Storage and Cross-linked Infrastructures (SCI)

4. Wissenschaftliches Treffen

DLR, Stuttgart, 21. September 2018

Flexibility options for large-scale electrical energy storage systems through power-to-heat integration

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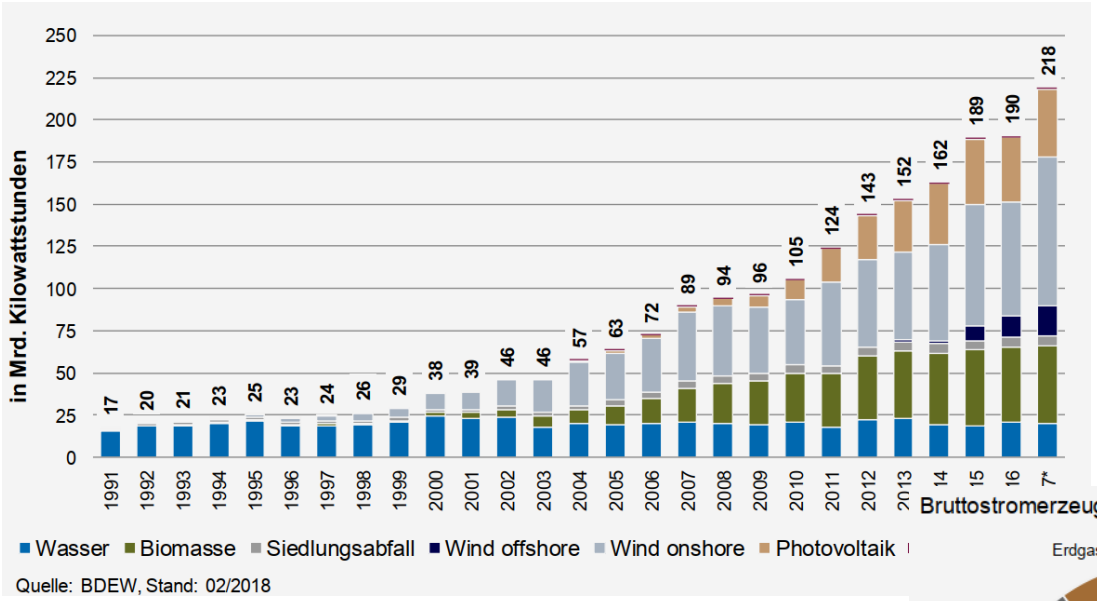
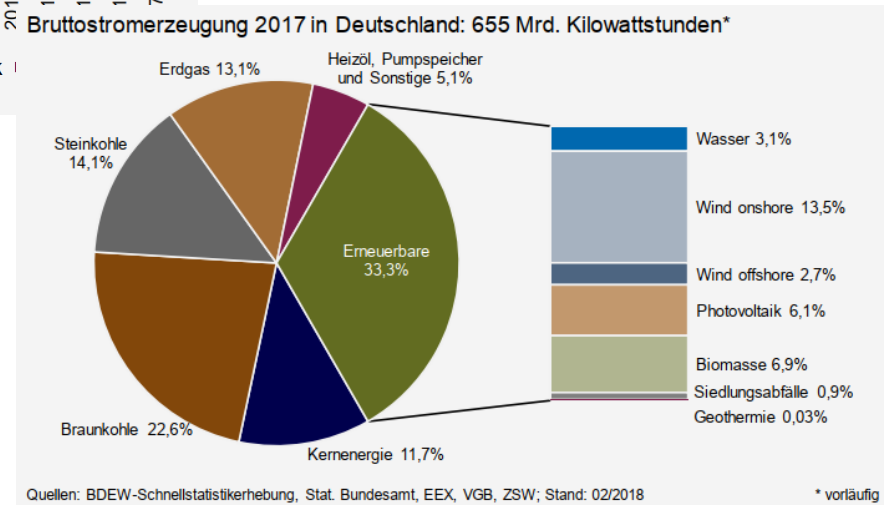
Background

German „Energiewende“: RE Targets





Political targets:

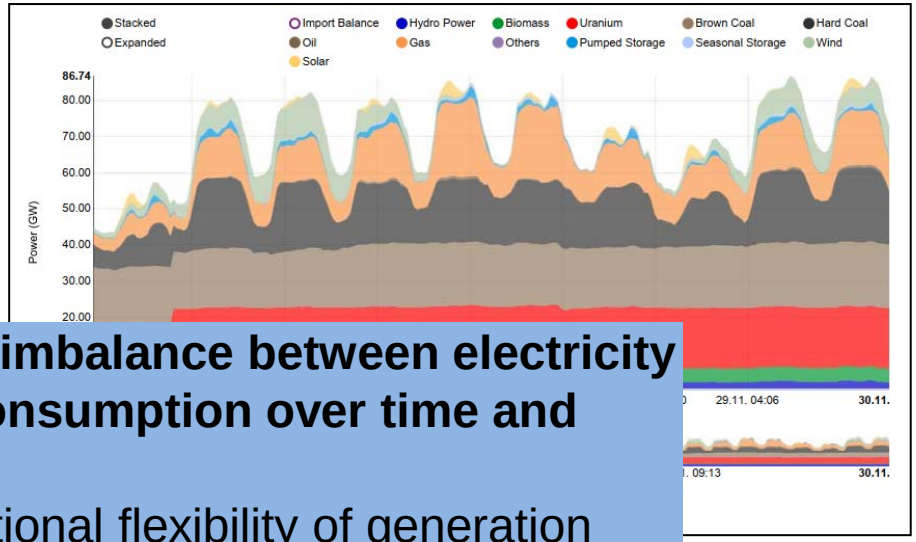
- 50% of gross electricity production from RE by 2030 (80% by 2050)
- Mostly by PV und Wind

Background

High penetration of RE & grid balancing

November 2010

- High baseload share
- Small variation of residual load

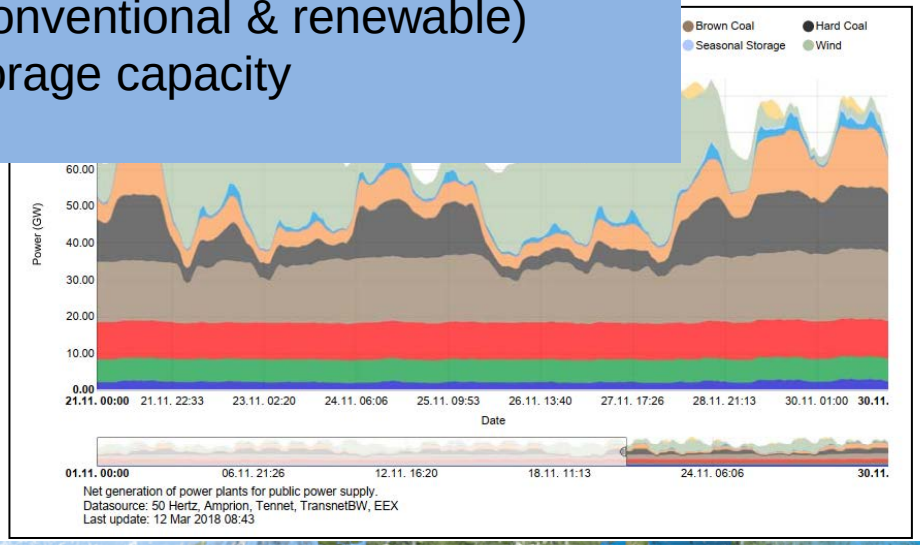


Compensation of imbalance between electricity generation and consumption over time and space is needed:

- Improved operational flexibility of generation capacity (both conventional & renewable)
- Expansion of storage capacity
- … and more

November 2017

- Share of baseload pov
  decreased & significan
  fluctuating power from RE
- → variation of residual load
  25..40 GW per day
- → pronounced gradients
- Increasing fluctuations of RE in the future expected!



Energy Lab 2.0 Project Objectives & Challenges

HELMHOLTZ | ASSOCIATION

KIT Karlsruhe Institute of Technology

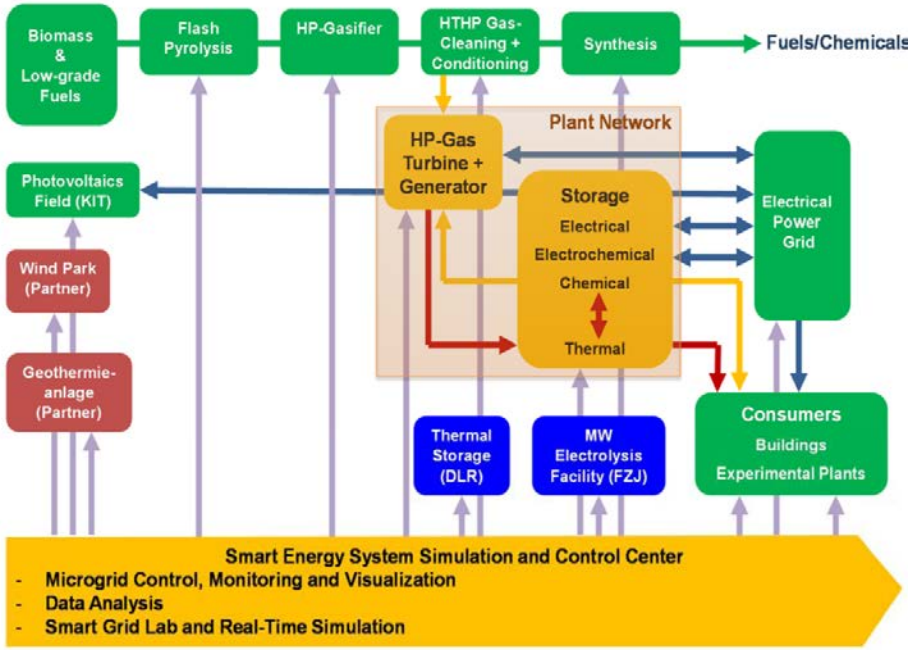
JÜLICH FORSCHUNGSZENTRUM

DLR

Realisation of a **research infrastructure** with simulation plattform for i.a. investigation of novel solutions for **grid balancing**:

- Focus on smart interconnection of plant components for **production, conversion and conservation** of various energy carriers
  → **Sector coupling**: linking of electrical, thermal and chemical energy flows

- Potential analysis for increasing the energy efficiency and flexibility of plant network



→ DLR focuses on Thermal Energy Storage (TES) and its Power-to-Heat (PtH) extension

DLR

Subproject: Thermal Energy Storage & PtH extension
Objectives and approach

Objectives

Design and implementation of flexible and energy-efficient high-temperature TES with PtH extension:

- Elaboration of wiring concepts for PtH integration
- Identification of compact build-up with:
  - Flexible operation management
  - High thermodynamic efficiency
  - High energy density

Approach

1. Development of various concepts for PtH integration
2. Elaboration of a compact modelling approach
3. Derivation of evaluation criteria
4. Simulation studies based on efficient modelling approach
5. Assessment of elaborated concepts
6. Selection of favoured integration concept

Achievements

Development of concepts for PtH integration

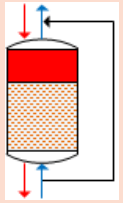
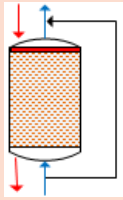
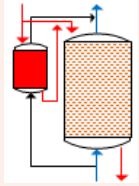
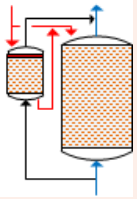
Requirements

- Flexible operation management
- High thermodynamic efficiency
- High energy density
- High thermal utilisation of the storage material
- Low drop in performance during discharging
- Low material costs
- ... and more

Concept development

- Wiring concepts for PtH integration
- Location of PtH component
- Material selection:
  - PtH material: construction steel
  - TES material: technical ceramics

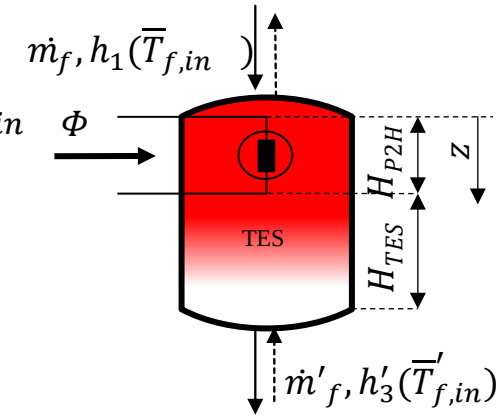
$$c_{p,TES} = 0.90 \frac{kJ}{kg\ K};\ \rho_{TES} = 2300\ kg/m^3;$$
$$c_{p,PtH} = 0.46 \frac{kJ}{kg\ K};\ \rho_{PtH} = 7800\ kg/m^3$$

Power-to-Heat integration	PtH media: heat storage media (PtH = Storage inventory)	PtH media: power converter (convective/conductive heat transfer to TES)
internal		
external		

Achievements

Modelling approach: Dimensionless 1D-model

Normalization in time, space and temperature: $\Delta T_{max} = \overline{T}_{f,in} - \overline{T}'_{f,in}$



$$\frac{\partial T_s}{\partial t^*} = \Phi + \Pi \frac{(\vartheta_f - \vartheta_s)}{\Delta T_{max}}$$

$$\frac{\partial T_f}{\partial z^*} = \Lambda \frac{(\vartheta_s - \vartheta_f)}{\Delta T_{max}} - \Gamma \frac{(\vartheta_f - \vartheta_0)}{\Delta T_{max}}$$

→ **Dimensionless parameters:**

- Reduced storage length: Λ
- Reduced period duration: Π
- Thermal losses: Γ
- Heating rate: Φ
- Heating length: $z_{PtH} = \frac{H_{PtH}}{H_{PtH}+H_{TES}}$

Derivation of evaluation criteria:

- Thermodynamic efficiency [%]:

$$\eta_{ETES} = \frac{\int_0^{t'^*=1} (T'_{f,out} - T'_{f,in}) dt^* * 100\%}{\int_0^{t^*=1} (T_{f,in} - T'_{f,in})\, dt^* + \frac{\Lambda}{\Pi} \frac{\Phi\, \tau}{f_{PtH}} z_{PtH\, \Delta T_{max}}}$$

- Energy density [J/kgK]: $q^*_{TES/PtH} = \frac{\Pi_{TES/PtH}}{\Lambda_{TES/PtH}} c_{p,TES/PtH} (\overline{T}'_{f,out} - \overline{T}'_{f,in})$ $q^*_{ETES} = q^*_{TES}(1 - z_{PtH}) + q^*_{PtH}\, z_{PtH}$

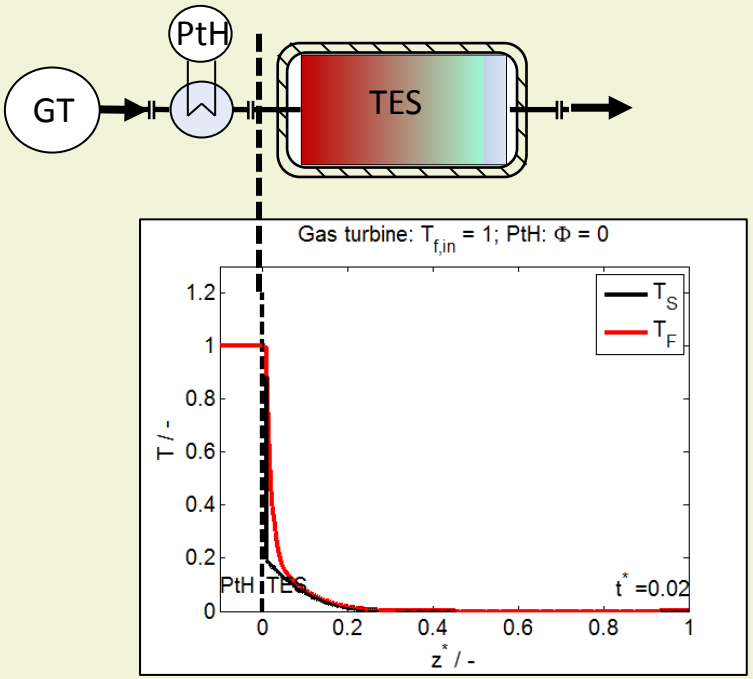
- Λ-Π-ratio [-]: $\frac{\Lambda}{\Pi} = \frac{m_s\, c_{p,s}}{\dot{m}_f\, c_{p,f}\, \tau}$

Achievements

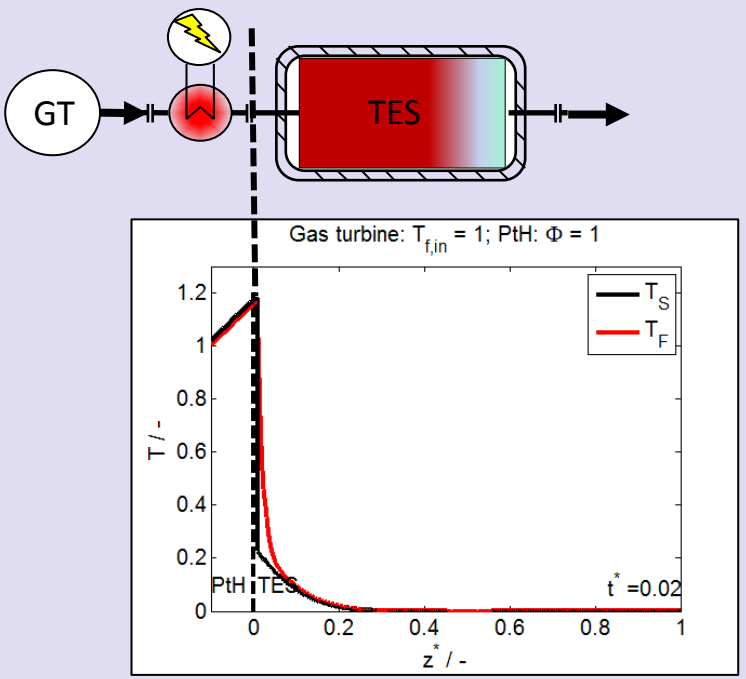
Case study: Stand-alone vs. parallel operation

Charging with external integration: Π = 100; Λ = 100; Γ = 0; z_{PtH} = 0.1

Stand-alone: waste heat from gas turbine



Parallel operation: waste heat + PtH

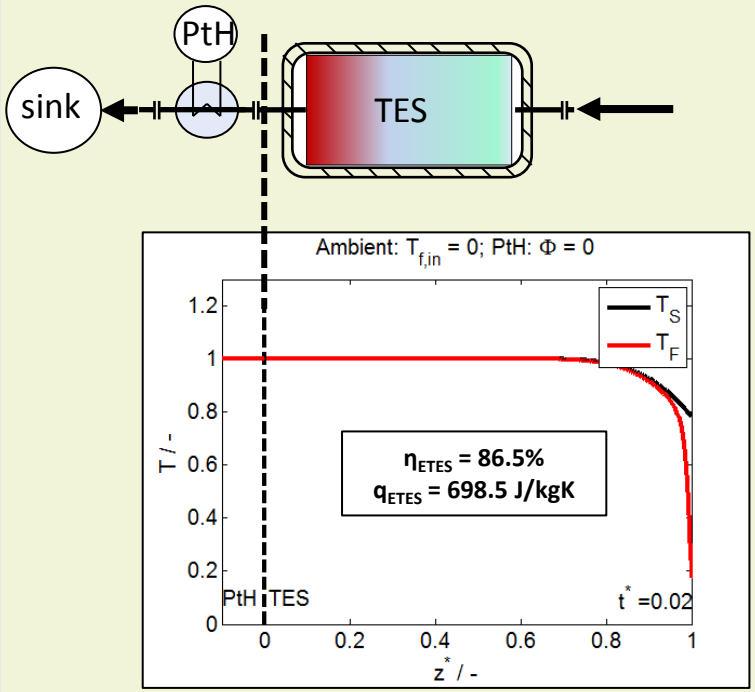


Achievements

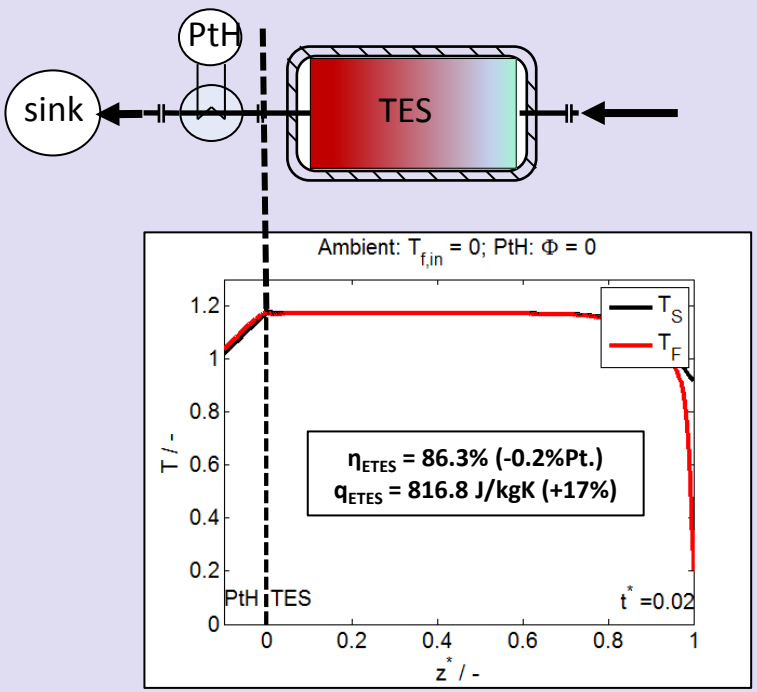
Case study: Stand-alone vs. parallel operation

Discharging with external integration: Π = 100; Λ = 100; Γ = 0; z_{PtH} = 0.1

Stand-alone: TES



Parallel operation : TES & PtH



→ **Significant increase in energy density vs. slight loss in efficiency**

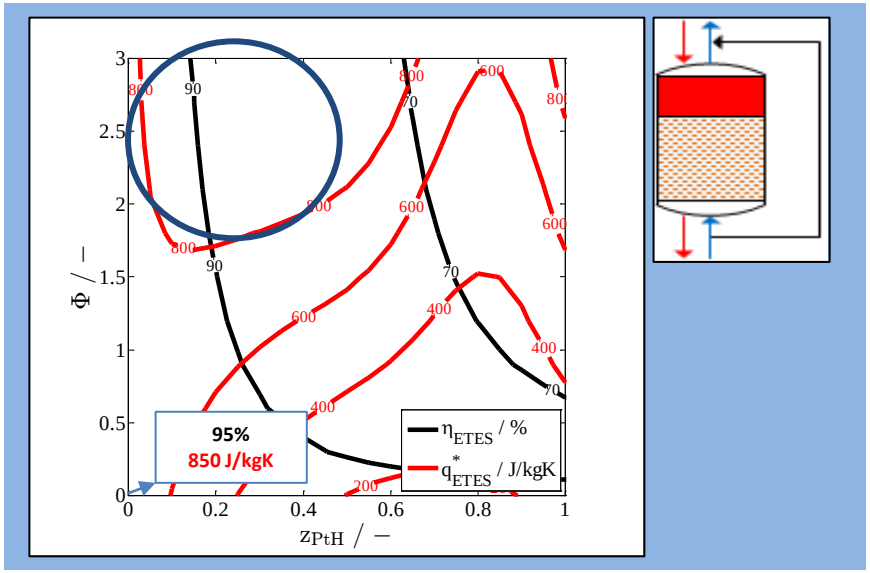
Achievements

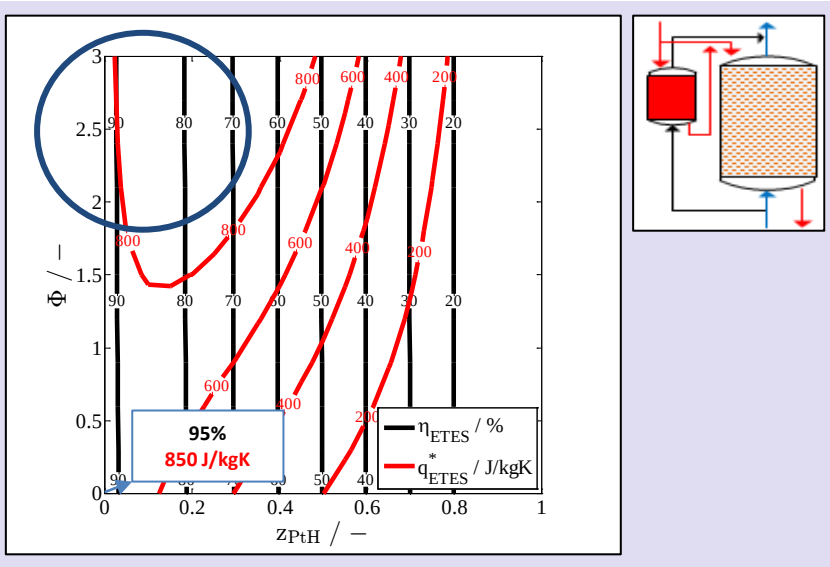
Simulation studies: Analysis of beneficial PtH integration

Specifications

- Exemplary design: $\Lambda = 100;\ \Pi = 100;\ \Gamma = 0;$
- Parameter variation: Heating rate $\Phi \in [0,3]$ and heating length $z_{P2H} \in [0,1]$

Results for cyclic operation: z_{P2H} = → 0: power converter; z_{P2H} = → 1: heat storage



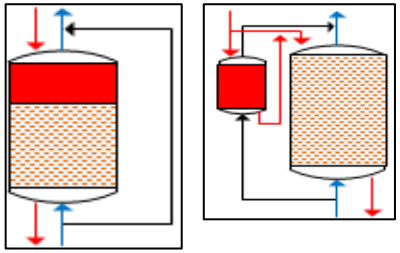


→ **Highest efficiency and energy density for internal configuration as ‚power converter'**

Achievements

Simulation studies: Energetic analysis

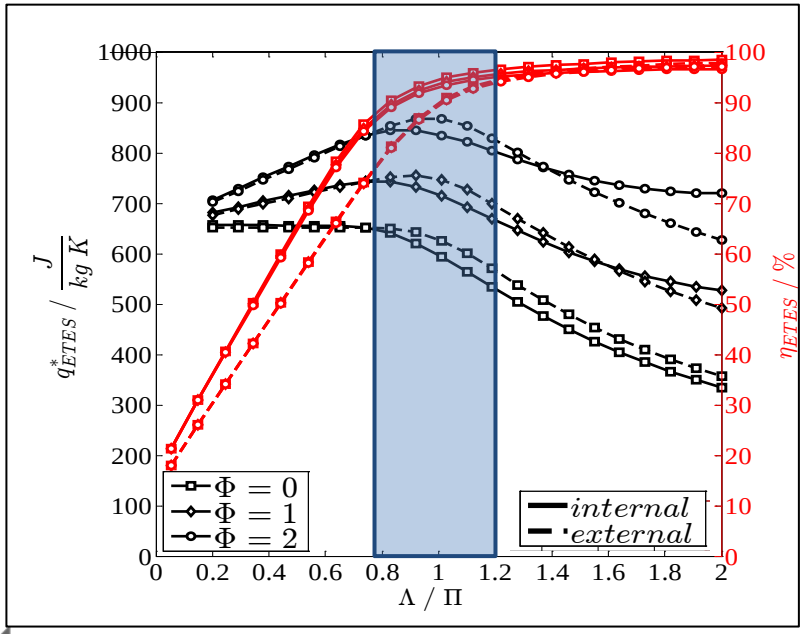
$$\frac{\Lambda}{\Pi} = \frac{m_s\, c_{p,s}}{\dot{m}_f\, c_{p,f}\, \tau}$$



Specifications

- Exemplary design: $z_{P2H} = 0.1$; $\Pi = 100$; $\Gamma = 0$;
- Parameter variation: Heating rate $\Phi \in [0,3]$ and $\Lambda \in [10,200]$

Results for cyclic operation:



Internal vs. external integration:

- For Λ/Π=0.8:

→ high efficiency for internal integration

→ Energy density is comparable

- For Λ/Π=1.2:

→ higher energy density for external integration

→ Efficiency is comparable

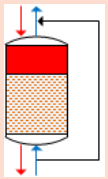
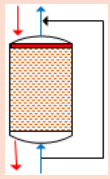
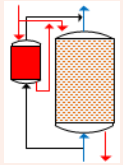
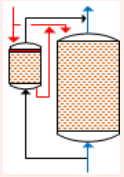
Achievements
Concept assessment

Nutzwertanalyse der Enwurfsoptionen		A1: Intern als Speicher (z.B. 20 Vol.%)		B1: Extern als Speicher (z.B. 2 Vol.%)		A2: Intern als Wandler (z.B. 20 Vol.%)		B2: Extern als Wandler (z.B. 2 Vol.%)				
Bewertung	Gewichtung									Max g_i	Max n_i	Max $g_i \times n_i$
Entscheidungsmatrix für Anforderungsmerkmal	g_i	n_i	$g_i \times n_i$	n_i	$g_i \times n_i$	n_i	$g_i \times n_i$	n_i	$g_i \times n_i$			
1 Leistungsabfall (Entladen)	12,2	3	36,5	2	24,4	4	48,7	3	36,5	12,2	4	48,7
2 Inventarausnutzung	11,5	4	46,2	4	46,2	3	34,6	2	23,1	11,5	4	46,2
3 Energieeffizienz	10,9	3	32,7	2	21,8	4	43,6	4	43,6	10,9	4	43,6
4 Exergieverluste	8,0	4	32,1	4	32,1	3	24,0	3	24,0	8,0	4	32,1
5 Flexibilität / Nutzen	11,9	2	23,7	4	47,4	1	11,9	3	35,6	11,9	4	47,4
6 Technischer Aufwand	7,1	1	7,1	3	21,2	1	7,1	2	14,1	7,1	3	21,2
7 Materialkosten	9,0	2	17,9	1	9,0	4	35,9	3	26,9	9,0	4	35,9
8 Systemeinbindung	6,4	4	25,6	1	6,4	2	12,8	3	19,2	6,4	4	25,6
9 Rückwirkung auf Verbund	9,6	2	19,2	4	38,5	3	28,8	4	38,5	9,6	4	38,5
10 Reifegrad	5,1	1	5,1	2	10,3	2	10,3	3	15,4	5,1	3	15,4
11 Skalierbarkeit	3,8	3	11,5	4	15,4	3	11,5	3	11,5	3,8	4	15,4
12 Nachrüstbarkeit	2,9	2	5,8	3	8,7	1	2,9	3	8,7	2,9	3	8,7
13 Wartbarkeit	1,6	1	1,6	3	4,8	1	1,6	4	6,4	1,6	4	6,4
Absoluter Gesamtnutzwert			265,1		285,9		273,7		303,5			384,9
Gesamtnutzwert in %			68,86		74,27		71,11		78,85			

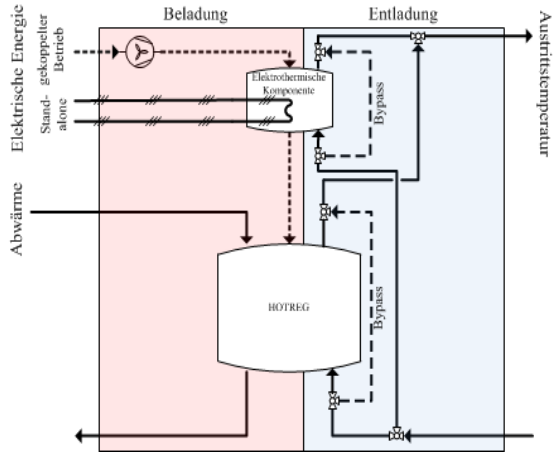
Methodology
Multiple criteria decision analysis

J. Wallenius *et al.*, "Multiple criteria decision making, multiattribute utility theory: Recent accomplishments and what lies ahead," *Manage. Sci.*, vol. 54, no. 7, pp. 1336–1349, 2008.

Results

Power-to-Heat integration	PtH media: heat storage media (PtH = Storageinventory)	PtH media: power converter (convective/conductive heat transfer to TES)
internal	69 % 	71% 
external	75 % 	79 % 

External power converter



→ High flexibility
→ High efficiency
→ High energy density

→ Favoured concept with **79 %** total utility: **External power converter**

Summary & Conclusions

Energy Lab 2.0

- focuses on smart interconnection of plant components for production, conversion and conservation of various energy carriers
- TES-subproject: conversion of electricity into heat (sector coupling) with subsequent conservation of thermal energy: **Power-to-Heat integration into TES (ETES)**

Electro-thermal energy storage based on solid media regenerator

- Cost-effective conservation of thermal energy on high temperature level

→ High values for: energy density, exergy flow and power during discharging

- PtH integration at the hot end as **'power converter'** leads to:

→ Significant increase in energy density with marginal loss in efficiency
→ Highest efficiency and energy density for ETES designs with ratios $0.8 < \Lambda/\Pi < 1.2$
→ Higher flexibility during charging and discharging (with additional bypass operation)

- PtH integration as **'external power converter'** with 79% of total utility meets the requirements stated for an application in a plant network:

→ Flexible operation management
→ High thermodynamic efficiency
→ High energy density

Thank you for your attention!

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