Market Design for Integrated Energy Systems

Part III: Focus on Sector Coupling

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June 24, 2022

DTU Summer School 2022

Why flexibility?

Electricity Market

Goal: meeting demand at the minimum system cost
(or the maximum social welfare)

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(or the maximum social welfare)

- **Renewables** (with stochastic generation) bring uncertainty and variability — inaccurate forecast may result in wrong commitment and dispatch decisions, with **increased** system cost

- **How to manage renewable power uncertainty:**
  - ✓ Flexibility integration (fast generators, demand response, etc)
  - ✓ Proper market design

Questions

What is the cost of wind uncertainty and value of flexibility?

How to reveal the (ideally full) operational flexibility of energy systems based on existing infrastructure?

Solutions

Potential **market-based** solutions for revealing the (ideally full) operational flexibility of energy systems based on existing assets:

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1- New market products
2- New market players
3- Proper (re-)design of energy markets
4- …

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These solutions need to be as compatible as possible with current market regulations!

Potential sources of flexibility

✓ Proper coordination of integrated energy systems (e.g., power, heat, natural gas, water), Power-to-X facilities, …

✓ Demand response

✓ Other potential sources (e.g., hydro units, grid flexibility, etc) – which are outside the scope of this talk!

Outline

- **Sources of operational flexibility**

  An example selected to be discussed:

  Coordination of power and heat systems

- **Solution 1: New market products**

  Two examples selected to be discussed:

  ✓ **Asymmetric block offers by demand response aggregators**

  ✓ **Price-region offers by any flexible resource**

- **Solution 2: New market players**

  An example selected to be discussed:

  Virtual bidders and self-schedulers in power and gas markets

- **Solution 3: Proper (re-)design of energy markets**

  An example selected to be discussed:

  Electricity-aware heat market clearing

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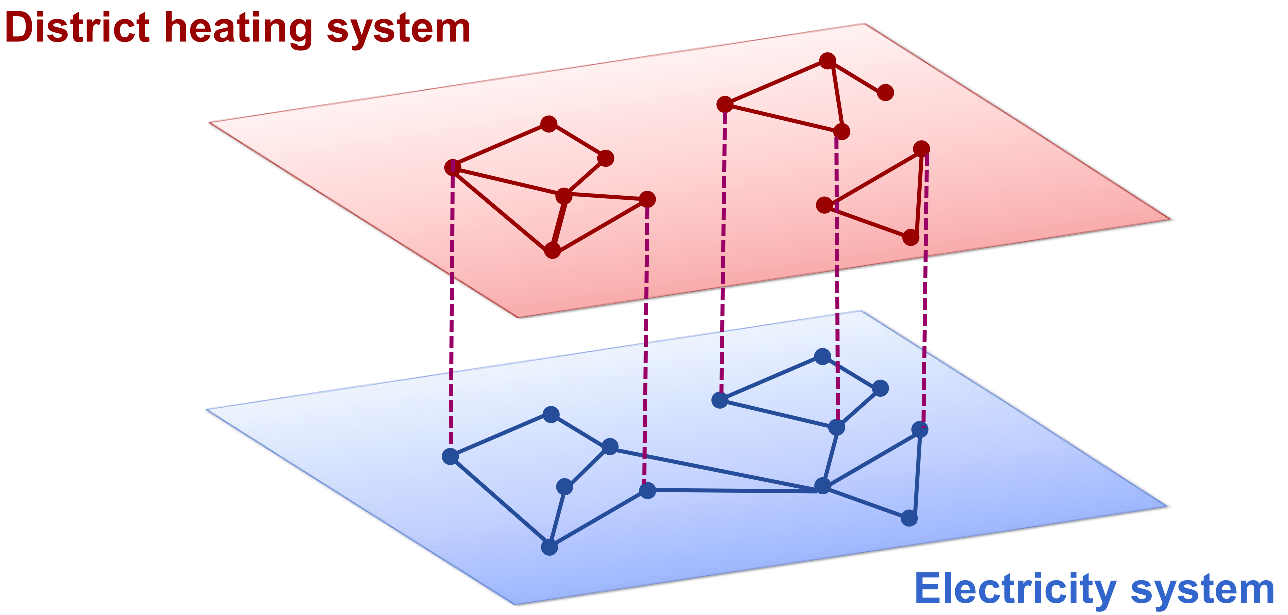
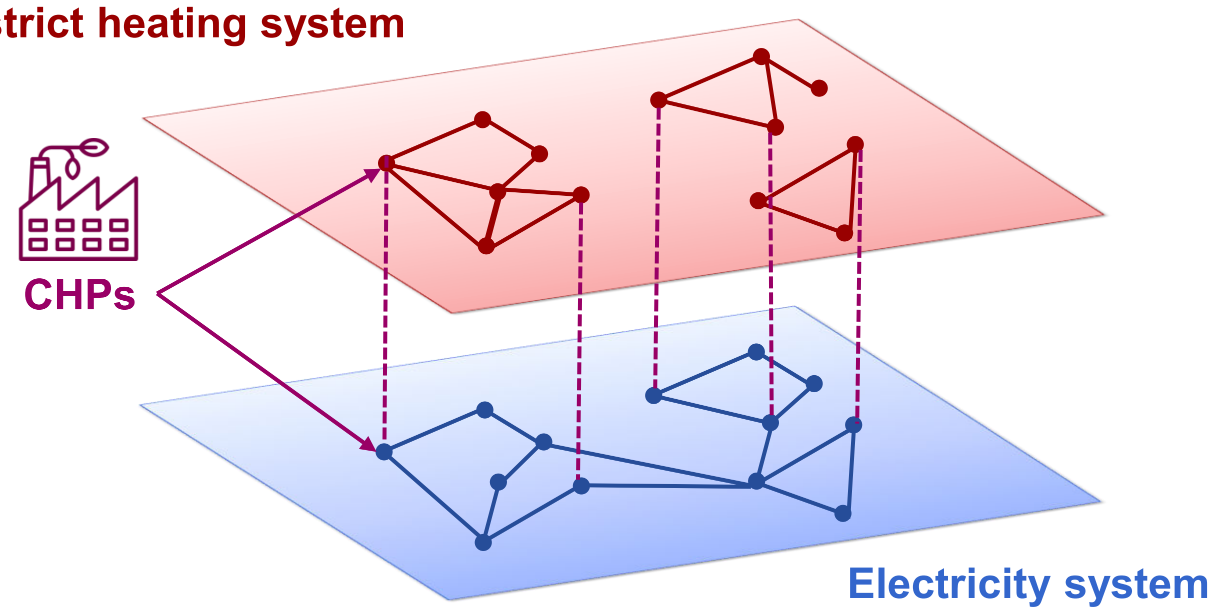
Interactions of heat and power systems

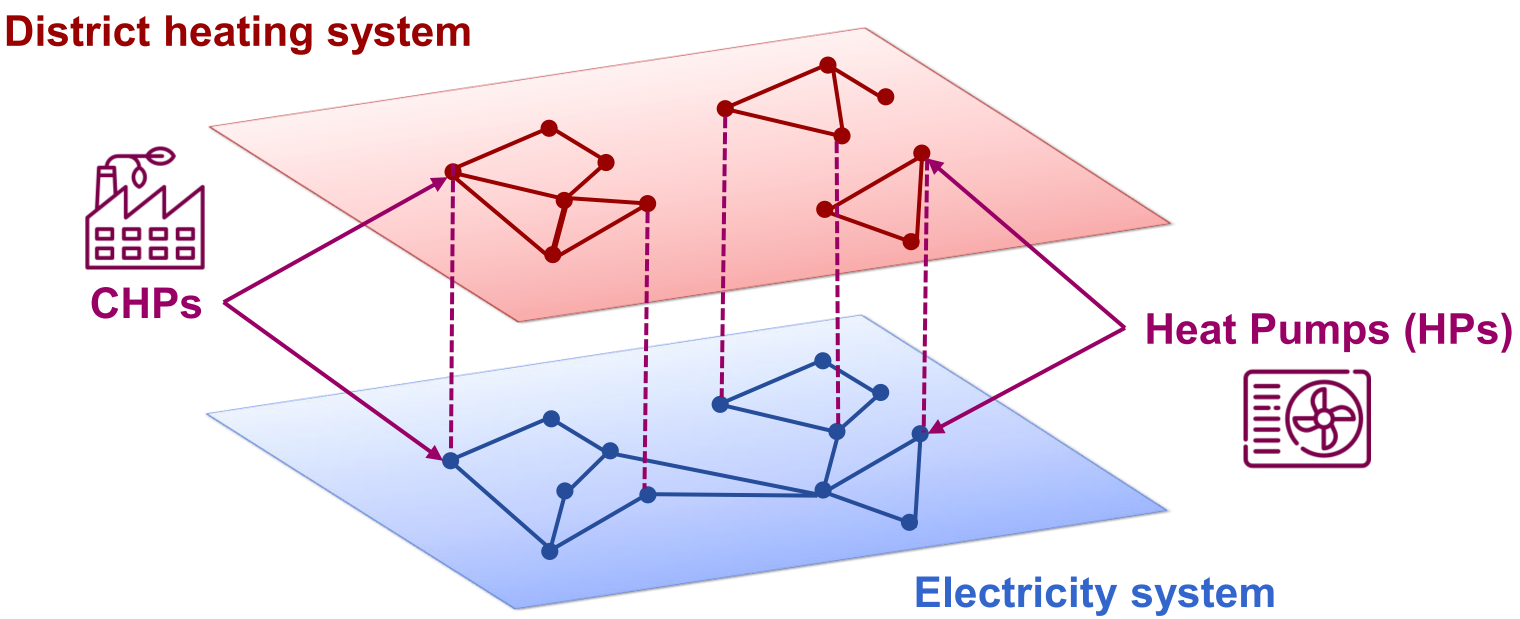


Interactions of heat and power systems



CHP: Combined heat and power

Interactions of heat and power systems



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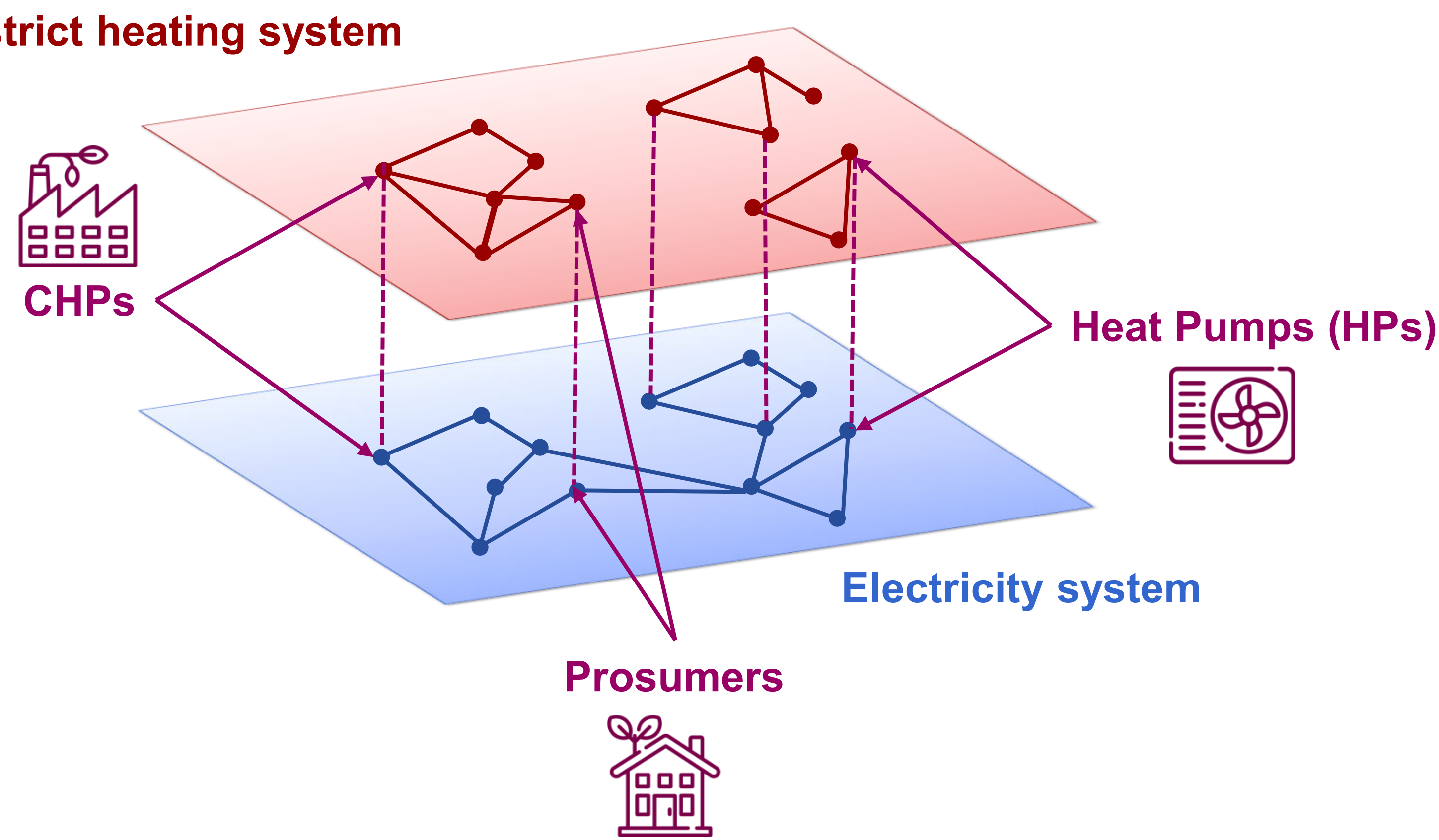

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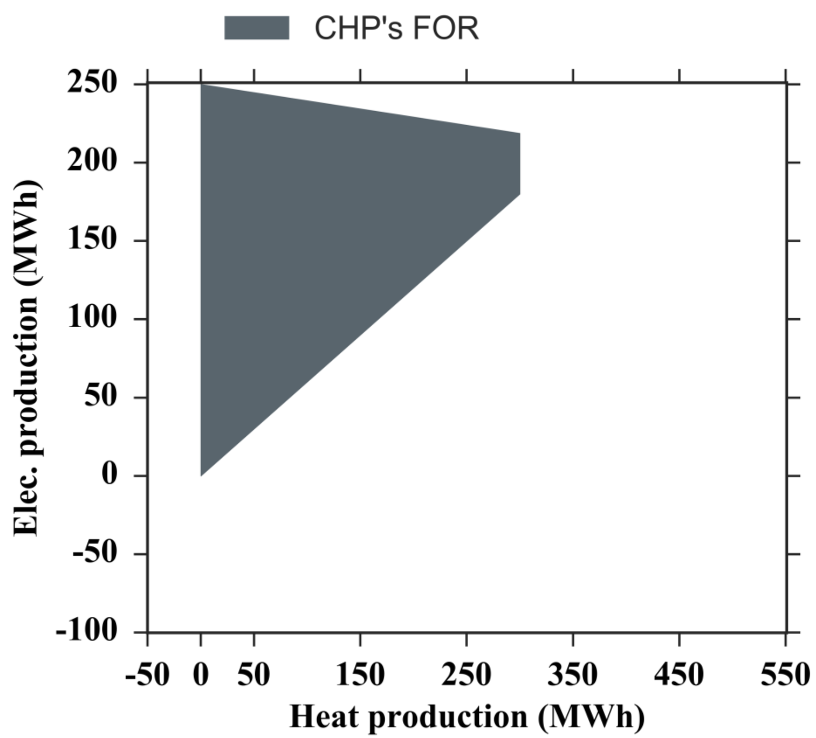
✓ Flexible operating region (FOR) of a typical CHP



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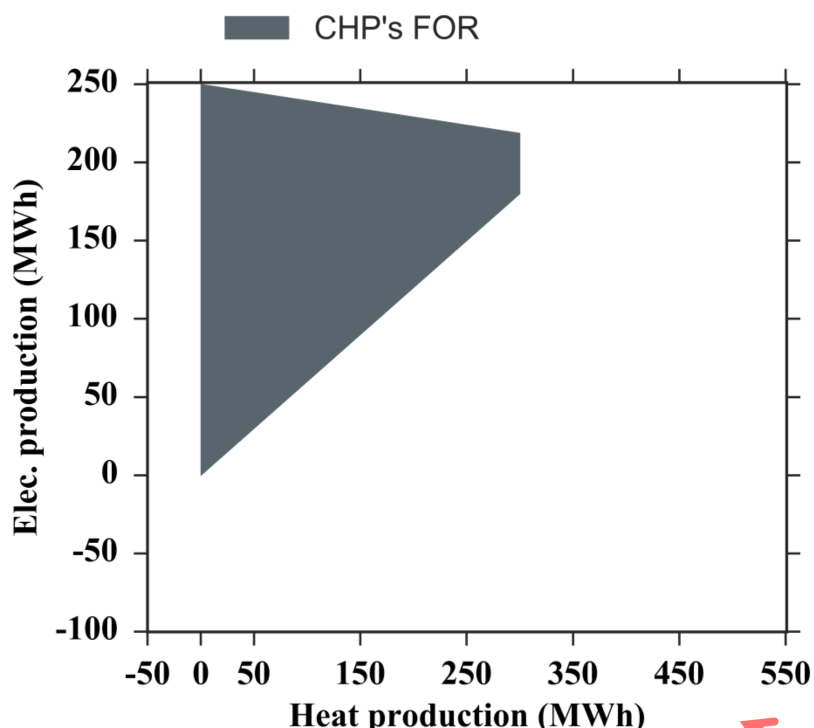
Electricity production

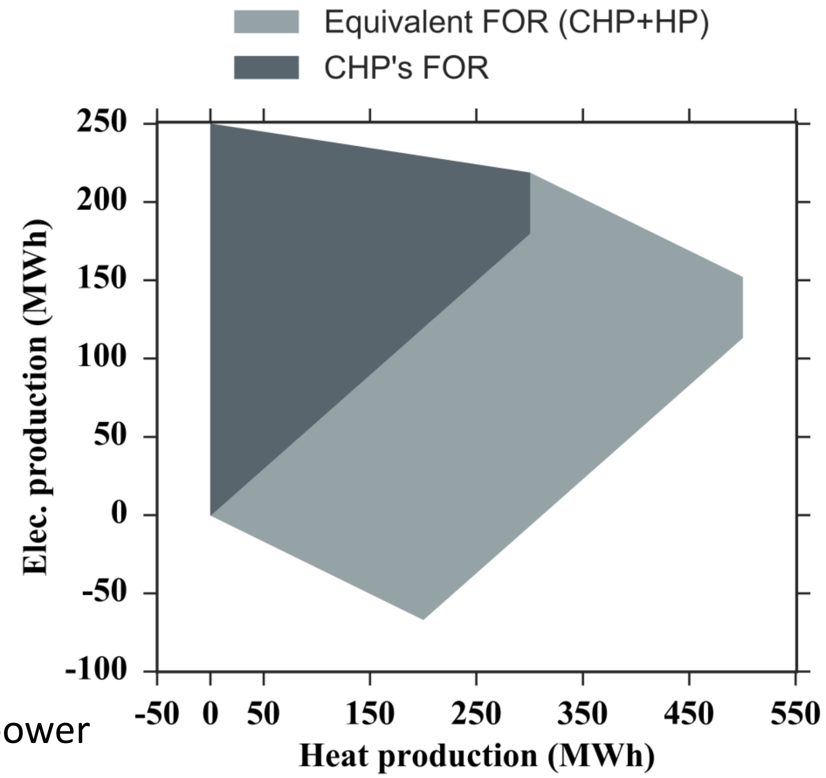


Heat production

CHP: Combined heat and power

Interactions of heat and power systems

✓ Flexible operating region (FOR) of a typical CHP + a HP

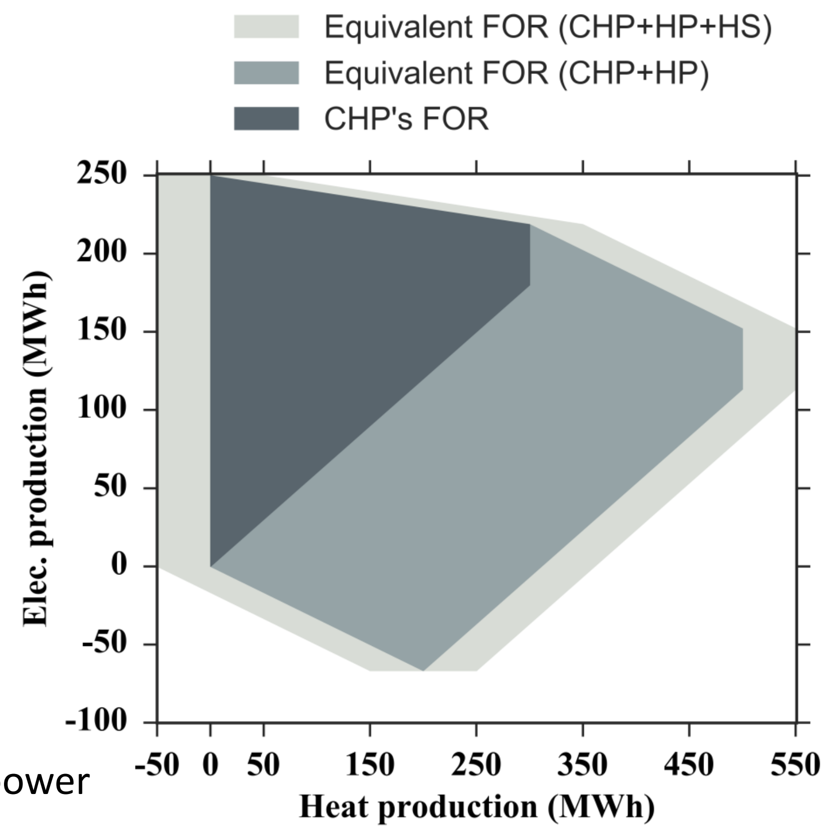


CHP: Combined heat and power
HP: Heat pump

Interactions of heat and power systems

✓ Flexible operating region (FOR) of a typical CHP + a HP

+ a HS

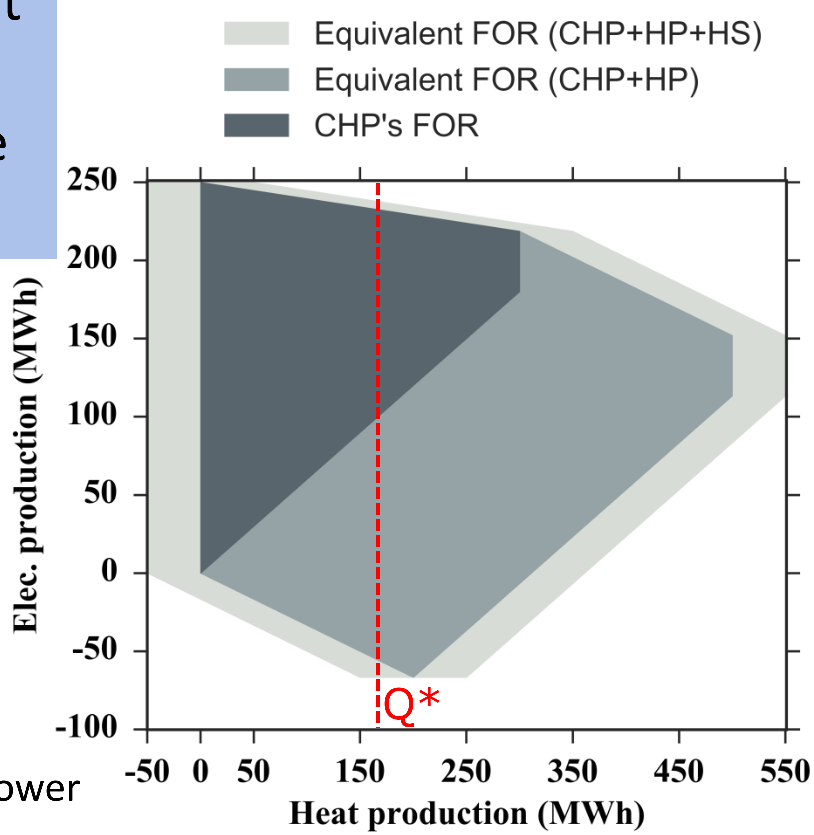


CHP: Combined heat and power
HP: Heat pump
HS: Heat storage

Interactions of heat and power systems

✓ Flexible operating region (FOR) of a typical CHP + a HP + a HS

In Denmark, the heat market is cleared every day before the power market!



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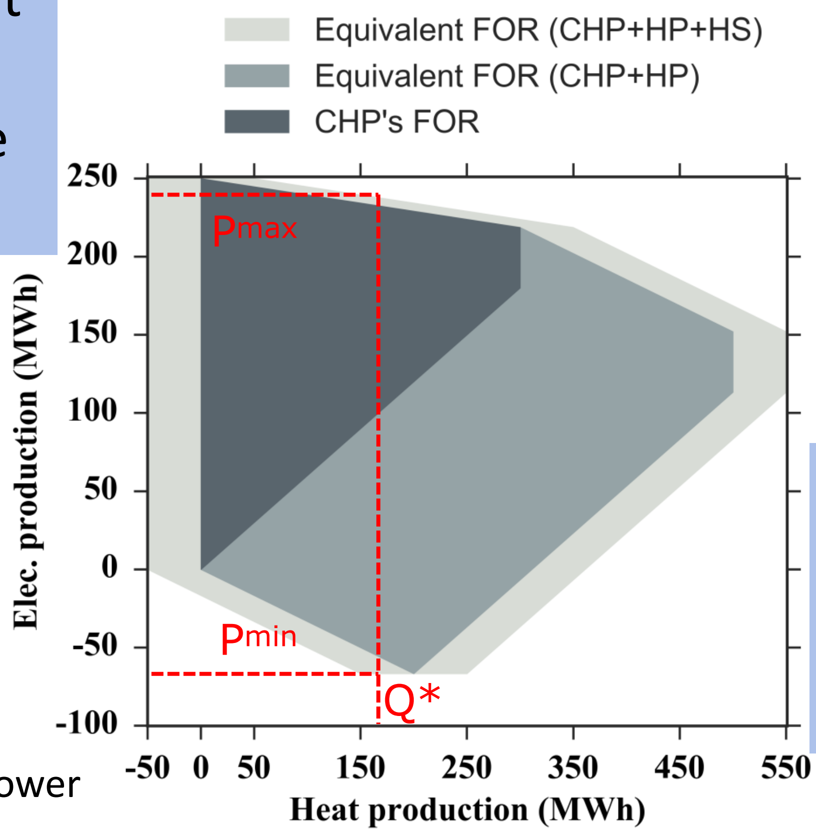

The heat dispatch (Q*) determines the power bounds (Pmin and Pmax)!

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Interactions of heat and power systems

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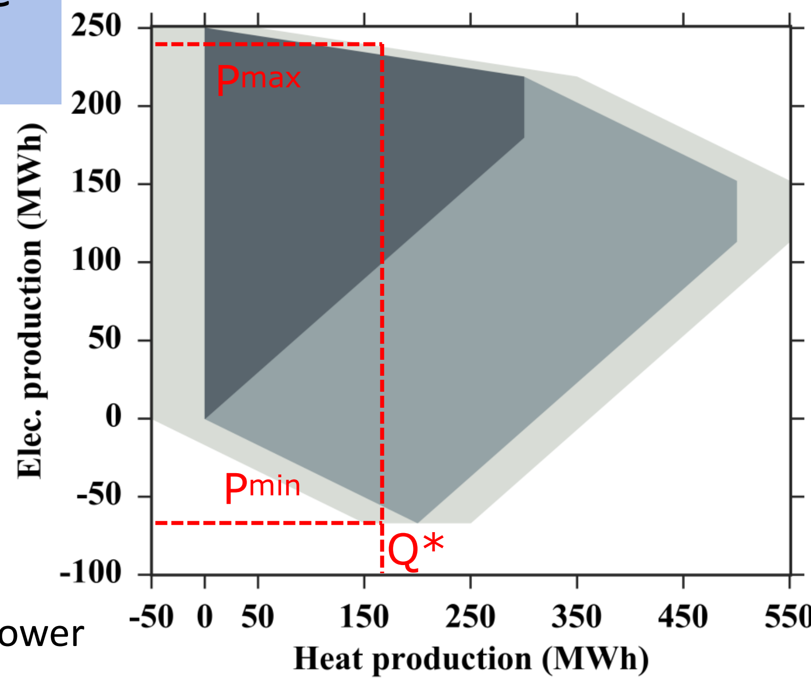
In Denmark, the heat market is cleared every day before the power market!

Coordination among different sectors is the key!



The heat dispatch (Q*) determines the power bounds (Pmin and Pmax)!

CHP: Combined heat and power
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Coordination: Definition

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Any **mechanism** that improves the overall system efficiency by allowing each sector to use the flexible resources belonging to the system of the other sectors, while respecting all operational restrictions and current regulations.

- ✓ Beneficial for the whole system,
- ✓ Every sector should also be happy!

Coordination: How?

Among others, the coordination between sectors could be achieved through

- **operational mechanisms** (example: [A]),
- **financial instruments** (example: [B]),
- **local information channels** (example: [C]).

[A] Silva, et al., “Estimating the active and reactive power flexibility area at the TSO-DSO interface,” *IEEE Transactions on Power Systems*, vol. 33, no. 5, pp. 4741–4750, 2018.

[B] A. Schwele, C. Ordoudis, P. Pinson, and JK, “Coordination of power and natural gas markets via financial instruments," *Computational Management Science*, vol. 18, pp. 505-538, 2021.

[C] M. A. Dahleh, A. Tahbaz-Salehi, J. N. Tsitsiklis, and S. I. Zoumpoulis, “Coordination with local information,” *Operations Research*, vol. 64 no. 3, pp. 622–637, 2016.

Coordination: Another perspective!

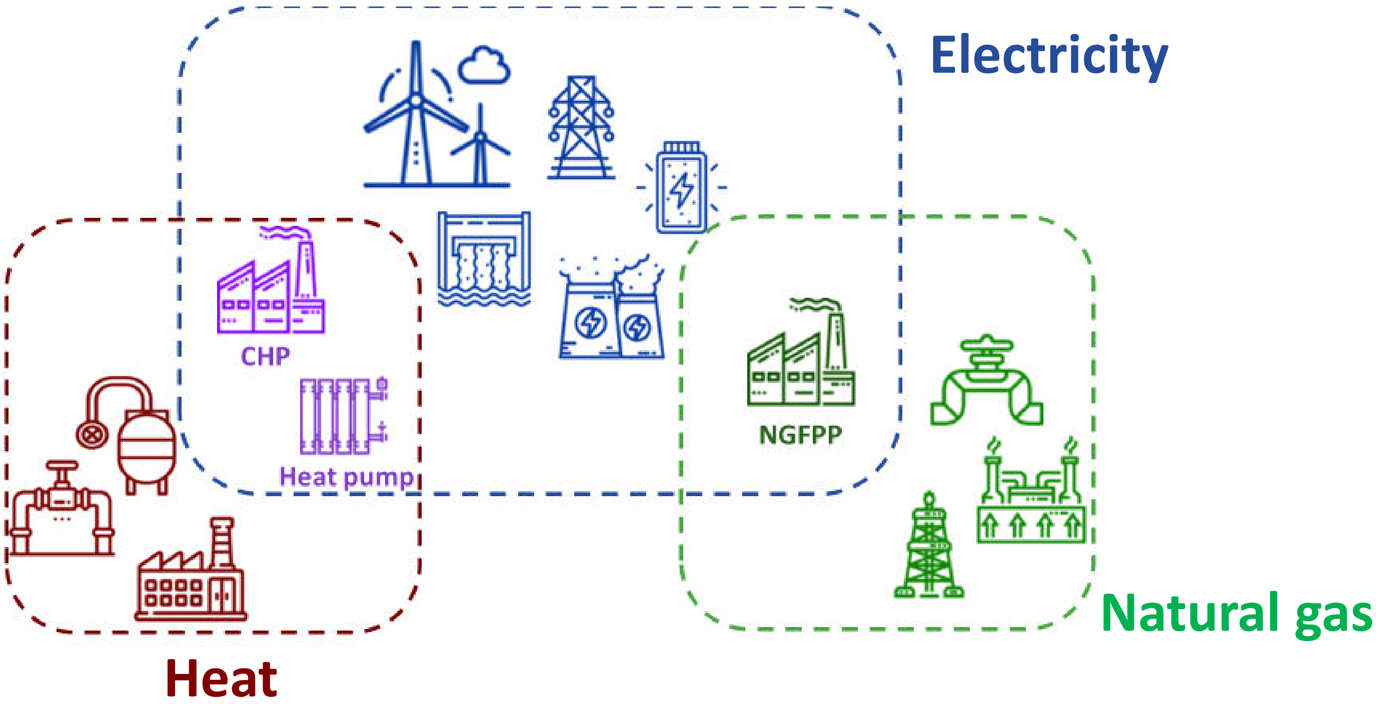
✓ The coordination mechanisms aim to enhance the information flow, either directly or indirectly, among entities.

Coordination: Another perspective!

- ✓ The coordination mechanisms aim to enhance the information flow, either directly or indirectly, among entities.

- ✓ In a market context, the information among entities could be indirectly exchanged through bids, market products, or players at the interface of sectors, while respecting the underlying regulations.

Interactions among energy systems



- Strong links between the electricity, natural gas and heat systems
- Natural gas and heat systems can play a major role in providing flexibility to the power system

NGFPP: Natural gas-fired power plants

Additional source of flexibility: "Linepack"

Linepack refers to the ability to store natural gas (or heat) in the natural gas (or heat) pipelines.

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- Linepack is able to provide short-term flexibility to the power system.
- Unlocking linepack flexibility requires accurate modeling of natural gas (or heat) flow dynamics along pipelines!

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- Linepack is able to provide short-term flexibility to the power system.
- Unlocking linepack flexibility requires accurate modeling of natural gas (or heat) flow dynamics along pipelines!

Challenge: the representation of gas (or heat) flow in the pipelines introduces non-linearity and non-convexity!

Additional source of flexibility: "Linepack"

<u>Natural gas</u> system constraints (mixed-integer and non-linear)

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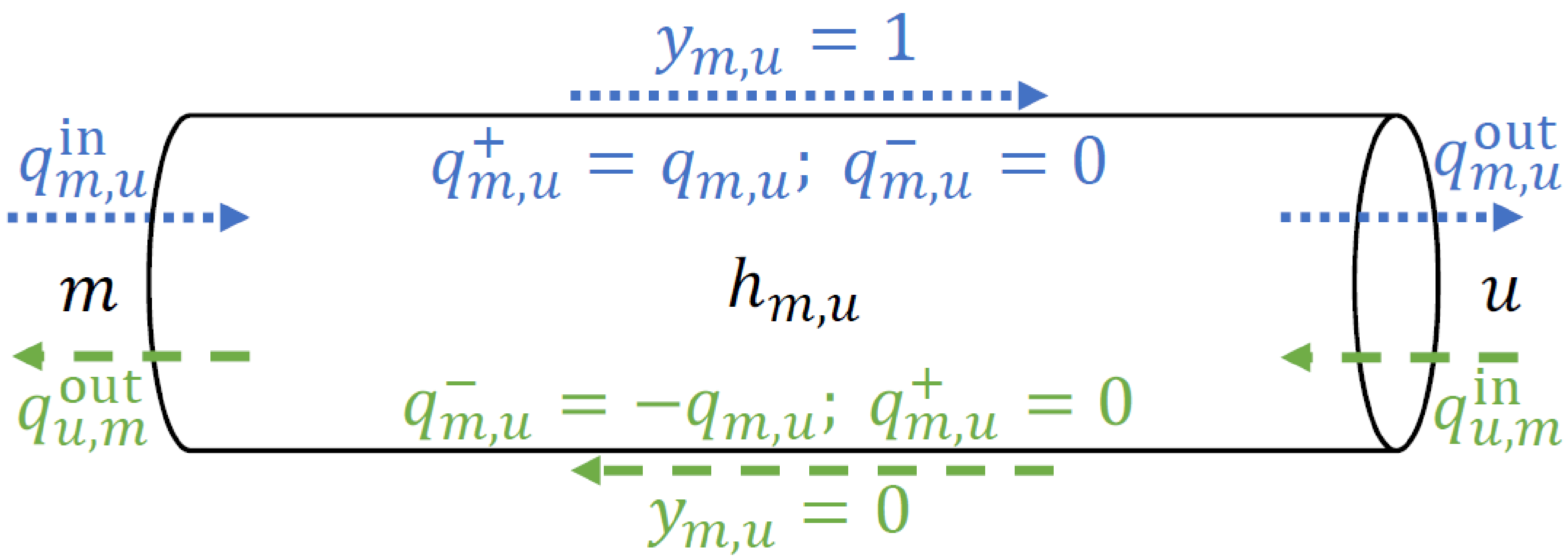
<u>Natural gas</u> system constraints (mixed-integer and non-linear)



Bidirectional gas flow along a pipeline

A. Schwele, C. Ordoudis, JK, P. Pinson, “Coordination of power and natural gas systems: Convexification approaches for linepack modeling,” *IEEE PowerTech,* 2019.

A. Schwele, A. Arrigo, C. Vervaeren, JK, and F. Vallee, “Coordination of electricity, heat, and natural gas systems accounting for network flexibilitv." *Electric Power Systems Research*, vol. 189, Article no. 106776, pp. 1-7, 2020.

Constraints of natural gas system (steady state model)

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Not the more realistic transient model with partial differential equations (PDEs)!

Constraints of natural gas system (steady state model)

$$0 \leq g_{k,t} \leq G_k^{\max}, \forall k, t, \quad (1h)$$ Gas supply limits

$$PR_m^{\min} \leq pr_{m,t} \leq PR_m^{\max}, \forall m, t, \quad (1i)$$ Nodal gas pressure limits

$$pr_{u,t} \leq \Gamma_{m,u}\ pr_{m,t}, \forall (m,u) \in \mathcal{Z}, t, \quad (1j)$$ Modeling compressor

$$q_{m,u,t}|q_{m,u,t}| = K_{m,u}^2 (pr_{m,t}^2 - pr_{u,t}^2), \forall (m,u) \in \mathcal{Z}, t, \quad (1k)$$ Gas flow (Weymouth equation)

$$q_{m,u,t} = q_{m,u,t}^+ - q_{m,u,t}^-, \forall (m,u) \in \mathcal{Z}, t, \quad (1l)$$

$$0 \leq q_{m,u,t}^+ \leq M\ y_{m,u,t}, \forall (m,u) \in \mathcal{Z}, t, \quad (1m)$$

$$0 \leq q_{m,u,t}^- \leq M(1 - y_{m,u,t}), \forall (m,u) \in \mathcal{Z}, t, \quad (1n)$$

$$q_{m,u,t}^+ = \frac{q_{m,u,t}^{\text{in}} + q_{m,u,t}^{\text{out}}}{2}, \forall (m,u) \in \mathcal{Z}, t, \quad (1o)$$

$$q_{m,u,t}^- = \frac{q_{u,m,t}^{\text{in}} + q_{u,m,t}^{\text{out}}}{2}, \forall (m,u) \in \mathcal{Z}, t, \quad (1p)$$

Modeling bidirectional gas flow

$$h_{m,u,t} = S_{m,u} \frac{pr_{m,t} + pr_{u,t}}{2}, \forall (m,u) \in \mathcal{Z}, t, \quad (1q)$$

$$h_{m,u,t} = h_{m,u,(t-1)} + q_{m,u,t}^{\text{in}} - q_{m,u,t}^{\text{out}} + q_{u,m,t}^{\text{in}} - q_{u,m,t}^{\text{out}}, \forall (m,u) \in \mathcal{Z}, t > 1, \quad (1r)$$

$$h_{m,u,t} = H_{m,u}^0 + q_{m,u,t}^{\text{in}} - q_{m,u,t}^{\text{out}} + q_{u,m,t}^{\text{in}} - q_{u,m,t}^{\text{out}}, \forall (m,u) \in \mathcal{Z}, t = 1, \quad (1s)$$

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Modeling linepack

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Binary variable indicating the flow direction

$q_{m,u,t}^{+}$ [illegible] $, t,$ (1o)

$$q_{m,u,t}^{-} = \frac{q_{u,m,t}^{\text{in}} + q_{u,m,t}^{\text{out}}}{2}, \forall (m,u) \in \mathcal{Z}, t, \tag{1p}$$

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Flow across pipeline (variable)

Nodal pressure (variable)

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Gas flow (Weymouth equation)

Quadratic equality constraint, which is non-convex!

$$q_{m,u,t} = \ldots \quad (1l)$$

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$$0 \leq q_{m,u,t}^- \leq \ldots \quad (1n)$$

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$q^{\text{in}} \ldots + q^{\text{out}} \ldots$

Quadratic equality constraint, which is non-convex!

Modeling bidirectional gas flow

This non-convexity is a challenge!

Potential solutions for convexification:

- **Approximation** by a set of linear cuts
- **Relaxation** (e.g., by a second-order cone relaxation, but may not be an exact relaxation)

$H_{m,u}^0 \leq h_{m,u,t}, \forall (m,u) \in \mathcal{Z}, t = |\mathcal{T}|$ (1t)

Uncertainty propagation: Should market be aware of it?

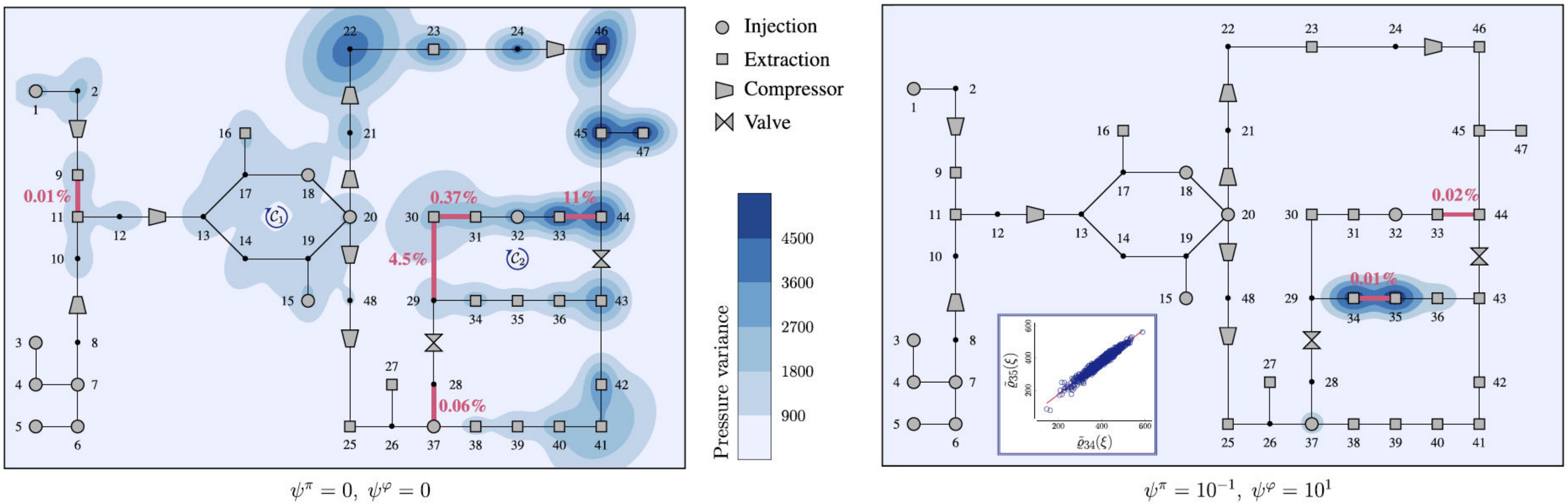


Fig. 1. Comparison of the variance-agnostic (left) and the variance-aware (right) chance-constrained control policies in terms of the state variables variance for $\varepsilon = 10\%$. The red values show the probability of flow reversal. The inset plot shows the correlation between the pressures at nodes 34 and 35.

V. Dvorkin, A. Ratha, P. Pinson, and JK, “Stochastic control and pricing for natural gas networks," *IEEE Transactions on Control of Network Systems*, vol. 9, no. 1, pp. 450-462, March 2022.

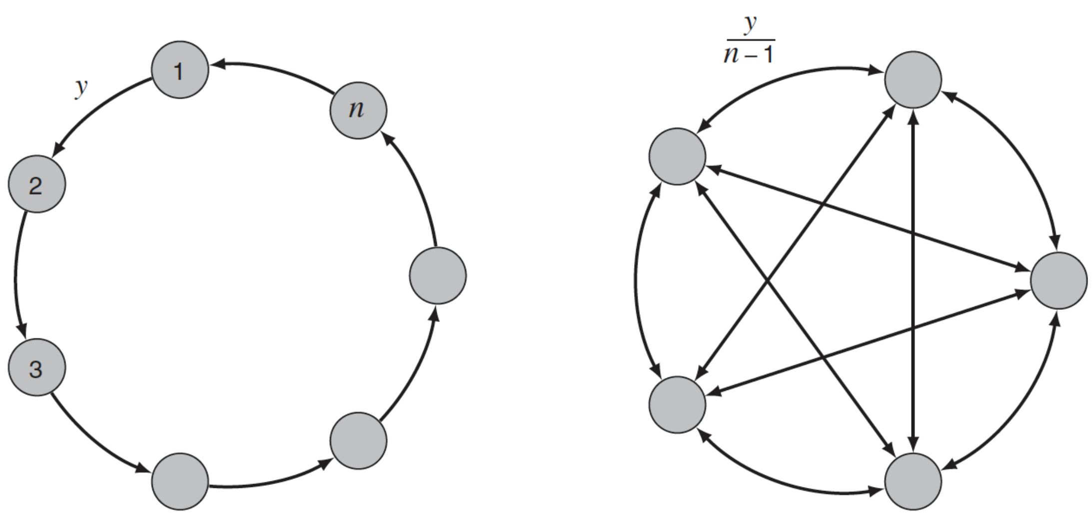
Uncertainty propagation and systemic risk

American Economic Review 2015, 105(2): 564–608
http://dx.doi.org/10.1257/aer.20130456

Systemic Risk and Stability in Financial Networks†

By Daron Acemoglu, Asuman Ozdaglar, and Alireza Tahbaz-Salehi*

Panel A. The ring financial network   Panel B. The complete financial network



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Demand response with “rebound” effect

The demand response resource, e.g., thermostatically controlled loads (TCLs), may have inherent rebound (kick-back) effect.

Demand response with "rebound" effect

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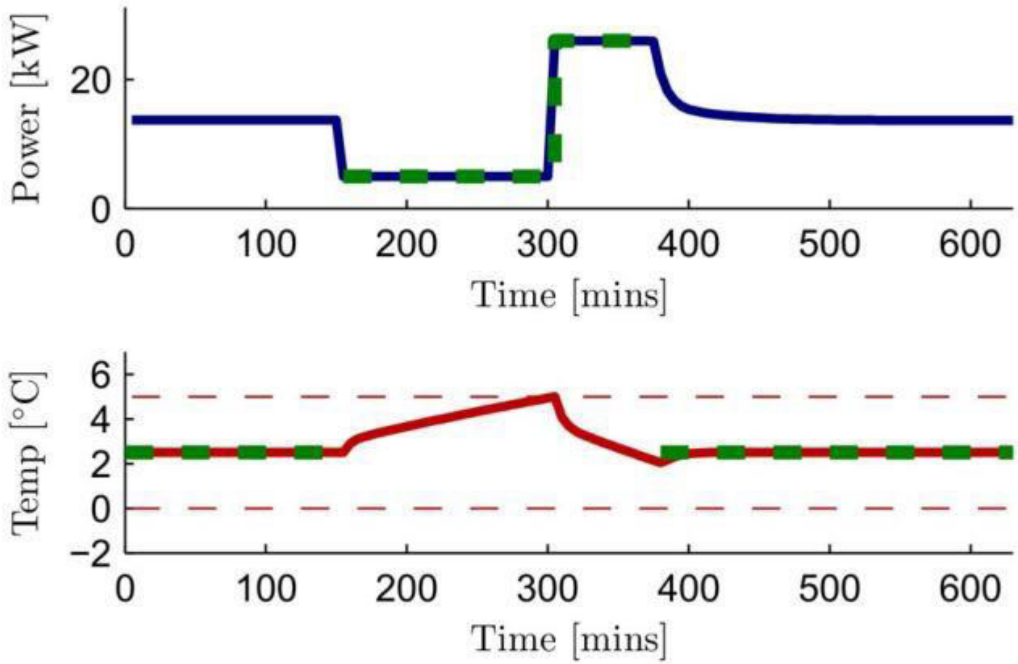
Power consumption of an aggregation of TCLs over time:

Power consumption

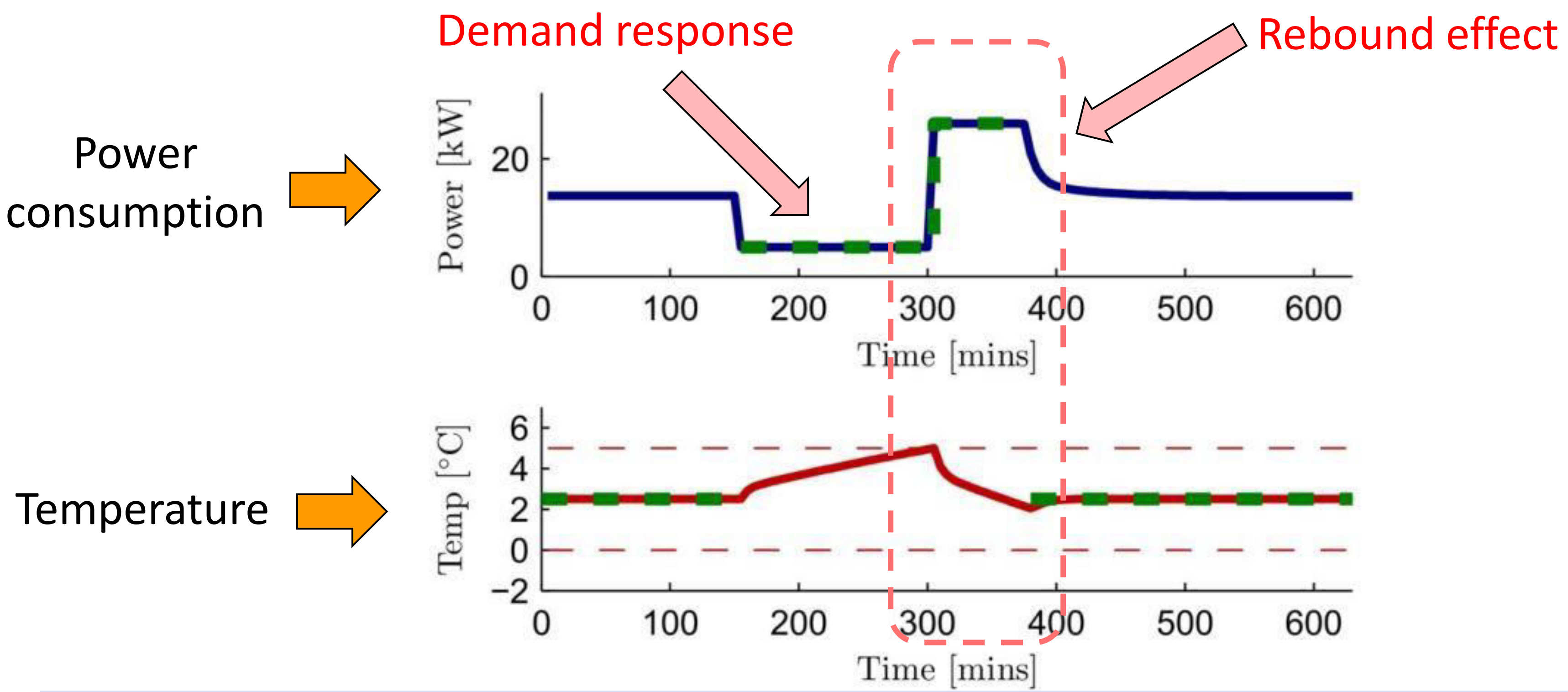
Temperature



N. O'Connell, P. Pinson, H. Madsen, and M. O'Malley, "Economic dispatch of demand response balancing through asymmetric block offers," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 2999–3007, 2016.

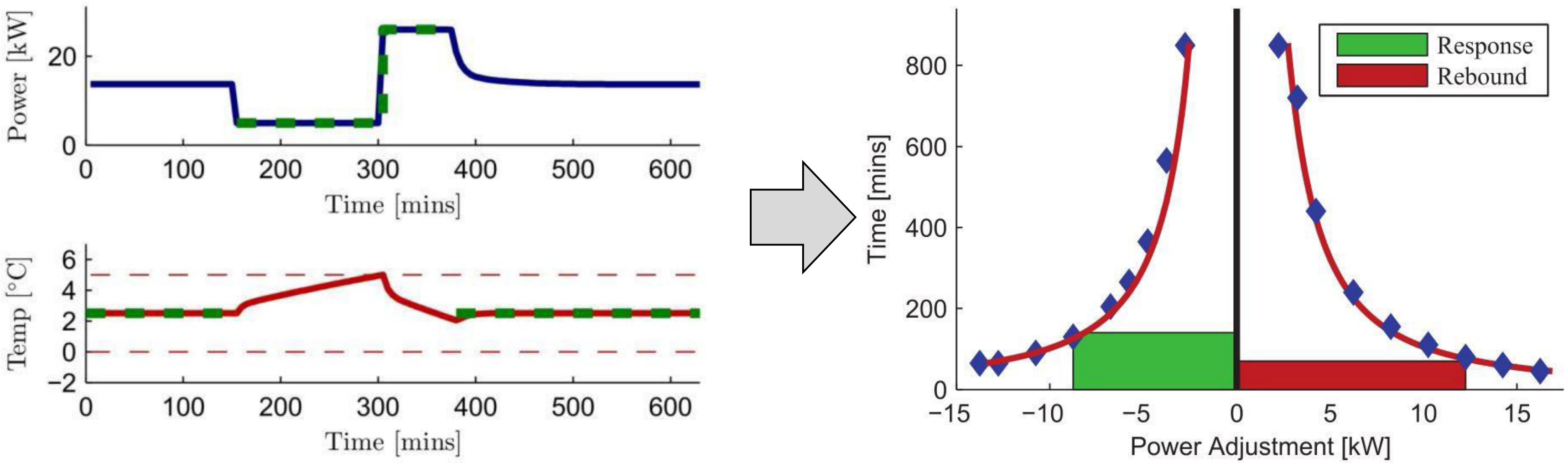
Demand response with "rebound" effect

The demand response resource, e.g., thermostatically controlled loads (TCLs), may have inherent rebound (kick-back) effect.



Rebound effect: a decrease in power demand (response) must be followed by an increase (rebound) or vice-versa!

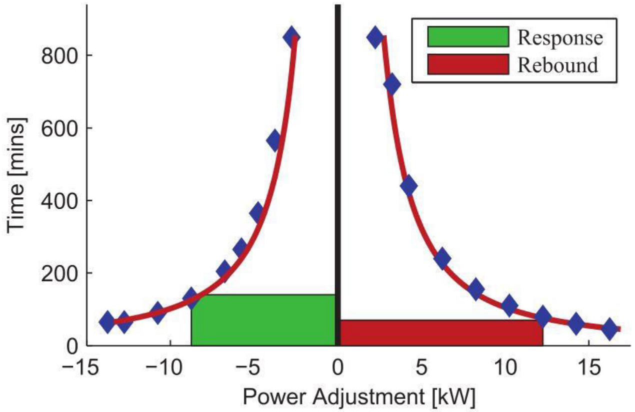
Asymmetric block offers



By **asymmetric**, it means that the two blocks (green and red) can have different power consumption levels and duration for response and rebound parts.

N. O'Connell, P. Pinson, H. Madsen, and M. O'Malley, "Economic dispatch of demand response balancing through asymmetric block offers," *IEEE Trans. Power Syst.*, vol. 31, no. 4, pp. 2999–3007, 2016.

Asymmetric block offers



Benefit:

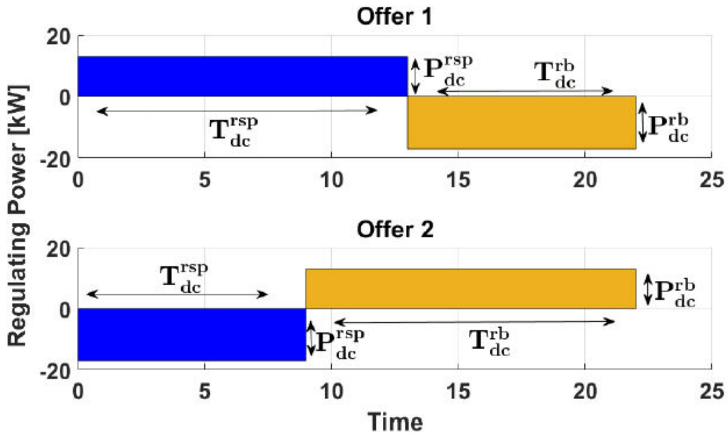
These block offers facilitate the integration of demand response aggregators in power markets!

Challenge:

They introduce integer variables to the market-clearing problem (similar to current block orders in Nord Pool)!

EcoGrid 2.0 project in Denmark

- To design a market allowing demand response aggregators (e.g., Insero) to provide flexibility while modeling demand response characteristics (e.g., rebound effect)



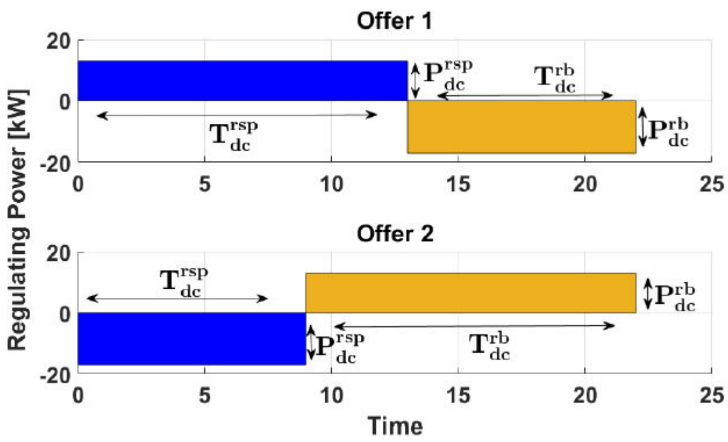
Sample asymmetric block offers as market products for demand response aggregators

Source: A. Hermann, JK, S. Huang, and J. Østergaard, "Congestion management in distribution networks with asymmetric block offers," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4382-4392, November 2019.

EcoGrid 2.0 project in Denmark

- To design a market allowing demand response aggregators (e.g., Insero) to provide flexibility while modeling demand response characteristics (e.g., rebound effect)

  - TSO-level balancing market (eight 15-minute time steps)
    - ✓ To be demonstrated in Bornholm island of Denmark
    - ✓ To develop aggregator's tools (portfolio estimation and offering strategy) and market platform
  - DSO-level capacity limitation market (a mid-term monthly market)
    - ✓ To be demonstrated in Bornholm island of Denmark
    - ✓ To develop aggregator's tools and market platform



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Outline

- ❑ Sources of operational flexibility

  An example selected to be discussed:

  Coordination of power and heat systems

- ❑ **Solution 1: New market products**

  Two examples selected to be discussed:

  ✓ Asymmetric block offers by demand response aggregators

  ✓ **Price-region offers by any flexible resource**

- ❑ Solution 2: New market players

  An example selected to be discussed:

  Virtual bidders and self-schedulers in power and gas markets

- ❑ Solution 3: Proper (re-)design of energy markets

  An example selected to be discussed:

  Electricity-aware heat market clearing

Existing bid formats: price-quantity bids

Existing bid formats: price-quantity bids

The most basic bidding format in the current markets!

Existing bid formats: price-quantity bids

Definition 1:

A **price-quantity** bid s at location n and time period k is defined as a set of parameters $(\underline{p}_s, \bar{p}_s, \alpha_s)$, so that:

- the feasible region $\boldsymbol{\Omega_s}$ of the injection profile $\boldsymbol{p_s}$ of a bid s is given by

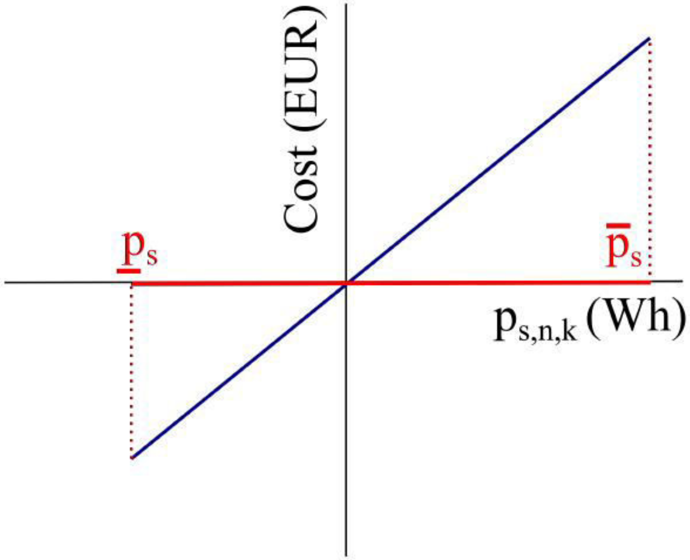
$$\boldsymbol{\Omega_s} = \left\{\boldsymbol{p_s} \middle| p_{s,n,k} \in \left[\underline{p}_s, \bar{p}_s\right], \qquad p_{s,\hat{n},\hat{k}} = 0 \; \forall (\hat{n}, \hat{k}) \neq (n, k)\right\}$$

- the cost associated with a feasible profile $\boldsymbol{p_s}$ writes as

$$\boldsymbol{F}_s^E(\boldsymbol{p_s}) = \alpha_s \, p_{s,n,k}.$$

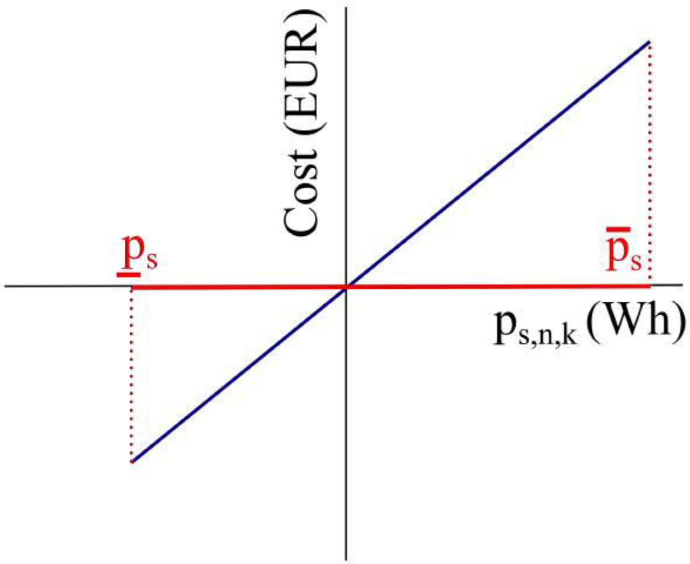
The parameters $\underline{p}_s$ and $\bar{p}_s$ denote lower and upper bounds for energy injection/withdrawal, while α_s denotes a bidding price.

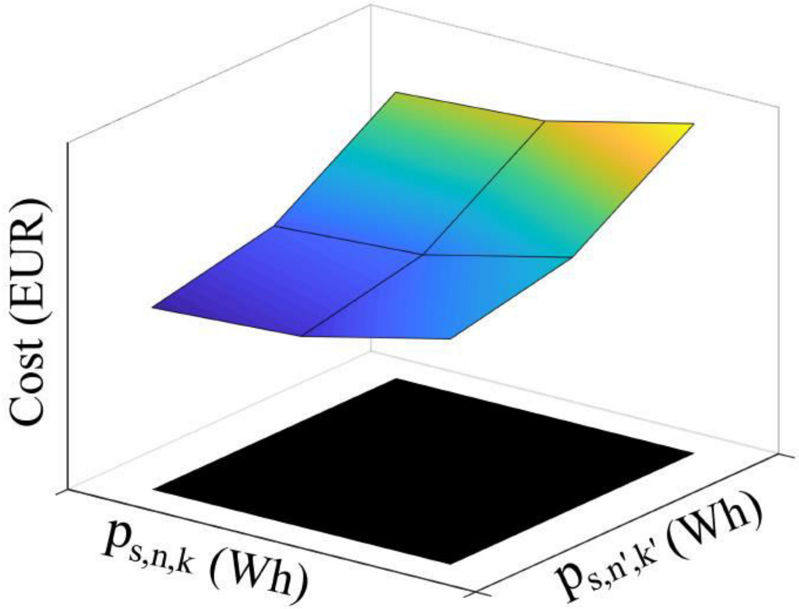
Existing bid formats: price-quantity bids



Illustrative example of a cost function and feasible region represented by **a single** price-quantity bid!

Existing bid formats: price-quantity bids





Illustrative example of a cost function and feasible region represented by **a single** price-quantity bid!

Illustrative example of a cost function (colored surface) and feasible region (block surface) represented by **a set of four** price-quantity bids!

Price-quantity bids: Why are they limiting?

The price-quantity bids can **only** describe box feasible regions and additively separable cost functions, as defined below.

Price-quantity bids: Why are they limiting?

The price-quantity bids can **only** describe box feasible regions and additively separable cost functions, as defined below.

Definition 2:

A feasible region $\boldsymbol{\Omega_s}$ is a box if there exists a convex region $\Omega_{s,n,k}$ for all n and k so that $\boldsymbol{p_s} \in \boldsymbol{\Omega_s} \Leftrightarrow p_{s,n,k} \in \Omega_{s,n,k}\ \forall n, k$.

Definition 3:

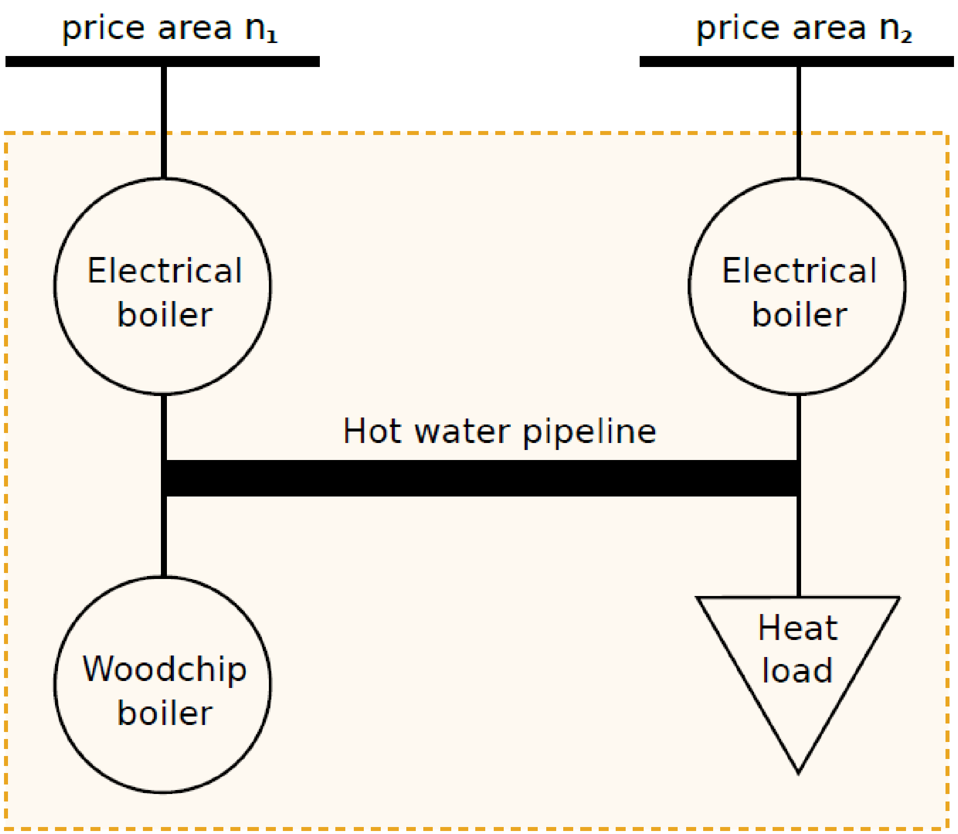
A cost function $\boldsymbol{F_s^E}$ is additively separable in its arguments $\boldsymbol{p_s}$ if for any n ={1,…,N} and k ={1,…,K} there exists a function $F_{s,n,k}^E$ so that

$$\boldsymbol{F_s^E}(\boldsymbol{p_s}) = \sum_{n,k} F_{s,n,k}^E(p_{s,n,k})$$

Limitations of price-quantity bids

A stylized motivating example: A simple district heating infrastructure connected to two price areas in a power system

- Two nodes: n_1 and n_2
- Two hours: k_1 and k_2

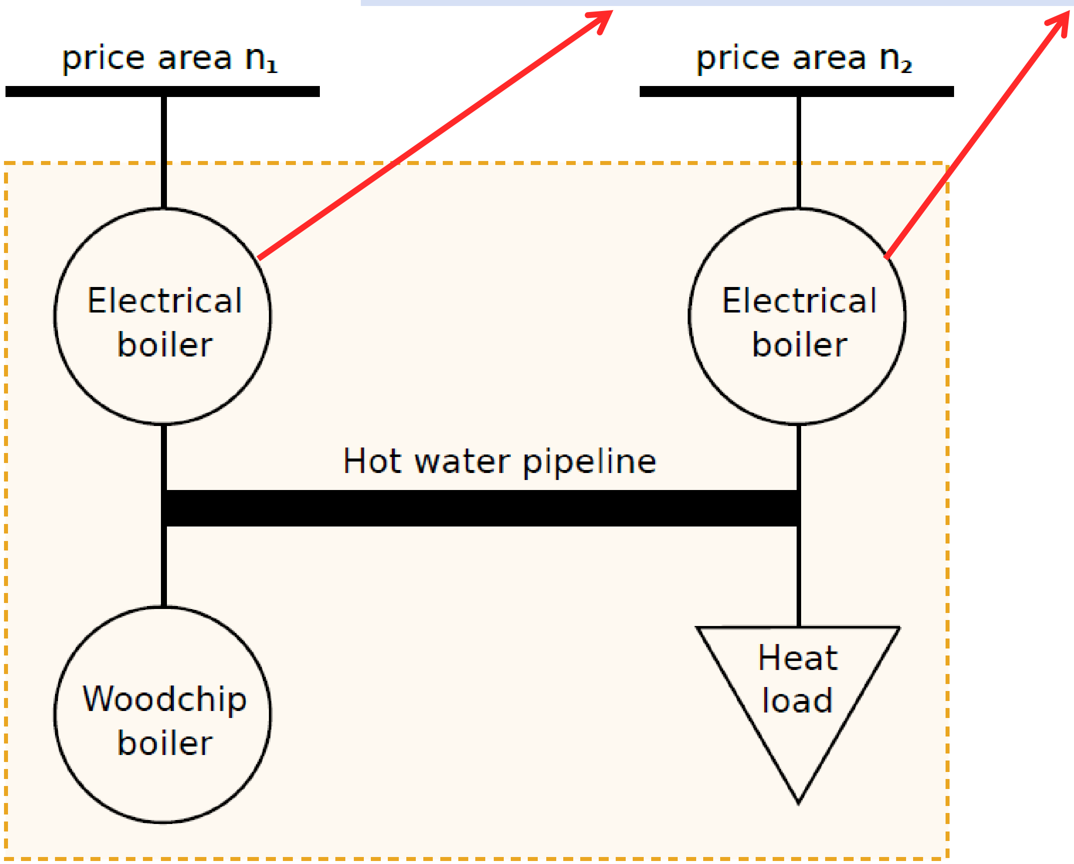


District heating infrastructure

Limitations of price-quantity bids

A stylized motivating example:

Two identical **electrical boilers**, both with an energy conversion efficiency of 100% (for concision) and a capacity of 5 MW

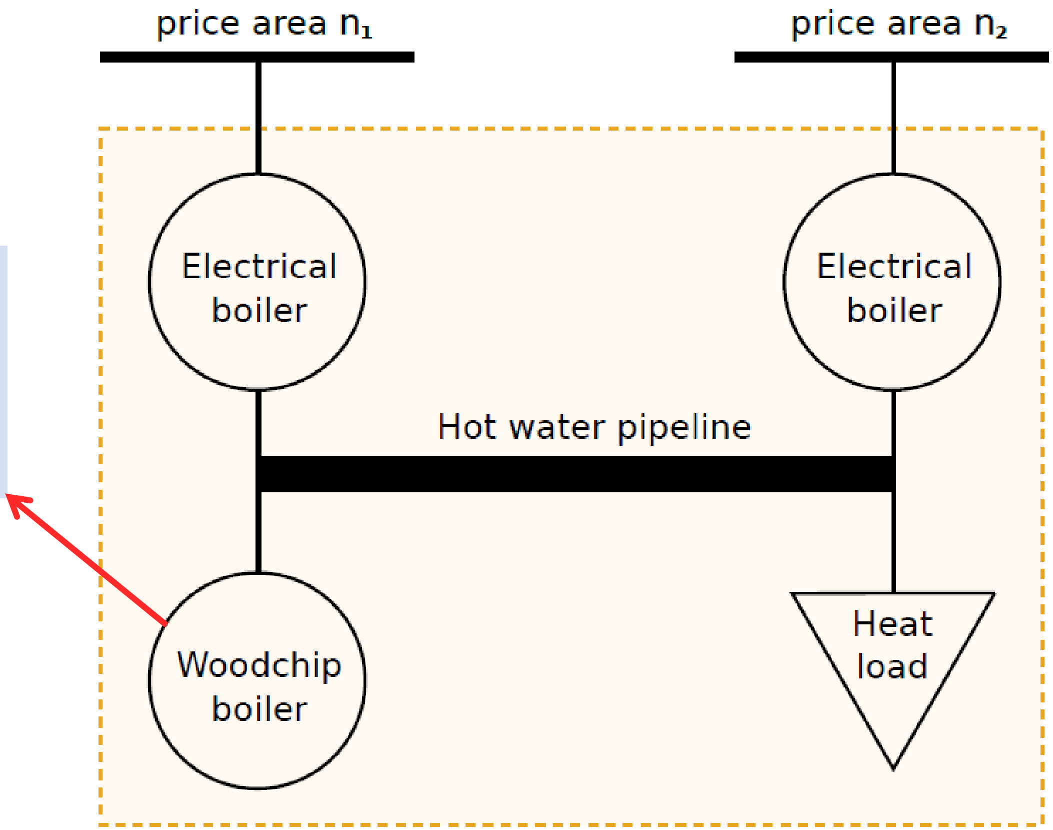


District heating infrastructure

Limitations of price-quantity bids

A stylized motivating example:

A **woodchip boiler** with a capacity of 3 MW and a fuel cost of 100 euro/MWh



District heating infrastructure

Limitations of price-quantity bids

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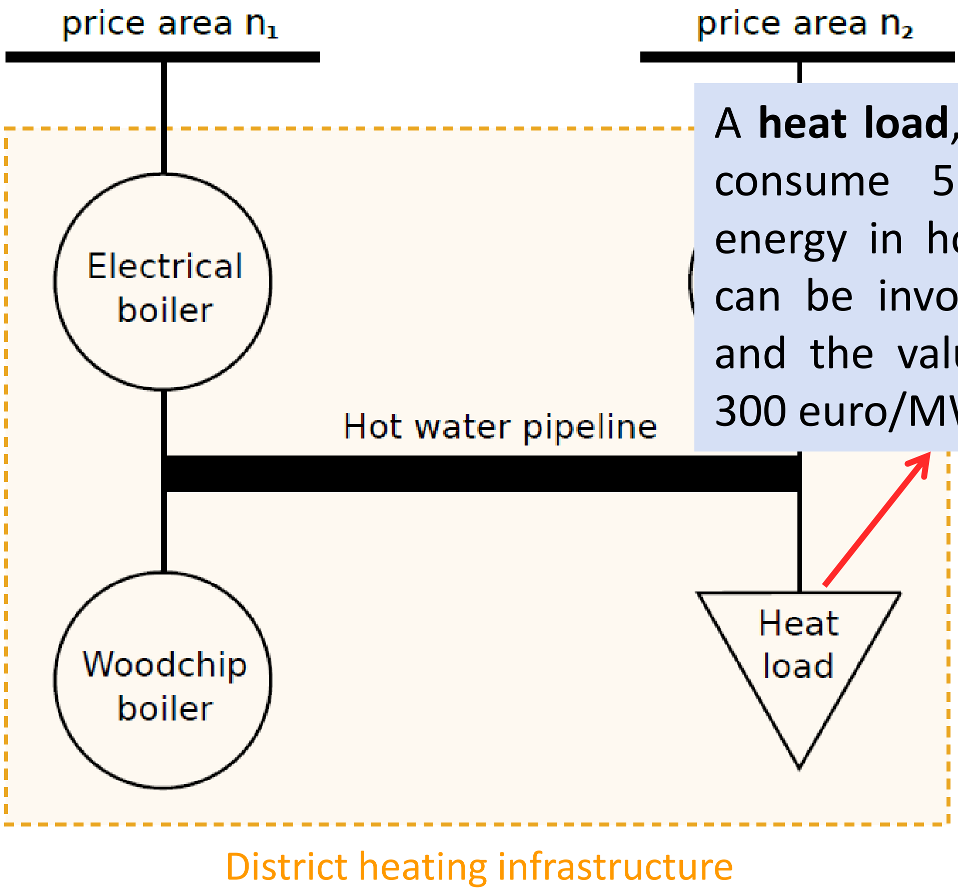
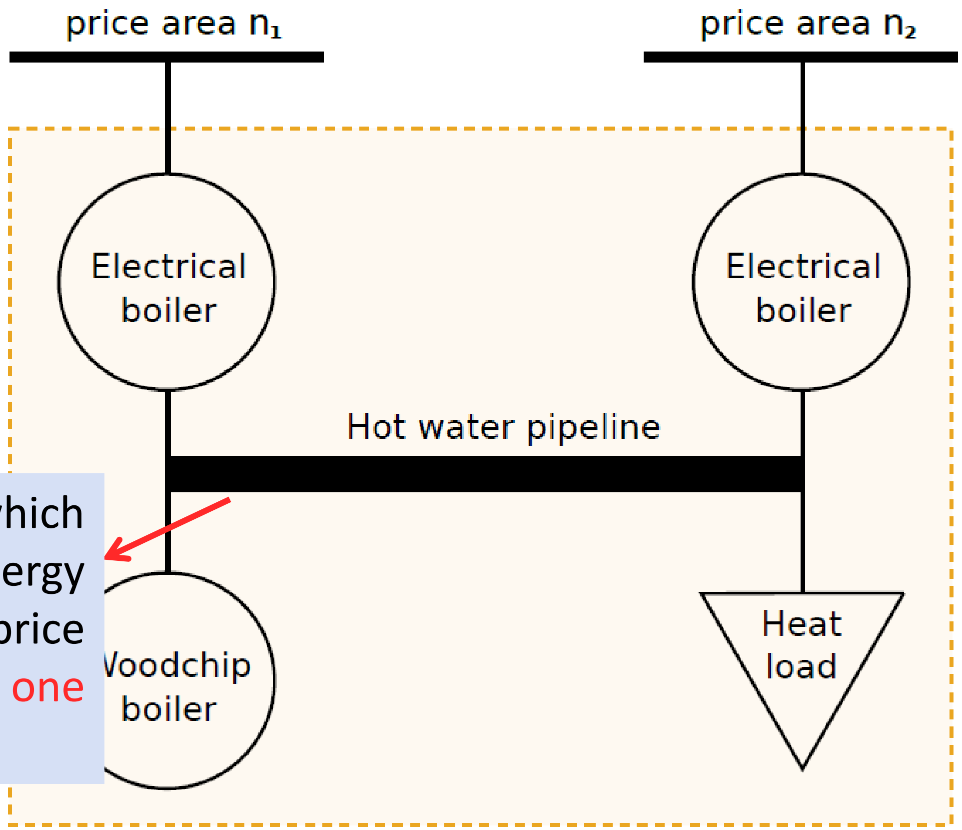


A **heat load**, which expects to consume 5 MWh of heat energy in hour k_2. This load can be involuntarily curtailed and the value of lost load is 300 euro/MWh.

Limitations of price-quantity bids

A stylized motivating example:



A **hot water pipeline**, which can transport heat energy from price area n_1 to price area n_2 with a delay of one hour, and without losses.

District heating infrastructure

Limitations of price-quantity bids

A stylized motivating example: the **operational constraints** of district heating utility

$$x_s - p_{s,n_1,k_1} - p_{s,n_2,k_2} \leq 5,$$

$$p_{s,n_1,k_2} = 0,$$

$$p_{s,n_2,k_1} = 0,$$

$$-5 \leq p_{s,n_1,k_1} \leq 0$$

$$-5 \leq p_{s,n_2,k_2} \leq 0$$

$$0 \leq x_s \leq 3.$$

Limitations of price-quantity bids

A stylized motivating example: the **operational constraints** of district heating utility

Heat production of woodchip boiler (**state variable**)

Power injection of electrical boilers

$$x_s - p_{s,n_1,k_1} - p_{s,n_2,k_2} \leq 5,$$

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$$0 \leq x_s \leq 3.$$

The 1-hour delay of transferring energy across pipeline is modeled!

(linking the electricity withdrawals across multiple time periods and price areas)

Limitations of price-quantity bids

A stylized motivating example:

For given electricity injection/withdrawal profile $\boldsymbol{p_s}$, the **operational cost** of district heating utility for electrical energy consumed is

$$\mathcal{F}^{\mathrm{H}}(\boldsymbol{p_s}, x_s) = 300\,(5 + p_{s,n_1,k_1} + p_{s,n_2,k_2} - x_s) + 100 x_s$$

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The district heating utility seeks to **minimize its operational cost**, which is defined as

Limitations of price-quantity bids

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The district heating utility seeks to **minimize its operational cost**, which is defined as

$$\mathcal{F}^{\mathrm{H}^*}(\boldsymbol{p_s}) = \min_{x_s} \left\{ \mathcal{F}^{\mathrm{H}}(\boldsymbol{p_s}, x_s),\ \text{s.t. operational constraints} \right\}$$

Limitations of price-quantity bids

A stylized motivating example:

The district heating utility is willing to pay for electrical energy according to the opportunity cost of not withdrawing quantity $\boldsymbol{p_s}$, so its **willingness to pay (WTP)** is

$$-\mathcal{F}^{\mathrm{E}}\left(\boldsymbol{p_s}\right) = \mathcal{F}^{\mathrm{H}^*}\left(\mathbf{0}_4\right) - \mathcal{F}^{\mathrm{H}^*}\left(\boldsymbol{p_s}\right)$$

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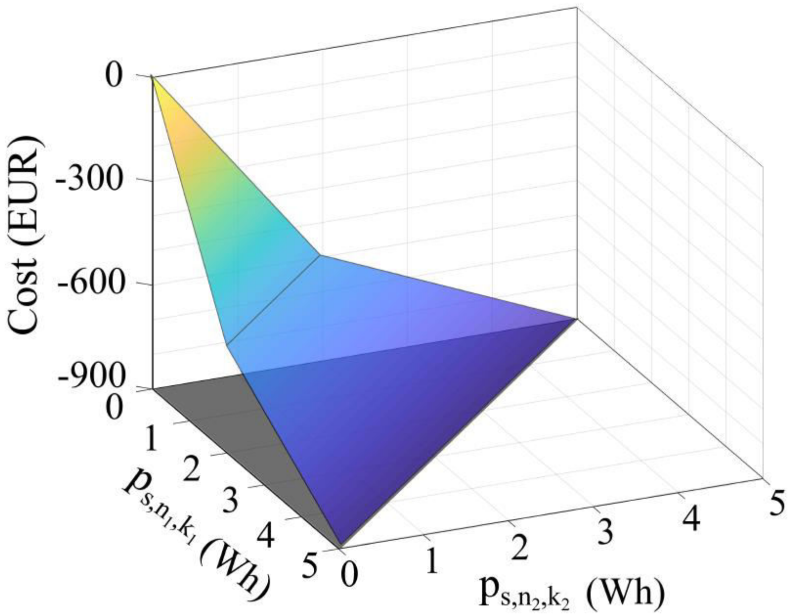
$$= \max_{x_s}\left\{300(-p_{s,n_1,k_1} - p_{s,n_2,k_2}) + 200x_s - 600,\ \text{s.t. operational constraints}\right\}$$

$$= \begin{cases} 300\left(-p_{s,n_1,k_1} - p_{s,n_2,k_2}\right), \text{ if } -p_{s,n_1,k_1} - p_{s,n_2,k_2} \leq 2 \\ 100\left(-p_{s,n_1,k_1} - p_{s,n_2,k_2}\right) + 400, \text{ otherwise.} \end{cases}$$

Limitations of price-quantity bids

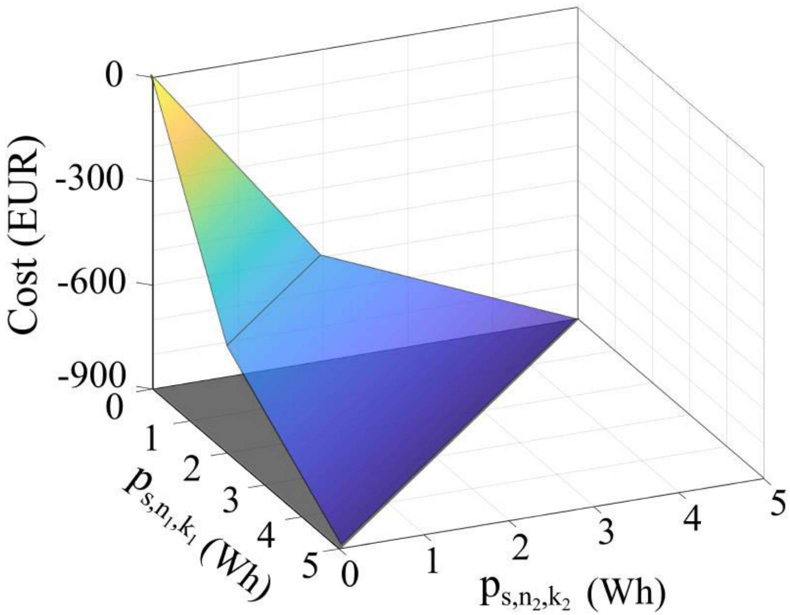
A stylized motivating example:



Cost function (transparent colored surface) and feasible region (gray surface) of the district heating utility

Limitations of price-quantity bids

A stylized motivating example:



Cost function (transparent colored surface) and feasible region (gray surface) of the district heating utility

Observations:

- The feasible region is not a box!
- The cost function is not additively separable piecewise linear!

Limitations of price-quantity bids

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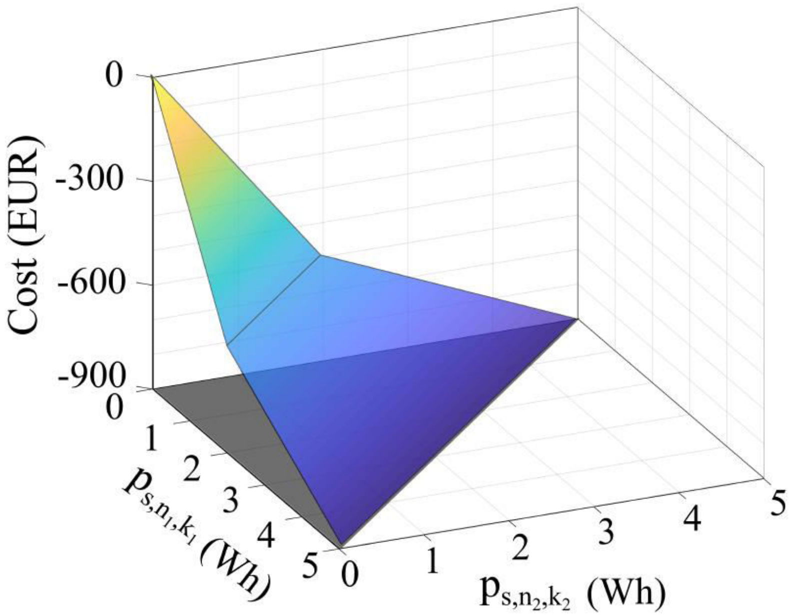


Cost function (transparent colored surface) and feasible region (gray surface) of the district heating utility

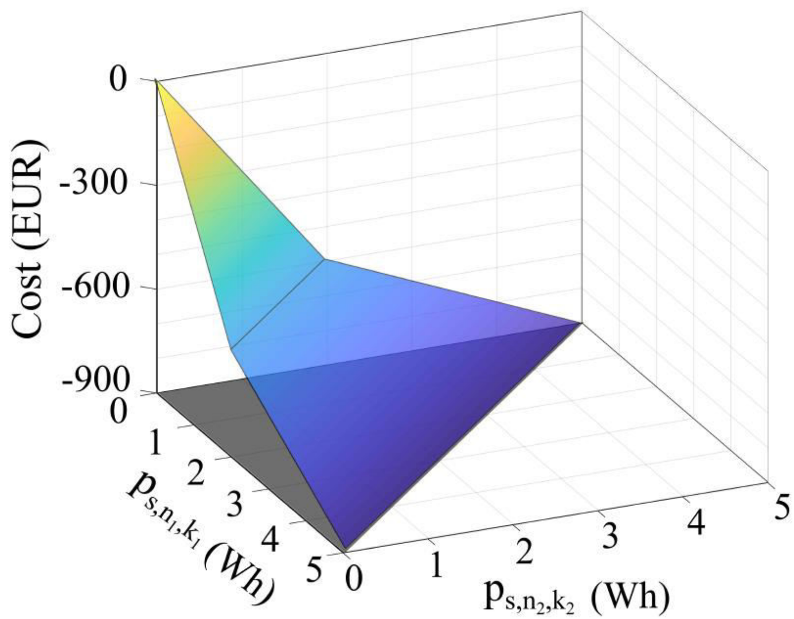
Observations:

- The feasible region is not a box!
- The cost function is not additively separable piecewise linear!

- So, this cost function and feasible space cannot be represented by a set of **price-quantity bids**, and approximation is needed!
- It cannot be also represented by a **block bid**!

Limitations of price-quantity bids

A stylized motivating example:



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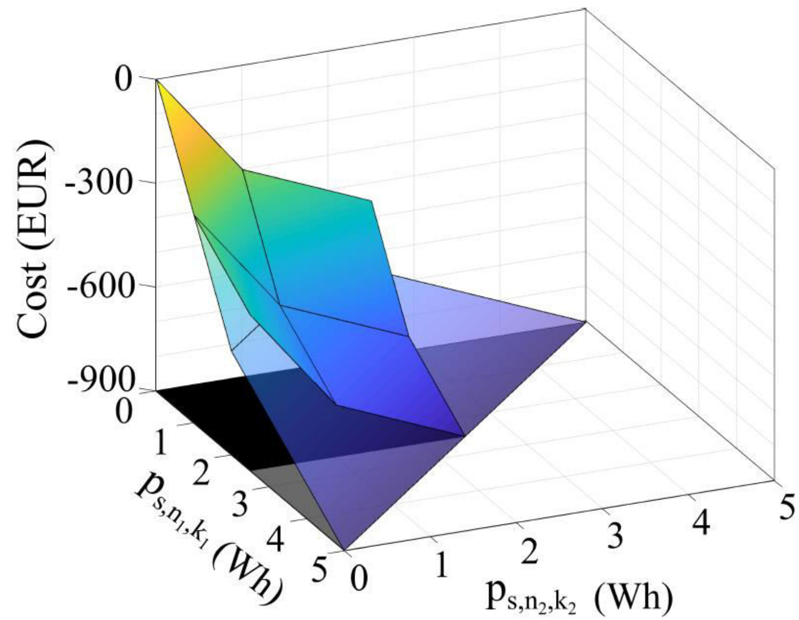

Approximation of the cost function as an additively separable piecewise linear cost function (solid colored surface) defined over a box feasible region (black rectangular surface).

Lesson learned by motivating example!

We need to design a **novel extended bid format** that allows a better representation of the technical and economic characteristics of a wide class of flexible assets across multiple locations and time periods.

Solution: Price-region bids

- ✓ From the perspective of the **electricity market operator**, this approach aims at revealing and exploiting additional flexibility from non-conventional assets in the power system.

- ✓ From the perspective of **market participants**, this approach aims at facilitating market access and revealing the value of their operational flexibility.

L. Bobo, L. Mitridati, J. A. Taylor, P. Pinson, and JK, ”Price-region bids in electricity markets," *European Journal of Operational Research*, vol. 295, no. 3, pp. 1056-1073, December 2021.

Price-region bids

Recall that the injection profile associated with a bid s is described by a vector $\boldsymbol{p_s} \in \mathbb{R}^{NK}$.

In addition, we introduce the vector $\boldsymbol{x_s}$ = $[x_{s,1}, \dots, x_{s,L_s}]$ whose entries are state variables associated with bid s.

Price-region bids

Definition 4:

A **price-region** bid s is defined as a pair of matrix $\boldsymbol{A_s} \in \mathbb{R}^{J_S \times (NK+L_S+1)}$ and vector $\boldsymbol{B_s} \in \mathbb{R}^{1 \times (NK+L_S)}$, so that

- the feasible region $\boldsymbol{\Omega_s}$ of the injection profile $\boldsymbol{p_s}$ of a bid s is given by

$$\boldsymbol{\Omega_s} = \left\{ \boldsymbol{p_s} \middle| \exists\, \boldsymbol{x_s} \in \mathbb{R}^{L_s}, \text{so that } \boldsymbol{A_s} \begin{bmatrix} \mathbf{1} \\ \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix} \le \mathbf{0}_{J_s} \right\},$$

- the cost associated with a feasible profile $\boldsymbol{p_s}$ writes as

$$\boldsymbol{F}_S^E(\boldsymbol{p_s}) = \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s} \begin{bmatrix} \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s.t. } \boldsymbol{A_s} \begin{bmatrix} \mathbf{1} \\ \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix} \le \mathbf{0}_{J_s} \right\} - \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s} \begin{bmatrix} \mathbf{0} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s.t. } \boldsymbol{A_s} \begin{bmatrix} \mathbf{1} \\ \mathbf{0} \\ \boldsymbol{x_s} \end{bmatrix} \le \mathbf{0}_{J_s} \right\}.$$

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- This matrix characterizes a set of linear constraints coupling the different variables in $\boldsymbol{p_s}$ and $\boldsymbol{x_s}$. a bid s is given by

$$\boldsymbol{\Omega_s} = \left\{ \boldsymbol{p_s} \middle| \; \exists \; \boldsymbol{x_s} \in \mathbb{R}^{L_s}, \text{so that } \boldsymbol{A_s} \begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix} \leq \boldsymbol{0}_{J_s} \right\},$$

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- This vector characterizes the economic value associated with each variable or combination of variables, i.e., the bidding prices.

$$F_S^E(\boldsymbol{p_s}) = \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s} \begin{bmatrix} \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s.t. } \boldsymbol{A_s} \begin{bmatrix} \mathbf{1} \\ \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix} \leq \mathbf{0}_{J_s} \right\} - \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s} \begin{bmatrix} \mathbf{0} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s.t. } \boldsymbol{A_s} \begin{bmatrix} \mathbf{1} \\ \mathbf{0} \\ \boldsymbol{x_s} \end{bmatrix} \leq \mathbf{0}_{J_s} \right\}.$$

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The opportunity cost, which is the difference between:

- the cost associated with a profile $\boldsymbol{p_s}$ given that the state variables $\boldsymbol{x_s}$ are set to their optimal values,
- the cost associated with no electricity injection/withdrawal given that the state variables $\boldsymbol{x_s}$ are set to their optimal values!

$$\boldsymbol{F}_S^E(\boldsymbol{p_s}) = \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s}\begin{bmatrix} \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s. t. } \boldsymbol{A_s}\begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{p_s} \\ \boldsymbol{x_s} \end{bmatrix} \leq \boldsymbol{0}_{J_s} \right\} - \min_{\boldsymbol{x_s}} \left\{ \boldsymbol{B_s}\begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{x_s} \end{bmatrix}, \text{s. t. } \boldsymbol{A_s}\begin{bmatrix} \boldsymbol{1} \\ \boldsymbol{0} \\ \boldsymbol{x_s} \end{bmatrix} \leq \boldsymbol{0}_{J_s} \right\}.$$

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Price-region bids

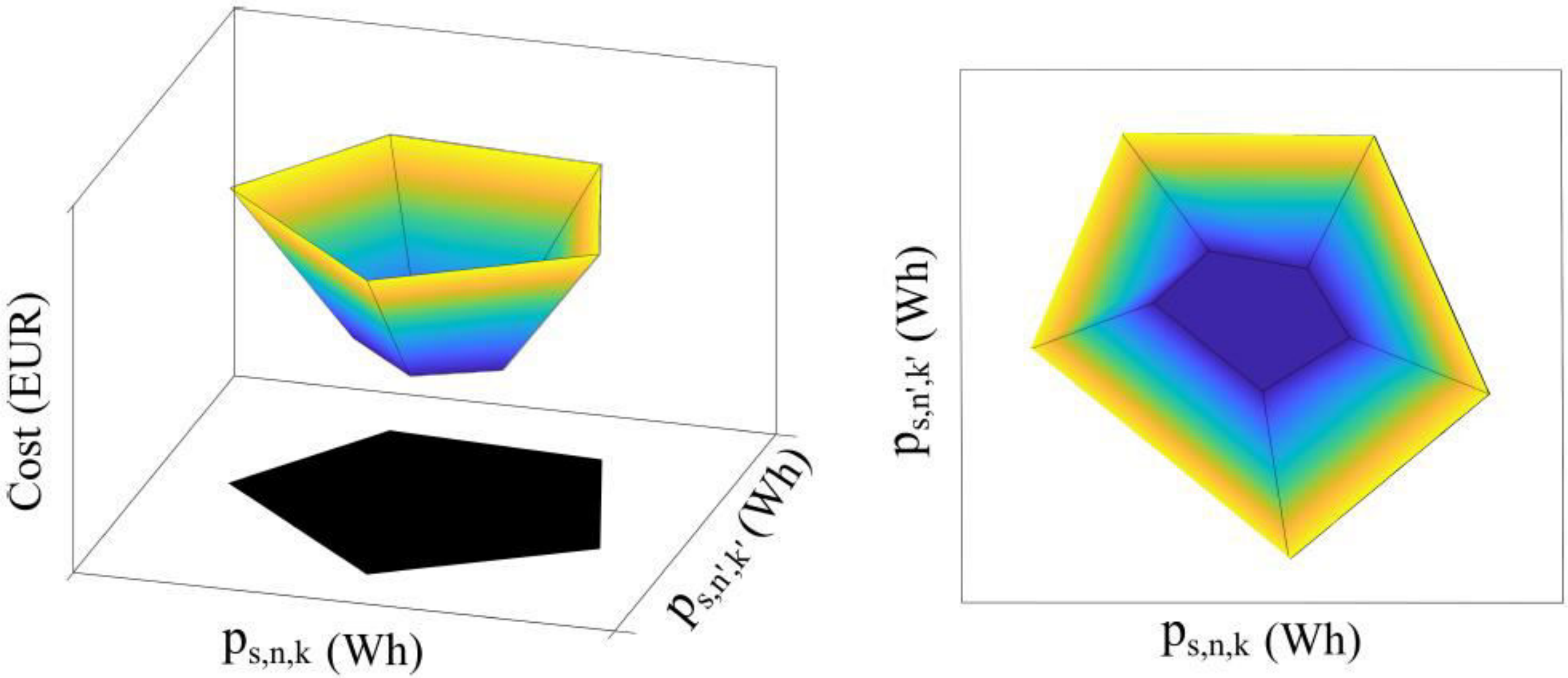

Illustration of an example price-region bid: Cost function (colored surface) defined over a linearly-constrained feasible region (black surface).

Price-region bids: For motivating example

$$\mathbf{A}_s = \begin{bmatrix} -5 & -1 & 0 & 0 & -1 & 1 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & -1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & -1 & 0 & 0 \\ -5 & -1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ -5 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ -3 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & -1 \end{bmatrix}, \quad \mathbf{B}_s^\top = \begin{bmatrix} 300 \\ 0 \\ 0 \\ 300 \\ -200 \end{bmatrix}$$

Generalized market clearing

Including both price-region (PR) and non-price-region bids:

$$\min_{\boldsymbol{p},\boldsymbol{x}} \sum_{s\in\Omega^{\mathrm{PR}}} \boldsymbol{b_s} \begin{bmatrix} \boldsymbol{p}_s \\ \boldsymbol{x}_s \end{bmatrix} + \sum_{s\notin\Omega^{\mathrm{PR}}} \mathcal{F}_s^{\mathrm{E}}(\boldsymbol{p}_s)$$

$$\text{s.t.} \quad \sum_{s=1}^{S} \boldsymbol{p_s} = \mathbf{0}_{NK} : \quad \boldsymbol{\lambda}^{\mathrm{E}}$$

$$A_s \begin{bmatrix} 1 \\ \boldsymbol{p}_s \\ \boldsymbol{x}_s \end{bmatrix} \leq 0, \quad \forall s \in \Omega^{\mathrm{PR}}$$

$$\boldsymbol{p_s} \in \Omega_s, \quad \forall s \notin \Omega^{\mathrm{PR}},$$

The intermediate steps for the reformulation of a clearing problem with price-region bids are provided in the original paper [A].

[A] L. Bobo, L. Mitridati, J. A. Taylor, P. Pinson, and JK, ”Price-region bids in electricity markets," *European Journal of Operational Research*, vol. 295, no. 3, pp. 1056-1073, December 2021.

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$$\boldsymbol{p_s} \in \Omega_s, \quad \forall s \notin \Omega^{\mathrm{PR}},$$

Note that variable $\boldsymbol{x}$ (i.e., state variables of flexible sources) has no physical meaning for the market operator!

The intermediate steps for the reformulation of a clearing problem with price-region bids are provided in the original paper [A].

[A] L. Bobo, L. Mitridati, J. A. Taylor, P. Pinson, and JK, "Price-region bids in electricity markets," *European Journal of Operational Research*, vol. 295, no. 3, pp. 1056-1073, December 2021.

Desirable market properties

Compared to desirable properties in a market with uniform pricing scheme and price-quantity bids, including

- Solution existence,
- Efficiency and incentive compatibility (under perfect competition assumption),
- Revenue adequacy and cost recovery,

the price-region bids do not violate any of those properties!

- All proofs are available in the paper.

Outline

- Sources of operational flexibility
  An example selected to be discussed:
  Coordination of power and heat systems

- Solution 1: New market products
  Two examples selected to be discussed:
  ✓ Asymmetric block offers by demand response aggregators
  ✓ Price-region offers by any flexible resource

- **Solution 2: New market players**
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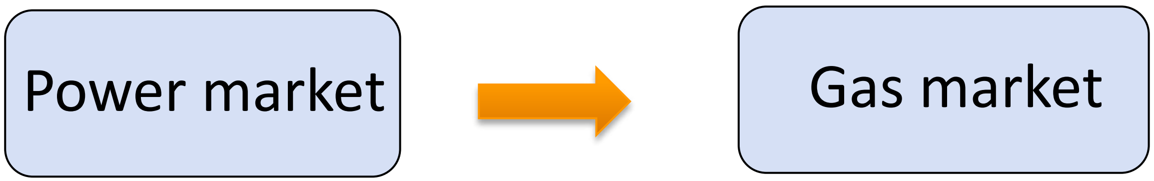
Sequence of power and gas markets in DK!

First power market clearing and then natural gas market clearing!



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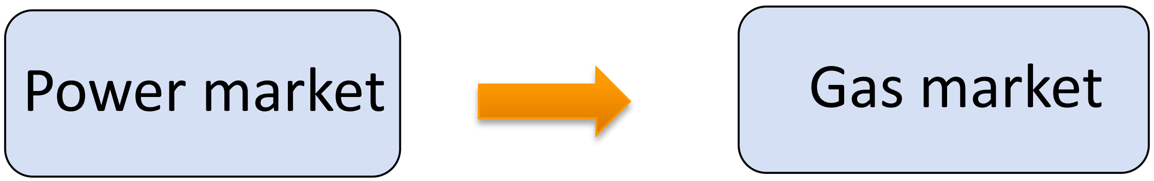
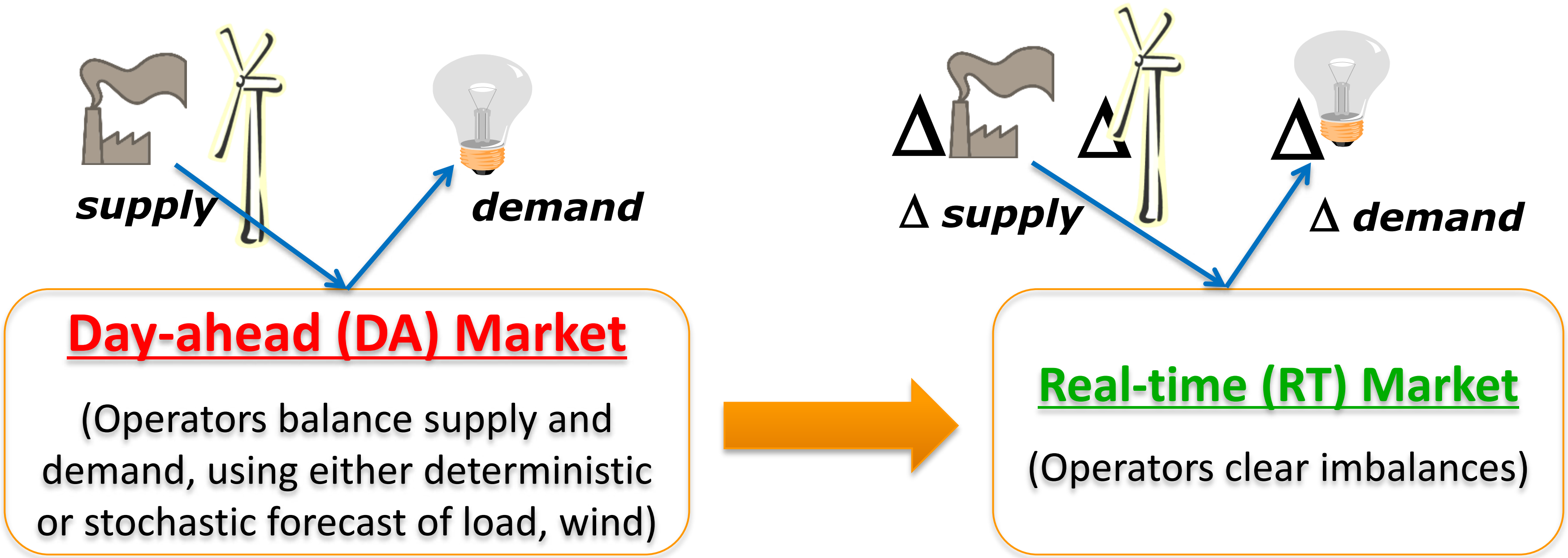


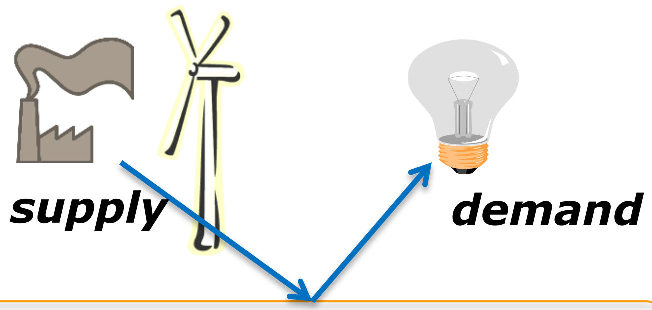
Each **gas-fired power plant**:

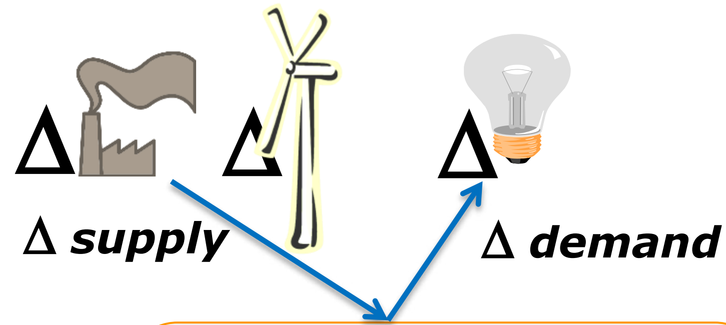
- first, estimates the gas price and accordingly offers in the power market as a producer
- then, based on dispatched quantity, bids in the gas market as a consumer

Two-Stage Settlement



Two-Stage Settlement





Day-ahead (DA) Market

(Operators balance supply and demand, using either deterministic or stochastic forecast of load, wind)

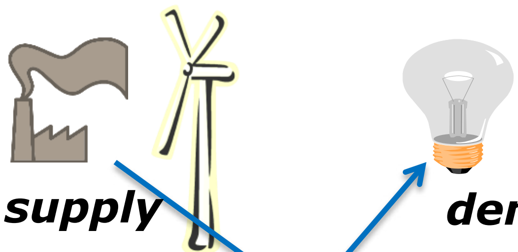
→

Real-time (RT) Market

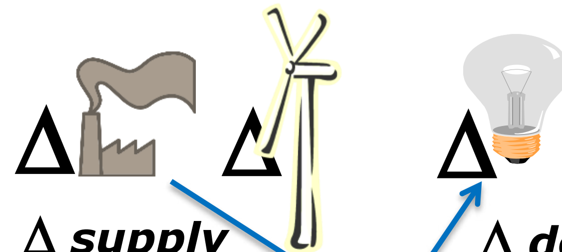
(Operators clear imbalances)

I Power market (DA)

Two-Stage Settlement



supply *demand*



Δ supply *Δ demand*

Day-ahead (DA) Market

(Operators balance supply and demand, using either deterministic or stochastic forecast of load, wind)

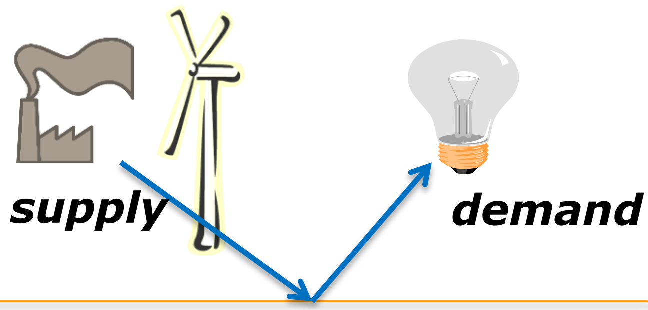
Real-time (RT) Market

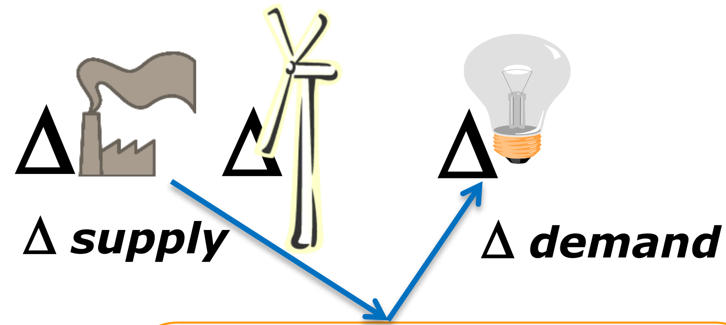
(Operators clear imbalances)

I Power market (DA)

II Gas market (DA)

Two-Stage Settlement





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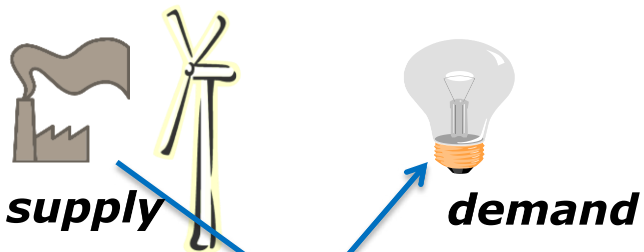

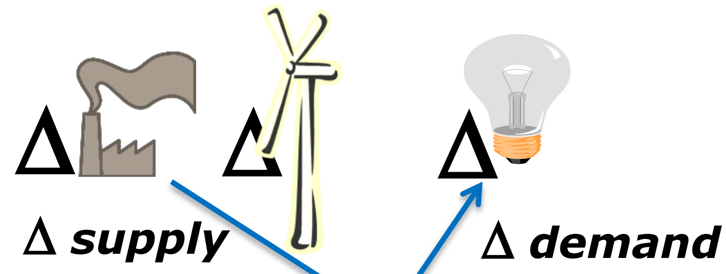

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Real-time (RT) Market

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I Power market (DA)

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III Power market (RT)

IV Gas market (RT)

Virtual Bidding

- It exists in current US electricity markets, e.g., CAISO, PJM and MISO
- The virtual bidder has no physical asset!
- The virtual bidder buys (sells) in the day-ahead market and then sells (buys) the same amount back in the real-time market.

- JK and B. F. Hobbs, "Value of flexible resources, virtual bidding, and self-scheduling in two-settlement electricity markets with wind generation -- Part I: Principles and competitive model," *IEEE Transactions on Power Systems*, vol. 33, no. 1, pp. 749-759, Jan. 2018.

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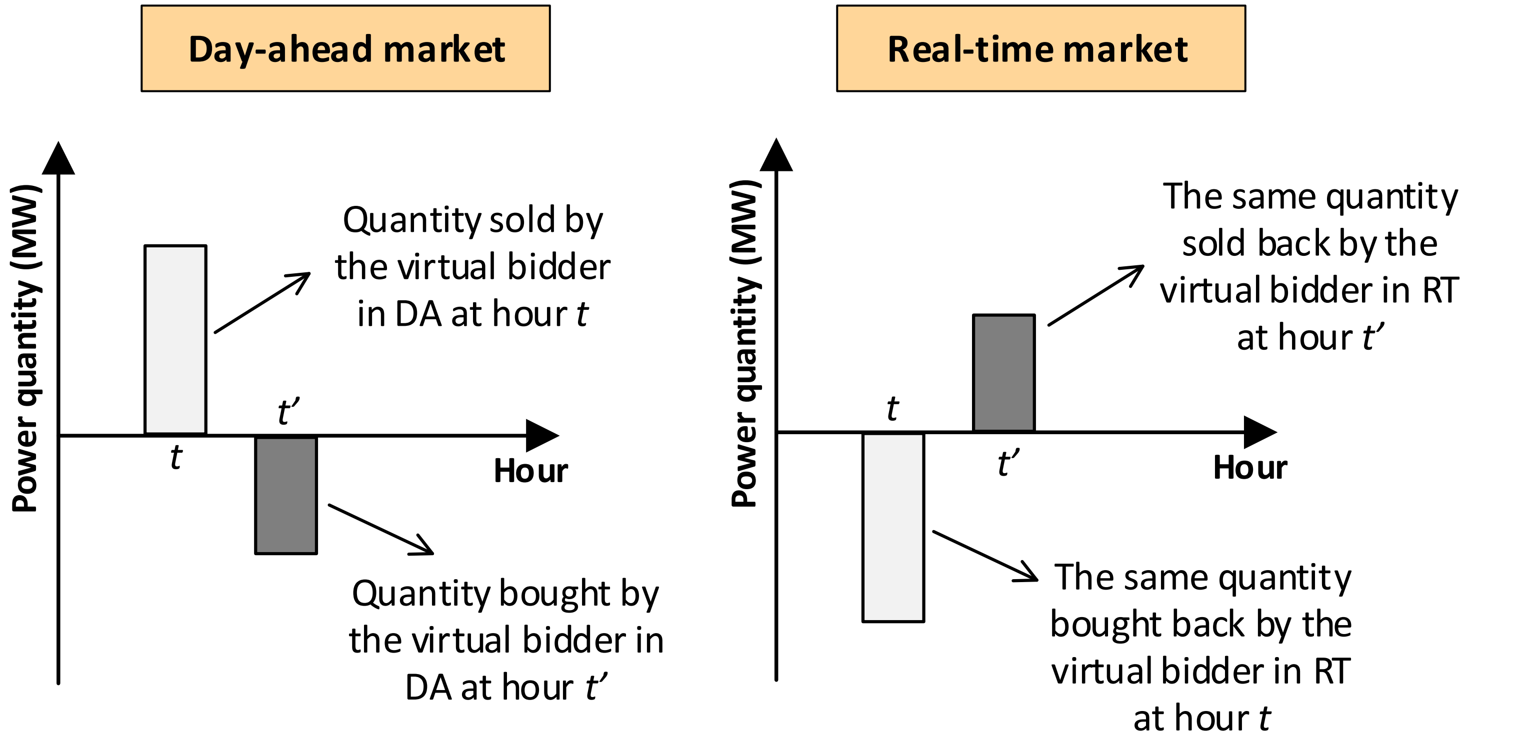

Alternative Market Clearing Models

Model 1: Stochastic Market Clearing (ideal solution)

Alternative Market Clearing Models

Model 1: Stochastic Market Clearing (ideal solution)

- The set of wind scenarios and their probabilities are known in day-ahead stage, but which one actually occurs in real-time stage is unknown.
- A joint system operator for power and gas sectors solves a single *stochastic* optimization problem, considering day-ahead and real-time power and gas markets *simultaneously*.

Total expected cost minimization:

Minimize [power cost in day ahead] + [expected power cost in real time]
+ [gas cost in day ahead] + [expected gas cost in real time]

Alternative Market Clearing Models

Model 1: Stochastic Market Clearing (ideal solution)

Challenges:

- Stochastic market clearing is *incompatible* with the current practice of real-world electricity markets!

- Its implementation would place a *large burden* on the system operator to develop this information and to obtain stakeholder consent for the procedures involved!

Alternative Market Clearing Models

Model 2: Sequential Market Clearing

Alternative Market Clearing Models

Model 2: Sequential Market Clearing

- ***First*,** the power and gas system operators clear the day-ahead power and then gas markets using a deterministic forecast, ***then*** clear the real-time markets.

- Each optimization is a ***deterministic*** problem!

Alternative Market Clearing Models

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Day-ahead market:

Minimize [power cost in day ahead]

Alternative Market Clearing Models

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Day-ahead market:

Minimize [power cost in day ahead] → Minimize [gas cost in day ahead]

Alternative Market Clearing Models

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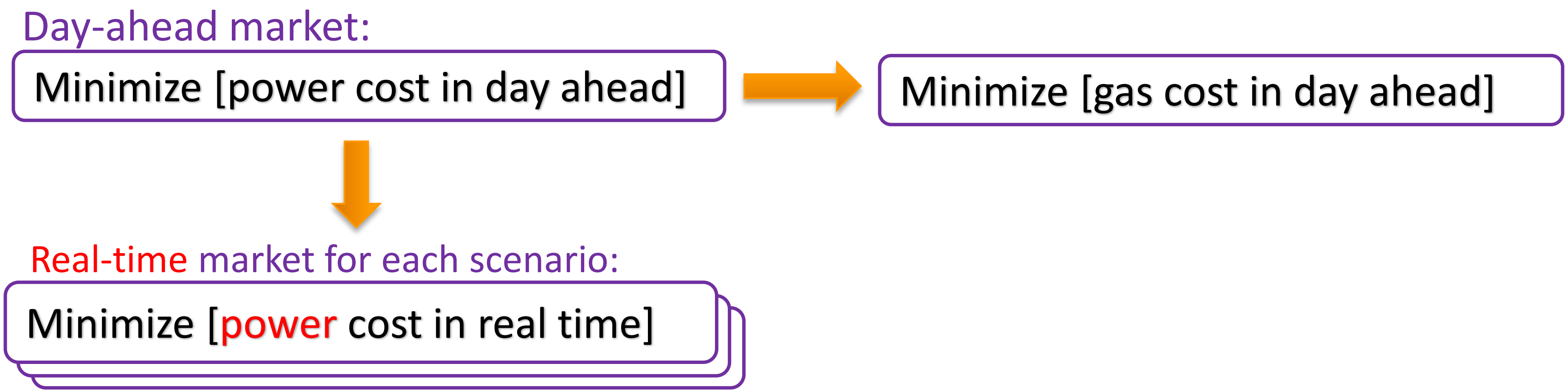

Alternative Market Clearing Models

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Day-ahead market:

Minimize [power cost in day ahead] → Minimize [gas cost in day ahead]

↓ ↓

Real-time market for each scenario:

Minimize [power cost in real time] → Minimize [gas cost in real time]

Real-time market for each scenario:

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders

Day-ahead market:

Minimize [power cost in day ahead]

Minimize [gas cost in day ahead]

Real-time market for each scenario:

Minimize [power cost in real time]

Real-time market for each scenario:

Minimize [gas cost in real time]

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders

Day-ahead market:

Minimize [power cost in day ahead]

Minimize [gas cost in day ahead]

Real-time market for each scenario:

Minimize [power cost in real time]

Real-time market for each scenario:

Minimize [gas cost in real time]

Each virtual bidder in power sector:

Maximize [expected profit]

Each virtual bidder in gas sector:

Maximize [expected profit]

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders

Day-ahead market:

Minimize [power co... ...day ahead]

Real-time market for ...ch scenario:

Minimize [power co... ...real time]

$$\underset{v^{\mathrm{DA}},v^{\mathrm{RT}}}{\text{maximize}} \ \left[v^{\mathrm{DA}} \times \lambda^{\mathrm{DA}}\right] + \sum_{\omega} \pi_{\omega} \left[v^{\mathrm{RT}} \times \lambda^{\mathrm{RT}}_{\omega}\right]$$

s.t.

$$v^{\mathrm{DA}} + v^{\mathrm{RT}} = 0$$

v^{DA}: trade in DA [MW]
v^{RT}: trade in RT [MW]
λ^{DA}: DA price [$/MWh]
$\lambda^{\mathrm{RT}}_{\omega}$: RT price per scenario [$/MWh]
π_{ω}: probabilities

Each virtual bidder in power sector:

Maximize [expected profit]

Each virtual bidder in gas sector:

Maximize [expected profit]

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders

Day-ahead market:

Minimize [power cost in day ahead] → Minimize [gas cost in day ahead]

↓ ↓

Real-time market for each scenario:

Minimize [power cost in real time] → Real-time market for each scenario: Minimize [gas cost in real time]

This problem is an **equilibrium** (not an optimization!)

Each virtual bidder in power sector:

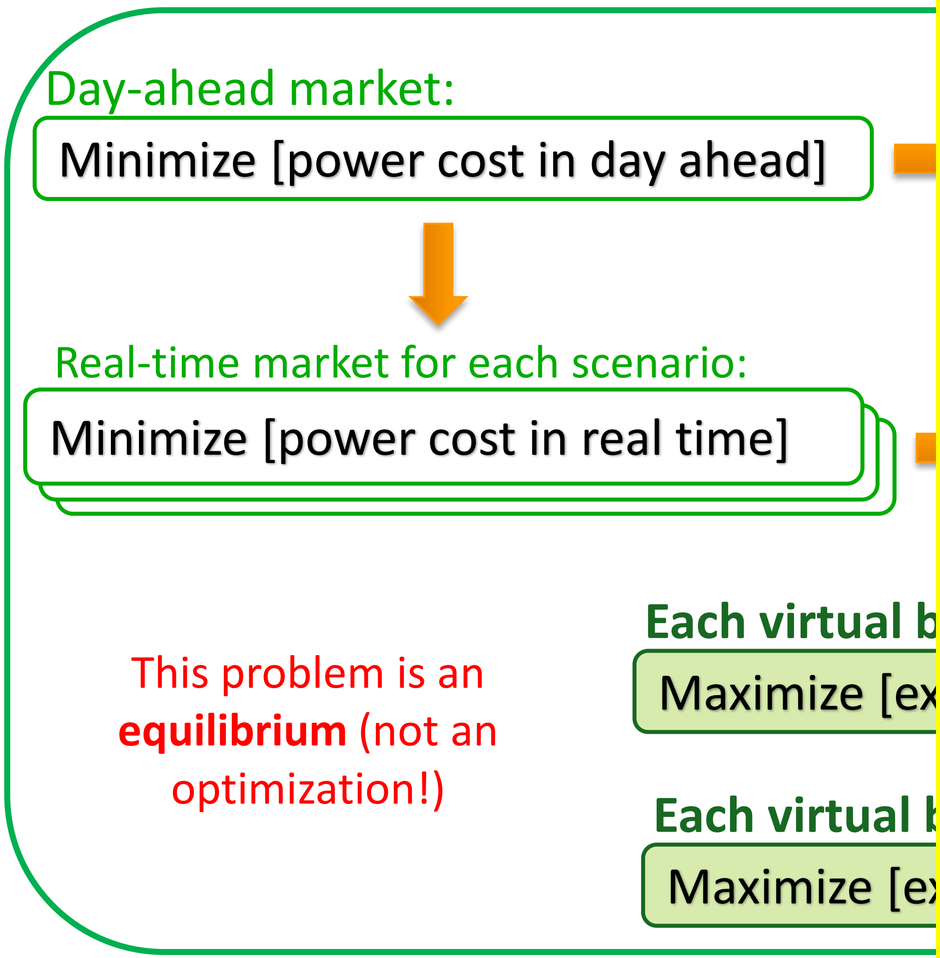
Maximize [expected profit]

Each virtual bidder in gas sector:

Maximize [expected profit]

Alternative Market Clearing Models

Model 3: Sequential Market Clearing with Virtual Bidders



- Extended version of Model 2 (sequential market clearing)
- Virtual bidders are the only market players who "**perfectly**" know the distribution of real-time prices across scenarios!
- Unlike the system operators who sequentially solve deterministic problems, each virtual bidder solves a two-stage stochastic problem.

Alternative Market Clearing Models

Model 4: Sequential Market Clearing with Virtual Bidders and Self-Scheduling Gas-fired Generators

Alternative Market Clearing Models

Model 4: Sequential Market Clearing with Virtual Bidders and Self-Scheduling Gas-fired Generators

Day-ahead market:

Minimize [power cost in day ahead]

Minimize [gas cost in day ahead]

Real-time market for each scenario:

Minimize [power cost in real time]

Real-time market for each scenario:

Minimize [gas cost in real time]

Each virtual bidder in power sector:

Maximize [expected profit]

Each self-scheduling gas-fired plant :

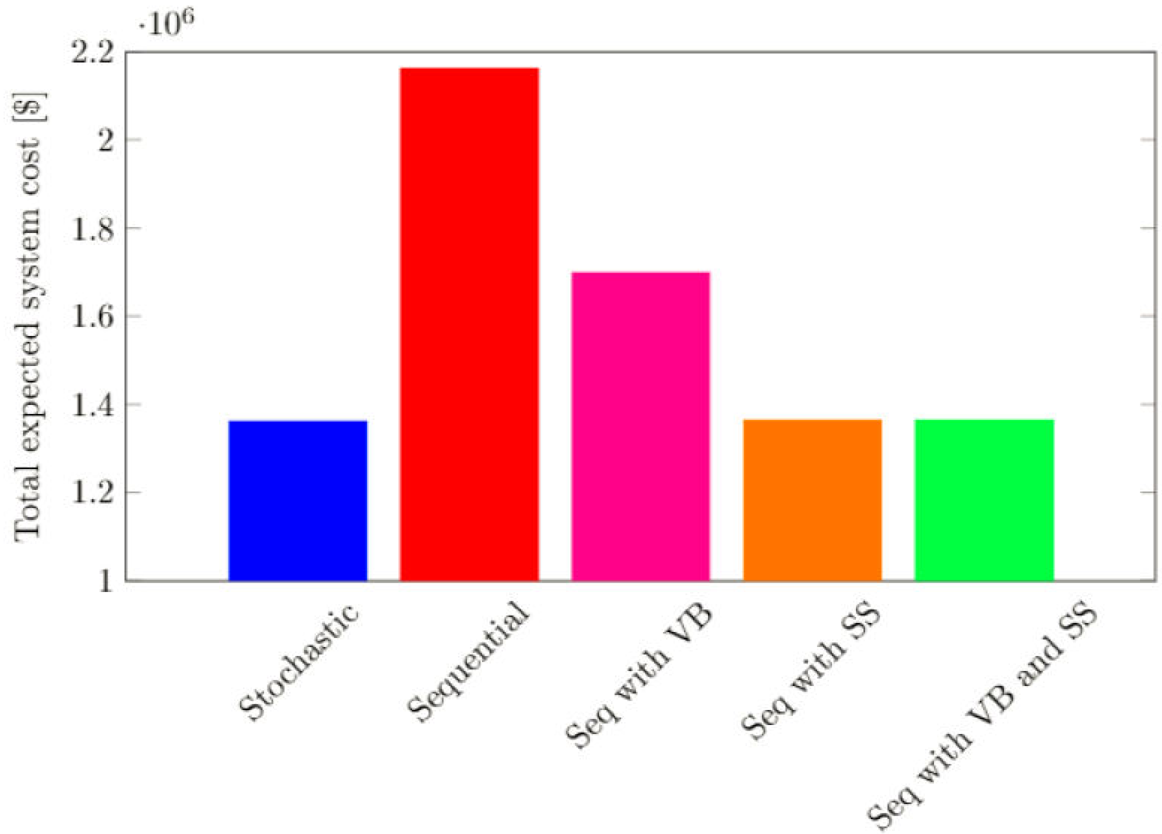
Maximize [expected profit]

Each virtual bidder in gas sector:

Maximize [expected profit]

A case study

- With 10 generators, 3 natural gas suppliers, 24 hours, 5 scenarios



VB: Virtual bidding

SS: Self-scheduling

Seq: Sequential

A. Schwele, C. Ordoudis, P. Pinson, and JK, "Coordination of power and natural gas markets via financial instruments," *Computational Management Science*, vol. 18, pp. 505-538, 2021.

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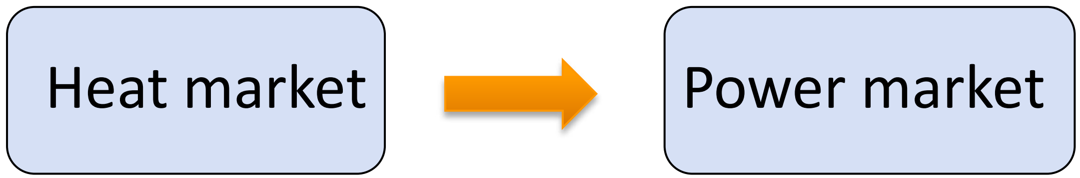
Coordination of heat and power markets

Three alternatives:

1- Sequential market clearing (current structure in Denmark)



Coordination of <u>heat</u> and <u>power</u> markets

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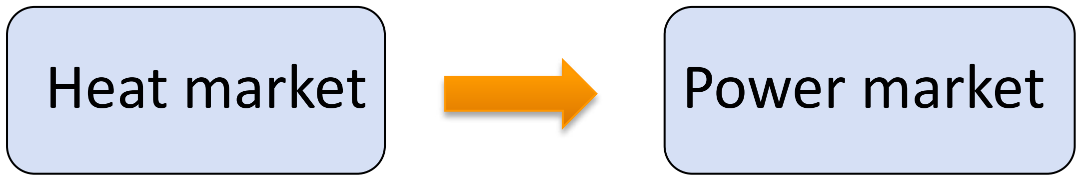
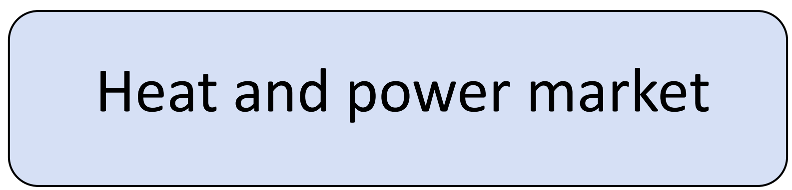


2- Co-optimization (ideal benchmark)



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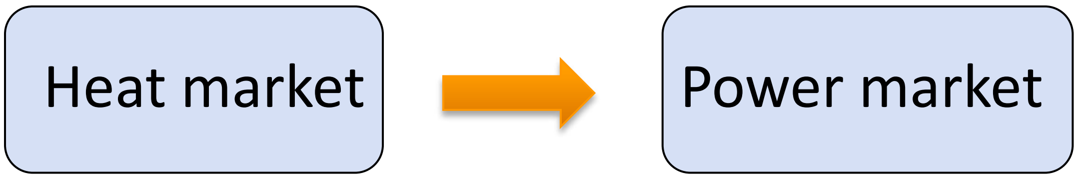

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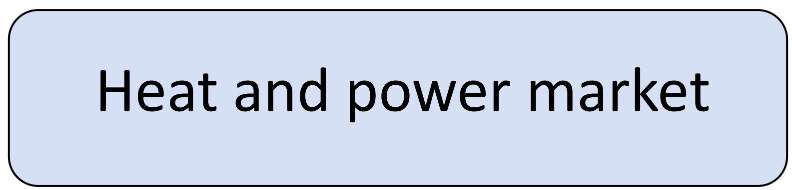
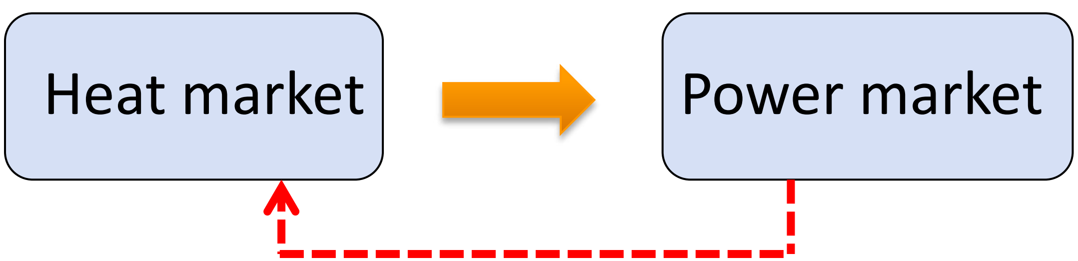


3- Improved sequential market clearing (*<u>electricity-aware</u>* heat market)



Coordination of heat and power markets

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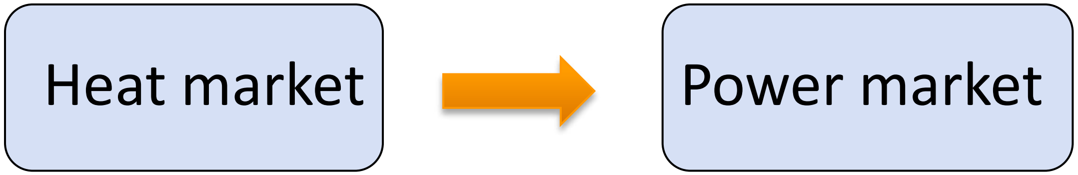


Step 1) Day-ahead heat market (Varmelast.dk)

Step2) Day-ahead electricity market (Nordpool)

Coordination of heat and power markets

1- Sequential market clearing (current structure in Denmark)

Heat market → Power market

- Simple, decoupled markets framework
- Interactions implicitely modelled through heat marginal costs

- Heat-driven dispatch: limited flexibility
- Need to anticipate impact of CHPs and HPs in electricity market
- Does not account for the uncertainty from the power system

Coordination of heat and power markets

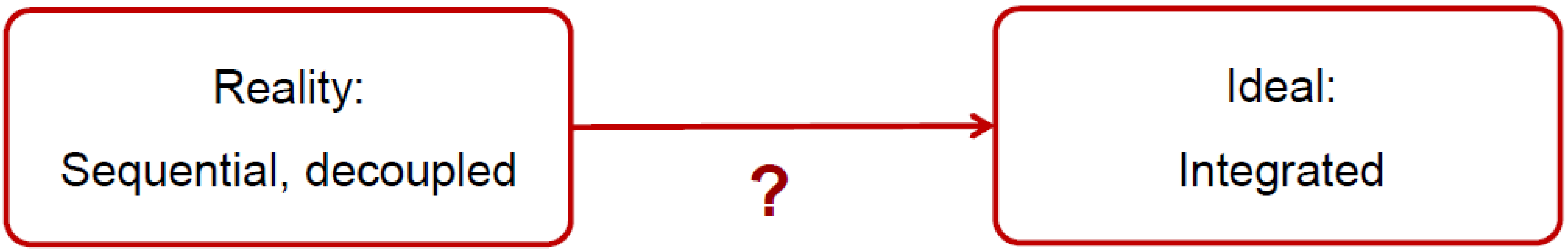
2- Co-optimization (ideal benchmark)

Heat and power market

- Exploit maximum operational flexibility from heat system
- Ideal benchmark for heat and electricity systems coordination

- Does not respect current market regulations!

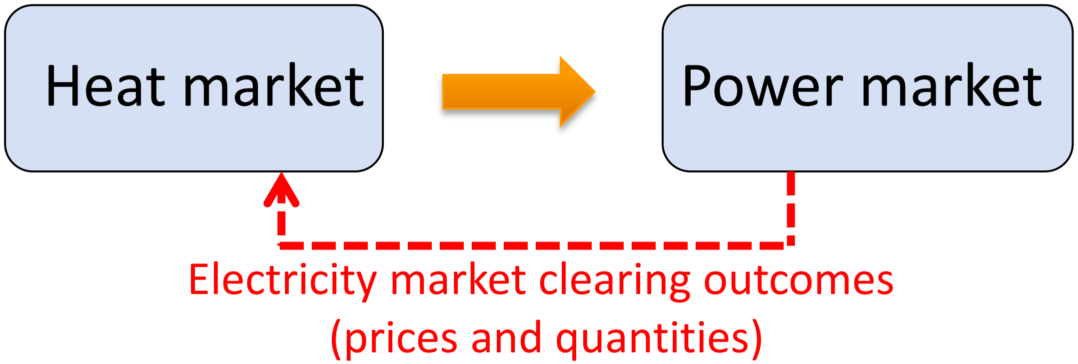
Coordination of heat and power markets



Question: How to increase the coordination between heat and power systems, while respecting current (sequential) markets regulations?

Coordination of heat and power markets

3- Improved sequential market clearing (*electricity-aware* heat market)



Sequential:

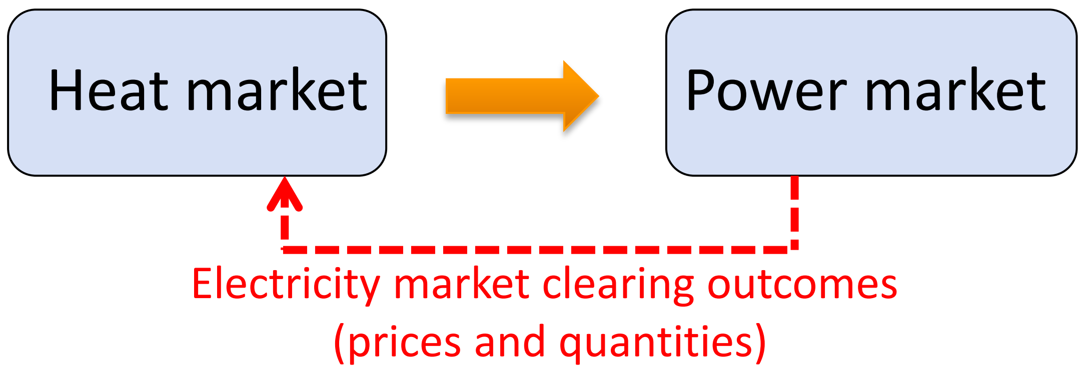
1- Heat market clearing

Constrained by power market clearing (under different scenarios)

2- Power market clearing

Coordination of heat and power markets

3- Improved sequential market clearing (*electricity-aware* heat market)



Sequential:

Stochastic bi-level optimization problem!

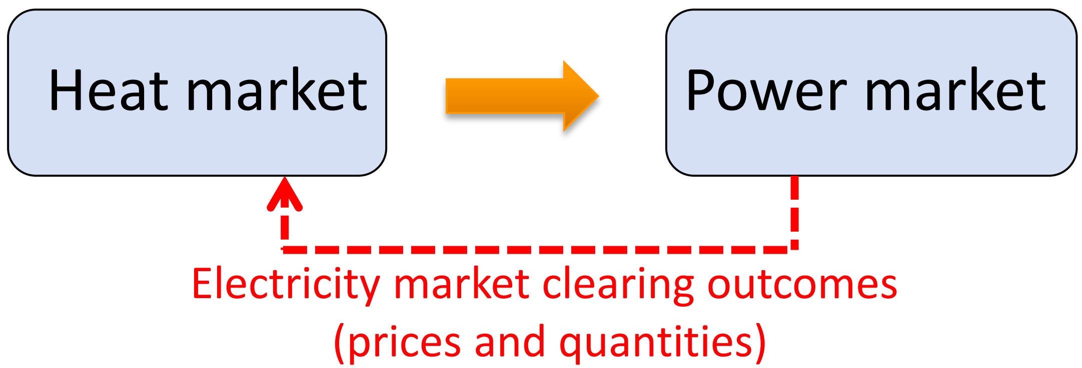
1- Heat market clearing

Constrained by power market clearing (under different scenarios)

2- Power market clearing

Coordination of heat and power markets

3- Improved sequential market clearing (*electricity-aware* heat market)



- Exploit operational flexibility
- Respects current markets regulations

- Computational complexity (large number of scenarios)

Coordination of heat and power markets

✓ Mitridati et al. implements a **regularized Benders decomposition** method to ease solving the proposed stochastic bi-level problem.

L. Mitridati, JK, and P. Pinson, “Heat and electricity market coordination: A scalable complementarity approach," *European Journal of Operational Research*, vol. 283, no. 3, pp. 1107-1123, June 2020.

Coordination of heat and power markets

✓ Mitridati et al. implements a regularized Benders decomposition method to ease solving the proposed stochastic bi-level problem.

✓ For a case study (24-bus RTS system, 4 CHPs, 6 HPs, 3 HSs, 24 hours, 216 scenarios):

	Sequential	Co-optimization	Improved sequential
Energy system cost ($)	48,526	39,064	41,149
Wind curtailment (MWh)	247	95	188

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Performance in terms of system cost:

Co-optimization > Improved sequential > Sequential

L. Mitridati, JK, and P. Pinson, "Heat and electricity market coordination: A scalable complementarity approach," *European Journal of Operational Research*, vol. 283, no. 3, pp. 1107-1123, June 2020.

Conclusion

➢ We present different market-based solutions for revealing (ideally the full) operational flexibility of existing assets in energy systems. These solutions are

- New market products,
- New market players,
- Proper (re-)design of energy markets.

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Discussion:

Any other solution? or any other example of market products, players or market (re-)design?

Thank you!

Jalal Kazempour

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www.jalalkazempour.com