Aalto University
School of Science

Power and Heat Market Model

Cross-Commodity Effects in the Nordic Energy System

Vilma Virasjoki[a], Afzal S. Siddiqui[b,c], Behnam Zakeri[d], and Ahti Salo[a]

[a] Department of Mathematics and Systems Analysis, Aalto University School of Science, Finland
[b] Department of Statistical Science, University College London, UK
[c] Department of Computer and Systems Sciences, Stockholm University, Sweden
[d] Department of Mechanical Engineering, Aalto University School of Engineering, Finland

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Systems Analysis Laboratory

Agenda

1. **Background and research objectives**

2. **Model: Problem formulation**

3. **Numerical example and conclusions**

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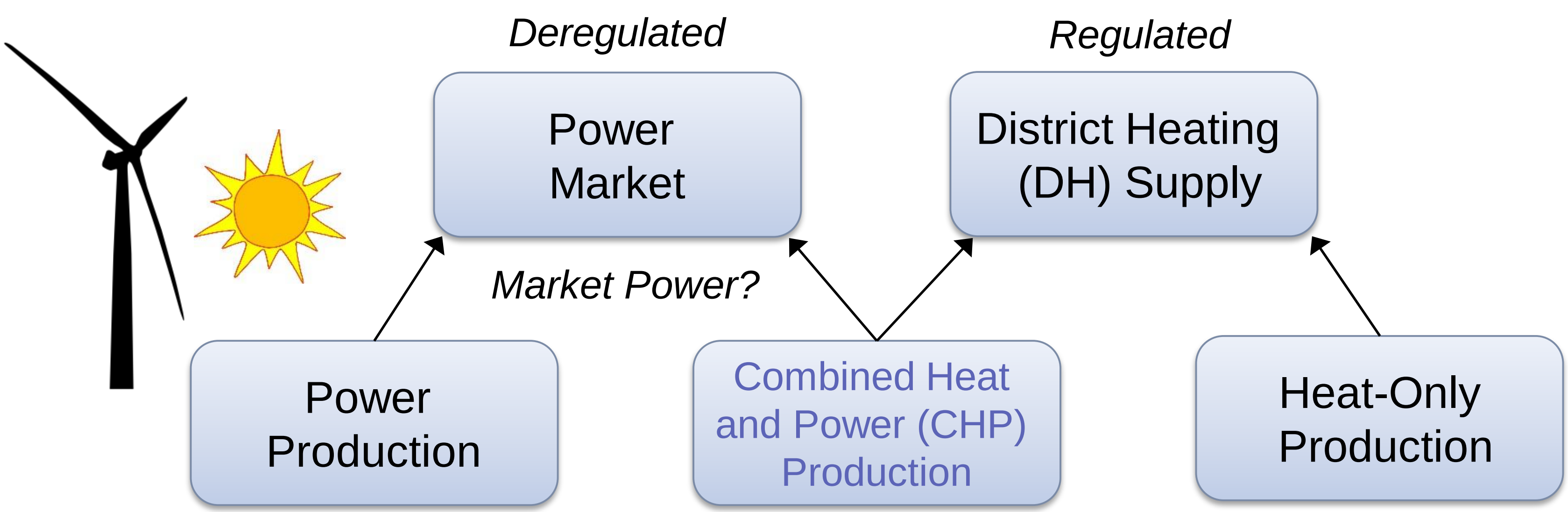
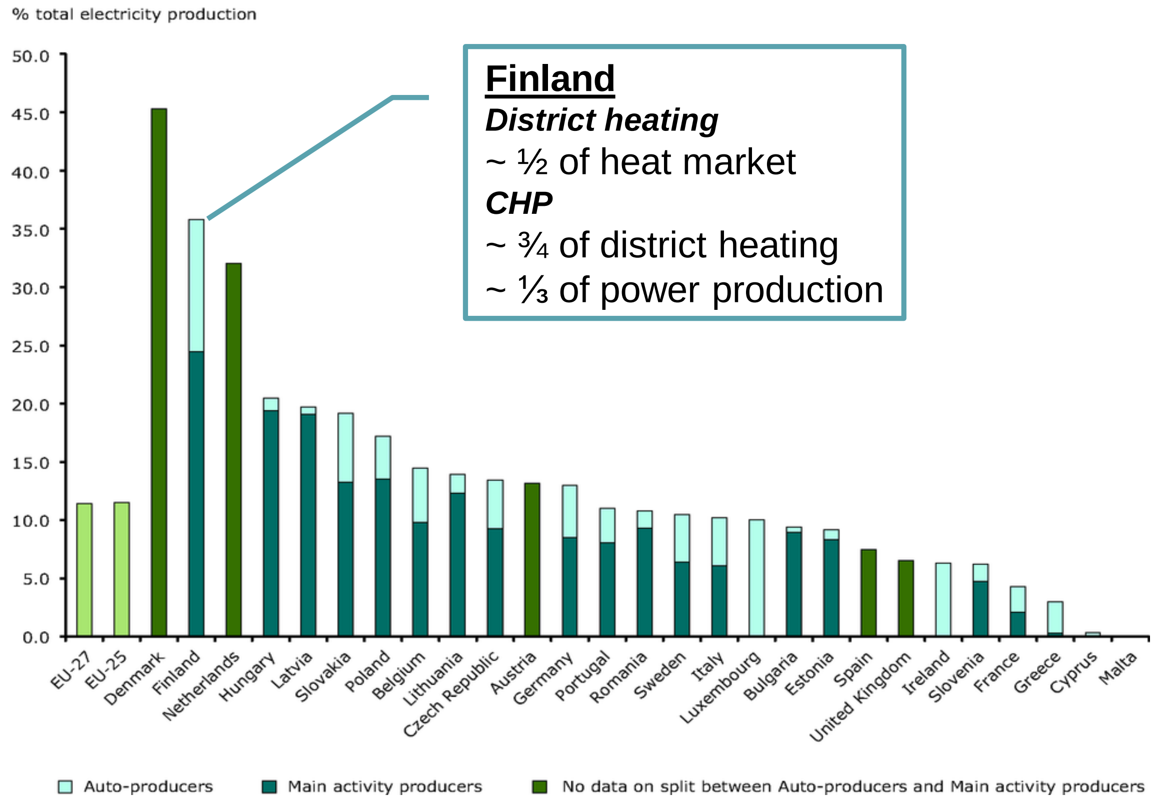
Background

- **Asymmetrically linked** power and heat markets
- **A paradigm shift**: Non-dispatchable renewables, decentralisation, efficiency requirements…



Is This Significant?

- CHP: ~12% of annual power production in the EU-28[1] and in the U.S.[2]
- CHP production
  1. increases **resource efficiency** and (thus)
  2. **creates less emissions**



[1] Eurostat 2013, [2] Combined Heat and Power (CHP) Technical Potential in the United States, US Department of Energy 2016.
Figure source: 2009, European Environment Agency (EEA), Eurostat

Literature Review: CHP

- **Wu & Rosen (1999):** ***An equilibrium model*** of a conventional power system and CHP-based district energy
  - Perfect competition; no network, VRE, or heat-only generation
  - ***Cogeneration has a positive impact on social welfare***

- **Lund et al. (2010):** In Denmark, the optimal heating solution is to gradually ***expand district heating (DH) to cover more from total heat supply*** – however, as a result of excess wind production, electric heating & heat pumps become more attractive to CHP

- **Lund et al. (2005):** To integrate wind power, an ***important flexibility would be to include CHP units into regulation***

Literature Review: Market Power

- **Joskow (2008):** ***Market power can arise e.g. from*** transmission constraints, concentrated generation ownership, vertically integrated systems, non-storability of electricity, or low elasticity of electricity demand
  - Evidence presented e.g. from the UK, Texas, and California

- **Fridolfsson & Tangerås (2009):** To what extent is market power used in Nord Pool? Review of studies in 2000-2008
  - Price higher than marginal cost: ***No evidence of systematic use***
  - Regional market power when transmission capacity insufficient?
  - Perspectives of long-term investments, entry deterrence, water value optimizing, and baseload capacity withholding

Research Objectives and Contribution

Research objectives

- Identify **market impacts** of **CHP & the asymmetrical link**
- In particular, how is **market power** reflected in such a system:
  - Does CHP's link to regulated markets mitigate market power?
  - Is market power reflected in the DH supply, too?

Framework

- Complementarity modeling
- Power & DH production, heat storage
- Perfect vs. imperfect competition (market power) at power markets
- Numerical example: Nord Pool Area

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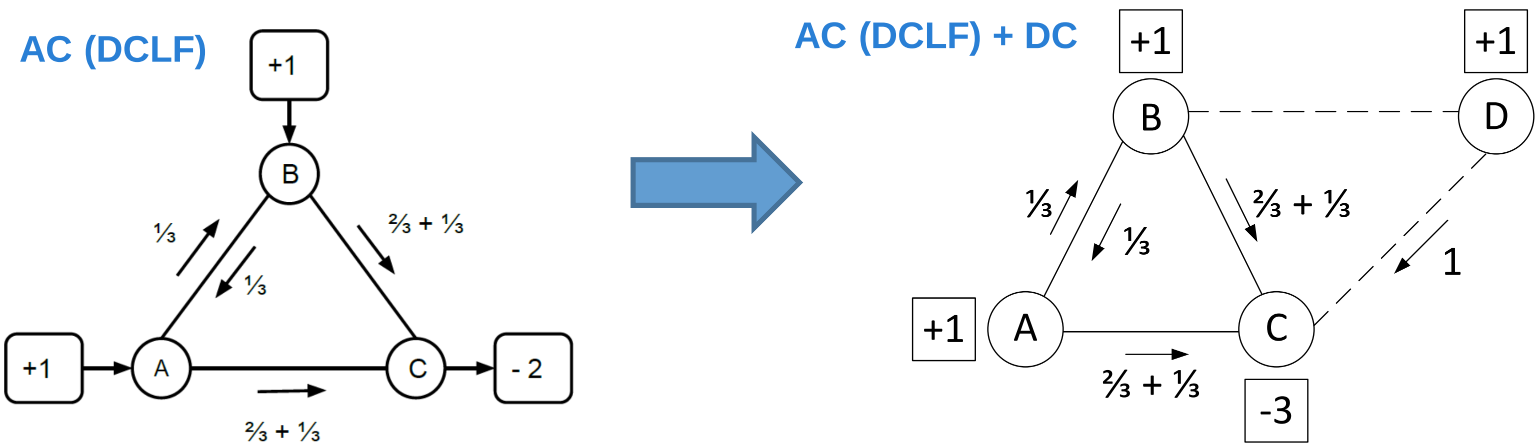
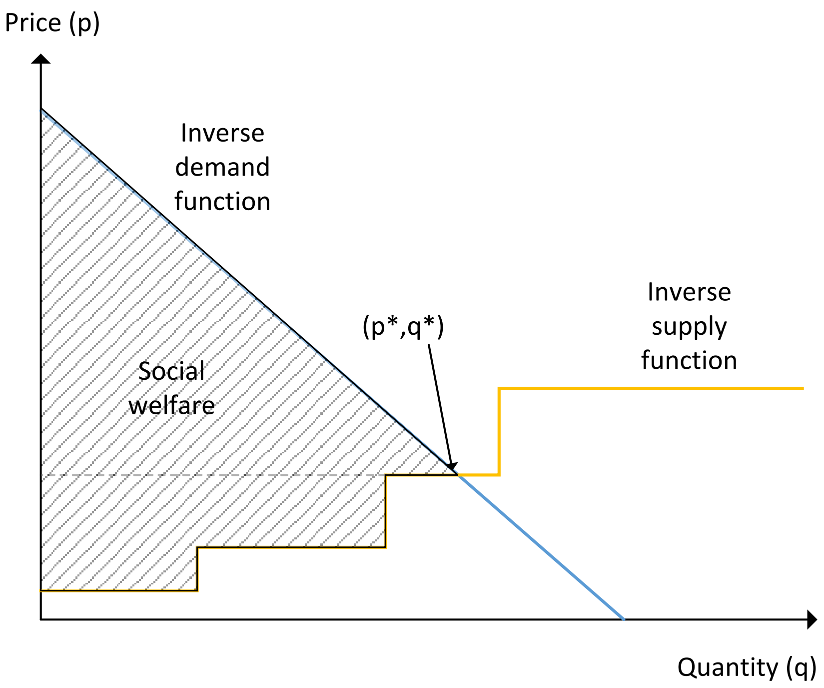
Problem Formulation: Assumptions

1. **Transmission grid** as A mix of AC lines (DCLF linearization) and DC lines
2. **District heating (DH)** within the nodes, electricity can be transmitted
3. **Heat** can be stored
4. **CHP** production determined by a fixed power-to-heat ratio
5. **RE** production based on availability factors, priority grid access
6. **Hydro** with calibrated water values, seasonal availability factors



Problem Formulation: Market Setting

1. **Perfect competition: Social welfare maximization**
   - Equivalent: Profit maximizing, price-taking producers
2. **Imperfect competition (Cournot oligopoly): Nash-Cournot equilibrium**
   - Decisions: production quantities
   - The impact of one's decisions seen on the total supply



- **Consumers: Linear inverse demand function**

Problem Formulation: Decision-Makers

- **Market participants' simultaneous optimization problems**

Producers:

A. Objective: **Maximize profit from power sales (incl. congestion fees) and heat sales**
B. Decisions: **Conventional power plants, CHP, heat-only, and heat storage**
C. Constraints:

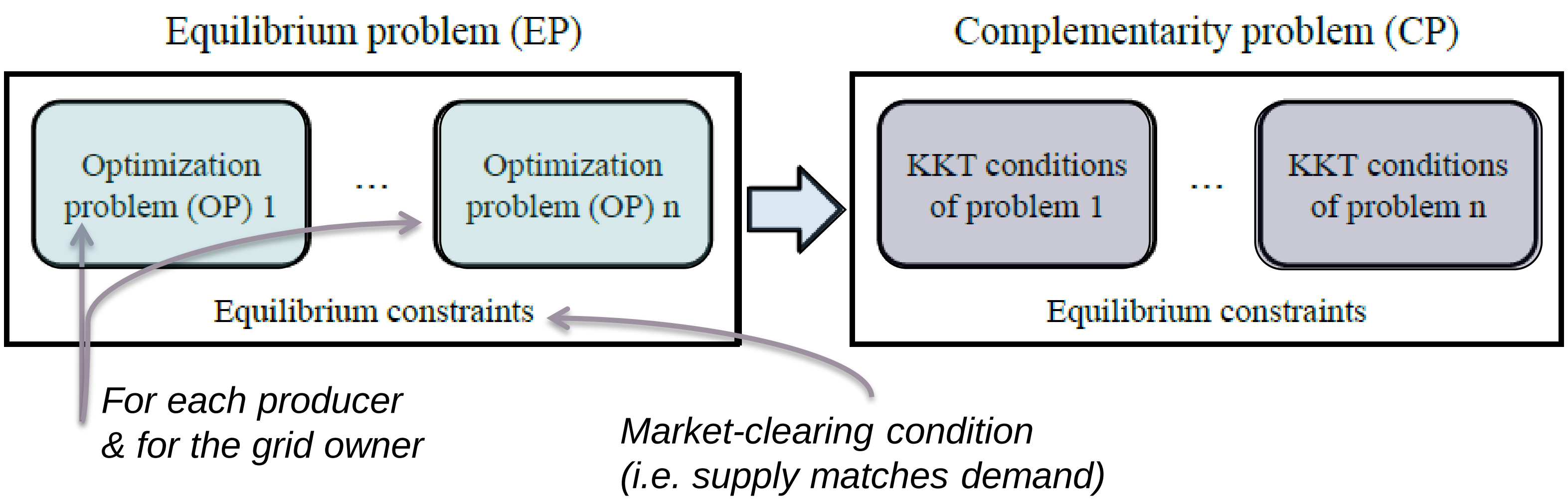
1. Energy balance (power and heat)
2. Maximum generation capacity (power, CHP, heat-only)
3. Generation ramping (power, CHP, heat-only)
4. Minimum share of heat from heat-only production
5. Storage constraints (min, max, balance, ramping rates)

Grid owner:

A. Objective: **Maximise profit from congestion fees** (Hobbs, 2001)
B. Decisions: **Electricity transmission between nodes** (voltage angle for AC grid, flow for DC lines)
C. Constraints:

1. Loopflow constraint for AC-lines
2. Maximum transmission capacity

Mixed Complementarity Problem (MCP)



$$\begin{aligned} &\min_x f(x) \\ s.t.\quad &h(x) = 0 \\ &g(x) \leq 0 \end{aligned}$$

$$\mathcal{L} = f(x) + \lambda^T h(x) + \mu^T g(x)$$

Lagrangian function

$$\begin{aligned} &\nabla_x f(x) + \lambda^T \nabla_x h(x) + \mu^T \nabla_x g(x) = 0 \\ &h(x) = 0 \\ &0 \leq \mu \perp g(x) \leq 0, \end{aligned}$$

Complementarity conditions

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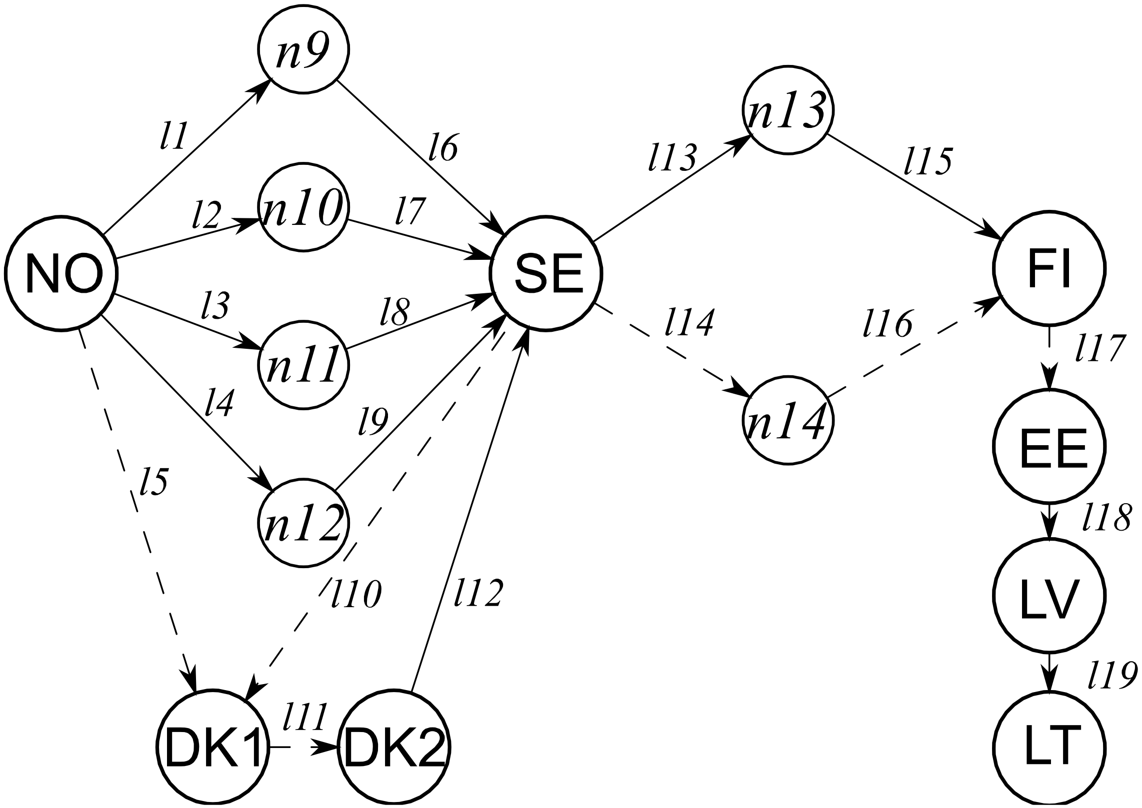
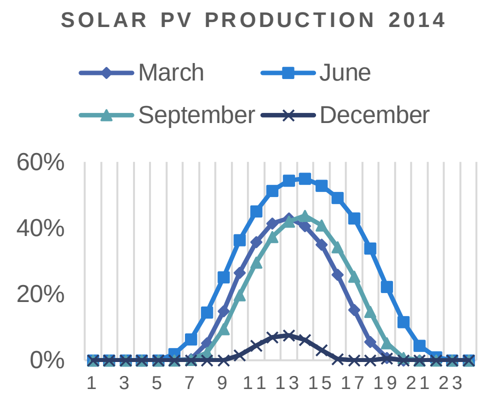
Numerical Example: Nord Pool

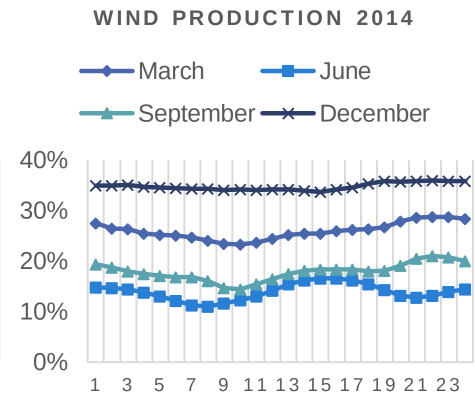
- **14-node, 19-line power network representing the Nordic and Baltic countries (Nord Pool)**
  - Dashed lines: DC
  - No demand or production in auxiliary nodes *n9 - n14*
  - Other nodes correspond to countries, except for Denmark (DK1 and DK2 price areas)

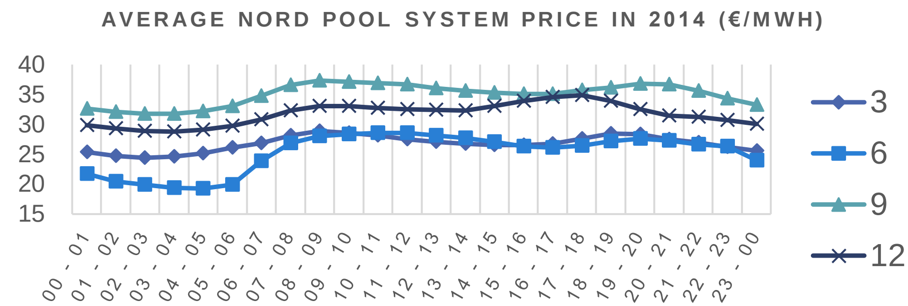


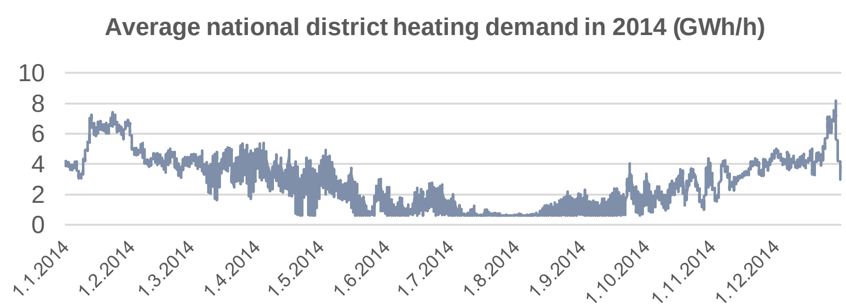
Numerical Example

- **High seasonality of the market → Four scenarios**
  - March – “Spring”
  - June – “Summer”
  - September – “Autumn”
  - December – “Winter”
- **Time horizon**: **‘an average day’ (24 hours)**
- Modeled in 2-hour blocks
- Production capacity, cost etc. data based on 2014
- Implemented in **GAMS**
  - MCP: Solver PATH
  - Reformulation as an equivalent QP due to faster computation (CPLEX)



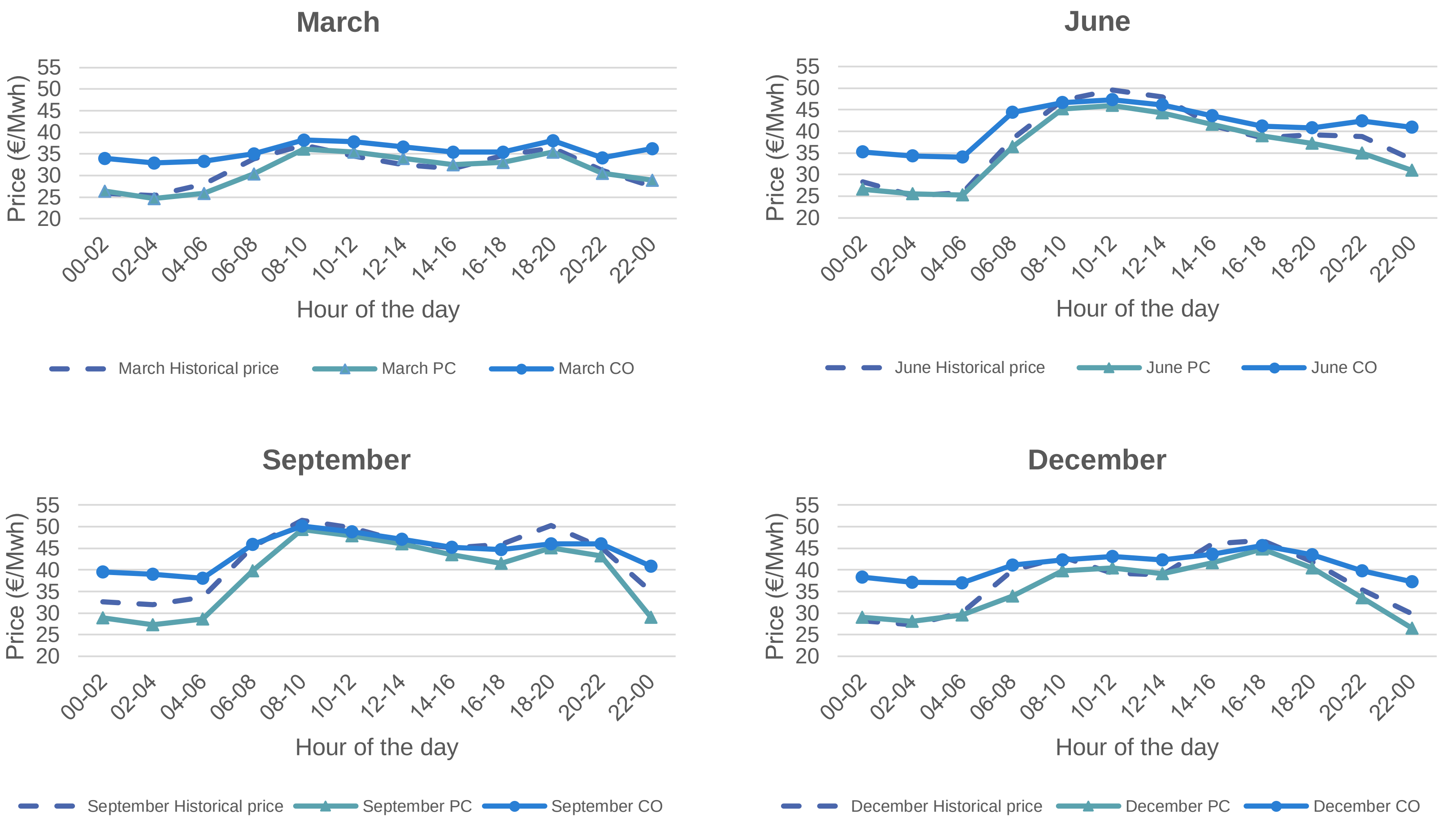






Results: Model Calibration

Average price in the grid for perfect competition (PC) and Cournot oligopoly (CO)

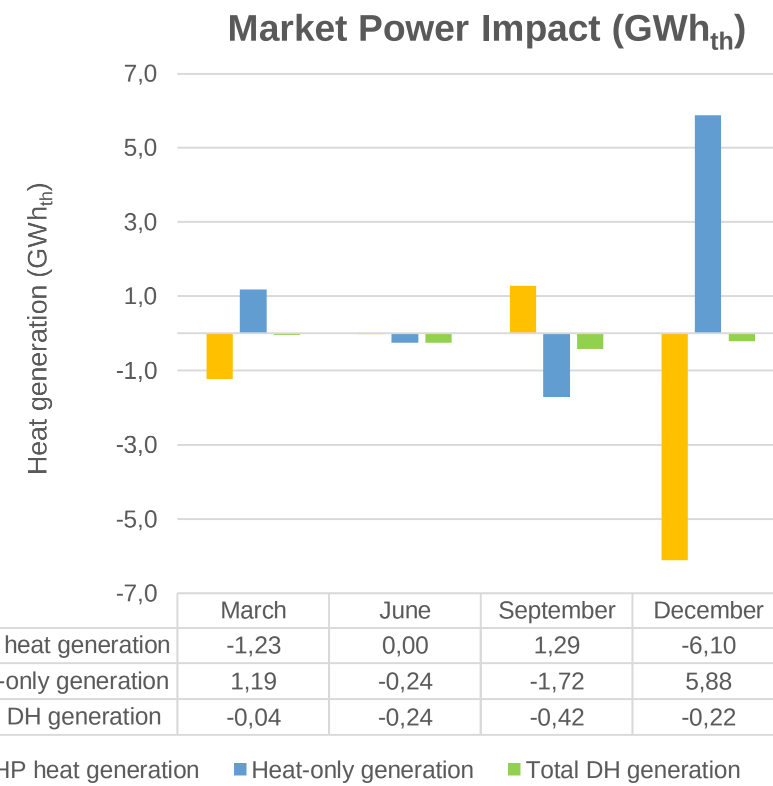


Results: Market Power

Market power impacts on CHP and district heating (DH) operations

Market power

- **Slightly shifts DH supply from CHP to heat-only plants**
  - Not necessarily, if the power price is high enough for some CHP producers
- **Decreases total DH production**
  - Heat profit is fixed, but during high power prices some surplus CHP production may still be attractive → less likely for producers to have this “extra” power supply
- **Decreases heat storage use in all seasonal scenarios by 0.4 – 4.3%**



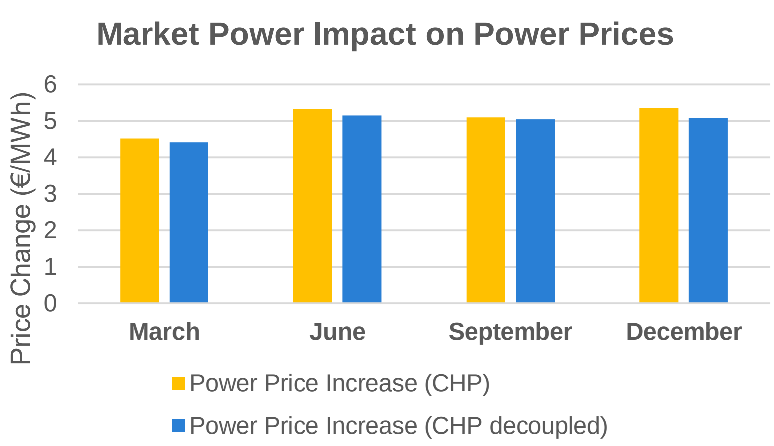
	March	June	September	December
CHP heat generation	-1,23	0,00	1,29	-6,10
Heat-only generation	1,19	-0,24	-1,72	5,88
Total DH generation	-0,04	-0,24	-0,42	-0,22

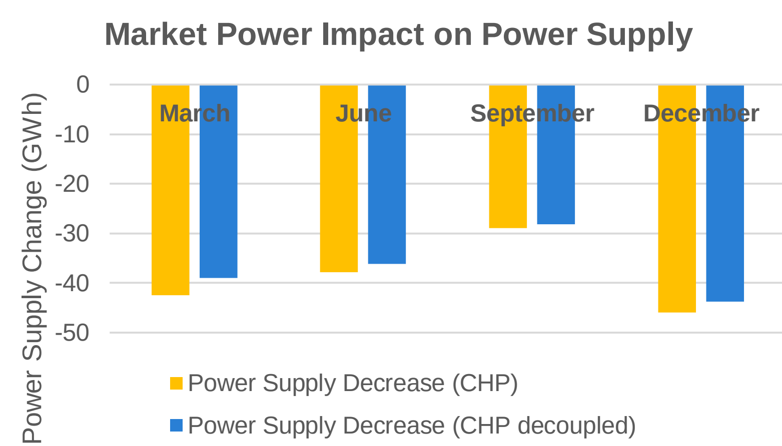
Results: CHP Decoupling

Does CHP’s link to regulated markets mitigate market power?

- **CHP decoupling: Capacity as “power-only” and “heat-only”**
  - Same cost allocation but effectively no production quantity link from power-to-heat-ratio
- **Market power impact on power prices is slightly higher with real, status quo CHP than when the capacity is decoupled**

  → Linkage to regulated markets **“increases”** the ability to withhold some of the supply. Why?

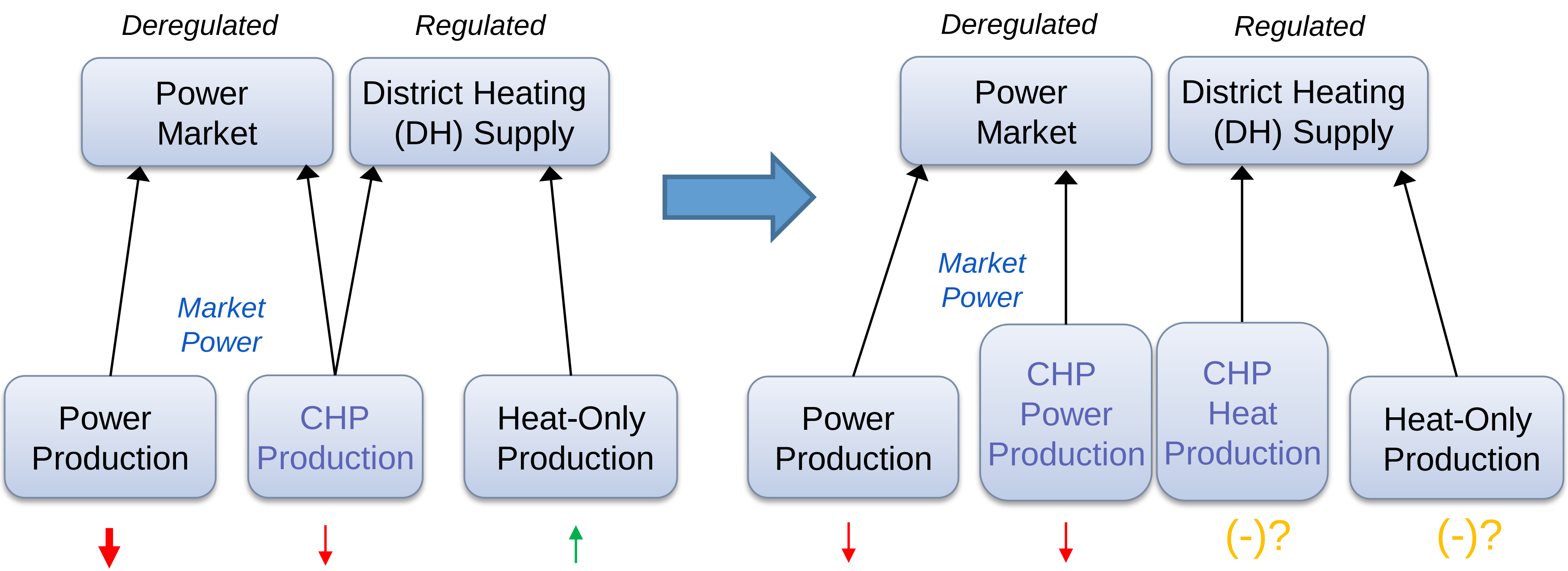




Results: CHP Decoupling

Why?

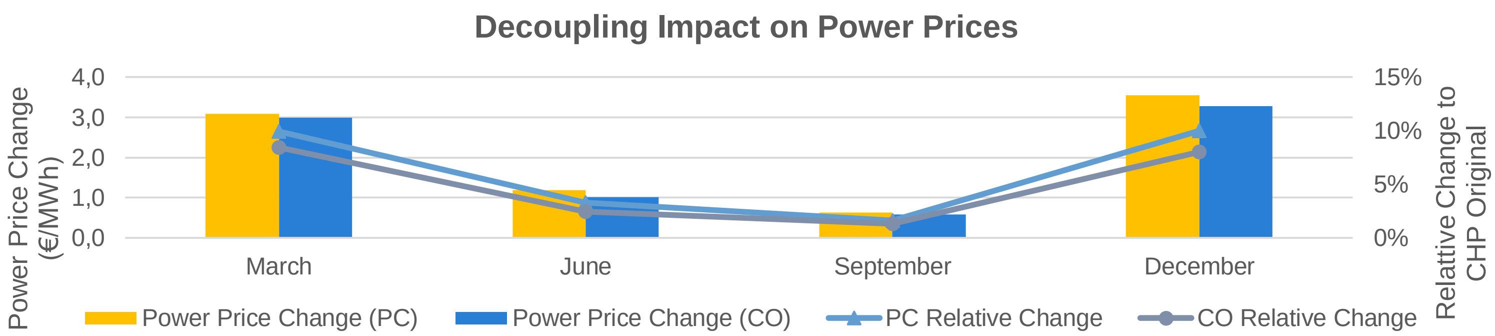
- CHP capacity withholding leads to an increase in heat-only production. ↑
- This is usually more costly and thus, **may lead to an incentive to increase power revenues more than under the decoupled case**
  → More power-only baseload withholding ↓



Results: CHP Decoupling

Other CHP decoupling impacts

- **CHP decoupling also**
  - Decreases social welfare (SW)
  - Increases emissions (loss of cogeneration efficiency)
- **Increases power prices & decreases power production, but more at colder than the warmer months → Less "secondary" power production**
  - March, December: Loss of cogeneration benefits
  - June, September: More flexibility gained when heating demand is low



Final Conclusions and Discussion

- **CHP can have an intensifying impact on market power (i.e. ability to increase prices)**
- **Market power shifts DH supply from CHP to heat-only plants**
  - Not necessarily for all players & at all seasons, if power price is sufficiently high

- **Model limitations**
  - Aggregated level of the data & operations
  - CHP operations highly simplified (fixed power-to-heat ratio)
  - District heating simplified (nodal, in reality more geographical dispersion)
- **Future research**
  - Computational difficulties: longer planning horizon with the QP?
  - Scenarios for VRE, higher VRE integration
  - More sophisticated hydro modelling

Thank you!

Vilma Virasjoki, M.Sc. (Tech)
Doctoral Student
vilma.virasjoki@aalto.fi

Systems Analysis Laboratory,
Department of Mathematics and Systems Analysis,
Aalto University School of Science
http://sal.aalto.fi/en/personnel/vilma.virasjoki/contact

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