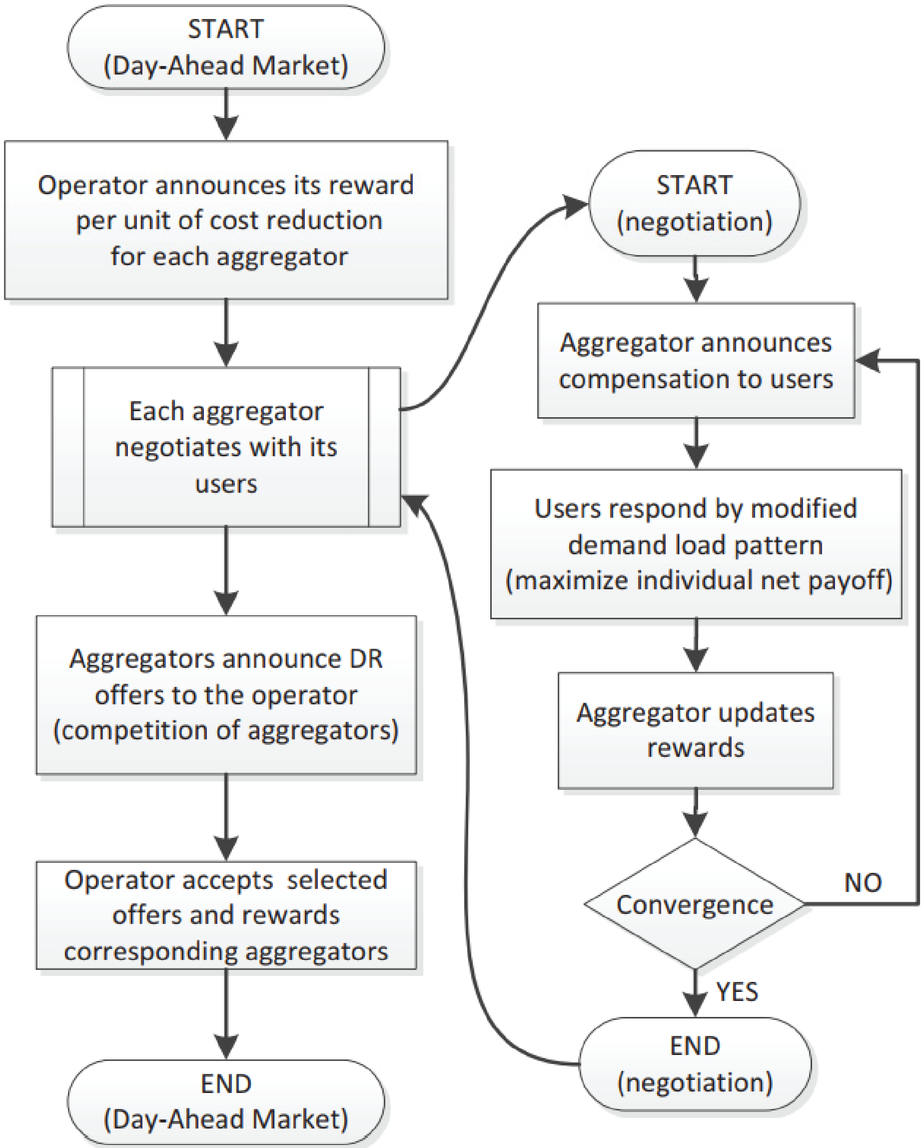
$$\text{subject to} \quad \sum_i y_i^{D,West} - \sum_j y_j^{G,West} = B\Delta\delta \ : \ \lambda^{S,West}$$

$$\sum_i y_i^{D,East} - \sum_j y_j^{G,East} = -B\Delta\delta \ : \ \lambda^{S,East}$$

$$0 \le y_i^D \le P_i^D, \ i = 1, \dots, N_D$$

$$0 \le y_j^G \le P_j^G, \ j = 1, \dots, N_G$$

$$-40 \le B\Delta\delta \le 40$$



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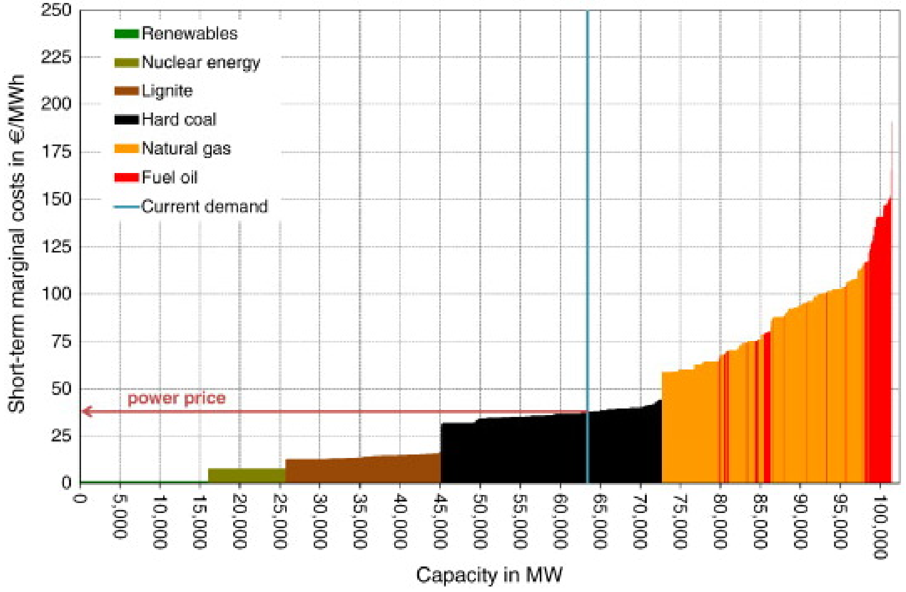
An application of VCG to DR



$$C_k(L_k) = a_k L_k^2 + b_k L_k + c_k,$$

$$U(x,\omega) = \begin{cases} 0, & \left|C_j^t - C_{j,sp}^t\right| \leq tol_j \\ \sum_{t\in[arr_i, dep_i]} \omega_j \cdot \left(C_j^t - C_{j,sp}^t\right)^2, & \left|C_j^t - C_{j,sp}^t\right| > tol_j \end{cases}$$

Objective

$$\underset{\mathbf{x}_n \in \mathcal{X}_n,\, n \in \mathcal{N}}{\text{maximize}} \sum_{n \in \mathcal{N}} U_n\left(\sum_{k \in \mathcal{K}} x_n^k\right) - \sum_{k \in \mathcal{K}} C_k\left(\sum_{n \in \mathcal{N}} x_n^k\right)$$

- Players: Registered users in set $\mathcal{N}$.
- Strategies: Each user $n \in \mathcal{N}$ selects its energy consumption level $\mathbf{x}_n \in \mathcal{X}_n$ to maximize its payoff.
- Payoffs: $Q_n(\mathbf{x}_n; \mathbf{x}_{-n})$ for each user $n \in \mathcal{N}$ as in (13).

$$Q_n(\mathbf{x}_n; \mathbf{x}_{-n}) = U_n\left(\sum_{k \in \mathcal{K}} x_n^k\right) - \sum_{k \in \mathcal{K}} x_n^k p_k\left(\sum_{m \in \mathcal{N}} x_m^k\right). \tag{13}$$

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VCG payments

$$t_n(\hat{\mathbf{I}}) = -\left(\sum_{m\in\mathcal{N}_{-n}} \hat{U}_m\left(\sum_{k\in\mathcal{K}} x_m^k(\hat{\mathbf{I}})\right) - \sum_{k\in\mathcal{K}} C_k\left(\sum_{m\in\mathcal{N}} x_m^k(\hat{\mathbf{I}})\right)\right)$$
$$+\left(\sum_{m\in\mathcal{N}_{-n}} \hat{U}_m\left(\sum_{k\in\mathcal{K}} x_m^k(\hat{\mathbf{I}}_{-n})\right) - \sum_{k\in\mathcal{K}} C_k\left(\sum_{m\in\mathcal{N}_{-n}} x_m^k(\hat{\mathbf{I}}_{-n})\right)\right).$$

Research issues

- Incentive compatibility (intelligent agents)
- Uncertainty
- Scalability
- Privacy
- Fairness (e.g. max–min)

G. Tsaousoglou, K. Steriotis, N. Efthymiopoulos, P. Makris, and E. Var-varigos, “Truthful, practical and privacy-aware demand response in thesmart grid via a distributed and optimal mechanism,”IEEE Transactionson Smart Grid, pp. 1–1, 2020

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Capacity Mechanisms

Main types of capacity mechanisms employed in the EU

Strategic reserve: A central agency (transmission system operator or government agency) decides upon the amount of capacity needed a few years in advance and contracts capacity – a strategic reserve – usually through a competitive tender. The contracted power plants cannot participate in the electricity market and are only activated in case of capacity shortfalls, according to pre-determined criteria. Strategic reserves are used in Belgium, Germany, Poland and Sweden.

Capacity auction: The total required capacity is decided upon a few years in advance and is centrally procured in an auction. Capacity providers bid to receive a capacity payment that reflects the cost of building new capacity. The new capacity participates in the energy-only market. Capacity auctions involve the risk that investors may not take investment decisions based on market price signals and that new capacity may undercut existing capacity. The UK uses capacity auctions to ensure security of supply.

Capacity obligation: An obligation for large consumers or electricity suppliers to contract an amount of capacity linked to their self-assessed future consumption or supply, plus a reserve margin. This is usually done by means of certificates that are issued by capacity providers. Suppliers or consumers are penalised financially if they have not contracted the required level of capacity. This type of capacity mechanism is used in France.