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Two – stage stochastic day-ahead scheduling for integrated heat, electricity and gas system

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Agenda

1. **Introduction & Day-ahead scheduling**
    - Stochastic programming approach under renewable generation uncertainty
2. **Mathematical models of two-stage stochastic programming approach**
    - Electrical power system
    - District heating system
    - Natural gas system
    - Coupling components for integrated multi-energy system
    - Linearization
3. **Scenario generation and scenario reduction**
4. **Integrated multi-energy test case system**
5. **Results**
6. **Conclusion & Future work**

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Introduction

Installed capacity of renewable energy sources is increasing at a high rate → ? → How to accommodate renewable energy sources? → Integration of gas, electricity and district heating network → The interactions among different energy sectors will provide more flexibility required by the future renewable energy system.

Day-ahead scheduling approaches

?

? → ? → ? → ? → ?

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Introduction …

Installed capacity of renewable energy sources is increasing at a high rate → ? → How to accommodate renewable energy sources? → Integration of gas, electricity and district heating network → The interactions among different energy sectors will provide more flexibility required by the future renewable energy system.

Day-ahead scheduling approaches

Deterministic approach? ?

? → ? → ? → ? → ?

Day-ahead scheduling approaches

- Day ahead (DA) market – balancing of supply and demand based on forecasted data (wind and load)
- Real-time (RT) market – clearing of imbalances using the actual real data

Deterministic models:

  - DA clearing based on single deterministic forecast

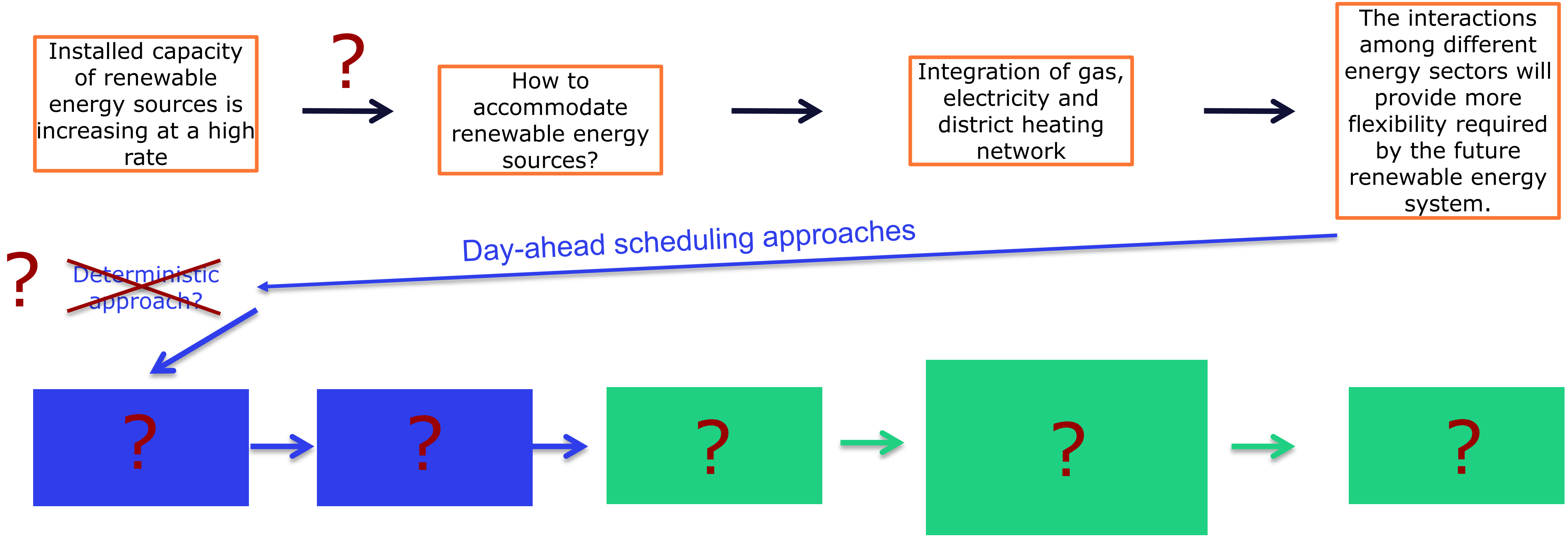
- Uncertain parameters (wind power production, solar PV, load)

- How to take uncertainties into account?

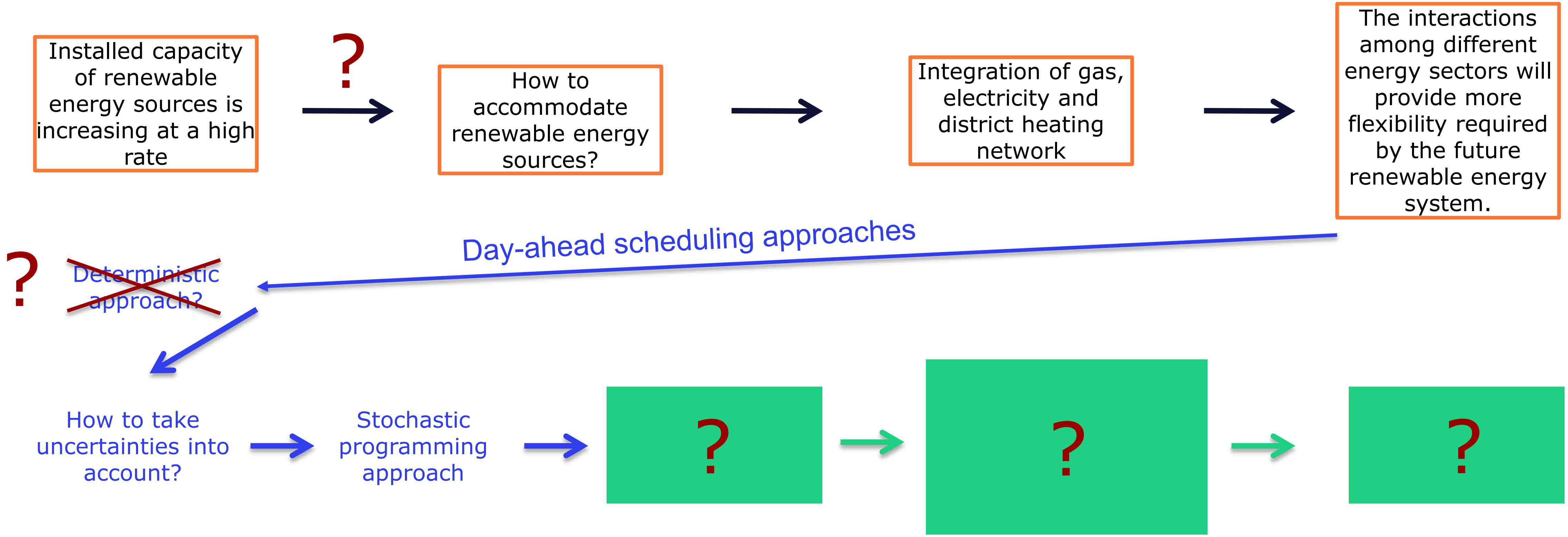
Stochastic programming approach

- Stochastic – clearing is based on stochastic forecast of uncertain parameters
- Interaction between scheduling stage and RT operation
- Lower expected system cost (reserves optimized)
- Realistic range and probabilities of scenarios are included

Introduction …



Introduction …



Uncertainties in IES and description of the stochasticity

- Wind and PV solar power production, demand, fuel prices,…
- Consider all possible scenarios! Huge number of scenarios to represent realistically future states of the uncertain parameters!

↳ Large model → Computational burden

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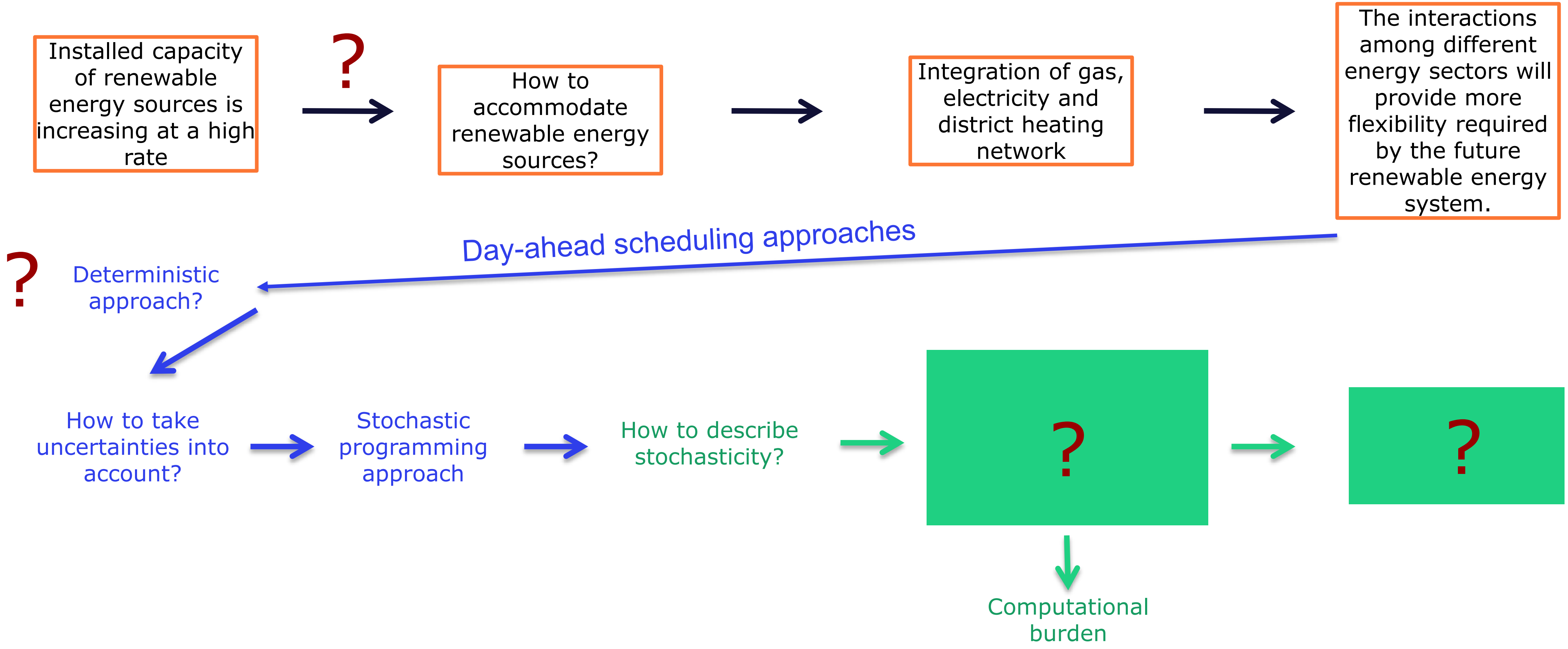
Introduction …



Introduction …

Installed capacity of renewable energy sources is increasing at a high rate

?

How to accommodate renewable energy sources?

Integration of gas, electricity and district heating network

The interactions among different energy sectors will provide more flexibility required by the future renewable energy system.

Day-ahead scheduling approaches

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Deterministic approach?

How to take uncertainties into account?

Stochastic programming approach

How to describe stochasticity?

Scenario generation method based on historical data to characterize uncertainties

?

Computational burden

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Two-stage stochastic DA scheduling for integrated multi-energy system under wind generation uncertainty

1. Uncertainty: Wind power output
2. Stochasticity described as generated scenarios based on historical data
3. Two-stage stochastic optimization problem
   - First (DA) – operating points of generating units and scheduled wind power output determined and dispatched
   - Second (RT) – realization of wind output power and accommodation of uncertainty through reserves

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Electrical Power System (EPS) – DA stage

- DC optimal power flow

Nodal balance equation

Variables

$$\sum_{j\in\Omega_n^{\mathrm{CHP}}} P_{j,t}^{\mathrm{CHP,DA}} + \sum_{f\in\Omega_n^{\mathrm{WF}}} W_{f,t}^{DA} - \sum_{k\in\Omega_n^{\mathrm{P2G}}} D_{k,t}^{\mathrm{P2G,DA}} - \sum_{e\in\Omega_n^{\mathrm{ED}}} D_{e,t}^{\mathrm{ED}} = \sum_{m\in\Lambda_n} B_{nm}\left(\delta_{n,t}^{DA} - \delta_{m,t}^{DA}\right), \quad \forall t\in T, \forall n\in\Lambda^{\mathrm{EPS}}$$

$$P_j^{\mathrm{CHP,min}} \le P_{j,t}^{\mathrm{CHP,DA}} \le P_j^{\mathrm{CHP,max}}, \quad \forall j\in\Omega^{\mathrm{CHP}}, \forall t\in T$$

$$\delta^{DA}{}_{\mathrm{REF},t} = 0, \quad \forall t\in T$$

$$P_{j,t-1}^{\mathrm{CHP,DA}} - P_{j,t}^{\mathrm{CHP,DA}} \le RLD_j^{\mathrm{CHP}}, \quad \forall j\in\Omega^{\mathrm{CHP}}, \forall t\in T$$

$$P_{j,t}^{\mathrm{CHP,DA}} - P_{j,t-1}^{\mathrm{CHP,DA}} \le RLU_j^{\mathrm{CHP}}, \quad \forall j\in\Omega^{\mathrm{CHP}}, \forall t\in T$$

$$-P_{nm}^{\max} \le B_{nm}\left(\delta_{n,t}^{DA} - \delta_{m,t}^{DA}\right) \le P_{nm}^{\max}, \quad \forall n,m\in\Lambda^{\mathrm{EPS}}, \forall t\in T$$

$$0 \le W_{f,t}^{DA} \le W_{f,t}^{\max}, \quad \forall f\in\Omega^{\mathrm{WF}}, \forall t\in T$$

$P_{j,t}^{\mathrm{CHP}}$	Power supply from CHP unit *j*
$W_{f,t}^{DA}$	Power output of wind unit *f* (DA)
$D_{k,t}^{P2G}$	Power demand in P2G unit *k*
$D_{e,t}^{ED}$	Electric demand of EPS
B_{nm}	Susceptance of transmission line *n-m*
$\delta_{n,\omega,t}$	Phase angle of bus *n*
RLD_j^{CHP}	Downward ramping rate limit of CHP unit *j*
RLU_j^{CHP}	Upward ramping rate limit of CHP unit *j*
$P_{j,t}^{CHP,\min/\max}$	Min/max power supply from CHP unit *j*
$W_{f,t}^{\max}$	Nominal output power of wind unit *f*

Electrical Power System (EPS) – RT stage

Nodal balance equation

$$\sum_{j\in\Omega_n^{CHP}}\left(R_{j,\omega,t}^{CHP,U}-R_{j,\omega,t}^{CHP,D}\right)+\sum_{f\in\Omega_n^{WF}}\left(W_{f,\omega,t}^{RT}-W_{f,\omega,t}^{spill}-W_{f,\omega,t}^{DA}\right)-\sum_{k\in\Omega_n^{P2G}}\left(D_{k,\omega,t}^{P2G,RT}-D_{k,t}^{P2G,DA}\right)+\sum_{e\in\Omega_n^{ED}}D_{e,\omega,t}^{ED,shed}=\sum_{m\in\Lambda_n}B_{nm}\left(\delta_{n,\omega,t}^{RT}-\delta_{m,\omega,t}^{RT}-\delta_{n,t}^{DA}+\delta_{m,t}^{DA}\right),\forall t\in T,\forall n\in\Lambda^{EPS},\forall\omega$$

Variables

Wind power realization under scenarios ω

$$\delta^{RT}{}_{REF,t}=0,\quad\forall t\in T$$

$$P_{j,t-1}^{CHP,DA}+\left(R_{j,\omega,t-1}^{CHP,U}-R_{j,\omega,t-1}^{CHP,D}\right)-P_{j,t}^{CHP,DA}-\left(R_{j,\omega,t}^{CHP,U}-R_{j,\omega,t}^{CHP,D}\right)\le RLD_j^{CHP},\quad\forall j\in\Omega^{CHP},\forall t\in T,\forall\omega$$

$$P_{j,t}^{CHP,DA}+\left(R_{j,\omega,t}^{CHP,U}-R_{j,\omega,t}^{CHP,D}\right)-P_{j,t-1}^{CHP,DA}-\left(R_{j,\omega,t-1}^{CHP,U}-R_{j,\omega,t-1}^{CHP,D}\right)\le RLU_j^{CHP},\quad\forall j\in\Omega^{CHP},\forall t\in T,\forall\omega$$

$$-P_{nm}^{max}\le B_{nm}\left(\delta_{n,\omega,t}^{RT}-\delta_{m,\omega,t}^{RT}\right)\le P_{nm}^{max},\quad\forall n,m\in\Lambda^{EPS},\forall t\in T$$

$$0\le W_{f,\omega,t}^{spill}\le W_{f,\omega,t}^{RT},\quad\forall f\in\Omega^{WF},\forall t\in T$$

$$0\le D_{e,\omega,t}^{ED,shed}\le D_{e,t}^{ED},\forall t\in T,\forall\omega$$

$$0\le R_{j,\omega,t}^{CHP,U}\le R_{j,t}^{CHP,U,max},\forall t\in T,\forall\omega$$

$$0\le R_{j,\omega,t}^{CHP,D}\le R_{j,t}^{CHP,D,max},\forall t\in T,\forall\omega$$

$$P_{j,t}^{CHP,min}\le P_{j,t}^{CHP,DA}+\left(R_{j,\omega,t}^{CHP,U}-R_{j,\omega,t}^{CHP,D}\right)\le P_{j,t}^{CHP,max},\forall t\in T,\forall\omega$$

Constraints linking DA and RT variables

$R_{j,\omega,t}^{CHP,U}, R_{j,\omega,t}^{CHP,D}$ Upward and downward reserves of CHP unit *j* in scenario *w*
$W_{f,\omega,t}^{spill}$ Power spillage for wind unit *f*
$W_{f,\omega,t}^{RT}$ Wind power output realization in RT stage
$D_{e,t}^{ED,shed}$ Load shedding in RT stage

District heating system (DHS)

- DHS consists of supply pipelines delivering heat from the heat source to the heat demand and return pipelines coming back to the heat source
- Water temperature - important parameter
- DHS model consists of *hydraulic* and *thermal* model

- **Hydraulic equation** presenting continuity of flow demonstrates that the mass flow entering the node equals to the mass flow leaving the node and mass flow consumption at that node

$m_{mn,t}$ Water flow rate in pipe m-n

$$\sum_{m \in \Lambda_n} m_{mn,t} = 0, \forall m, n \in \Lambda^{\mathrm{DHS}}, \forall t \in T$$

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District heating system (DHS)

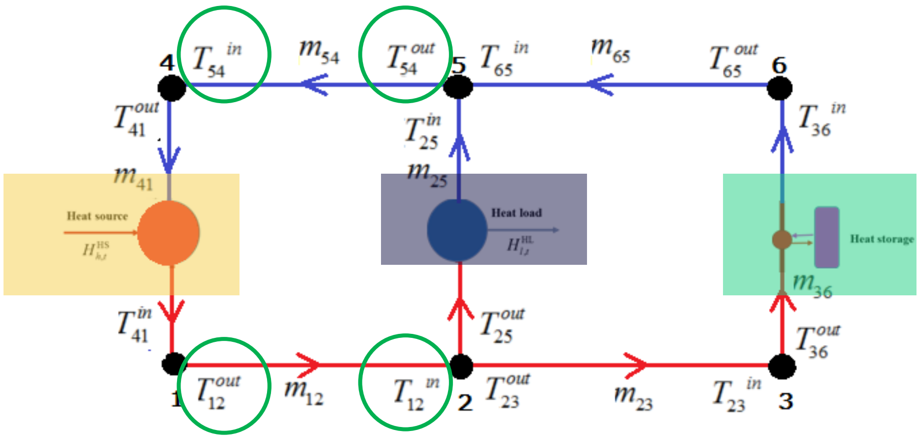
- **Thermal model** consists of nodal heat balance equation, temperature drop and temperature mix equations
- Heat balance of DHS consisting of heat source, heat load and storage:

$$\sum_{j\in\Omega_n^{\mathrm{CHP}}} H_{j,t}^{\mathrm{CHP}} + \sum_{s\in\Omega_n^{\mathrm{HS}}} \left(H_{s,t}^{\mathrm{HS,in}} - H_{s,t}^{\mathrm{HS,out}}\right) - \sum_{l\in\Omega_n^{\mathrm{HL}}} H_{l,t}^{\mathrm{HL}} = c\cdot m_{mn,t}\cdot\left(\tau_{mn,t}^{in} - \tau_{mn,t}^{out}\right), \quad \forall m,n\in\Lambda^{\mathrm{DHS}}, \forall t\in T$$

- Temperature drop :

○ The heat loss of each pipeline is due to the heat transfer along the pipe from high water temperature to the ambient temperature.

$$\tau_{mn,t}^{in} - \tau_{mn,t}^{\mathrm{a}} = e^{\frac{-\lambda_{mn,t}L_{mn}}{c m_{mn,t}}}\left(\tau_{mn,t}^{out} - \tau_{mn,t}^{\mathrm{a}}\right), \forall m,n\in\Lambda^{\mathrm{DHS}}, \forall t\in T$$



- H_j^{CHP} heat supply from CHP unit j
- $H_{h,t}^{HS,in}$ Heat output of heat storage h to heat network
- $H_{h,t}^{HS,out}$ Heat output of heat network to heat storage h
- $H_{l,t}^{HL}$ Heat demand
- $\tau_{mn,t}^{in}$ Temperature of inlet to node n of pipe m-n
- $\tau_{mn,t}^{out}$ Temperature of outlet of node m of pipe m-n
- τ^{a} Ambient temperature
- c Specific heat capacity of water

District heating system (DHS)

- Temperature mix equation

$$\tau^{out}_{mn,t}\sum_{m\in\Lambda_n} m_{mn,t} = \sum_{m\in\Lambda_n}\left(m_{nm,t}\cdot\tau^{in}_{nm,t}\right), \forall m,n\in\Lambda^{\text{DHS}}, \forall t\in T$$

- Heat storage balance

$$HS_{h,t+1} = HS_{h,t} + \left(H^{\text{HS,out}}_{h,t} - H^{\text{HS,in}}_{h,t}\right), \quad \forall h\in\Omega^{\text{HS}}, \forall t\in T$$

$HS_{h,t}$: Heat stocks in heat storage h

- Operational limits

$$H^{\text{CHP,min}}_{j} \le H^{\text{CHP,DA}}_{j,t} \le H^{\text{CHP,max}}_{j}, \quad \forall j\in\Omega^{\text{CHP}}, \forall t\in T$$

Minimum and maximum heat supply from CHP unit j

$$H^{\text{HS,in/out,min}}_{h} \le H^{\text{HS,in/out,DA}}_{h,t} \le H^{\text{HS,in/out,max}}_{h}, \quad \forall h\in\Omega^{\text{HS}}, \forall t\in T$$

Minimum and maximum heat input/output capacity of heat storage h

$$HS^{\min}_{h} \le HS^{DA}_{h,t} \le HS^{\max}_{h}, \quad \forall h\in\Omega^{\text{HS}}, \forall t\in T$$

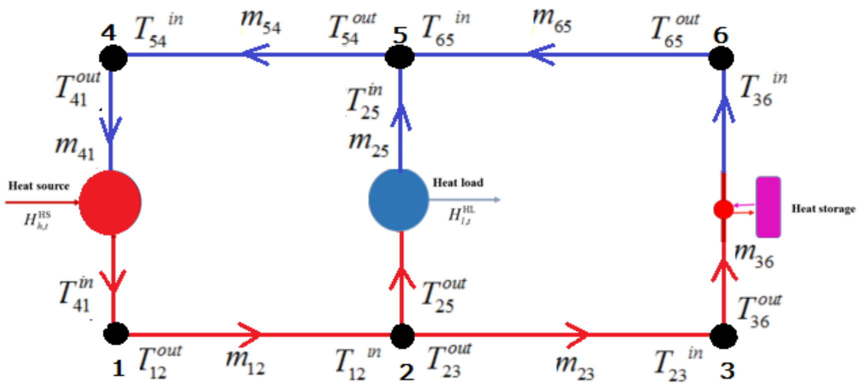
Minimum and maximum heat reserve in heat storage h

$$m^{\min}_{mn} \le m^{DA}_{mn,t} \le m^{\max}_{mn,t}, \forall m,n\in\Lambda^{\text{DHS}}, \forall t\in T$$

Minimum and maximum water flow rate in pipe m-n

$$\tau^{\text{in/out,min}}_{mn} \le \tau^{\text{in/out,DA}}_{mn,t} \le \tau^{\text{in/out,max}}_{mn}, \forall m,n\in\Lambda^{\text{DHS}}, \forall t\in T$$

Minimum and maximum water temperature of inlet/outlet of pipe m-n



Natural gas system (NGS)

- NGS consists of loads, pipes, gas compressors (GC), storages and P2G plants
- Pipeline gas flow equation

$$p_{n,t}^2 - p_{m,t}^2 = Z_{nm}\left(S_{nm,t}\right)^2, \quad \forall n,m \in \Lambda^{\mathrm{NGS}}, \forall t \in T$$

- Nodal gas flow balance

$$\sum_{g\in\Omega_n^{\mathrm{GS}}} Q_{g,t}^{\mathrm{GS}} + \sum_{s\in\Omega_n^{\mathrm{ST}}}\left(Q_{s,t}^{\mathrm{ST,out}} - Q_{s,t}^{\mathrm{ST,in}}\right) + \sum_{k\in\Omega_n^{\mathrm{P2G}}} Q_{k,t}^{\mathrm{P2G}} - \sum_{d\in\Omega_n^{\mathrm{GD}}} D_{d,t}^{\mathrm{GD}} - \sum_{g\in\Omega_n^{\mathrm{GC}}} D_{g,t}^{\mathrm{GC}} - \sum_{j\in\Omega_n^{\mathrm{CHP}}} D_{j,t}^{\mathrm{CHP}} = \sum_{m\in\Lambda_n} S_{nm,t}, \quad \forall m,n \in \Lambda^{\mathrm{NGS}}, \forall t \in T$$

- Energy consumption by GC is provided

$$D_{g,t}^{\mathrm{GC}} = \lambda_g^{\mathrm{GC}} S_{g,t}^{\mathrm{GC}} = K^{\mathrm{GC}} Z_a \left[\frac{T_s}{E^{\mathrm{GC}}\eta^{\mathrm{GC}}}\right]\left[\frac{c_k}{c_k - 1}\right]\left[(CR)^{\frac{c_k-1}{c_k}} - 1\right] S_{g,t}^{\mathrm{GC}}, \quad \forall g \in \Omega^{\mathrm{GC}}, \forall t \in T$$

- Gas storage balance

$$ST_{s,t} = ST_{s,0} + \sum_{t=1}^{t}\left(Q_{s,t}^{\mathrm{ST,in}} - Q_{s,t}^{\mathrm{ST,out}}\right), \forall s \in \Omega^{\mathrm{ST}}, \forall t \in T$$

- Operational limits

$Q_g^{\mathrm{GS,min}} \le Q_{g,t}^{\mathrm{GS}} \le Q_g^{\mathrm{GS,max}}, \quad \forall g \in \Omega^{\mathrm{GS}}, \forall t \in T$	Minimum and maximum gas supply from gas source
$Q_k^{\mathrm{P2G,min}} \le Q_{k,t}^{\mathrm{P2G}} \le Q_k^{\mathrm{P2G,max}}, \quad \forall k \in \Omega^{\mathrm{P2G}}, \forall t \in T$	Minimum and maximum level of P2G
$0 \le Q_{s,t}^{\mathrm{ST,in/out}} \le Q_s^{\mathrm{ST,in/out,max}}, \quad \forall s \in \Omega^{\mathrm{ST}}, \forall t \in T$	Maximum input/output capacity of the gas storage
$(p_{n,t}^2)^{\min} \le p_{n,t}^2 \le (p_{n,t}^2)^{\max}, \quad \forall n \in \Lambda^{\mathrm{NGS}}, \forall t \in T$	Minimum and maximum operating limits for gas pressure
$-S_{nm}^{\max} \le S_{nm,t} \le S_{nm}^{\max}, \quad \forall m,n \in \Lambda^{\mathrm{NGS}}, \forall t \in T$	Maximum transmission capacity of gas pipeline
$ST_s^{\min} \le ST_{s,t} \le ST_s^{\max}, \quad \forall s \in \Omega^{\mathrm{ST}}, \forall t \in T$	Minimum and maximum gas stock in gas storage

$p_{n,t}^2$	Gas pressure of node n
Z_{nm}	Resistance coefficient of the pipeline
$S_{nm,t}$	Gas flow rate of gas pipeline *n-m*
$Q_{g,t}^{\mathrm{GS}}$	Gas supply from gas source *g*
$Q_{s,t}^{\mathrm{ST,in/out}}$	Gas input/output of gas storage *s*
$Q_{k,t}^{\mathrm{P2G}}$	Gas supply from P2G unit *k*
$D_{d,t}^{\mathrm{GD}}$	Gas demand
$D_{j,t}^{\mathrm{CHP}}$	Gas consumption in CHP unit *j*
$D_{g,t}^{\mathrm{GC}}$	Gas consumption in GC *g*
$ST_{s,t}$	Gas stocks in gas storage *s*

Coupling components

- **Combined heat and power (CHP)**
- Relationship between gas consumption of CHP unit based on electricity and heat generation

$$P_{j,t}^{\mathrm{CHP,DA}} = D_{j,t}^{\mathrm{CHP,DA}} \eta_j^{e}$$
$$H_{j,t}^{\mathrm{CHP,DA}} = D_{j,t}^{\mathrm{CHP,DA}} \eta_j^{h};$$

DA

$$\left(R_{j,\omega,t}^{\mathrm{CHP,U}} - R_{j,\omega,t}^{\mathrm{CHP,D}}\right) = \left(D_{j,\omega,t}^{\mathrm{CHP,RT}} - D_{j,t}^{\mathrm{CHP,DA}}\right)\eta_j^{e}, \quad \forall j \in \Omega^{\mathrm{CHP}}, \forall t \in T, \forall \omega \in \Theta$$
$$\left(H_{j,\omega,t}^{\mathrm{CHP,RT}} - H_{j,t}^{\mathrm{CHP,DA}}\right) = \left(D_{j,\omega,t}^{\mathrm{CHP,RT}} - D_{j,t}^{\mathrm{CHP,DA}}\right)\eta_j^{h}, \quad \forall j \in \Omega^{\mathrm{CHP}}, \forall t \in T, \forall \omega \in \Theta$$

RT

- **Power to gas (P2G)**
- Converting electricity to hydrogen using electrolysis or methane through methanation process.
- The hydrogen can be used as fuel in industrial and transport sector, while methane can be used in all natural gas pipelines and for meeting the gas demand

$$Q_{k,t}^{\mathrm{P2G,DA}} = \eta_k^{\mathrm{P2G}} D_{k,t}^{\mathrm{P2G,DA}}$$

DA

$$Q_{k,t}^{\mathrm{P2G,DA}} + \left(R_{k,\omega,t}^{P2G,U} - R_{k,\omega,t}^{P2G,D}\right) = \eta_k^{\mathrm{P2G}} D_{k,\omega,t}^{\mathrm{P2G,RT}}, \quad \forall k \in \Omega^{\mathrm{P2G}}, \forall t \in T, \forall \omega \in \Theta$$

RT

η_j^{e}, η_j^{h} Generating electrical and thermal efficiency of CHP unit j

η_k^{P2G} The energy conversion efficiency of at P2G unit

Optimization problem – Objective function

IES mathematical model – non-linear ⟶ no guarantee a global optimum can be reached

Linearization: NLP ⟶ MILP

Minimize (system cost in DA) + (expected system cost in RT)

subject to:

Equality and inequality constraints for EPS, DHS and NGS and linking units in the first and second stage

- Focus on decreasing the expected cost and improving efficiency of integrated system, as well as meeting the demands
- The objective is to perform optimal scheduling which is allocating generation among every generation unit and storage maintaining the total expected cost minimized

Agenda

Scenario generation method

Find historical data of forecasted and measured wind power output →

The historical data pairs in the data box are sorted into power bins based on the each bin forecast value range →

The data box gives approximation of the distribution for a specific point forecast →

Distribution? →

Calculate ECDF of measured historical data for each power bin:

- ECDF for measured values for each forecast bin is obtained
- Based on historical observations
- Characterizing the uncertainty of the wind power
- Not assuming any theoretical distribution

Create covariance matrix:

- Representing correlation between wind power at two periods - temporal correlation

→ Generate Gaussian random vector while obeying normal distribution ~ N(0, Σ)

→ Inverse transformation is applied to N scenarios of random vectors

→ Obtain values of wind power for all the scenarios

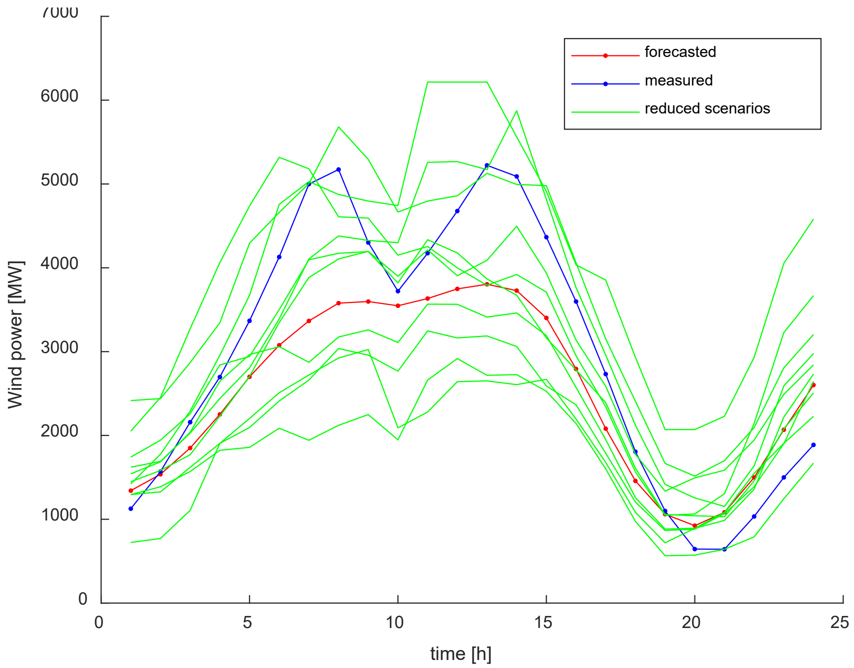
Scenario reduction

Backward-reduction algorithm

– Reduced scenarios should be as close as possible to the original generated scenarios

– Aggregate similar scenario

– Based on probability metrics - creating a new initial scenario set consisting of the preserved scenarios and assigning new probabilities to the preserved scenarios



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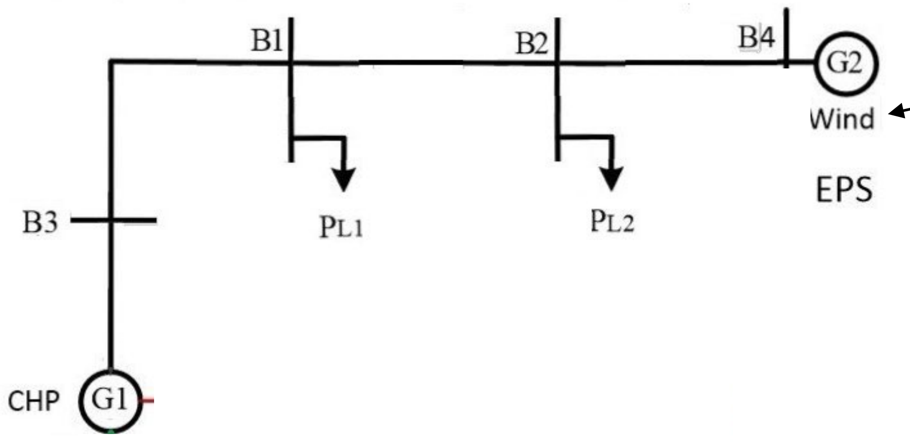
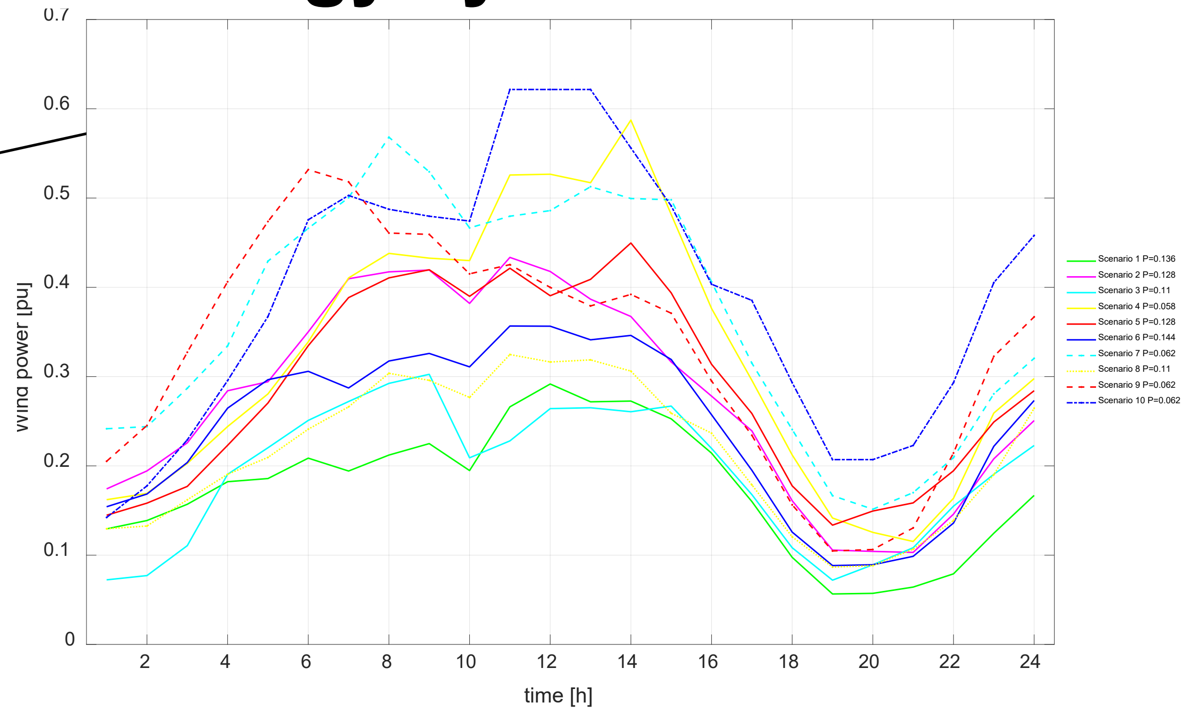
Test case of integrated multi-energy system





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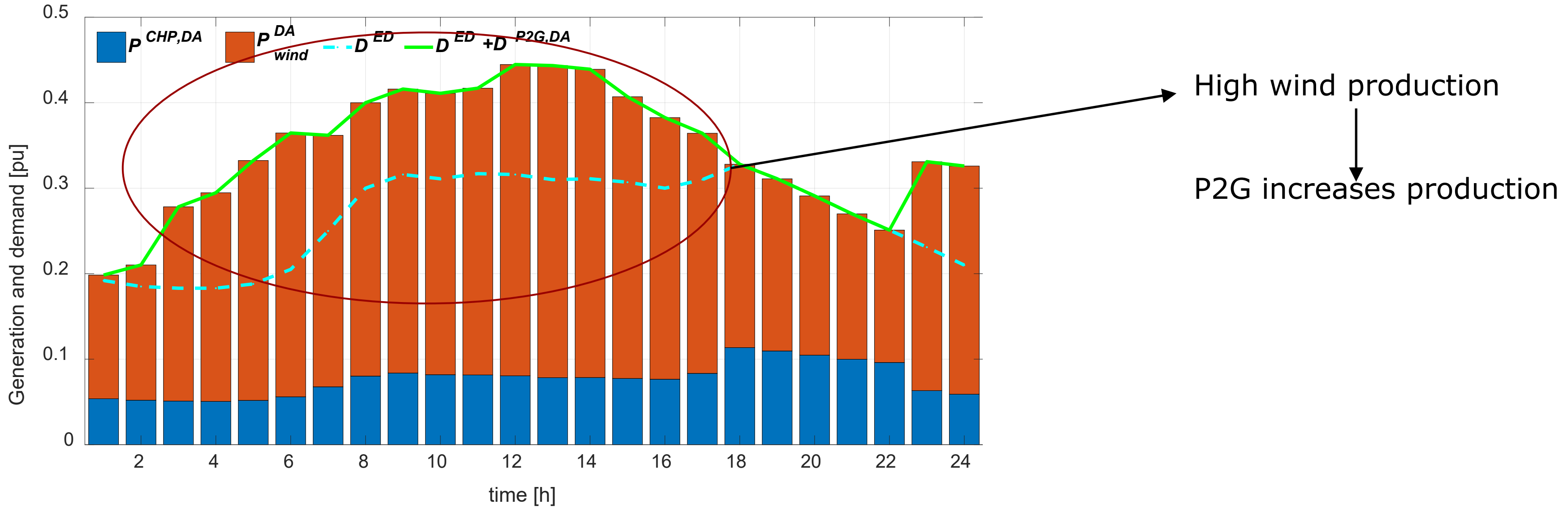
Results for EPS in the first stage

Generation – active output power of wind farm and CHP

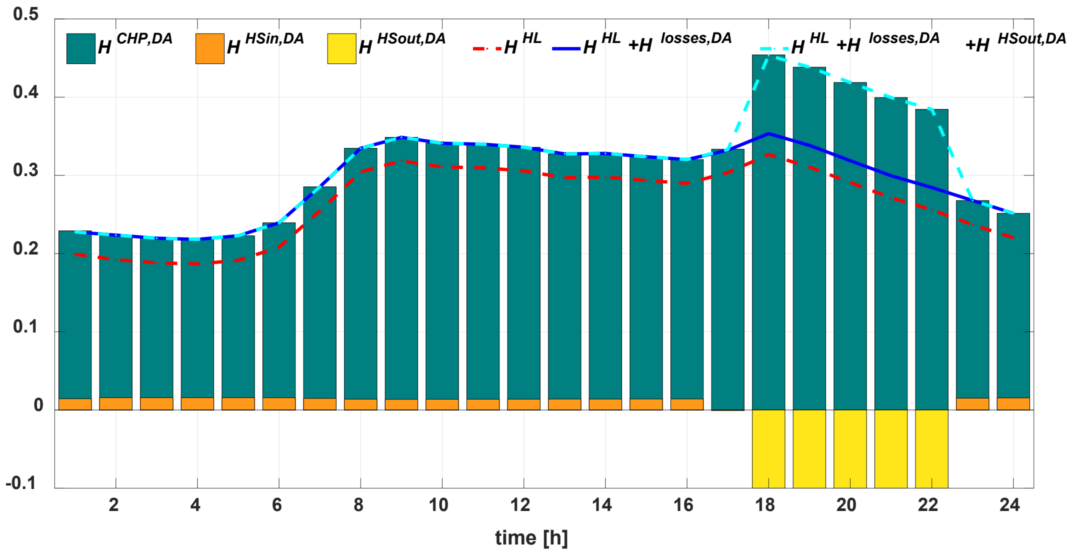
Demand – electrical demand and electricity consumed by P2G



- High dispatched wind production in the first stage
- P2G consumes excess electricity from wind farm and converts it into gas

Results for DHS in the first stage

Heat generation and demand in DA stage in DHS



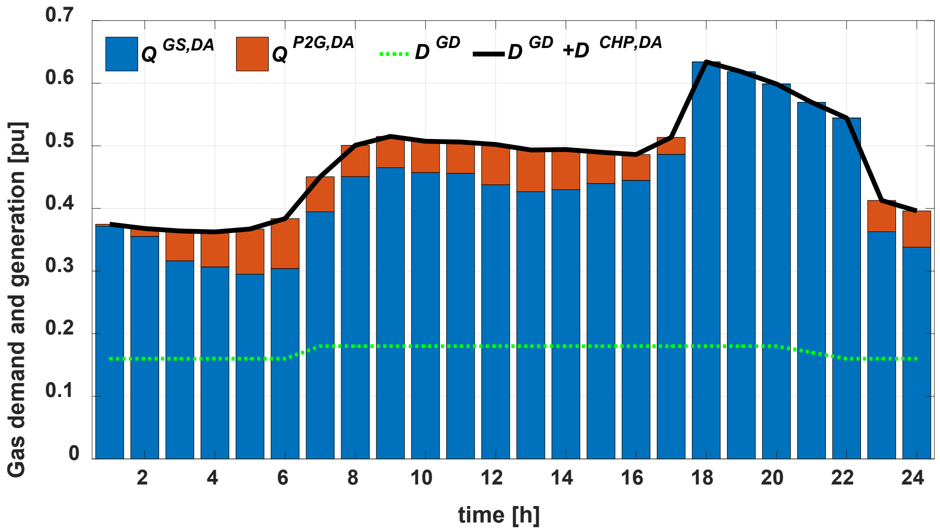
Results of DA stage for DHS

- Heat provided by CHP and heat storage

Results for NGS in the first stage

The gas supply - gas source, P2G

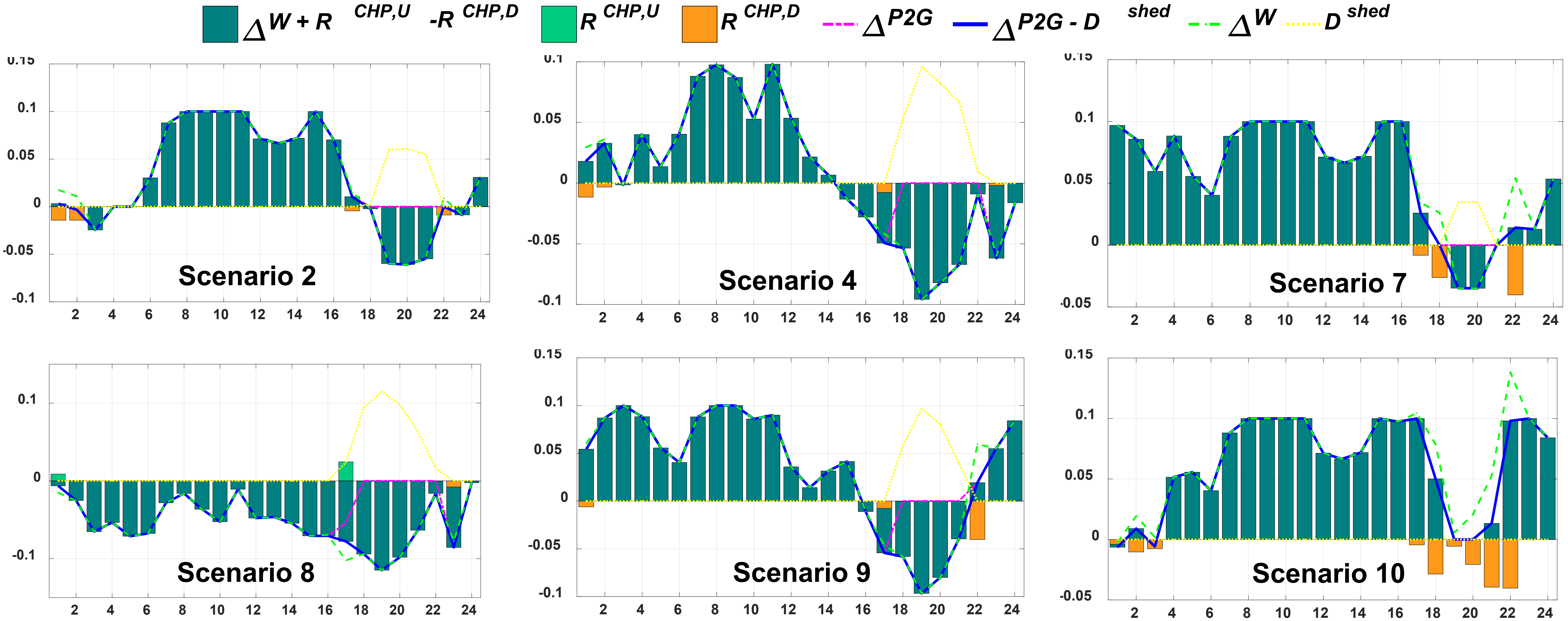
Demand (black curve) - gas load and gas consumption of CHP



Results of DA stage for NGS

- P2G is supplying higher amount of gas at the moments of higher excess electricity from wind turbines

Results for EPS in the RT stage



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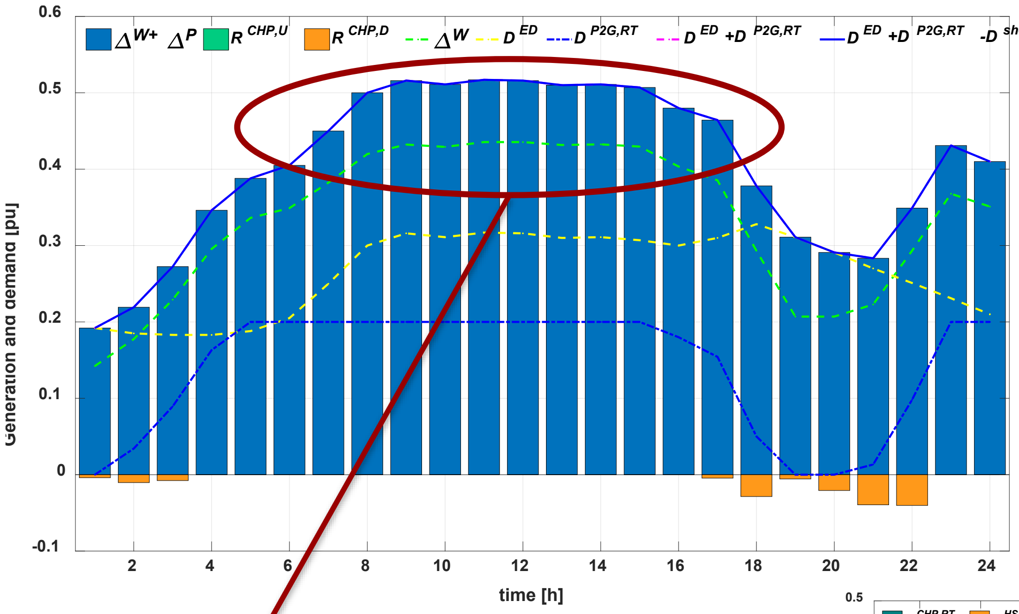
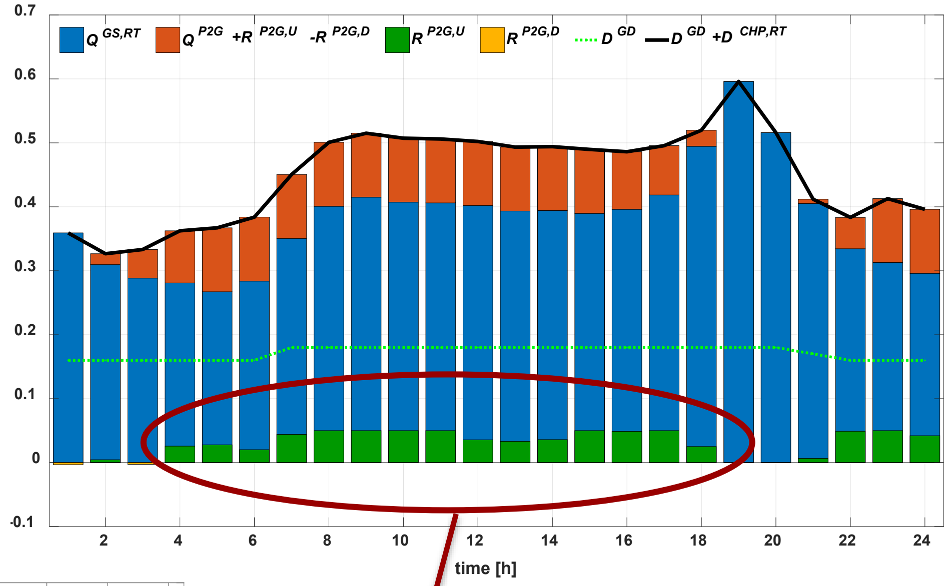
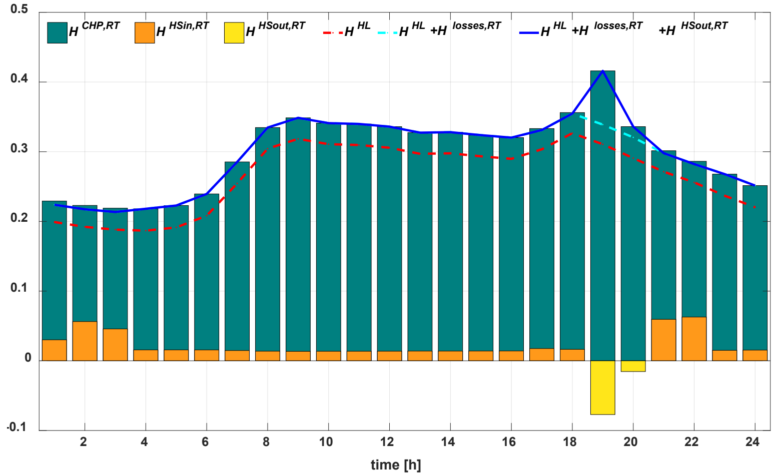
Results for RT stage – Scenario 10



High wind realization
P2G consumes excess electricity



Upward reserves provided by P2G



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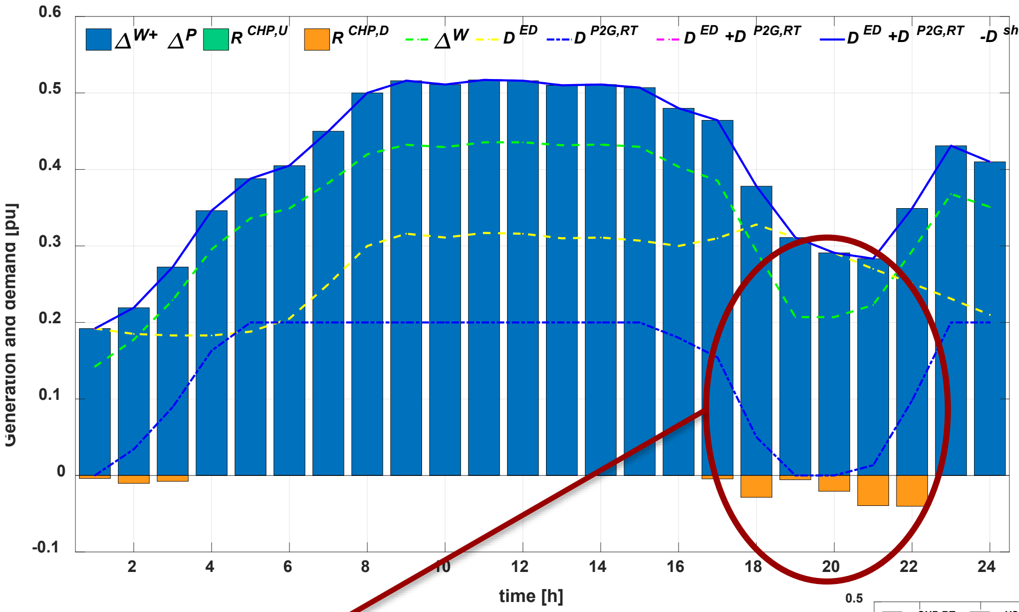
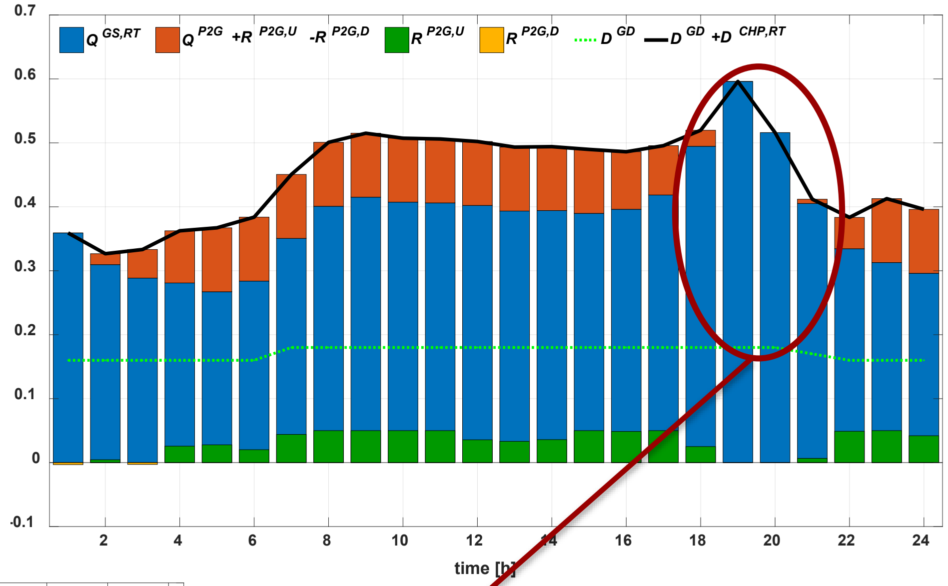
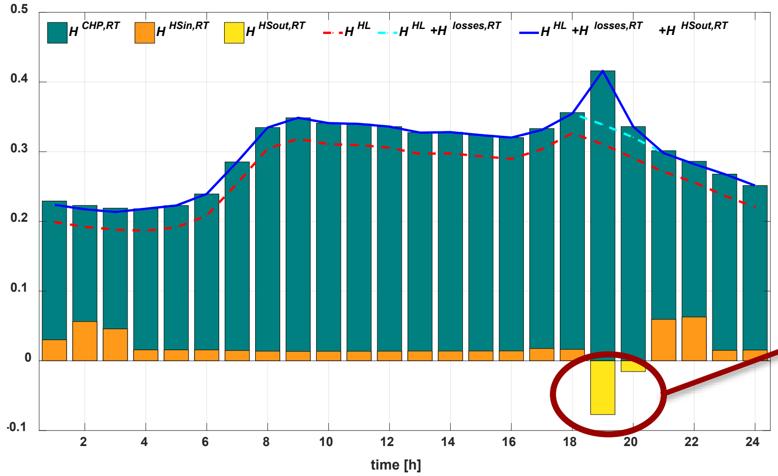
Results for RT stage – Scenario 10







Downward reserves provided by CHP

P2G not providing gas

The excess heat is stored in the storage

Agenda

1. Introduction & Day-ahead scheduling
    - Stochastic programming approach under renewable generation uncertainty
2. Mathematical models of two-stage stochastic programming approach
    - Electrical power system
    - District heating system
    - Natural gas system
    - Coupling components for integrated multi-energy system
    - Linearization
3. Scenario generation and scenario reduction
4. Integrated multi-energy test case system
5. Results
6. **Conclusion & Future work**

Conclusion

- Integration and coordination between EPS, DHS and NGS
- Stochastic day-ahead scheduling

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- Excess electricity can be converted to gas through P2G unit
- Wind curtailment can be reduced
- Low wind realization leads to higher costs and high wind realization to lower costs

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To conclude

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- Integration of EPS, DHS and NGS is a prominent solution for providing flexibility to the power system.
- Scenario generation is proven technique taking into account temporal correlation of the wind power and can be applied to estimate future wind power variability and uncertainty.
- Total expected system cost are decreased and reserves optimized.

- Future work …

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Thank you!

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WEBSITE: https://coreproject-dk.com/approach/