The Energy Hub -
A Powerful Concept for Future Energy Systems

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Presentation outline

• Project background

• The hub concept

• Examples

• Concluding remarks
Visions of Future Energy Networks: Motivation

• Today‘s system is necessarily not optimal to meet future requirements from customers and power producers

• New technologies are emerging both with regard to primary systems and secondary and enabling systems

• Environmental and regulatory requirements are changing
Greenfield Approach

Today's System

Backcasting

Bridging Systems

Forecasting

"Optimal"

"Sub-optimal"

Overall Performance

Time

2000

2050

ETH

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich
Interaction System Requirements - Technology

System

Technology

Customer req.
Layout
Operation - Control
Optimisation
Regulation
...

Features
Costs
Requirements
...
Project sponsors:
ABB
AREVA TD
Siemens
Bundesamt für Energie (CH)
SwissPower, Novatlantis, ...
ETH

Academic partners: TU Delft, RWTH Aachen,
NTNU Trondheim, CEPE ETHZ,
Principle network layout – multicarrier system

- Biogas

- Electrical energy
- Chemical energy
- Heat
The Energy Hub – a key element
The Energy Hub – an example
Energy Hub Model

\[
\begin{bmatrix}
    P^\alpha_{\text{out}} \\
    P^\beta_{\text{out}} \\
    \vdots \\
    P^\zeta_{\text{out}}
\end{bmatrix}
= 
\begin{bmatrix}
    C_{\alpha\alpha} & C_{\beta\alpha} & \cdots & C_{\zeta\alpha} \\
    C_{\alpha\beta} & C_{\beta\beta} & \cdots & C_{\zeta\beta} \\
    \vdots & \vdots & \ddots & \vdots \\
    C_{\alpha\zeta} & C_{\beta\zeta} & \cdots & C_{\zeta\zeta}
\end{bmatrix}
\begin{bmatrix}
    P^\alpha_{\text{in}} \\
    P^\beta_{\text{in}} \\
    \vdots \\
    P^\zeta_{\text{in}}
\end{bmatrix}
\]

Output Power Vector \quad Coupling Matrix \quad Input Power Vector
The energy interconnector

Approach: Common transmission device for several energy carriers

- electricity
- chemical energy
- heat
Three step procedure

1. Requirements of the (future) grid participants
   - Extrapolation, scenarios

2. Identification of necessary technology
   - Databases, eco-balancing, techn. forecasts

3. Modelling, optimisation, analysis
   - Implementation proposals

Local energy demand (chemical, thermal, electric)
General Results

- Power conversion ⇔ price conversion

![Diagram showing power conversion and price conversion in an energy hub system.](image-url)

System marginal prices:
- \( P, \Psi = \Lambda C \)

Hub marginal prices:
- \( L = C P, \Lambda \)
Comparison with classical case

<table>
<thead>
<tr>
<th>Electricity optimal dispatch</th>
<th>Multi-carrier optimal dispatch</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Diagram showing a Lossless network with generators $G_1, G_2, \ldots, G_N$ connected to a common bus, with constraints $P_1 + P_2 + \ldots + P_N = P_L$ and optimality condition $\lambda_1 = \lambda_2 = \ldots = \lambda_N = \lambda_L$." /></td>
<td><img src="image" alt="Diagram showing a Linear hub with inputs $P_\alpha, P_\beta, P_\omega$ and outputs $L_\alpha, L_\beta, L_\omega$, with constraint $L = CP$ and optimality condition $\Psi = \Lambda C$." /></td>
</tr>
</tbody>
</table>

**Constraint:**  
$P_1 + P_2 + \ldots + P_N = P_L$

**Optimality condition:**  
$\lambda_1 = \lambda_2 = \ldots = \lambda_N = \lambda_L$

**Constraint:**  
$L = CP$

**Optimality condition:**  
$\Psi = \Lambda C$
Example for hub evaluation

- Goal: optimal operation of an energy hub

- Given
  - Energy cost (electr. = 0.1 €/kWh, gas, heat = 0.05 €/kWh)
  - Hub characteristics

\[
C = \begin{bmatrix} 1 & \eta_{ge}(P_g) & 0 \\ 0 & \eta_{gt}(P_g) & 1 \end{bmatrix} \quad E_{CO_2} = 0.7 \text{ kg/kWh}_{gas}
\]

- Wanted: optimal hub inputs due to minimal energy cost
Operational Optimization

- Result

![Graph showing energy cost and CO2 emissions as functions of gas input. The graph indicates a minimum CO2 output at 65 kW gas input.]
Investment evaluation

The diagram illustrates the present value in k€/MWe at different total efficiencies in %.

- At 70% efficiency, the present value is 482 k€/MWe.
- At 80% efficiency, the present value is 675 k€/MWe.
- At 90% efficiency, the present value is 824 k€/MWe.

The dashed line indicates the realistic present value today, which is at 675 k€/MWe.
Optimal Hub Coupling

Electricity

Natural gas

District heat

\[ C = ? \]
Table 5.10: Optimal Inputs for Different Loads.

<table>
<thead>
<tr>
<th>Case</th>
<th>Required $L^T$ in pu</th>
<th>Optimal $P^T$ in pu</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>[1 1 1]</td>
<td>[0.00 1.76 1.24]</td>
</tr>
<tr>
<td>(b)</td>
<td>[1 0 1]</td>
<td>[0.00 1.17 0.83]</td>
</tr>
<tr>
<td>(c)</td>
<td>[2 0 2]</td>
<td>[0.77 1.89 1.34]</td>
</tr>
<tr>
<td>(d)</td>
<td>[1 0 2]</td>
<td>[0.00 1.76 1.24]</td>
</tr>
<tr>
<td>(e)</td>
<td>[1 0 5]</td>
<td>[2.51 2.04 1.45]</td>
</tr>
<tr>
<td>(f)</td>
<td>[2 0 10]</td>
<td>[7.84 2.44 1.72]</td>
</tr>
</tbody>
</table>
Example: coupling of electrical and gaseous chemical power

Assumptions:
- Electrical input power constant
- Inlet (20 °C) and outlet (120 °C) temperature fixed
- Inlet pressure
- Outlet pressure

Conclusion: For given electrical losses economical chemical throughput is limited within the range: \( \dot{m}_{min} < \dot{m} < \dot{m}_{max} \)
Reliability of an Energy Hub

Expected Energy Not Supplied:
1h/a → 27.6 Min/a
Practical Case: Regionalwerke Baden
Other results

- Detailed reliability modeling and analysis
- Optimal sizing and use of storage devices
- Modeling of stochastic (non-dispatchable) power sources
Future homework

- Expand models from steady state to dynamic, develop control strategies
- Develop investment strategies (bridging systems)
- Identify and evaluate necessary technology
- Apply the hub idea to a Swiss city (Baden, Swiss Power)
- Integrate coupling with mobility
- *Develop Road Maps for the European system*
Conclusions

• Sources, load and network are strongly interactive

• Systems and technology aspects are strongly interactive as well

 ➔ research approach has to consider all these interactions

• The hybrid network is closer to reality than it looks in a first view
More information

http://www.eeh.ee.ethz.ch/psl/research/vofen.html