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Swiss Federal Institute of Technology Zurich

Optimal Energy Flow of Integrated Energy Systems with Hydrogen Economy Considerations

A. Hajimiragha, C. Canizares, M. Fowler
University of Waterloo
Waterloo, Ontario, Canada

M. Geidl, G. Andersson
ETH Zurich
Switzerland

Sustainable Development Workshop 2007

Outline

- ♦ Motivation.
- ♦ Background.
- ♦ Case Study.
- ♦ Selected Results.
- ♦ Conclusions.

Motivation

- Energy demand is permanently increasing.
- Environmental concerns:
  - Global climate change.
  - Local and regional environmental issues (e.g. air quality).
  - Impact of fossil fuels (CO2, NOx, SOx).

Motivation

- Reduce energy and environmental footprint via:
  - Efficient energy utilization.
  - Distributed generation.
  - Demand side management.
  - *Integration of various energy infrastructures.*

Motivation

- Previously developed modeling and analysis tools are largely dedicated to electricity, natural gas, and district heating systems.
- The idea proposed in this paper is the consideration of *Hydrogen Economy* issues in the framework of integrated energy systems.
- A key issue to be addressed is the understanding all interactions among the involved energy vectors, based on the models developed for integrated energy system and optimal energy flows (OEF).

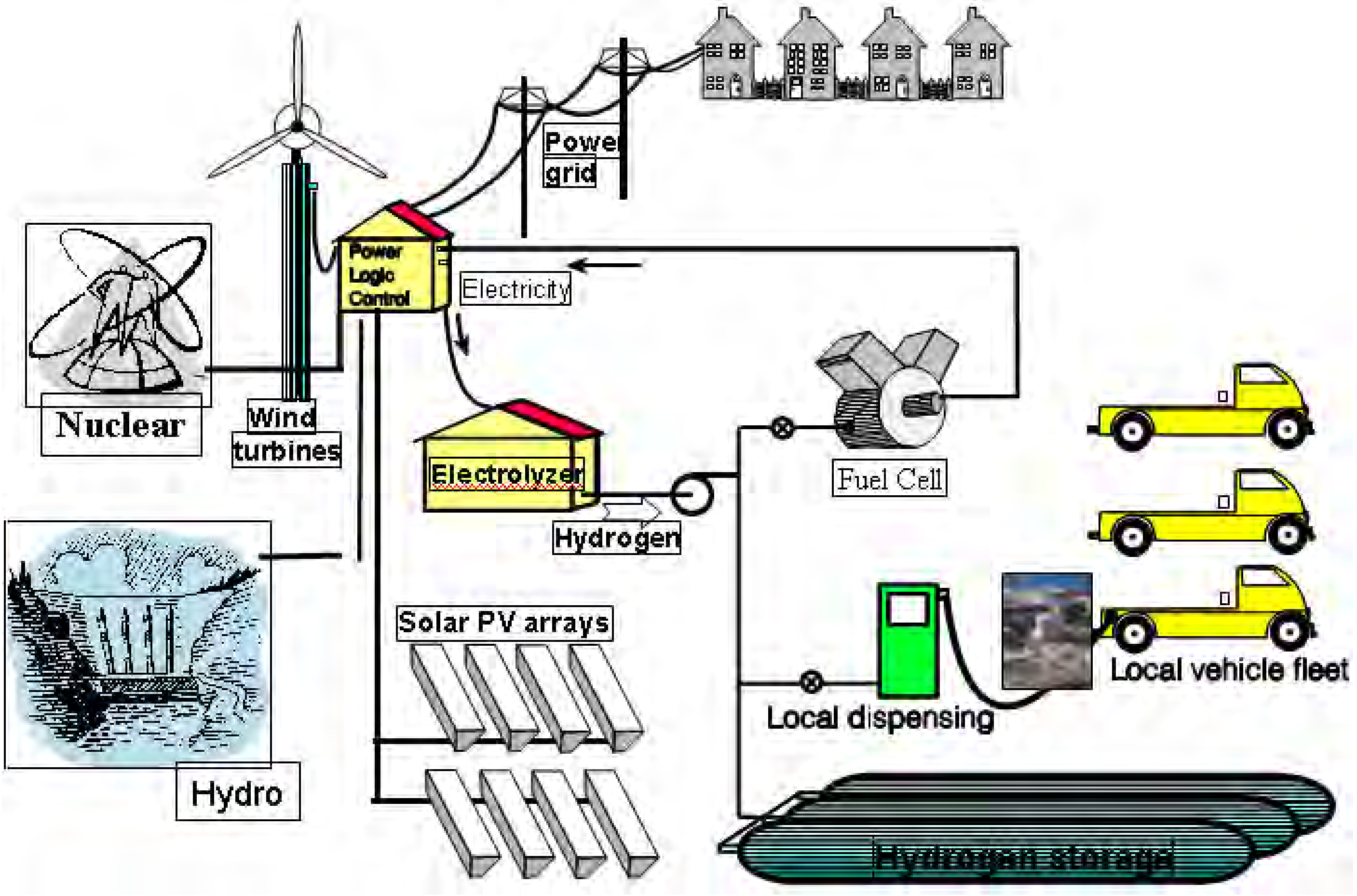
Hydrogen Economy

- Definition: It concentrates on the study of the economic and technical aspects associated with hydrogen production, storage, distribution, and utilization.
- History: It was introduced in the early 1970s, but has attracted a great deal of attention in the last few years.
- Motivation: Mainly, environmental issues and resource depletion.

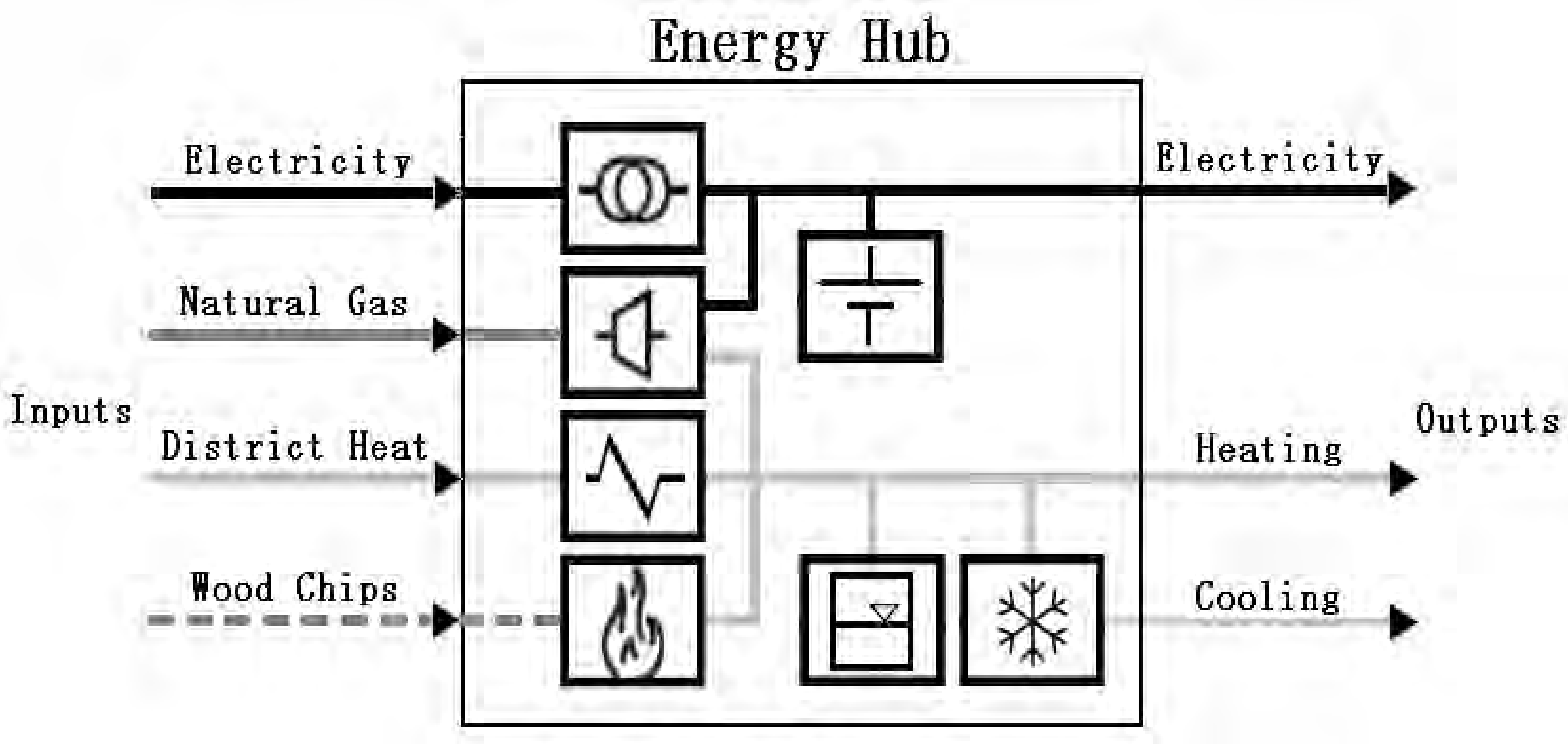
Hydrogen Economy

- Main advantages:
  - Potential for energy storage and use in transport applications.
  - Decrease in urban air pollution and greenhouse gas emissions.
  - Diversification of energy production and security of supply.

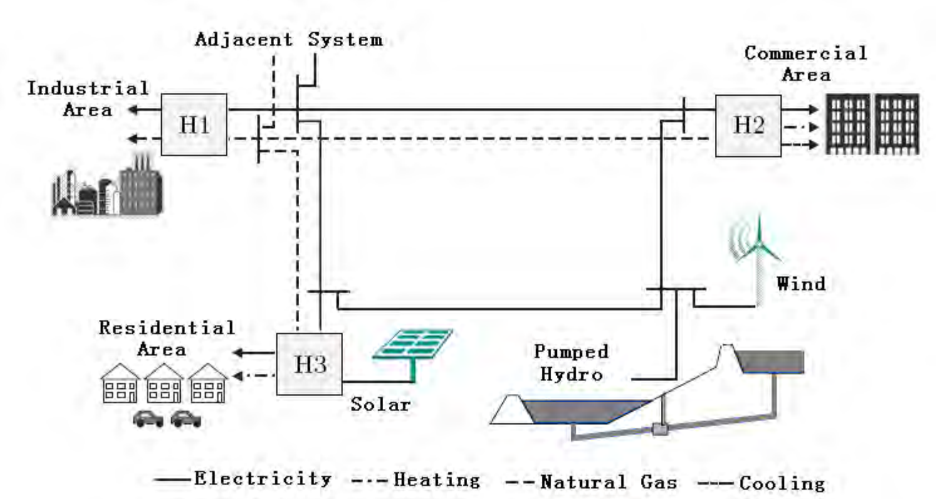
Hydrogen Economy



Background: Energy Hubs

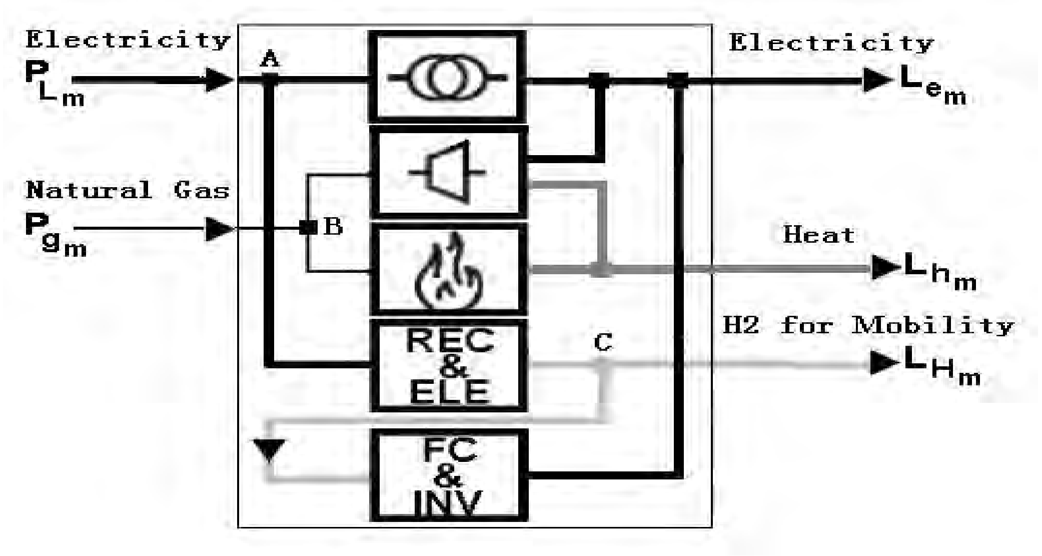


Background: Energy Hubs



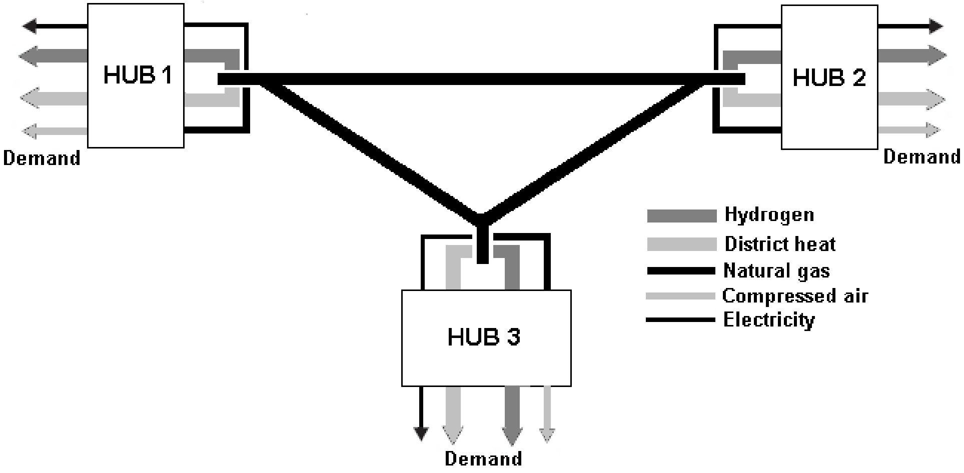
- Applications: Industrial plants, large building complexes, rural and urban districts.
- Benefits:
  - Reduction of energy cost and system emissions.
  - Increased security and availability of supply.
  - Relief from congestion in energy distribution systems.
  - Overall energy efficiency improvement.

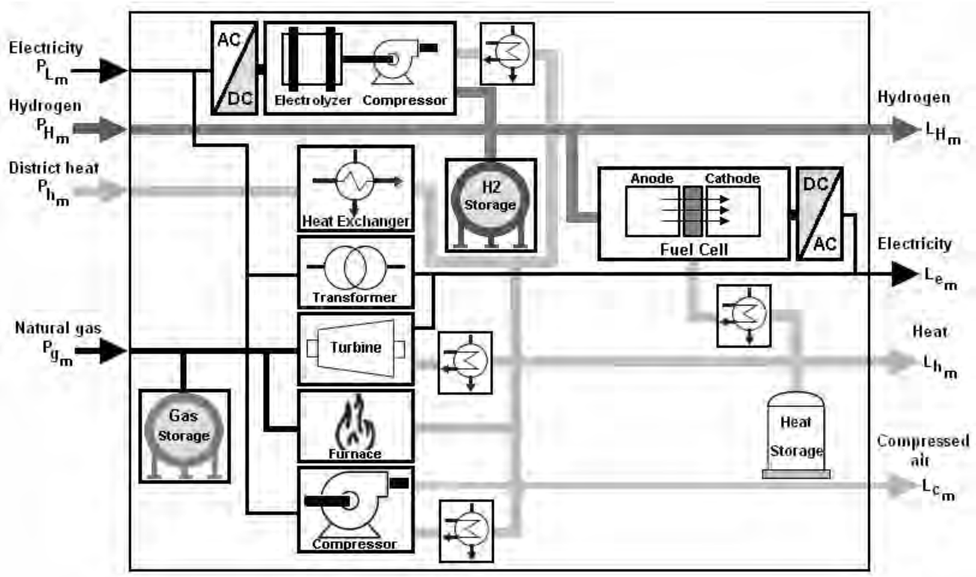
Background: OEF



- ♦ OEF within a hub:
  - Objective function.
  - Equality constraints.
  - Inequality constraints.
  - Optimization candidates.
- ♦ OEF in a system of interconnected energy hubs requires additional constraints.
- ♦ Inclusion of energy storage devices yields new variables and parameters to be considered.

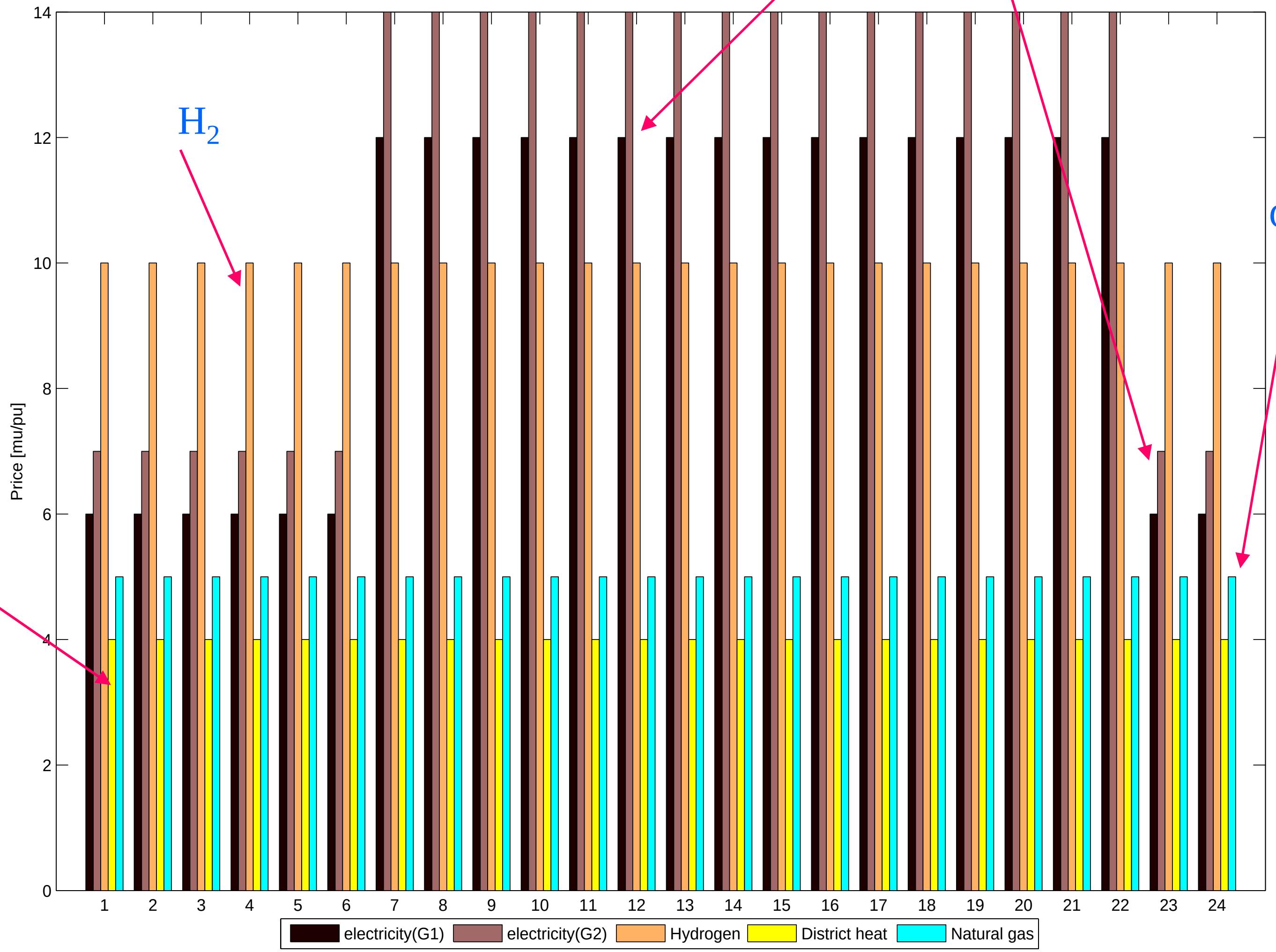
Case Study


HUB 1
HUB 2
HUB 3
Demand
Demand
Demand
Hydrogen
District heat
Natural gas
Compressed air
Electricity


Electricity
P_{L_m}
Hydrogen
P_{H_m}
District heat
P_{h_m}
Natural gas
P_{g_m}
AC
DC
Electrolyzer
Compressor
Heat Exchanger
H2 Storage
Transformer
Turbine
Furnace
Compressor
Gas Storage
Anode
Cathode
Fuel Cell
DC
AC
Heat Storage
Hydrogen
L_{H_m}
Electricity
L_{e_m}
Heat
L_{h_m}
Compressed air
L_{c_m}

Case Study

- Energy costs:



G_1 and G_2 prices (peak and off-peak)

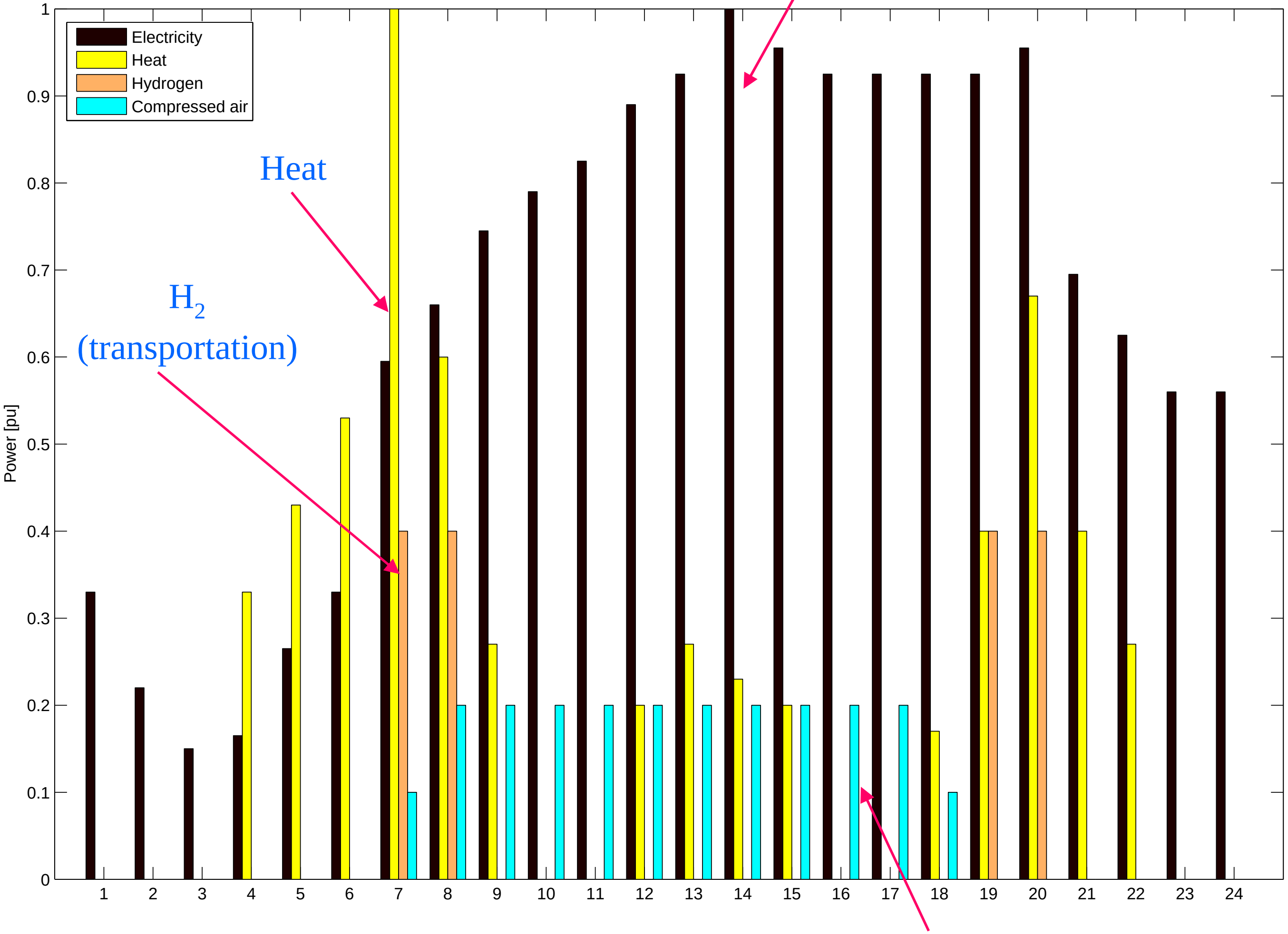
H_2

Gas

Heat

Case Study

- Energy demands:



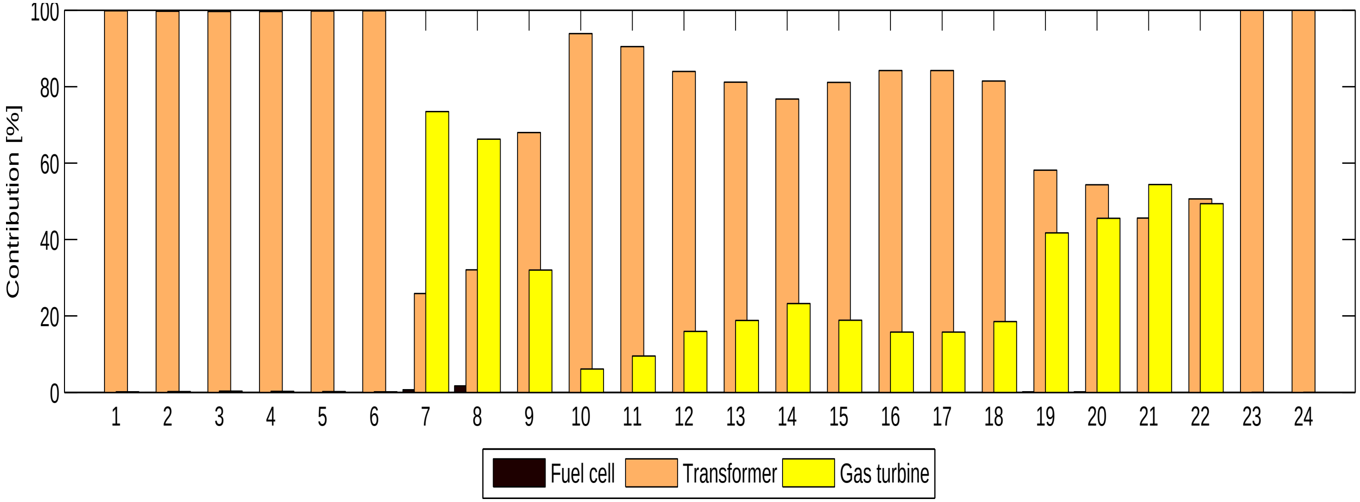
Electricity

Heat

H_2 (transportation)

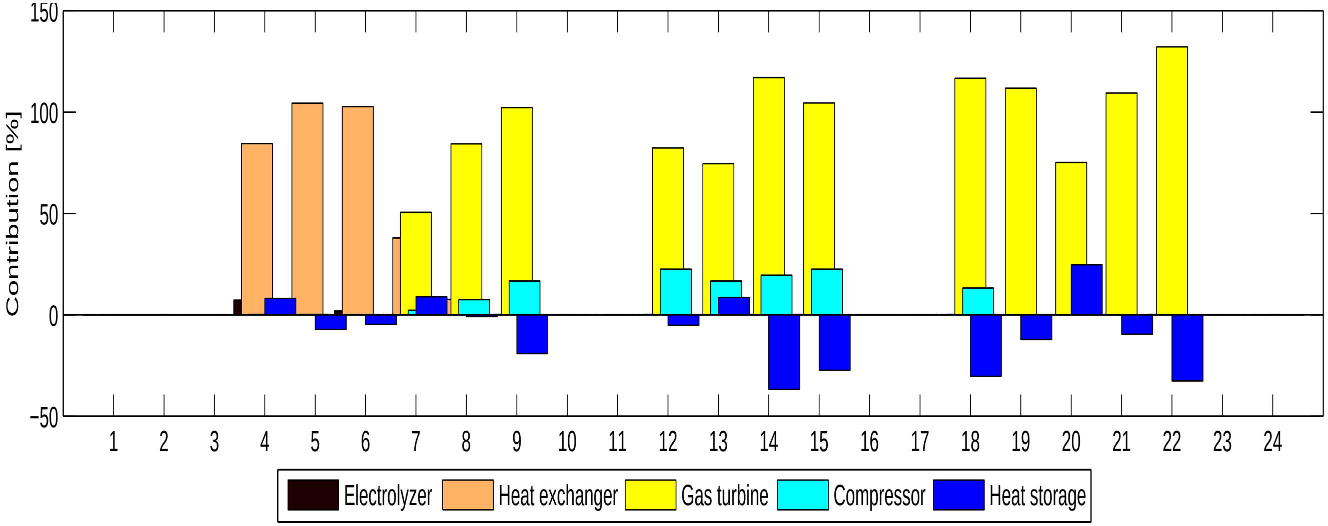
Compressed Air

Results



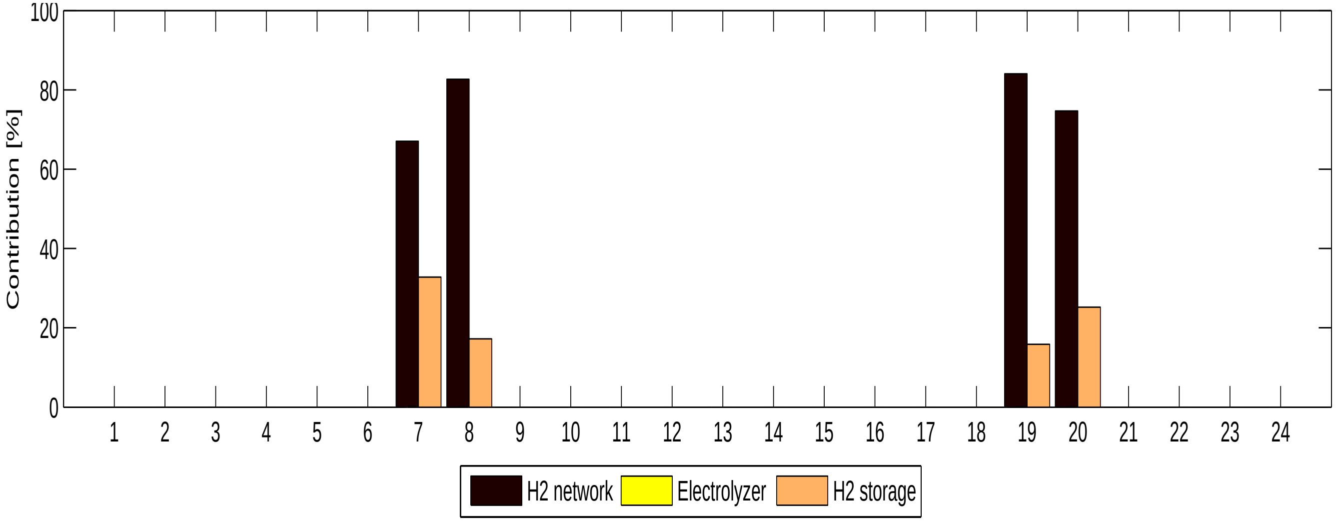
- Percentage of contributions to electricity demand (similar for all hubs):
  - Microturbine (35% efficiency) highly utilized at high electricity prices.
  - Fuel cell low efficiency (55%) compared to the transformer's (98%) leads to its low utilization, in view of the price differences between hydrogen and electricity.

Results



- Percentage of contributions to heat demand (similar for all hubs):
  - Electrolyzer (15% efficiency) is utilized very little overall.
  - Microturbine (45% efficiency) is highly utilized and provides “free’’ heat.
  - District heat (heat exchangers with 90% efficiency and low cost) is used when microturbine is not on.
  - There is some heat storage mainly from the electrolyzer and compressor.

Results



- Percentage of contributions to H_2 demand (similar for all hubs):
  - H_2 storage is somewhat significant.
  - Electrolyzer is used to store H_2 at off-peak hours, based on the price differential between H_2 and electricity.

Conclusions

- More flexibility in energy conversion inside the hub, and more freedom in system planning and operation is observed.
- Hydrogen production and storage through a high efficiency energy pathway (electrolyzer) makes sense when there is a “large” price difference between electricity and H_2 prices.
- Microturbine plays a significant role in supplying both electricity and heat.
- Fuel cells does not make sense for electricity production, unless electricity prices are higher and/or efficiencies are improved.
- Further studies:
  - More price and demand scenarios need to be analyzed.
  - Wind, solar and/or bio fuels should be considered.
  - Environmental “costs” should be factored in.

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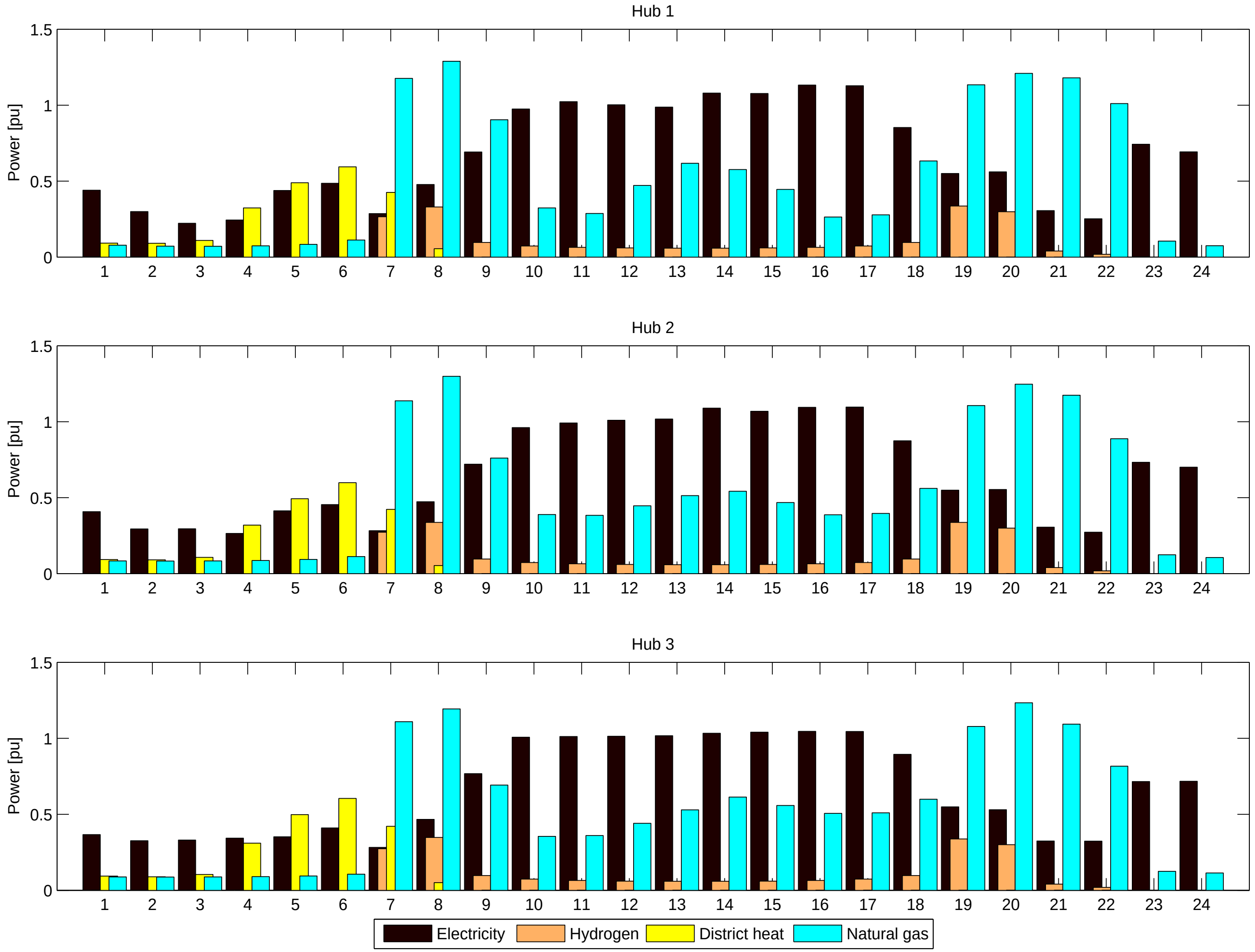
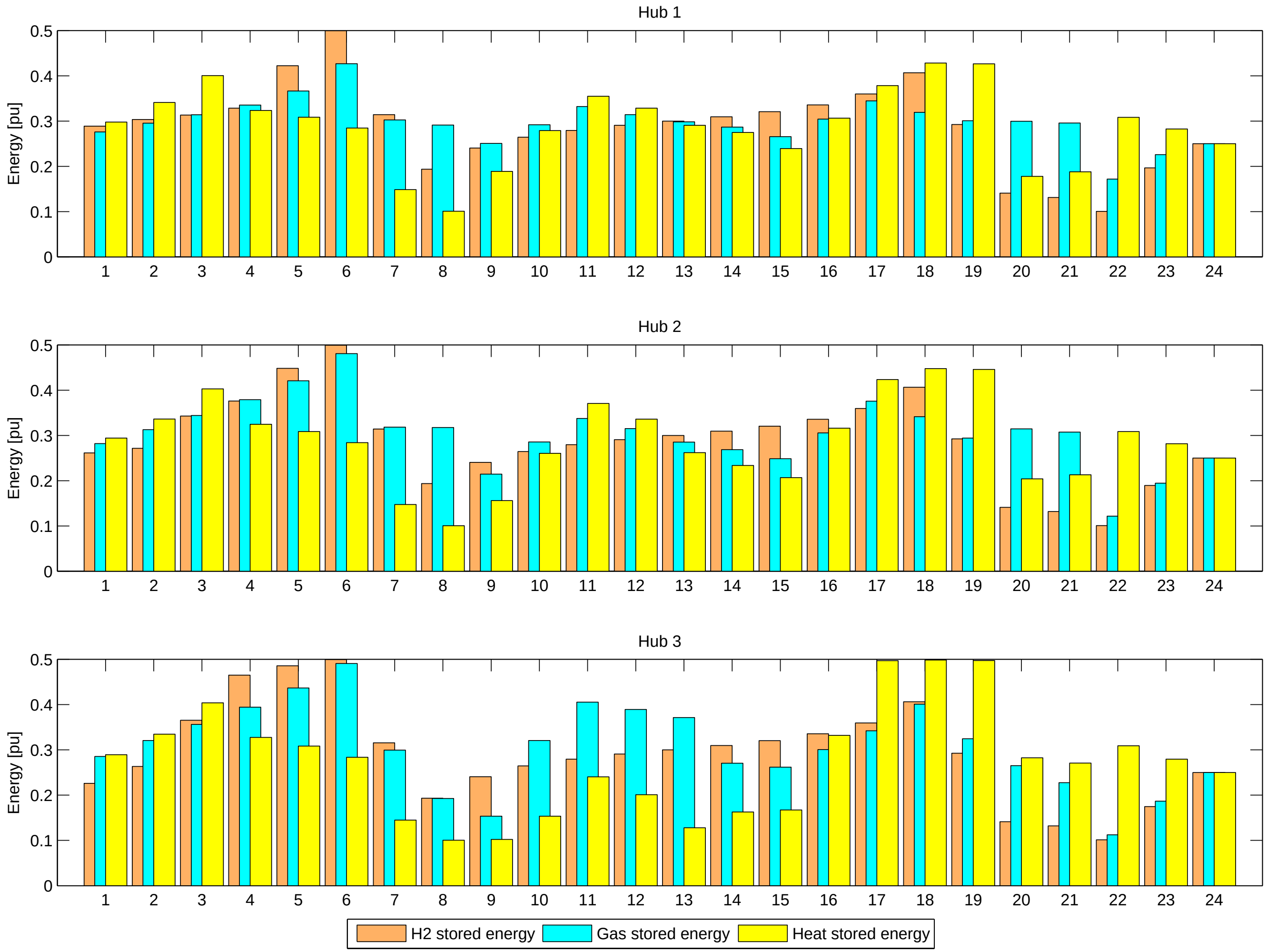
Results

- Hub input powers:



Results

- Stored energy:



$$TC = \sum_{s \in \Omega} \sum_{t=1}^{T} (a_s^t + b_s^t P_s^t + c_s^t P_s^{t2}) \tag{3.1}$$

$$\left.\begin{aligned} \mathbf{G}_\alpha^t &= 0 \\ \underline{\mathbf{F}}_\alpha \leq \mathbf{F}_\alpha^t &\leq \overline{\mathbf{F}}_\alpha \end{aligned}\right. \quad \forall \alpha \in \mathcal{E} \wedge t \in \mathcal{T} \tag{3.2}$$

$$\left.\begin{aligned} \underline{V}_m &\leq V_m^t \leq \overline{V}_m \\ \underline{P}_{G_m} &\leq P_{G_m}^t \leq \overline{P}_{G_m} \\ \underline{Q}_{G_m} &\leq Q_{G_m}^t \leq \overline{Q}_{G_m} \\ \underline{S}_{G_m} &\leq S_{G_m}^t \leq \overline{S}_{G_m} \end{aligned}\right. \quad \forall m \in \mathcal{M} \wedge t \in \mathcal{T} \tag{3.3}$$

$$\left.\begin{aligned} \underline{\pi}_{mr} &\leq \pi_{mr}^t \leq \overline{\pi}_{mr} \\ \underline{\pi}_{mc} &\leq \frac{\pi_{mr}^t}{\pi_{cr}^t} \leq \overline{\pi}_{mc} \end{aligned}\right. \quad \forall m \in \mathcal{M} \wedge r \in \mathcal{G} \wedge c \in \mathcal{C} \wedge t \in \mathcal{T} \tag{3.4}$$

$$\mathbf{L}_m^t - \mathbf{C}_m^t \mathbf{P}_m^t + \mathbf{M}_m^{\mathbf{eq}\,t} = \mathbf{0} \quad \forall m \in \mathcal{M} \wedge t \in \mathcal{T} \tag{3.5}$$

$$\mathbf{M}_m^{\mathbf{eq}\;t} = \mathbf{S}_m^t \frac{\mathrm{d}\mathbf{E}_m^t}{\mathrm{d}t} = \mathbf{S}_m^t \left[\mathbf{E}_m^t - \mathbf{E}_m^{(t-1)} + \mathbf{E}_m^{stb}\right] \;\; \forall m \in \mathcal{M} \wedge t \in \mathcal{T} \tag{3.6}$$

$$0 \leq \nu_{m\alpha k}^t \leq 1 \;\; \forall m \in \mathcal{M} \wedge \alpha \in \mathcal{E} \wedge k \in \mathcal{K} \tag{3.7}$$

$$0 \leq \eta_{m\alpha k} \nu_{m\alpha k}^t P_{m\alpha}^t \leq \overline{P}_{m\alpha k} \;\; \forall m \in \mathcal{M} \wedge \alpha \in \mathcal{E} \wedge k \in \mathcal{K} \tag{3.8}$$

$$\left.\begin{array}{l} \underline{\mathbf{E}}_m \leq \mathbf{E}_m^t \leq \overline{\mathbf{E}}_m \\ \underline{Q}_{m\sigma} \leq Q_{m\sigma}^t \leq \overline{Q}_{m\sigma} \\ \underline{M}_{m\gamma} \leq M_{m\gamma}^t \leq \overline{M}_{m\gamma} \end{array}\right. \quad \forall m \in \mathcal{M} \wedge \sigma, \gamma \in \mathcal{S} \tag{3.9}$$

$$\mathbf{E}_m^0 = \mathbf{E}_m^T \;\; \forall m \in \mathcal{M} \tag{3.10}$$

$$L^t_{H_m} = (\eta_{ELEH}\nu^t_{ELE}\nu^t_{FC})P^t_{L_m} + \nu^t_{FC}P^t_{H_m} - \frac{\nu^t_{FC}}{e_{H_2}}(E^t_{H_2} - E^{(t-1)}_{H_2} + E^{stb}_{H_2}) \tag{C.4}$$

$$\begin{aligned} L^t_{e_m} = {} & [\eta_{FCe}\eta_{ELEH}\nu^t_{ELE}(1-\nu^t_{FC}) + \eta_T\nu^t_{Tr}(1-\nu^t_{ELE})]\, P^t_{L_m} \\ & + \ \eta_{FCe}(1-\nu^t_{FC})P^t_{H_m} + \eta_{GTe}\nu^t_{Tu}P^t_{g_m} \\ & - \ \frac{\eta_{FCe}}{e_H}(1-\nu^t_{FC})(E^t_{H_2} - E^{(t-1)}_{H_2} + E^{stb}_{H_2}) \\ & - \ \frac{\eta_{GTe}}{e_g}\nu^t_{Tu}(E^t_g - E^{(t-1)}_g + E^{stb}_g) \end{aligned} \tag{C.5}$$

$$\begin{aligned} L^t_{h_m} = {} & [\eta_{HE_1}\eta_{ELEh}\nu^t_{ELE} + \eta_{HE_4}\eta_{FCh}\eta_{ELEH}\nu^t_{ELE}(1-\nu^t_{FC}) \\ & + \eta_{HE_5}\eta_{Ch}(1-\nu^t_{ELE})(1-\nu^t_{Tr})]P^t_{L_m} \\ & + \ [\eta_{HE_4}\eta_{FCh}(1-\nu^t_{FC})]\, P^t_{H_m} + \eta_{HE_2}P^t_{h_m} \\ & + \ [\eta_{HE_3}\eta_{GTh}\nu^t_{Tu} + \eta_F(1-\nu^t_{Tu})]\, P^t_{g_m} \\ & - \ \frac{1}{e_g}\,[\eta_{HE_3}\eta_{GTh}\nu^t_{Tu} + \eta_F(1-\nu^t_{Tu})]\,(E^t_g - E^{(t-1)}_g + E^{stb}_g) \\ & - \ \frac{1}{e_{H_2}}\,[\eta_{HE_4}\eta_{FCh}(1-\nu^t_{FC})]\,(E^t_{H_2} - E^{(t-1)}_{H_2} + E^{stb}_{H_2}) \\ & - \ \frac{1}{e_h}(E^t_h - E^{(t-1)}_h + E^{stb}_h) \end{aligned} \tag{C.6}$$

$$L^t_{c_m} = [\eta_{Ca}(1-\nu^t_{ELE})(1-\nu^t_{Tr})]\, P^t_{L_m} \tag{C.7}$$

$$m \in \mathcal{M}=\{1,2,3\} \text{ and } t \in \mathcal{T}=\{1,...,24\}$$

Table B.1: Data of electricity network (sample system 2)

G_1	Slack, $a^t_{G_1} = 0$ [mu], $c^t_{G_1} = (10^{-4}).b^t_{G_1}$ [mu.pu^{-2}]
G_2	PQ, $a^t_{G_2} = 0$ [mu], $c^t_{G_2} = (10^{-4}).b^t_{G_2}$ [mu.pu^{-2}] $0 \leq P^t_{G_2} \leq 4, 0 \leq Q^t_{G_2} \leq 4, 0 \leq S^t_{G_2} \leq 5$ all in [pu]
Load	as in Fig. 3.11
Bus Voltage	$0.9 \leq V^t_m \leq 1.1$ [pu]
Line 1-2	$\overline{Z}_{12} = 0.3 + j0.9$ [pu], $\overline{Y}_{12} = j1.5(10^{-6})$ [pu]
Line 1-3	$\overline{Z}_{13} = 0.2 + j0.6$ [pu], $\overline{Y}_{13} = j2.5(10^{-6})$ [pu]
Line 2-3	$\overline{Z}_{23} = 0.1 + j0.4$ [pu], $\overline{Y}_{23} = j3.5(10^{-6})$ [pu]

Table B.2: Data of natural gas network (sample system 2)

N	Known-Pressure, $a^t_N = 0$ [mu], $b^t_N = 5$ [mu.pu^{-1}], $c^t_N = 0$ [mu.pu^{-2}]
Load	as in Fig. 3.11
Nodal Pressure	$0.8 \leq \pi^t_m \leq 1.2$ [pu]
Pipe 1-2	$GHV.k_{12} = 4.5$ [pu^{-1}]
Pipe 1-3	$GHV.k_{13} = 3.0$ [pu^{-1}]
Pipe 2-3	$GHV.k_{23} = 2.0$ [pu^{-1}]
C_{12}, C_{13}	$GHV.k_{c_{12}} = GHV.k_{c_{13}} = 0.5$ [pu^{-1}] $1.2 \leq \pi^t_m/\pi^t_k \leq 1.8$

Table B.3: Data of heat & hydrogen networks (sample system 2)

H_2	locally available with: $0 \leq P^t_H \leq 3$ [pu]
h	locally available with: $0 \leq P^t_h \leq 3$ [pu]

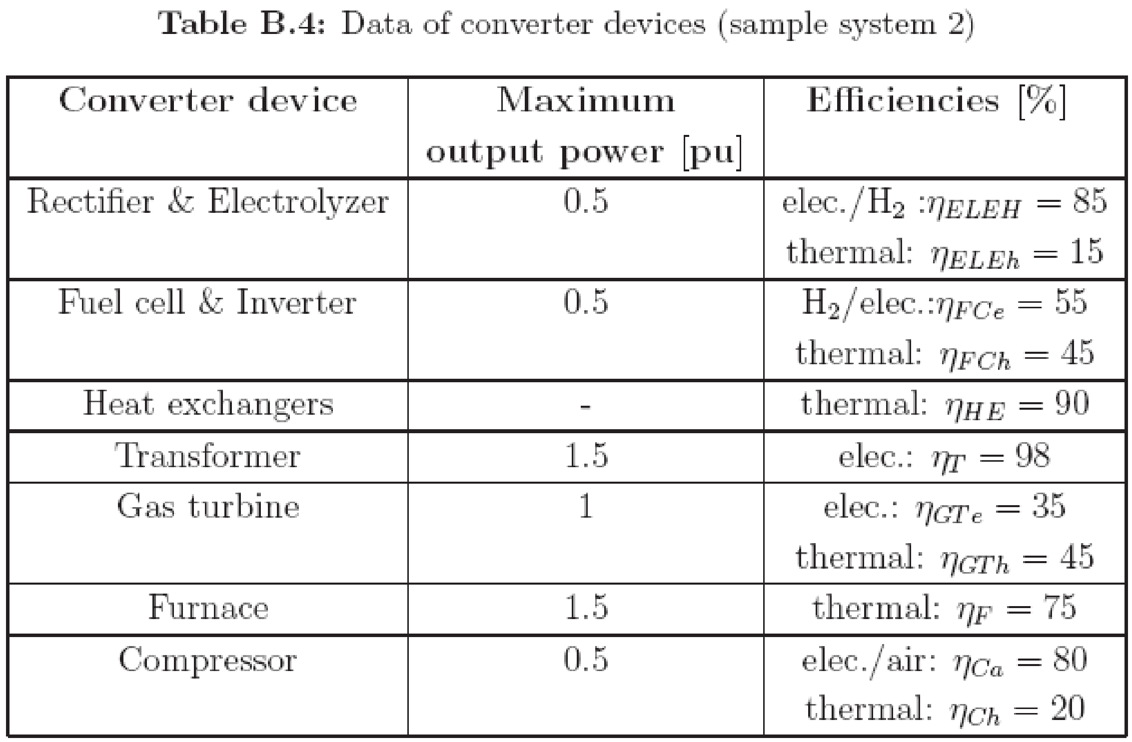


Table B.4: Data of converter devices (sample system 2)

Converter device	Maximum output power [pu]	Efficiencies [%]
Rectifier & Electrolyzer	0.5	elec./H_2 :$\eta_{ELEH}=85$ thermal: $\eta_{ELEh}=15$
Fuel cell & Inverter	0.5	H_2/elec.:$\eta_{FCe}=55$ thermal: $\eta_{FCh}=45$
Heat exchangers	-	thermal: $\eta_{HE}=90$
Transformer	1.5	elec.: $\eta_{T}=98$
Gas turbine	1	elec.: $\eta_{GTe}=35$ thermal: $\eta_{GTh}=45$
Furnace	1.5	thermal: $\eta_{F}=75$
Compressor	0.5	elec./air: $\eta_{Ca}=80$ thermal: $\eta_{Ch}=20$

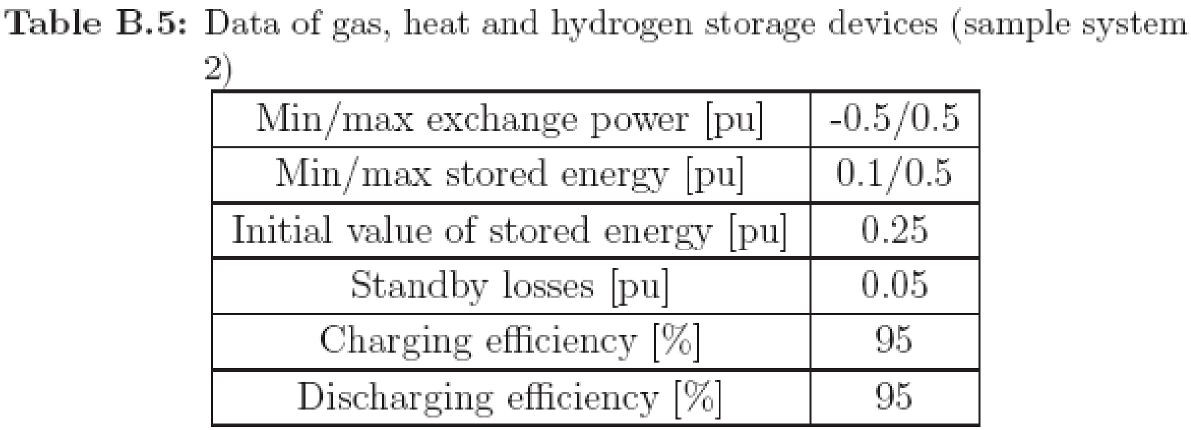


Table B.5: Data of gas, heat and hydrogen storage devices (sample system 2)

Min/max exchange power [pu]	-0.5/0.5
Min/max stored energy [pu]	0.1/0.5
Initial value of stored energy [pu]	0.25
Standby losses [pu]	0.05
Charging efficiency [%]	95
Discharging efficiency [%]	95