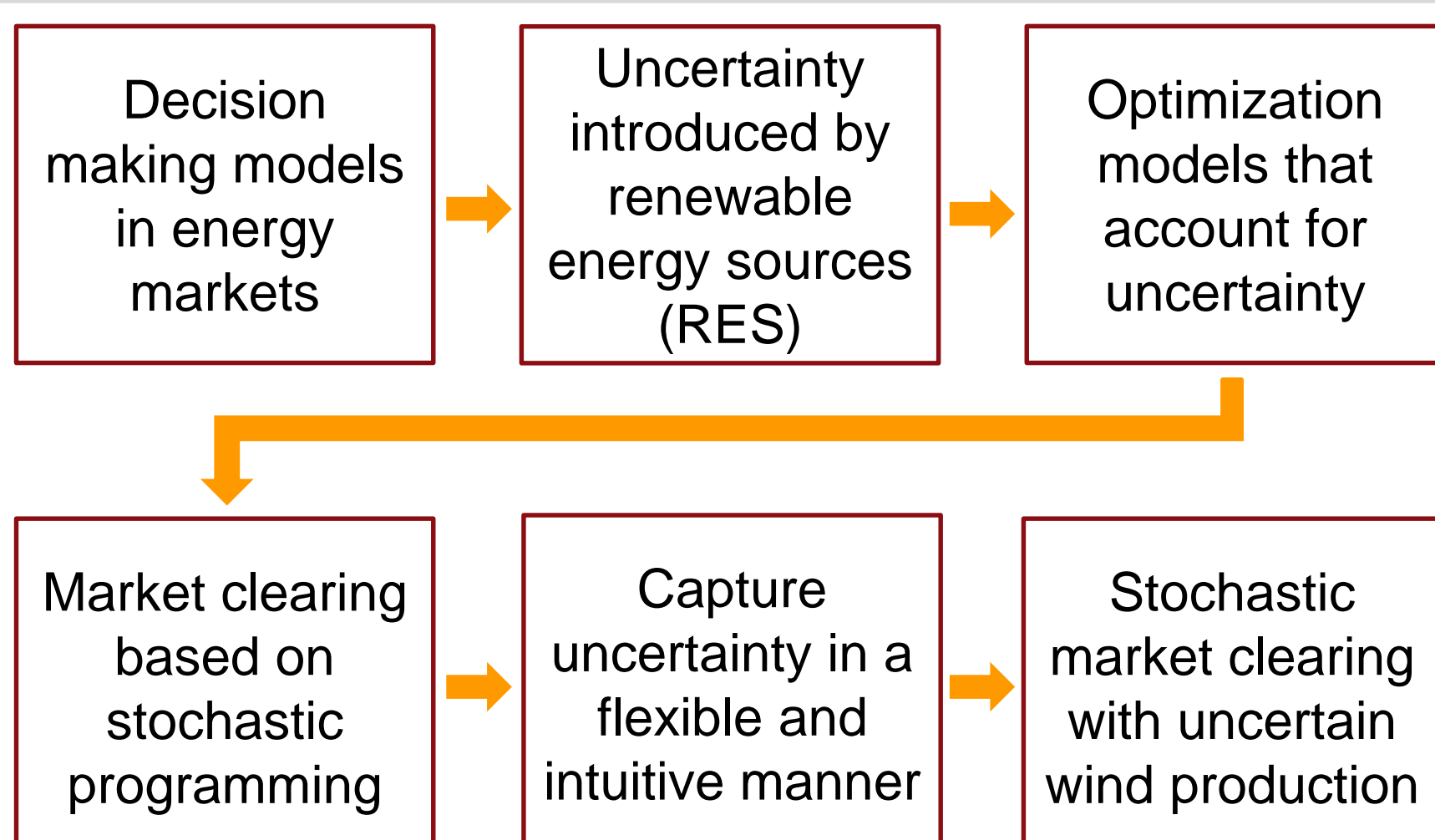


# Stochastic Integrated Market for Electric Power and Natural Gas Systems

Christos Ordoudis, Pierre Pinson, Juan M. Morales

Technical University of Denmark

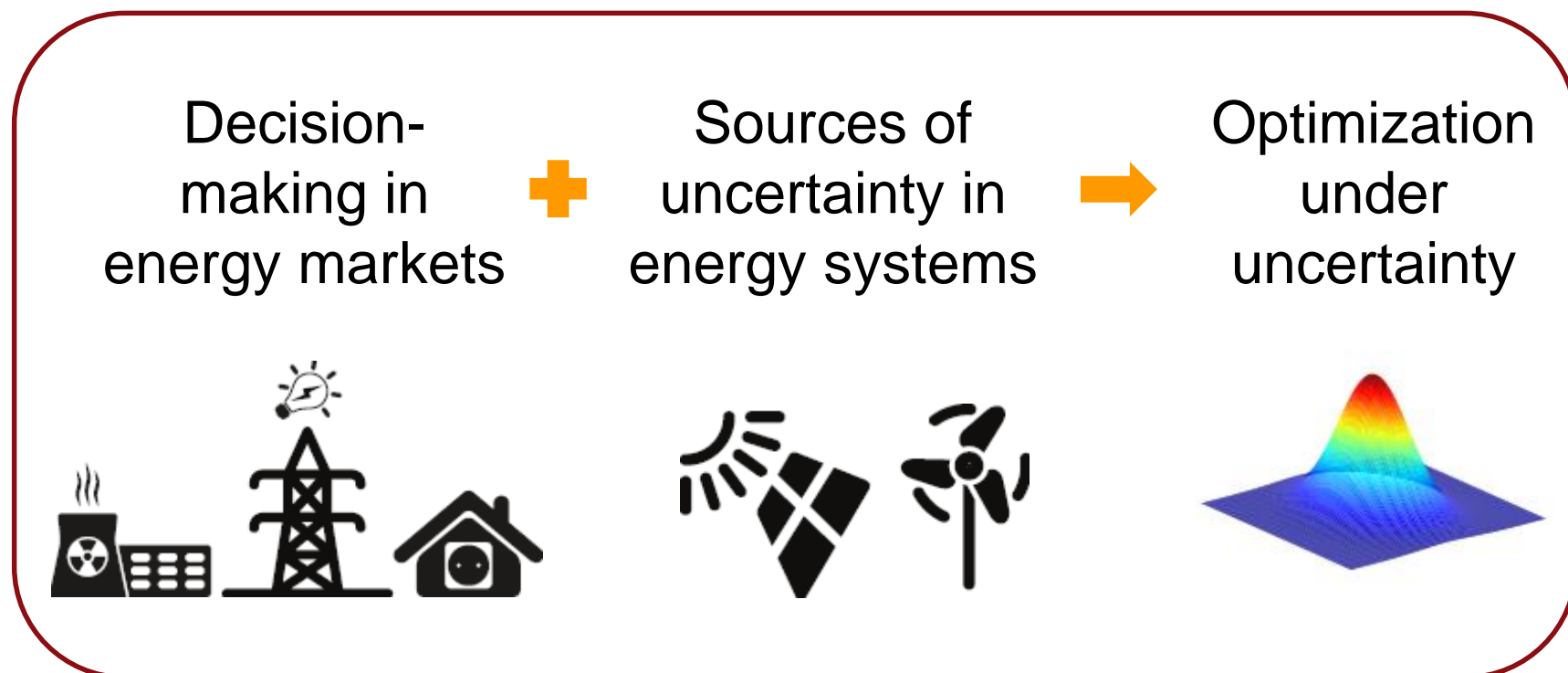
## Introduction



## Energy System Integration

### Aim

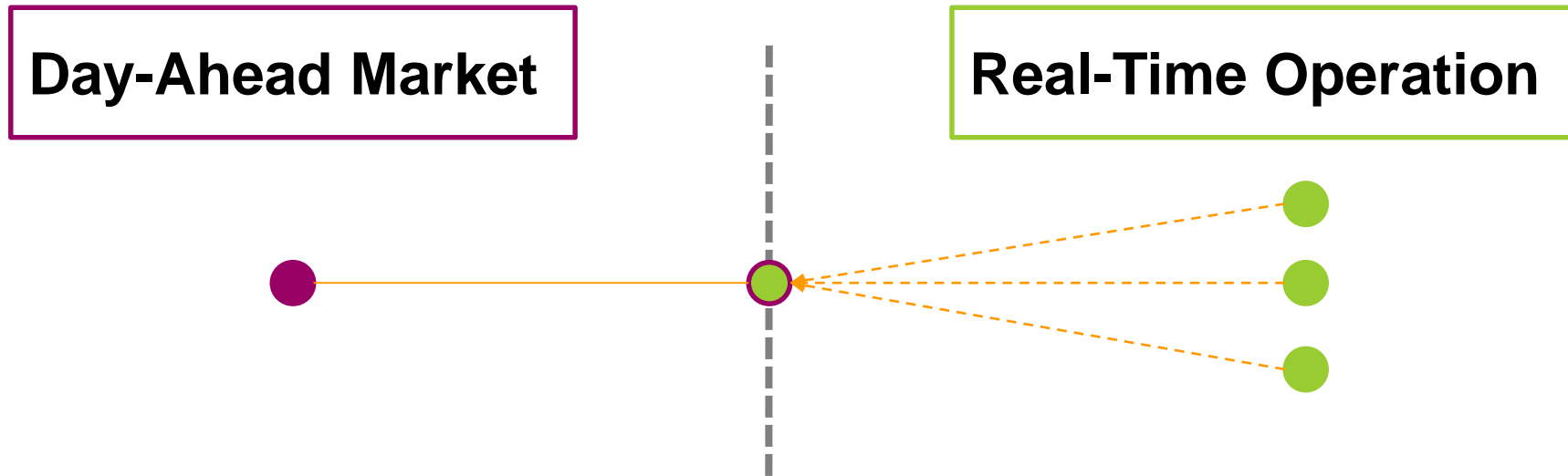
- Efficiently align existing synergies towards the optimal operation of energy systems.
- Propose **new market structures** to provide adequate incentives to all market participants.
- Manage high **uncertainty** on both supply and demand sides.



### Electricity and Natural Gas

Strong link between the electricity and natural gas systems is increased by integration of **renewable energy sources** and the need for flexible reserves provided by GFPPs.

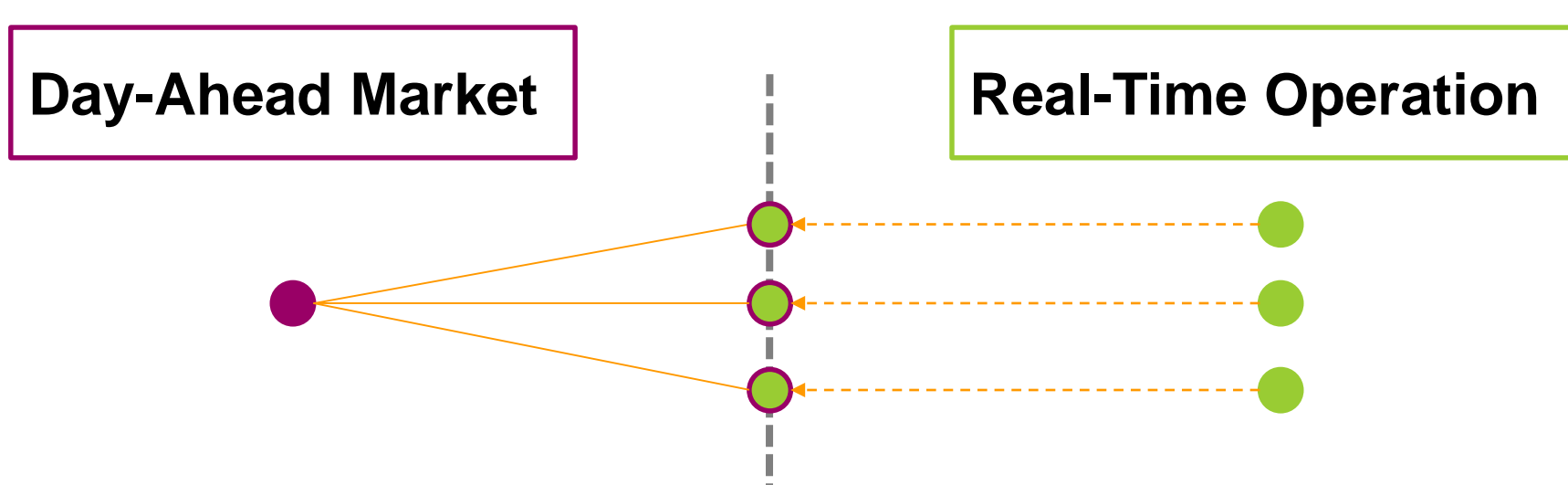
## Market Clearing Approaches



### Conventional market clearing

#### Sequential clearing of two trading floors:

- Day-ahead market is cleared based on deterministic description of uncertain wind power production.
- A balancing market is cleared for real-time operation.



### Stochastic market clearing

#### Co-optimization of two trading floors:

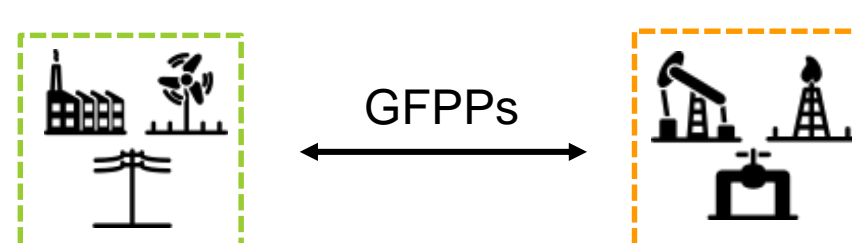
- Day-ahead dispatch is determined by co-optimizing day-ahead and real-time dispatch, where wind power uncertainty is probabilistically described.
- A balancing market is cleared for real-time operation.

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

## Electricity and Natural Gas Markets

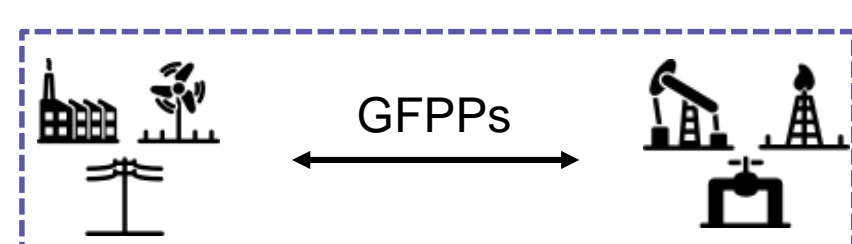
### Decoupled Approach

- Economic dispatch of electricity system is solved and the natural consumption of GFPPs is determined.
- Economic dispatch of natural gas system is solved.



### Integrated Approach

Simultaneously solve the economic dispatch of electricity and natural gas systems.



## Optimization Models

The following models are used to determine the day-ahead dispatch of the electricity and natural gas systems.

### Conventional – Decoupled

**Minimize**  
Day-ahead electricity cost.

**Subject to**

- Day-ahead operating constraints of electricity system.
- Wind power is constrained by its expected value.

↓  
GFPPs NG consumption is determined.

**Minimize**  
Day-ahead natural gas cost.

**Subject to**

- Day-ahead operating constraints of natural gas system.

### Conventional – Integrated

**Minimize**  
Day-ahead electricity and natural gas cost.

**Subject to**

- Day-ahead operating constraints of electricity and natural gas systems.
- Wind power is constrained by its expected value.

### Stochastic – Integrated

**Minimize**  
Day-ahead electricity and natural gas cost + expected electricity and natural gas balancing cost.

**Subject to**

- Day-ahead operating constraints of electricity and natural gas systems.
- Real-time operating constraints of electricity and natural gas systems.
- Wind power uncertainty is characterized by wind power scenarios.

The following model represents real-time operation. It is solved for a specific realization of wind power production.

### Balancing

**Minimize**  
Balancing electricity and natural gas cost.

**Subject to**

- Real-time operating constraints of electricity and natural gas systems.
- Wind power production is considered known.

### Model details

- The optimization models recast as MILP problems.
- Balancing actions are provided only by GFPPs.
- Power flow is modelled by DC approximation.
- A Taylor series expansion is used to linearize the constraints related to the natural gas network.
- A dynamic gas system with line pack is considered.

## Application Results

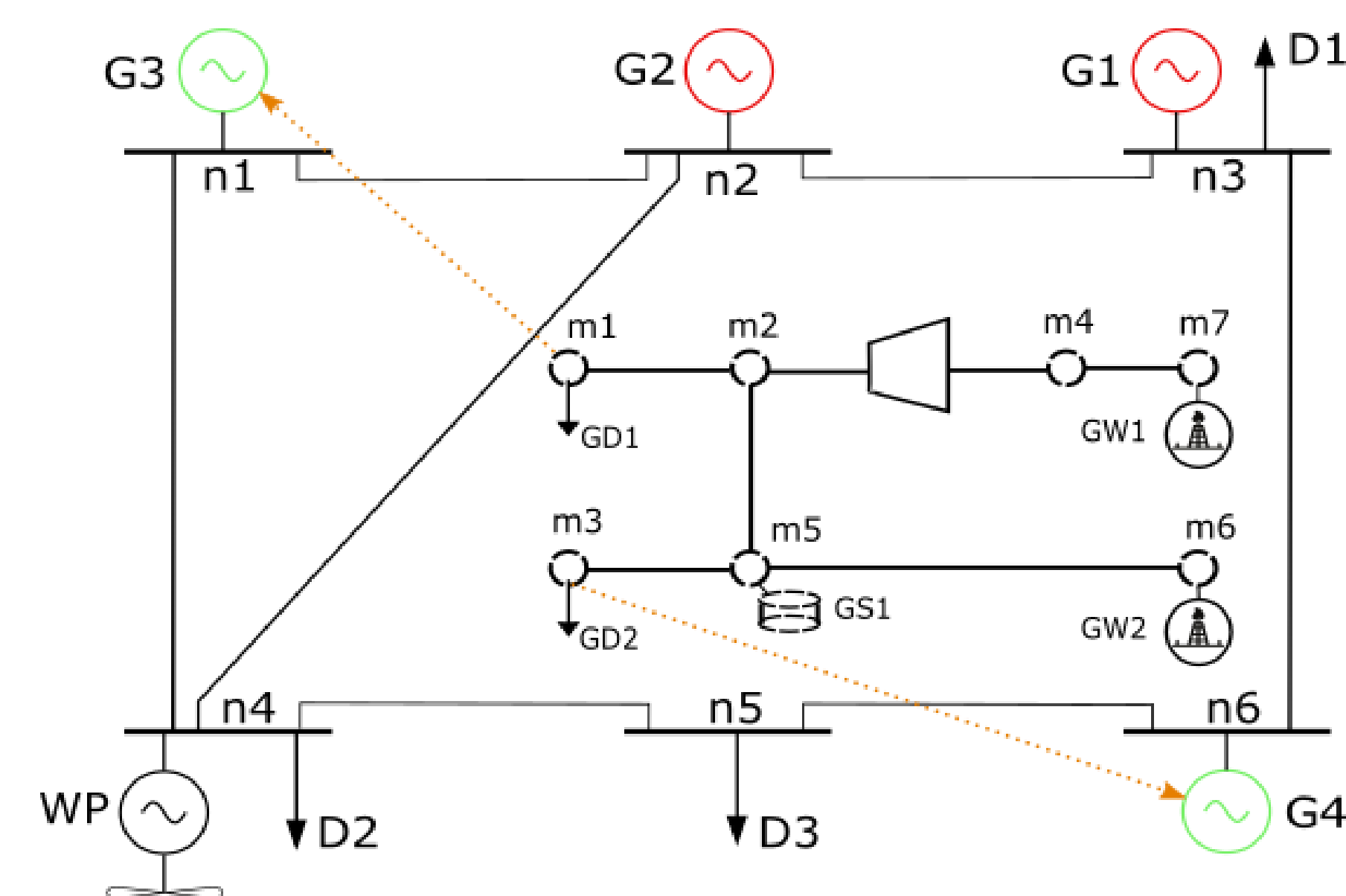


Fig. 1: Power and natural gas systems.

	$P_{max}$ (MW)	$R^{(+/-)}$ (MW)	$\eta$ (km <sup>3</sup> /MW)	$C$ (\$/MWh)
G1	100	0	-	20
G2	80	0	-	35
G3	60	60	0.205	-
G4	60	60	0.264	-
WP	200	-	-	0
	$G_{max}$ (km <sup>3</sup> )	Initial storage level (km <sup>3</sup> )	Max in/outflow rate (km <sup>3</sup> /h)	$C$ (\$/km <sup>3</sup> )
GW1	150	-	-	184
GW2	170	-	-	110
GS1	150	75	50	147
Max Electricity Load	280 MW		Max NG Load	192 km <sup>3</sup>

Table 1: Technical and economic data of generating units, natural gas suppliers and natural gas storage unit.

### Solution procedure

- Day-ahead dispatch of power and natural gas systems is determined. Models **Conv-Dec**, **Conv-Int** and **Stoch-Int** are solved and 10 wind power scenarios are given as input.
- In **Conv-Dec**, we introduce parameter  $k$  that helps us define the electricity marginal cost of GFPPs ( $C=k \cdot LMP_{gas} \cdot \eta$ ). The  $LMP_{gas}$  is determined from **Conv-Int** model.
- Given the day-ahead dispatch from (1), **balancing** model is evaluated for 30 different wind power realizations to determine the total operating cost.

Optimization model	Total cost (\$)	Relative to Stoch-Int (%)
Stoch-Int	558 726	-
Conv-Int	588 836	5.38
Conv-Dec (k=1)	588 836	5.38
Conv-Dec (k=1.1)	589 292	5.47
Conv-Dec (k=0.9)	591 815	5.92

Table 2: Total operating cost.

## Conclusions and Future Plans

- Integrating the operation of power and natural gas systems under stochastic market clearing results in a significant reduction of daily operating cost.
- The case of  $k=1$  reflects the case when GFPPs have perfectly foreseen the ideal natural gas price (i.e., the one stemming from Conv-Int model).
- It is noticed that the total operating cost further increases in the cases of  $k \neq 1$ .
- In future work, the introduction of CHP plants to cover heat demand will be examined, as well as power-to-gas technology.

## Acknowledgements

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