DTU Electrical Engineering
Department of Electrical Engineering

CITIES
Centre for IT Intelligent Energy Systems

DTU

Exploiting Flexibility in Coupled Electricity and Natural Gas Markets: A Price-Based Approach

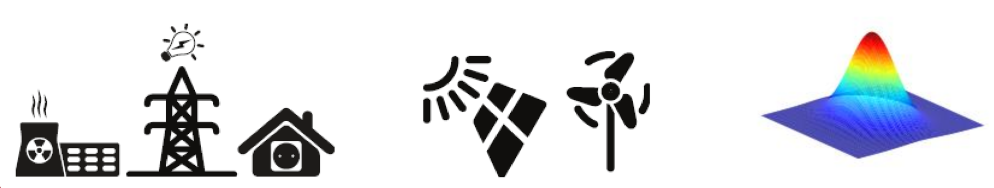
Christos Ordoudis

Supervisors: Pierre Pinson, Juan M. Morales and Jalal Kazempour

Introduction

- Renewable energy sources make up a **high share** of electricity production.
- GFPPs are an ideal choice to facilitate the transition to a **green energy system**.

Decision-making in energy markets + Sources of uncertainty in energy systems → Optimization under uncertainty

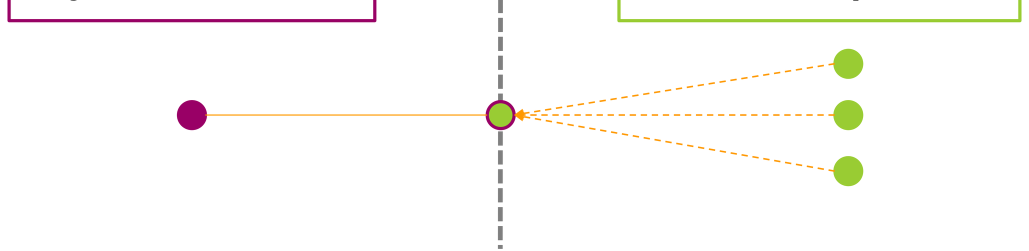


- **Tighter coupling** of electricity and natural gas markets can promote the **integration of renewables** in the energy system.
- Coupling these two markets is a natural way to **increase the coordination** between the two systems that have existing synergies mainly through the GFPPs.
- Manage high uncertainty on both supply and demand sides.

Aim

- Design **market-based coordination mechanisms** and decision support tools to harness flexibility and promote integration of renewables.
- Preserve existing sequential market structure.
- Optimal tuning of market parameters to enhance temporal coordination.
- **Implicit coordination** via proper flexibility price signals.

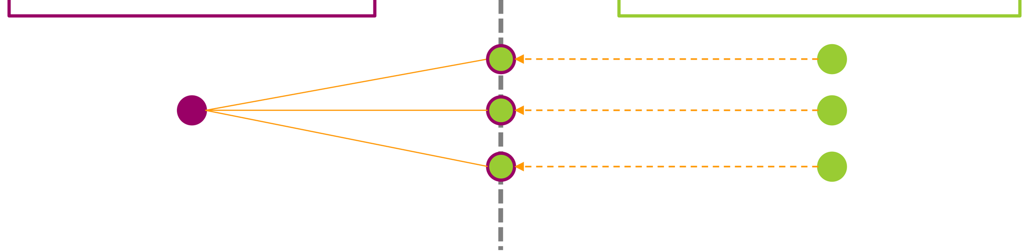
Market Clearing Approaches



Sequential market clearing

Sequential clearing of two trading floors:

1) Day-ahead market is cleared based on deterministic description of uncertain wind power production.
2) A balancing market is cleared for real-time operation.
3) Imperfect temporal coordination.



Stochastic market clearing

Co-optimization of two trading floors:

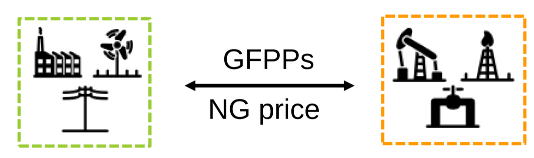
1) Day-ahead dispatch is determined by co-optimizing day-ahead and real-time dispatch, where wind power uncertainty is probabilistically described.
2) A balancing market is cleared for real-time operation.
3) Perfect temporal coordination.

GFPPs: Gas-fired power plants
NG: Natural gas
LMP: Locational marginal price

Electricity and Natural Gas Markets

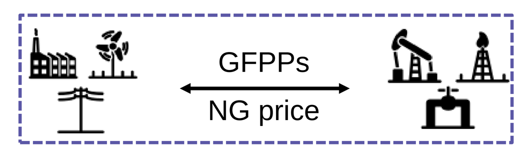
Decoupled Market

Partial price coordination: GFPPs price-quantity offers based on estimated natural gas price.



Coupled Market

Perfect price coordination: GFPPs price offers based on true value of natural gas.



Optimization Models

Sequential coupled electricity and natural gas model

Day-ahead Market → Balancing Market

$$\min\ \mathcal{C}_e^D + \mathcal{C}_g^D \quad \text{s.t. } \mathcal{Q}_e^D,\ \mathcal{Q}_g^D$$

ξ_e^D, ξ_g^D →

$$\min\ \mathcal{C}_e^B(s') + \mathcal{C}_g^B(s') \quad \text{s.t. } \mathcal{Q}_e^B(s'),\ \mathcal{Q}_g^B(s')$$

ξ_e^D / ξ_g^D Day-ahead dispatch decisions Electricity/Gas

$\mathcal{C}_e^D$ / $\mathcal{C}_g^D$ Day-ahead dispatch cost Electricity/Gas.

$\mathcal{C}_e^B(s')$ / $\mathcal{C}_g^B(s')$ Balancing re-dispatch cost Electricity/Gas for realization s'.

Stochastic coupled electricity and natural gas model

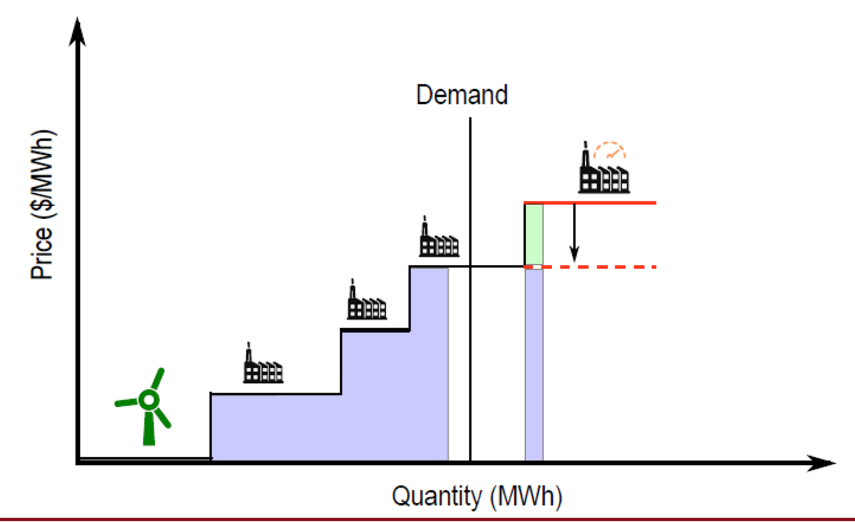
$$\min\ \mathcal{C}_e^D + \mathcal{C}_g^D + \mathbb{E}_s[\mathcal{C}_e^B(s) + \mathcal{C}_g^B(s)]$$
$$\text{s.t. } \mathcal{Q}_e^D;\ \mathcal{Q}_g^D$$
$$\mathcal{Q}_e^B(s), \mathcal{Q}_g^B(s),\ \forall s \in \mathcal{S}$$

The stochastic coupled market model establishes an **ideal benchmark** in terms of minimum expected system cost.

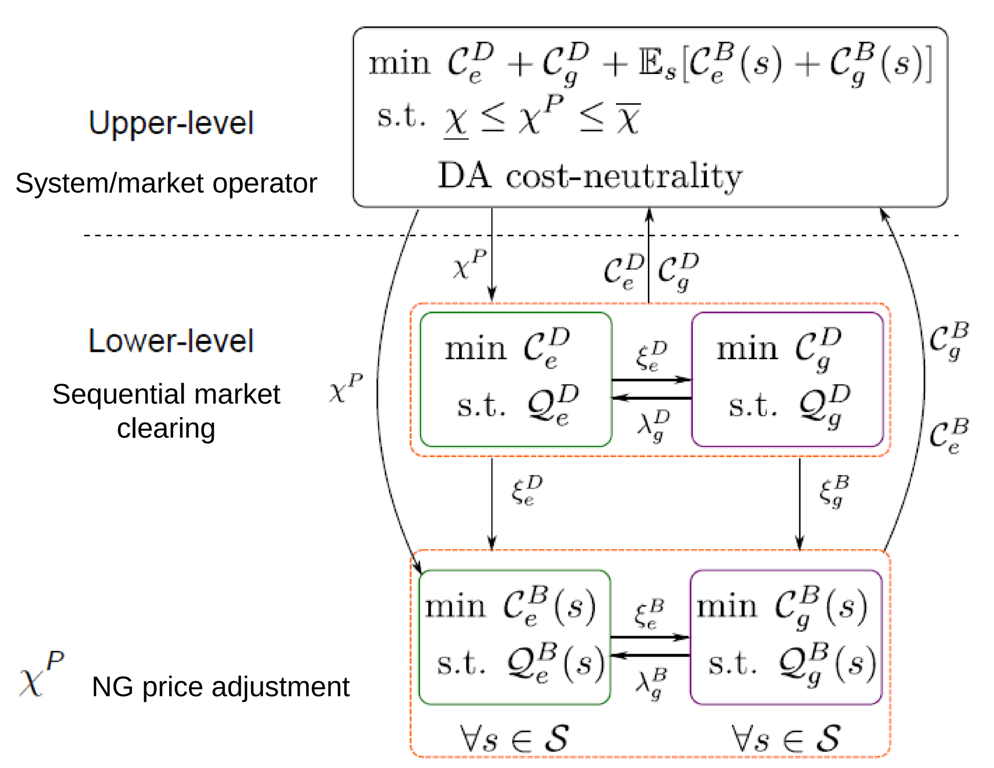
Implicit coordination mechanisms

- Reveal adequate flexibility to cope with real-time imbalances.
- **Respect merit-order principle** of sequential market.
- Ensure **cost-neutrality** at the day-ahead stage.

Flexibility price signals



Price-based coupled electricity and natural gas model



Results

Three thermal units -- Two GFPPs -- Two NG producers

Unit i	1	2	3	4	5	Unit k	1	2
P_i^{max}	80	110	50	100	100	G_k^{max}	150	100
P_i^+	10	0	30	25	20	G_k^+	50	20
P_i^-	10	0	30	25	20	G_k^-	50	20
C_i	30	10	-	-	60	C_k	120	160
ϕ_{i_g}	-	-	0.2	0.3	-			

Table 1: Electricity and natural gas system data.

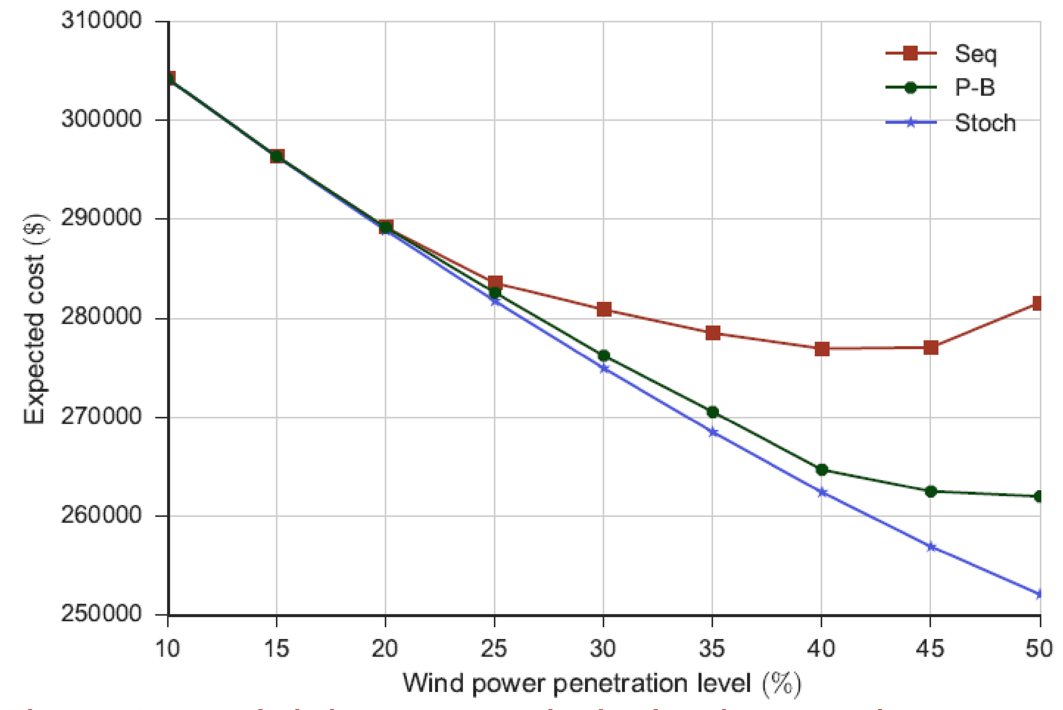


Figure 1: Impact of wind power penetration level on the expected system cost.

Wind power penetration level (%)	25	30	35	40	45	50
Exp. savings ($)	971.5	4 663	8 035.6	12 251.8	14 562.4	19 601.6
Exp. payment/charge ($)	-352.1	-177.1	-21.4	133.5	2.2	302.3

Table 2: Expected payment/charge to generate flexibility price signal.

Real-time surplus/deficit can be addressed through proper regulation, e.g., flexible capacity remuneration mechanisms.

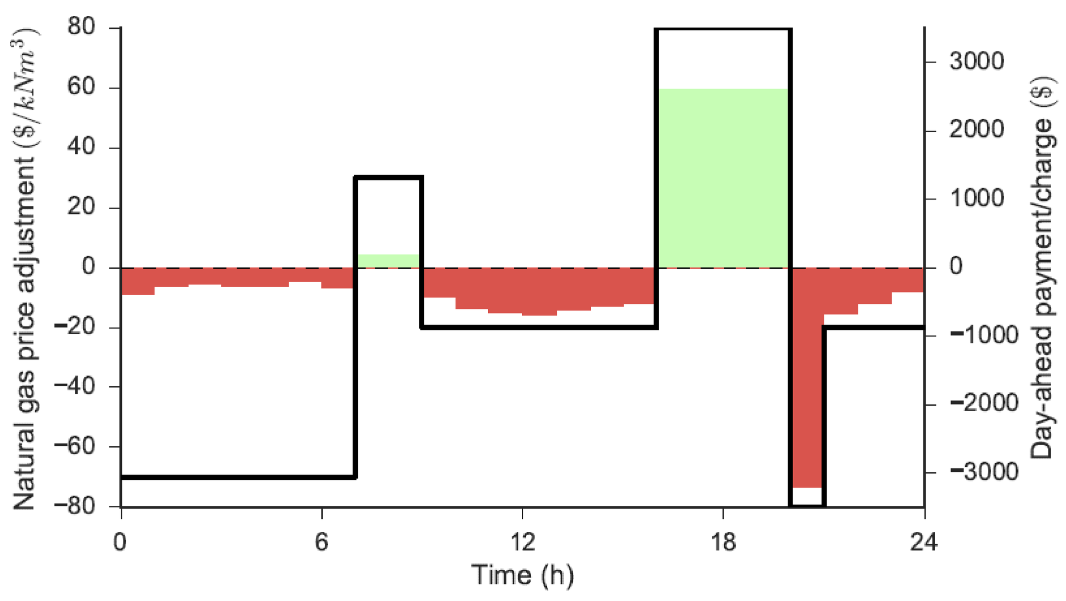


Figure 2: Hourly natural gas price adjustment (black line: left y-axis) and day-ahead financial settlement of the system operator to adjust the natural gas price (colored areas: right y-axis). Wind power penetration 50%.

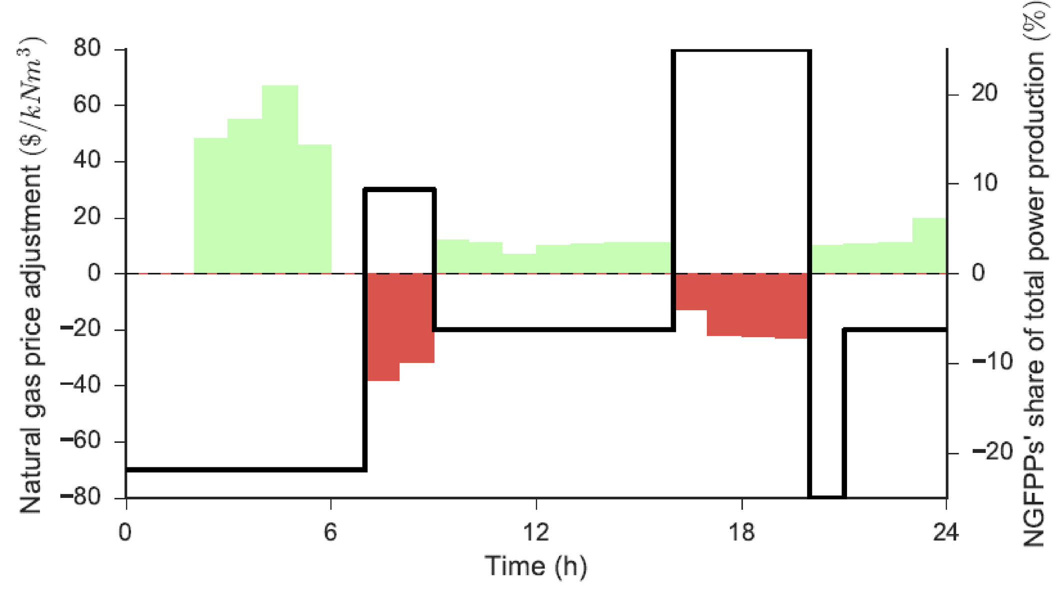


Figure 3: Hourly natural gas price adjustment (black line: left y-axis) and difference in NGFPPs' share of total power production between P-B and Seq (colored areas: right y-axis). Wind power penetration 50%.

Conclusions

- The proposed mechanism enables an **implicit temporal coupling** of the day-ahead and balancing markets, while preserving the existing sequential market clearing of those trading floors.
- The adjustment of natural gas price **affects the dispatch of units** and **reveals available flexibility** to handle wind power uncertainty.
- Cost-neutrality at the day-ahead stage is **ensured,** while the natural gas price adjustment only affects the payment/charge at the balancing stage.

Acknowledgements

This research was funded by the CITIES project, Grant No. DSF 1305-00027B.

Contact: Christos Ordoudis, PhD student, Email: chror@elektro.dtu.dk