Eidgenössische Technische Hochschule Zürich
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eeh power systems laboratory

# Location-Dependent Valuation of Energy Hubs with Storage in Multi-Carrier Energy Systems

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FAEE student chapter workshop

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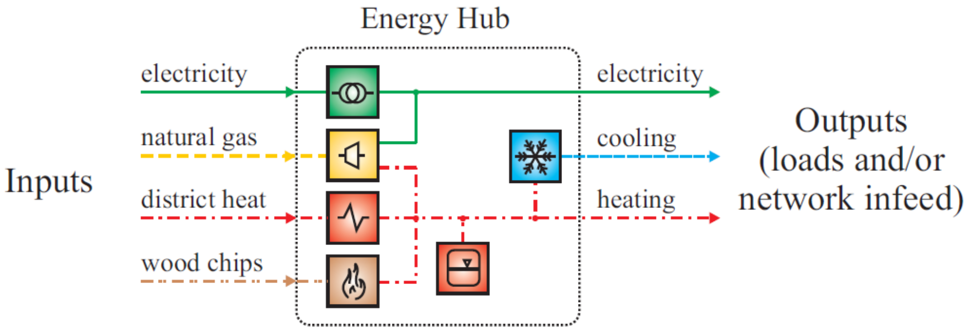
# Outline

- Introduction
- Methods and modeling (energy hubs and real options)
- Application examples
  - Location-dependent valuation
  - Valuation of energy hubs with storage
- Conclusions

# Introduction

- “Vision of Future Energy Networks” project (6 PhD students)
  - How should energy systems look like in 30 to 50 years?
  - Partners: ABB, Areva T&D, Siemens, SFOE
  - Key aspect: Multiple energy carriers
  - Key concept: Energy hub
- What is an energy hub?

## Schematically




## Mathematically

$$\underbrace{\begin{bmatrix} P_\alpha^{out} \\ P_\beta^{out} \\ \vdots \\ P_\omega^{out} \end{bmatrix}}_{\mathbf{P}^{\mathbf{out}}} = \underbrace{\begin{bmatrix} c_{\alpha\alpha} & c_{\beta\alpha} & \cdots & c_{\omega\alpha} \\ c_{\alpha\beta} & c_{\beta\beta} & \cdots & c_{\omega\beta} \\ \vdots & \vdots & \ddots & \vdots \\ c_{\alpha\omega} & c_{\beta\omega} & \cdots & c_{\omega\omega} \end{bmatrix}}_{\mathbf{C}} \underbrace{\begin{bmatrix} P_\alpha^{in} \\ P_\beta^{in} \\ \vdots \\ P_\omega^{in} \end{bmatrix}}_{\mathbf{P}^{\mathbf{in}}}$$

With storage: $\mathbf{P}^{\mathbf{out}} = \mathbf{C}\,\mathbf{P}^{\mathbf{in}} - \mathbf{S}\,\dot{\mathbf{E}}$

# Introduction

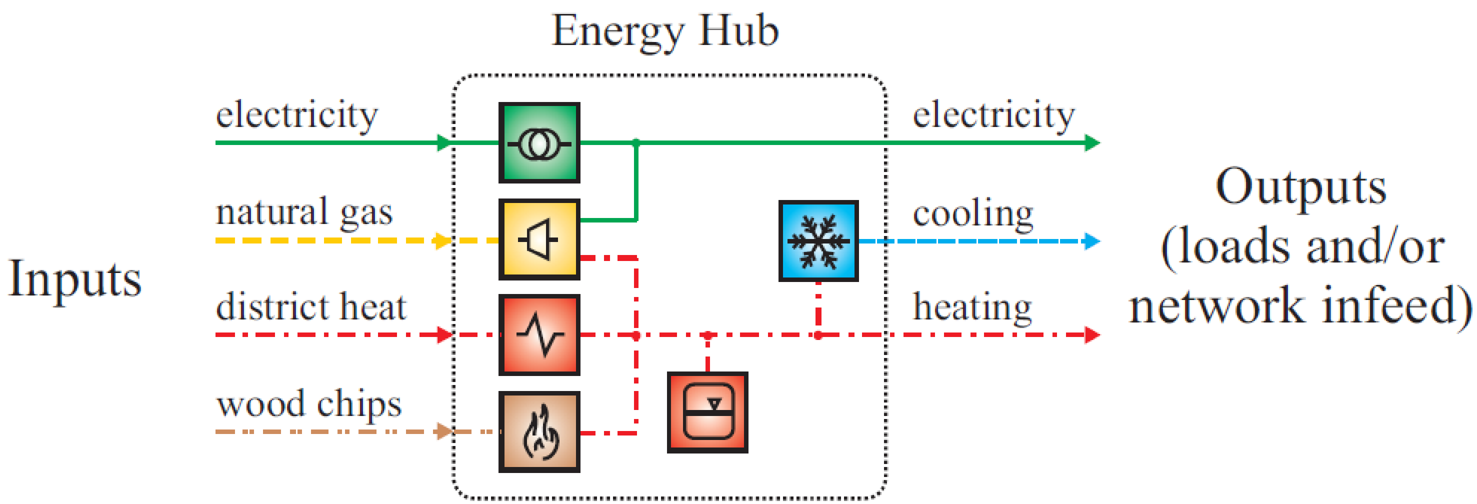
- Energy hub: profit-maximizing multi-energy generator
- Operational flexibility:
  - One output can be produced with different inputs
  - Adapt production to fluctuating energy prices
  - Energy hub can be kept idle if operation would not be profitable
- Take into account this flexibility: real options approach
- Model an energy hub as a real option

General real option valuation method
for multi-energy generation plants

# Methods and Modeling

## *Energy Hub Real Option Model*

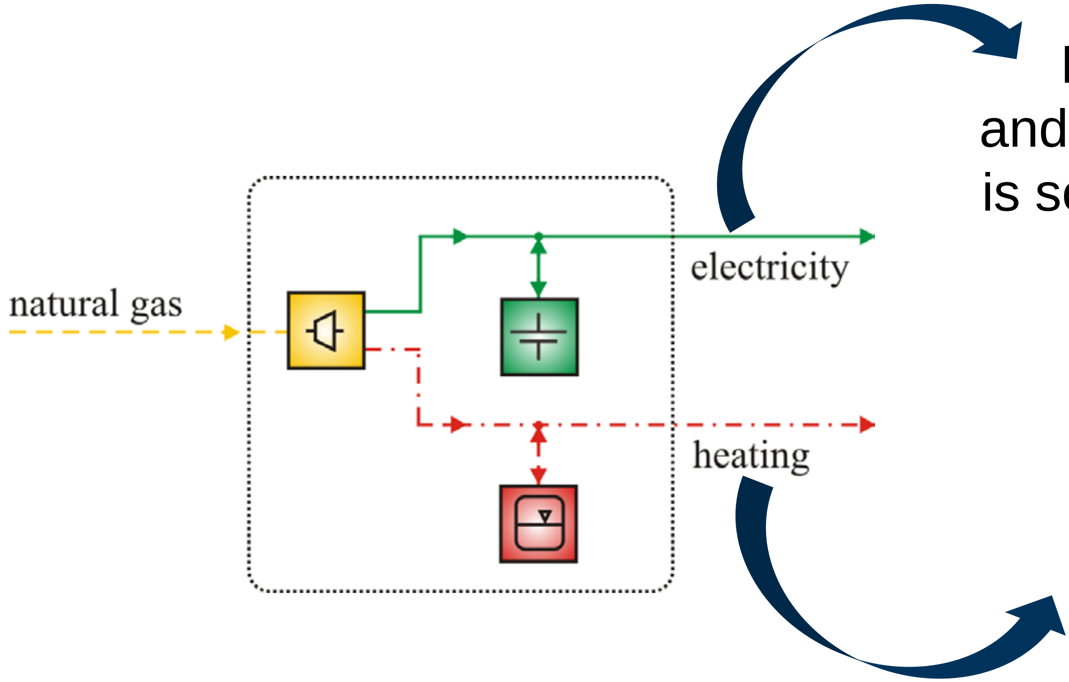
- Owning an energy hub = disposing of a series of call options
- Each call option gives the right to generate energy carriers
- Profits = Revenues minus Costs
- Option-like features:
  - If profits < 0 $\rightarrow$ Energy hub is not operated
  - Flexible adaption of output to fluctuating prices (optimal dispatch)



# Methods and Modeling

## *Energy Hub Real Option Model with Storage*

- Using the energy hub real option model to value hubs with storage devices
- Multi-period optimization necessary (e.g. hourly price and load profiles)
- Optimal dispatch for a complete day




Electric CHP output and stored electric energy is sold in electricity market

Thermal CHP output and heat storage guarantee supply of heat load

# Methods and Modeling

## *Monte Carlo Real Options Approach*

- Analytic solutions for (real) options valuation exist only for special cases
  - Black-Scholes: one random factor
  - Margrabe: two random possibly correlated factors
- For more complex valuation problems with multiple sources of uncertainty, *Monte Carlo simulation* is a powerful technique
- Basic idea of the Monte Carlo method:
  - Use a price process model and random numbers to simulate possible price paths for the underlying assets
  - Repeat the simulations many times
  - Calculate the payoff for each price path and discount it back to today
  - Option value = Average of a large number of simulations
- Advantage: Complexity can be handled
- Main barrier: significant amount of computing time needed

# Methods and Modeling

## *Energy Price Modeling*

- The natural logarithms of the energy prices are modeled as correlated *mean-reverting* price processes

$$dy = \kappa\left(b - y\right)dt + \sigma dz \qquad (1)$$

where

- $y = \ln \pi$
- $\pi$ is the price of an energy carrier
- $\kappa$ is the rate of mean reversion
- $b$ is the long-term equilibrium value of $y$
- $\sigma$ is the volatility
- $dz$ is a random normally distributed variable with mean 1 and variance $dt$

# Methods and Modeling

## *Energy Price Modeling*

- Discrete approximation of (1) for Monte Carlo simulation:

$$y_{t+1} = y_t + \kappa\left(b - y_t\right)\Delta t + \sigma\varepsilon\sqrt{\Delta t} \qquad (2)$$

where $\varepsilon$ is a normally distributed number with a mean of 0 and a variance of 1

- Method to take account of the correlation between energy prices: *Cholesky decomposition*
- Cholesky decomposition factorizes the correlation matrix:

$$\mathbf{\Omega} = \mathbf{L}\mathbf{L}^T \qquad (3)$$

where **L** is a lower triangular matrix

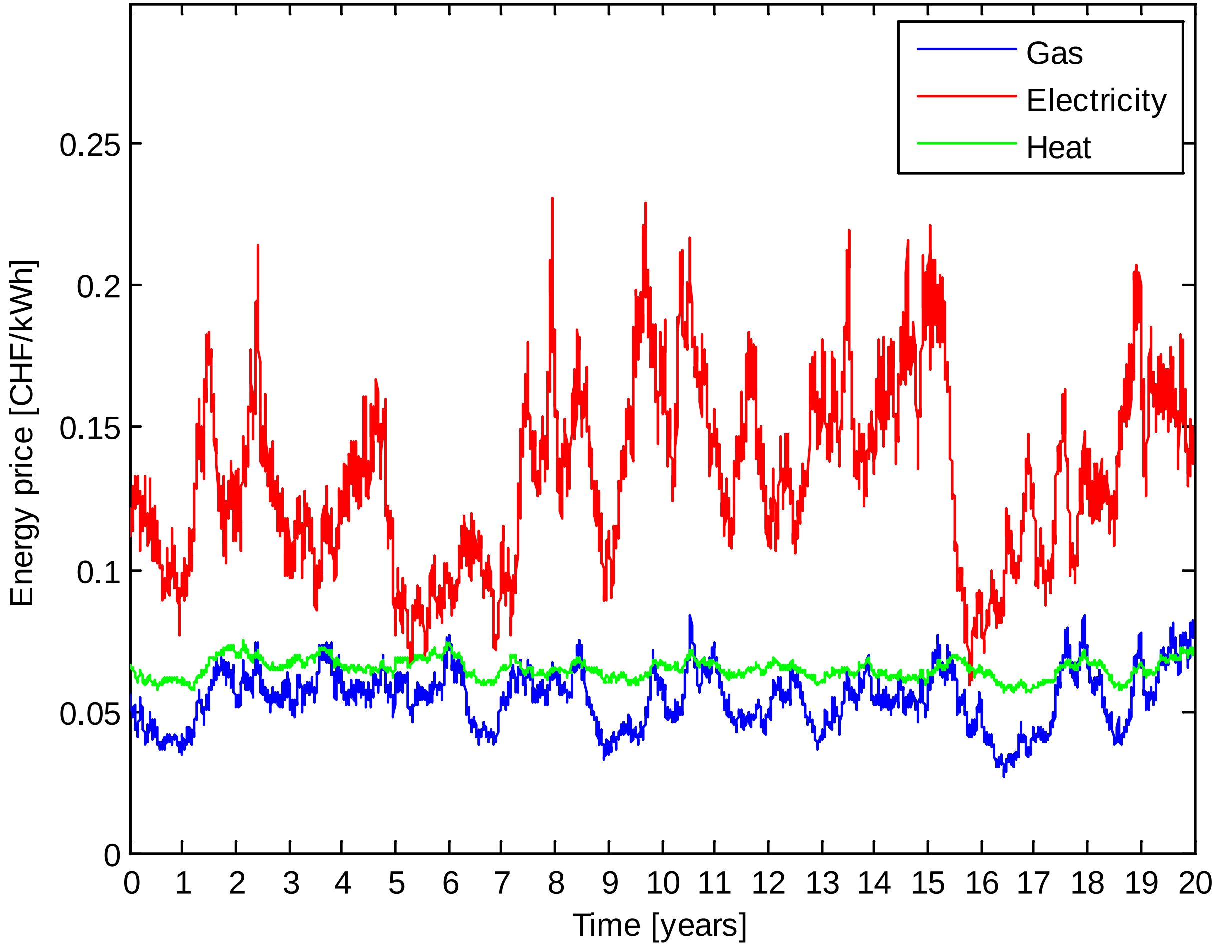
Then: $$\boldsymbol{\varepsilon}_{\mathbf{corr}} = \mathbf{L}\boldsymbol{\varepsilon} \qquad (4)$$

where $\boldsymbol{\varepsilon}$ is a vector of independent normalized variates and $\boldsymbol{\varepsilon}_{\mathbf{corr}}$ a vector of correlated normalized variates

# Methods and Modeling

## *Energy Price Modeling*

- Sample paths of correlated gas, electricity and heat prices




$$\omega_{gas,el} = 0.4$$

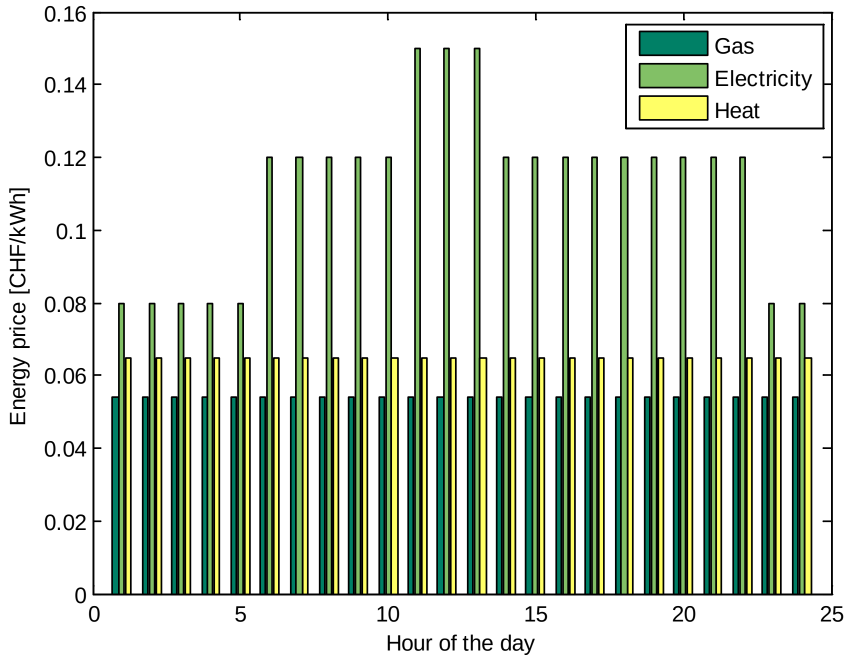
$$\omega_{gas,heat} = 0.8$$

$$\omega_{el,heat} = 0.2$$

# Methods and Modeling

## *Energy Price Modeling*

- Base profiles with hourly energy prices for storage valuation




- For each day of the simulation, the base price profile of each energy carrier is multiplied with its random scaling factor
- For constant prices of energy carrier *i*, $\sigma_i$ is set to 0

# Methods and Modeling

## *Optimal Dispatch and Option Valuation*

- For each set of simulated price paths, the daily energy hub profits are calculated:

$$F_d = \sum_{t=1}^{N_t}\left(\left(\mathbf{P}_t^{out}\cdot \pi_t^{out}\right) - \left(\mathbf{P}_t^{in}\cdot \pi_t^{in}\right)\right)$$

where

  - $F_d$ are the daily profits
  - $\mathbf{P}^{out}$ and $\mathbf{P}^{in}$ are the output and input powers respectively
  - $\pi^{out}$ and $\pi^{in}$ are the output and input prices respectively

- Determination of $\mathbf{P}^{out}$ and $\mathbf{P}^{in}$ by multi-period optimal dispatch:

Maximize

$$f\left(\mathbf{P}_t^{in}, \boldsymbol{\nu}_t, \mathbf{E}_t\right) = \sum_{t=1}^{N_t}\left(\left(\mathbf{P}_t^{out}\cdot \boldsymbol{\pi}_t^{out}\right) - \left(\mathbf{P}_t^{in}\cdot \boldsymbol{\pi}_t^{in}\right)\right)$$

subject to

$$\mathbf{P}_t^{out} - \mathbf{C}\,\mathbf{P}_t^{in} - \mathbf{S}\,\dot{\mathbf{E}}_t = \mathbf{0}$$
$$\mathbf{E}(t=1) = \mathbf{E_1}$$
$$\mathbf{E}(t=N_t) = \mathbf{E_{N_t}}$$

and

$$\mathbf{P}_{min}^{out} \le \mathbf{P}_t^{out} \le \mathbf{P}_{max}^{out}$$
$$0 \le \boldsymbol{\nu}_t \le 1$$

# Methods and Modeling

## *Optimal Dispatch and Option Valuation*

- Calculation of daily option payoffs if $F_d$ can become negative:

$$H_d = \max\left[F_d; 0\right] \quad (6)$$

- Discounted option payoffs for each simulation run:

$$H_{run} = \sum_{t=0}^{T}\left(H_{d,t} \cdot e^{-rt}\right) \quad (7)$$

where *r* is the continuous risk-adjusted discount rate

- Value of the energy hub:

$$V = \sum_{n=1}^{N} H_{run,n} \cdot \frac{1}{N} \quad (8)$$

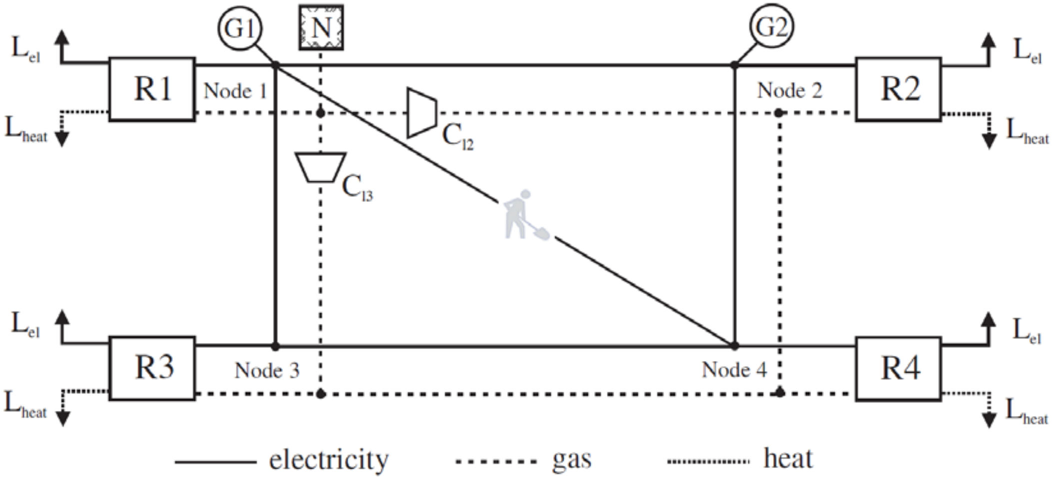
where *N* is the number of simulation runs

- The value of the energy hub *V* is then compared to its capital investment costs *I*
  - If *V* > *I*: Invest
  - If *V* < *I*: Do not invest

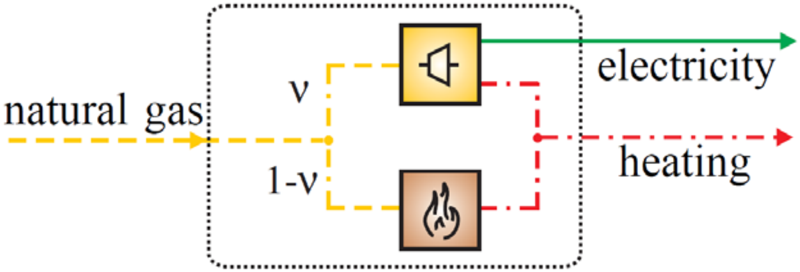
# Application examples

## *Location-dependent valuation*

- System with 4 hubs interconnected by a natural gas and electricity system:



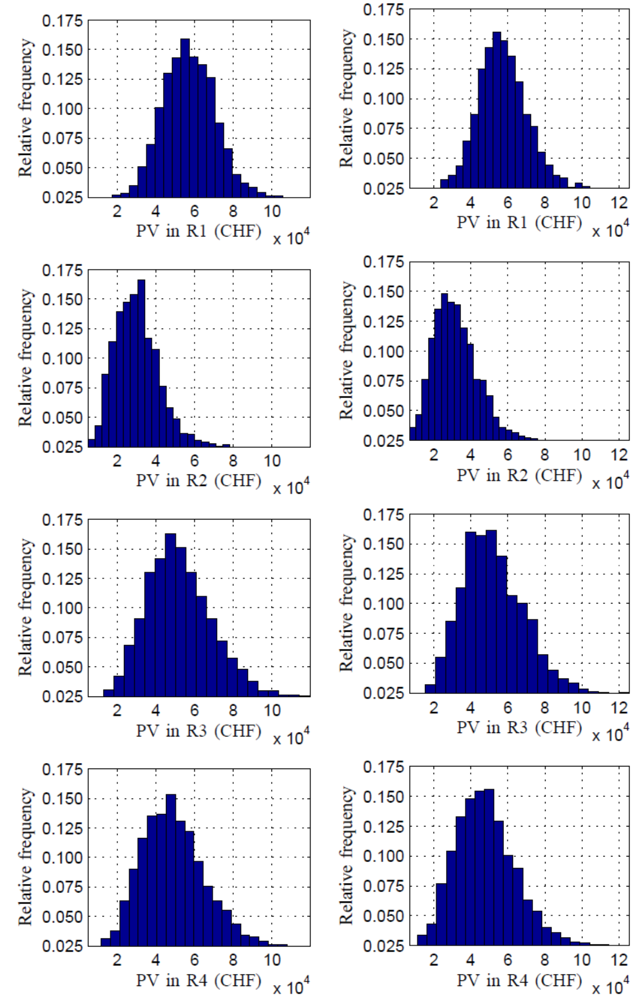

- Local energy conversion devices in the regions are represented by an energy hub:



# Application examples

## *Location-dependent valuation*

- Assuming certain system parameters, an annual electricity load growth of 2% in region R4 is simulated
- An optimal power flow (OPF) analysis is run for each year of a period of 20 years
- Two cases are distinguished:
  - No line from node 1 to node 4 (a)
  - Line built from node 1 to node 4 after 10 years (b)
- The resulting nodal energy prices are used as long-term mean values in the log-of-price mean reversion price model
- Monte Carlo real option valuation with a total of 2000 runs



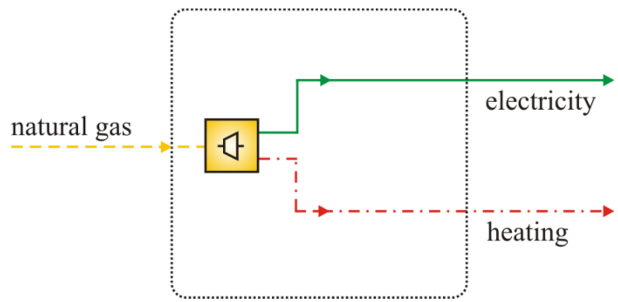

(a) No Line Built (b) Line Built

# Application examples

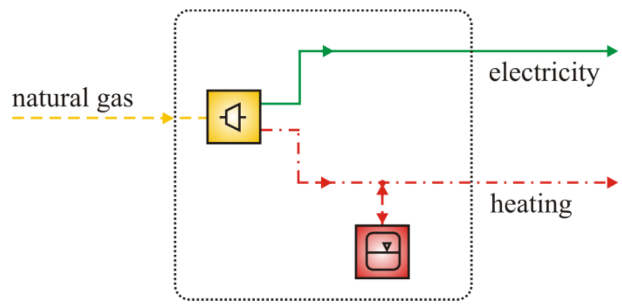
## *Valuation of energy hubs with storage*

- Comparison of three hub structures

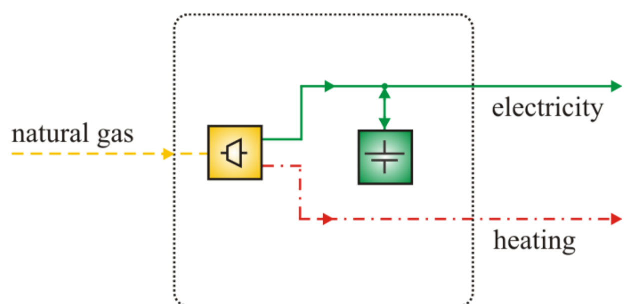
1) Without storage




2) With heat storage




3) With electricity storage




CHP

$$P_{CHP,el,\max} = 20\,p.u.$$
$$\eta_{CHP,el} = 0.33$$
$$\eta_{CHP,heat} = 0.57$$

Storage (heat and el.)

$$E_{\max} = 10\,p.u.$$
$$E_{\min} = 0.5\,p.u.$$
$$M_{\max} = 3\,p.u.$$
$$M_{\min} = -3\,p.u.$$
$$\eta_{storage+} = 0.9$$
$$\eta_{storage-} = 0.9$$
$$E_{stb} = 0.1\,p.u.$$
$$E_0 = E_N = \frac{E_{\max}}{2} = 5\,p.u.$$

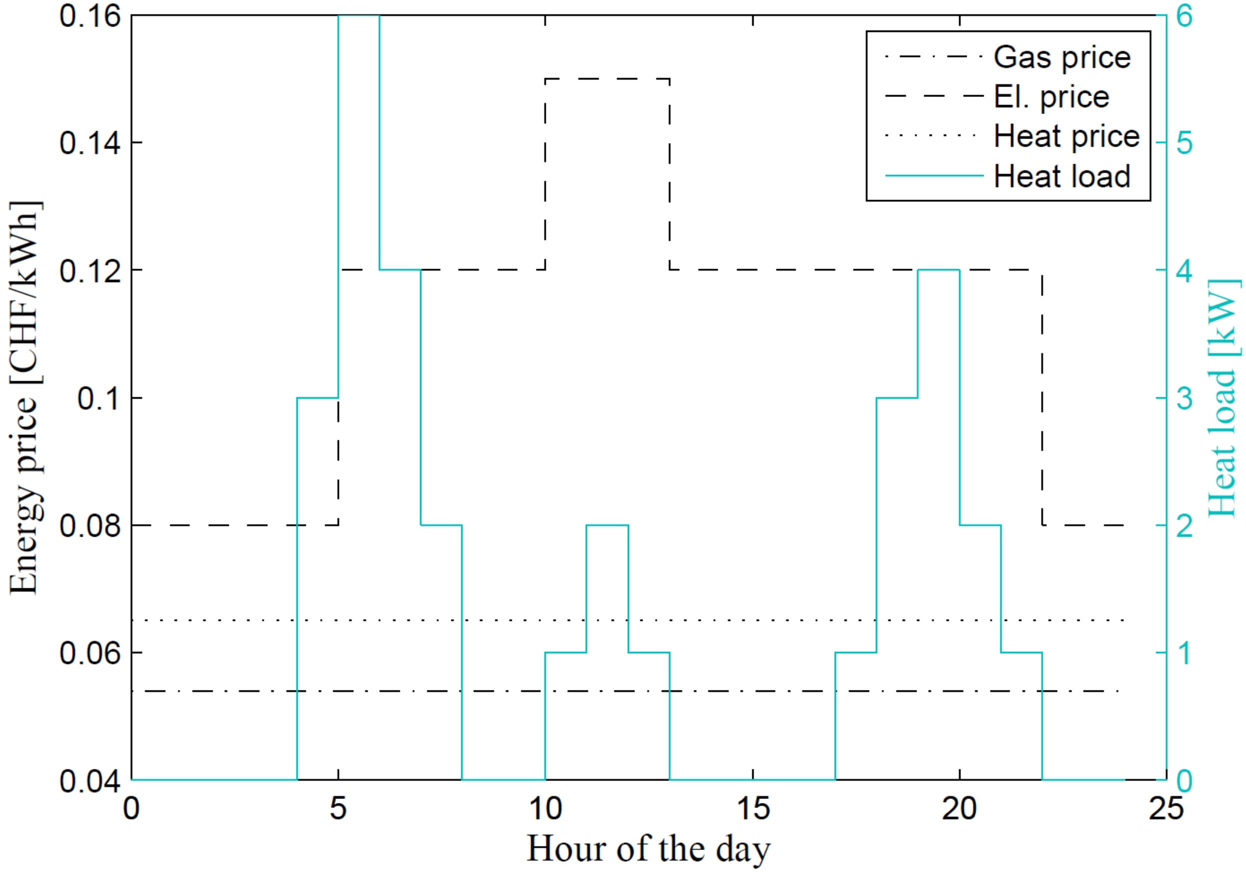
Price processes

$$\sigma_{el} = 0.5$$
$$\sigma_{gas} = 0.4$$
$$\sigma_{heat} = 0.1$$

# Application examples

## *Valuation of energy hubs with storage*

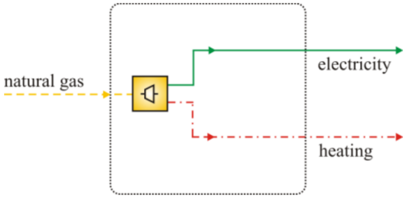
- Base profiles of hourly energy prices and heat load

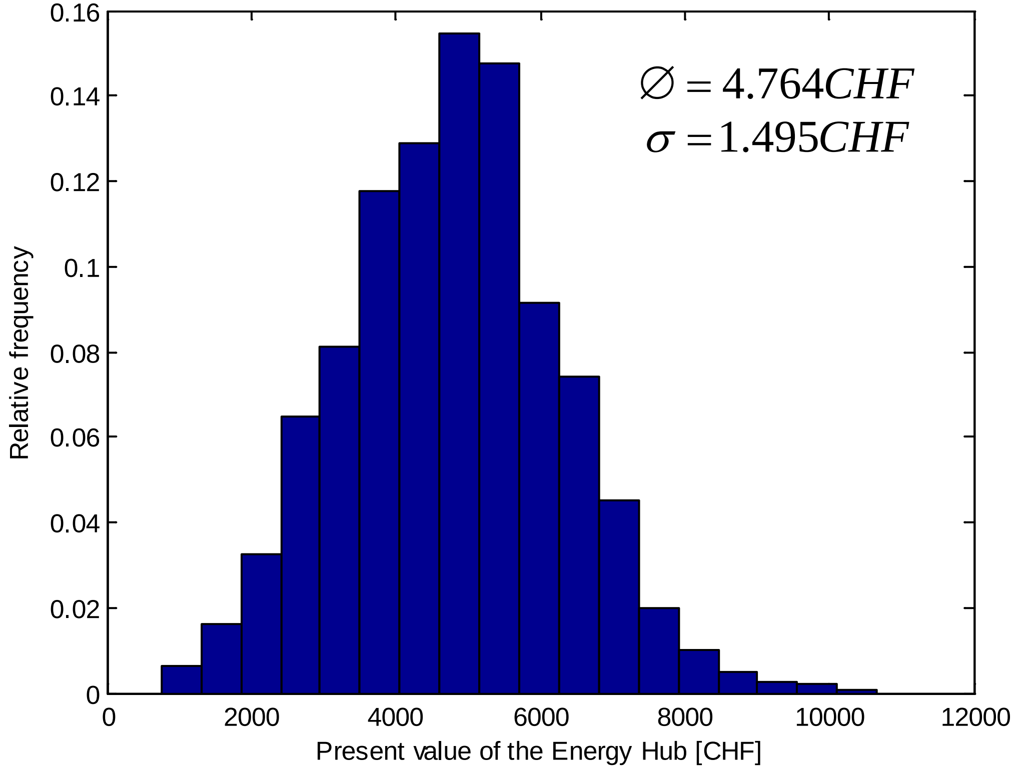


# Application examples

## *Valuation of energy hubs with storage*

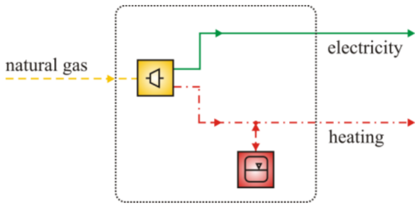
- Without storage

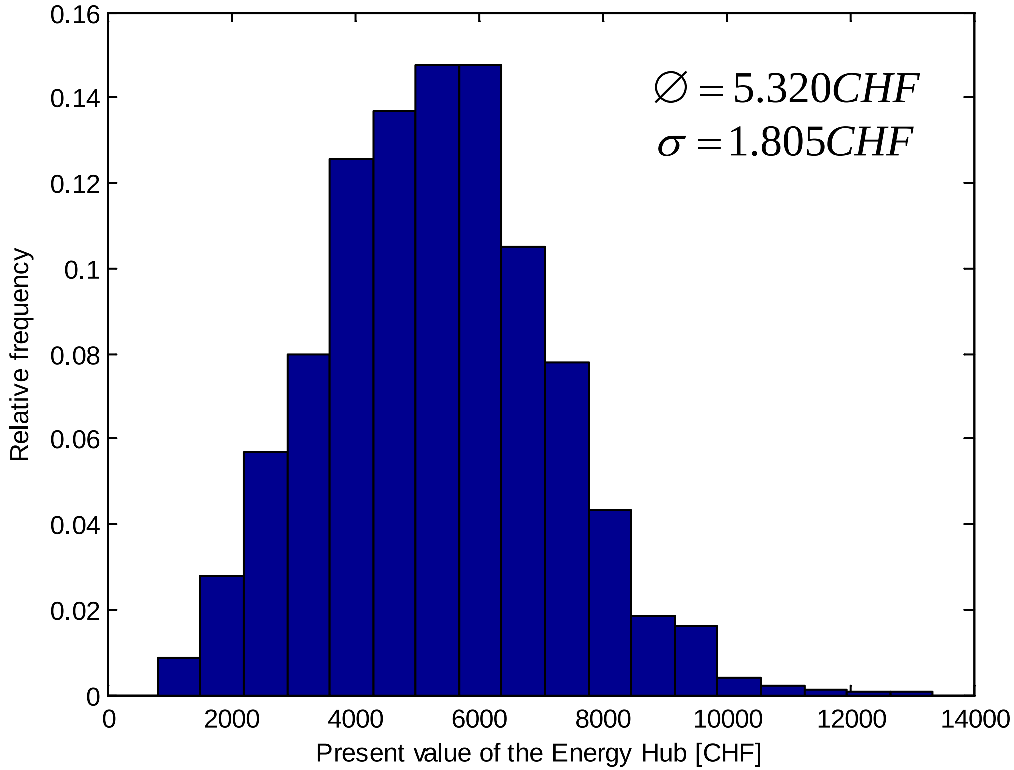


# Application examples
## *Valuation of energy hubs with storage*

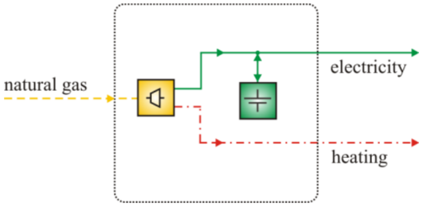
- With heat storage

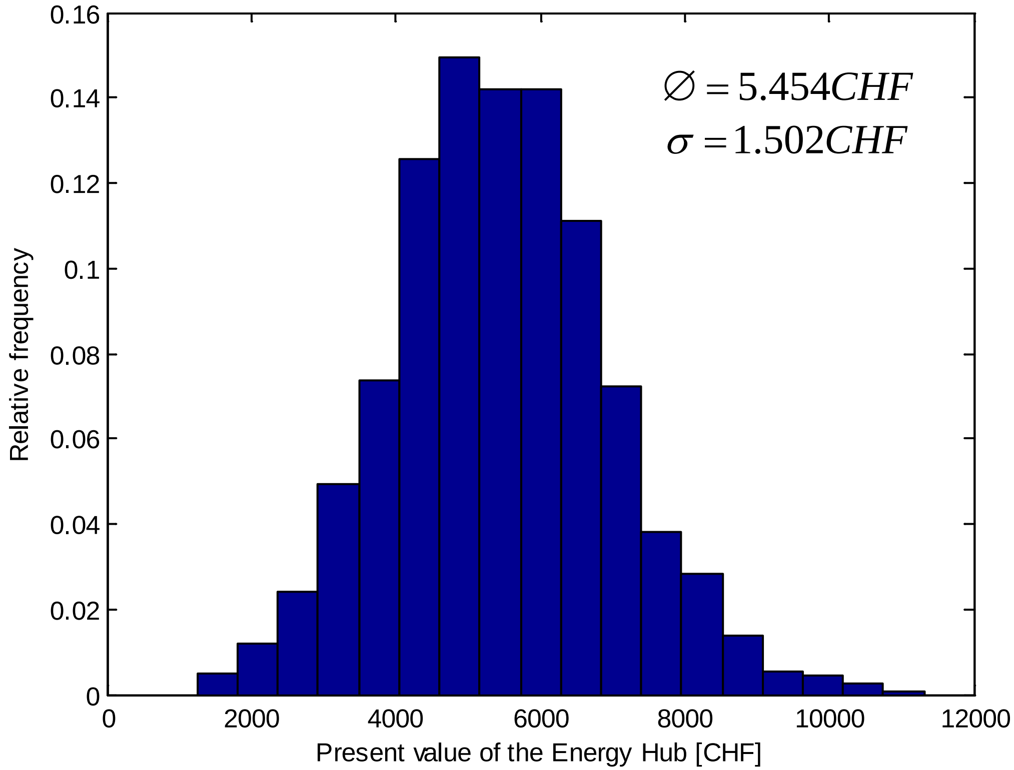


# Application examples
## *Valuation of energy hubs with storage*

- With electricity storage



# Conclusions

- With the presented energy hub real options model, integrated systems of conversion and storage devices with an arbitrary number of energy inputs and outputs can be valued
- Location-dependent information can be conveniently integrated into the model
- By comparing hubs with and without storage, the value of adding storage to existing structures can be determined
- The real options model takes into account operational flexibility, which is particularly important given the expected role of real time pricing in future power systems

# Merci de votre attention!

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