# Improving the Energy Efficiency of Compressed Air Systems by Use of Pressure Equalizing Modules

Kai J. Rolland, Marcus Budt

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# Agenda

- Fundamentals
- Concept of isobaric storage on the basis of pressure equalizing modules (PEQM)
- Investigation of PEQM
- Energy savings in compressed air system with PEQM

# Compressed air usage in industry

## Compressed air is a widely used energy carrier

Pneumatic tools, control of plants and machines,
air supply in hospitals

- Around 291,000 compressors are in operation in Germany [1]
- Accounts for ca. 8 % of the industrial electricity consumption in Germany [1]


## Compressed air systems (CAS) have an overall low energy efficiency

- Only 7 % of the compressors energy consumption is usable [2]
- Control of the compressor affects the energy efficiency

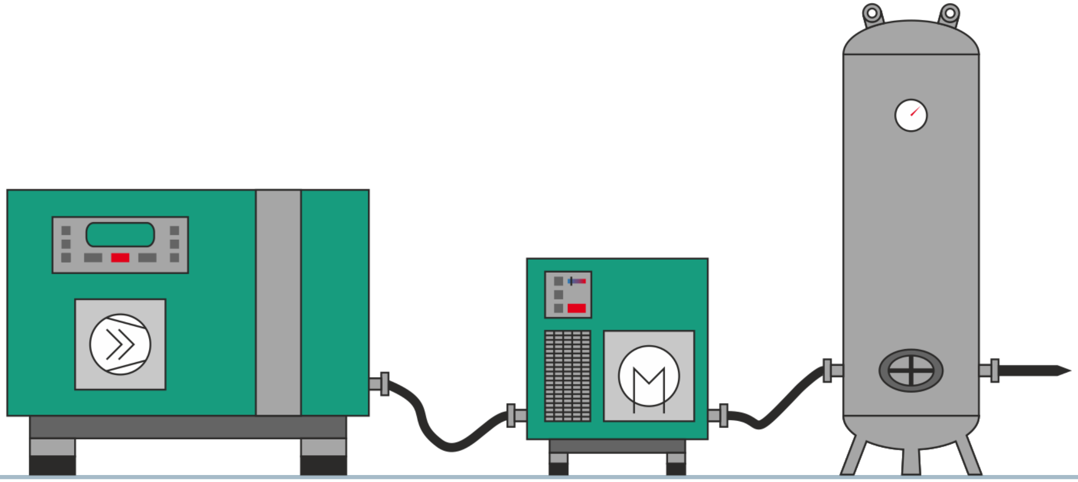
[1] Blesl und Kessler: Energieeffizienz in der Industrie, 2018
[2] Ilmberger und Seyfried: Druckluftversorgungskonzepte für Industriebetriebe, 1994

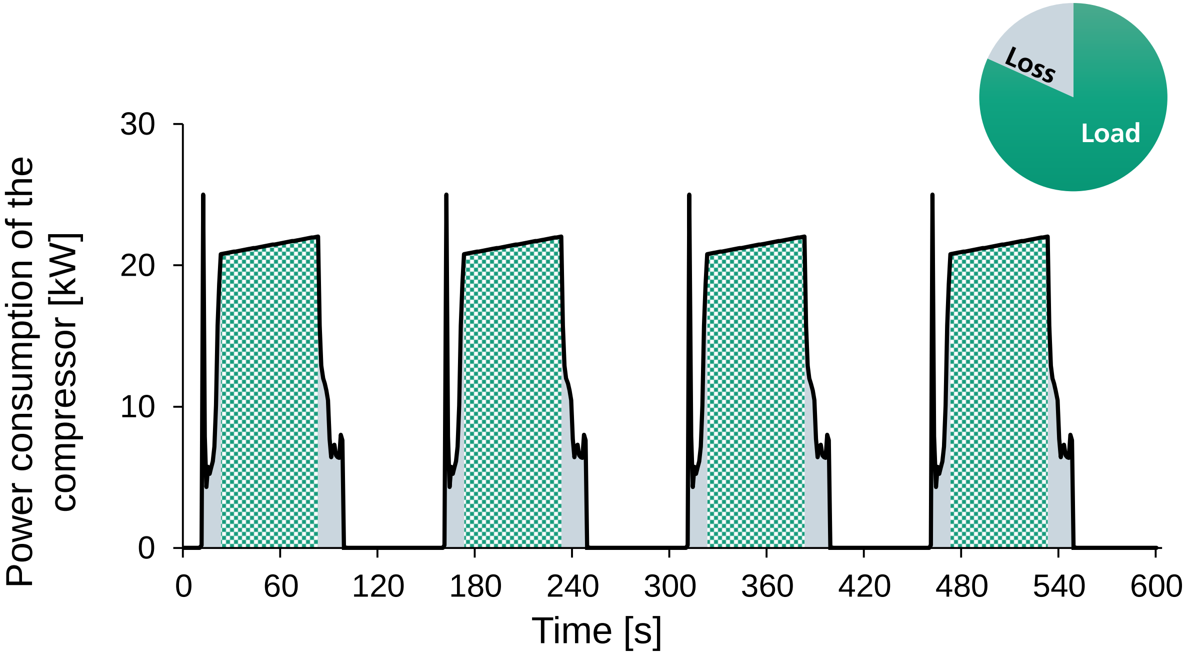
# Increasing the efficiency of CAS

**Compressed air receivers are important components in CAS**

- Buffering of the discontinuous compressed air demand
- Reducing the cycling frequency of the engine

➔ **Significant influence on the energy efficiency of CAS**





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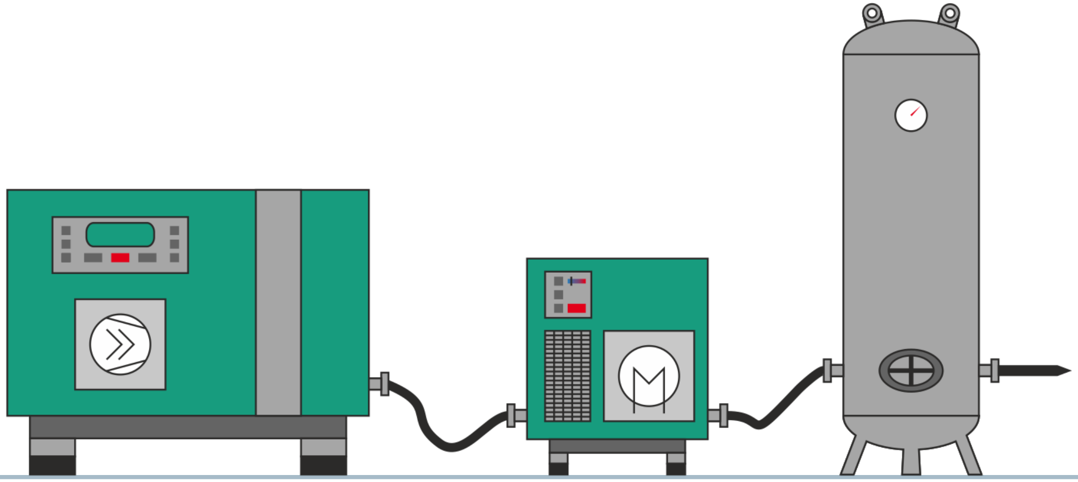

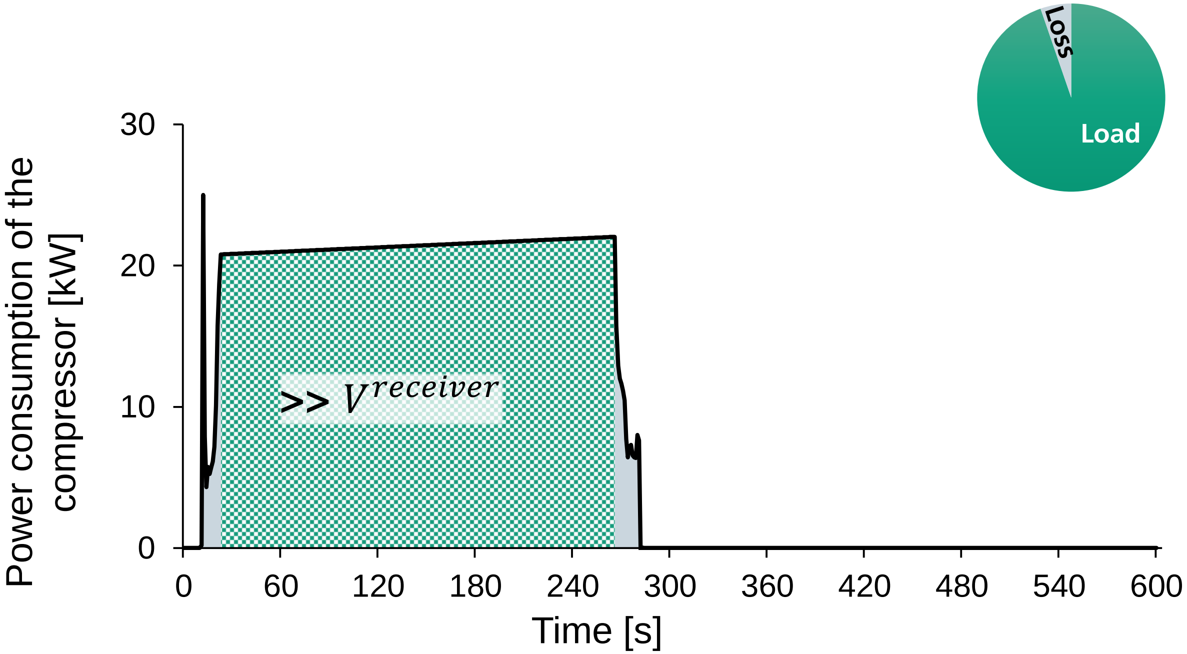


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# Combined-isobaric-isochoric compressed air receiver

## Concept with phase change materials

**Significant capacity increase**

- Isochoric (isc): $V^{receiver} = 1000$ l, $\Delta p = 0.5$ bar $\rightarrow \hat{V}_{isc_{1,2}} = 500\ l_n$
- Combined-isobaric-isochoric (cii): $\Delta V^{receiver} = 1000$ l, $p_{2',3'} = 7\ bar_a$ $\rightarrow \hat{V}_{cii_{1,4'}} = 7000\ l_n$

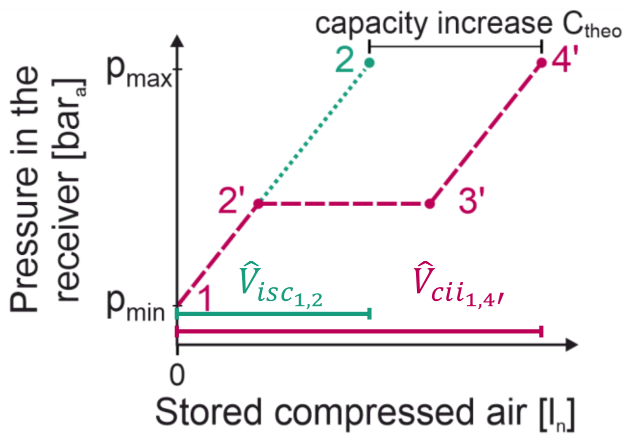
➢ Capacity change: $C_{theo} = \frac{\hat{V}_{cii_{1,4'}}}{\hat{V}_{isc_{1,2}}} - 1 = 13$

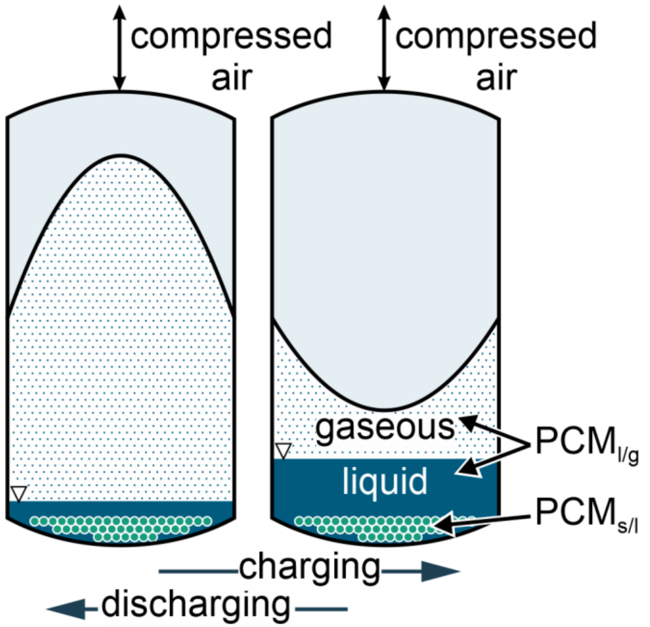
**Counter pressure by phase change material ($PCM_{l/g}$)**

- Isobaric and isothermal phase change between liquid and gaseous state
- Separation of $PCM_{l/g}$ and compressed air by flexible membrane

**Heat management with phase change material ($PCM_{s/l}$)**

- Storage of heat of condensation
- Encapsulation of $PCM_{s/l}$ avoids mixing with $PCM_{l/g}$

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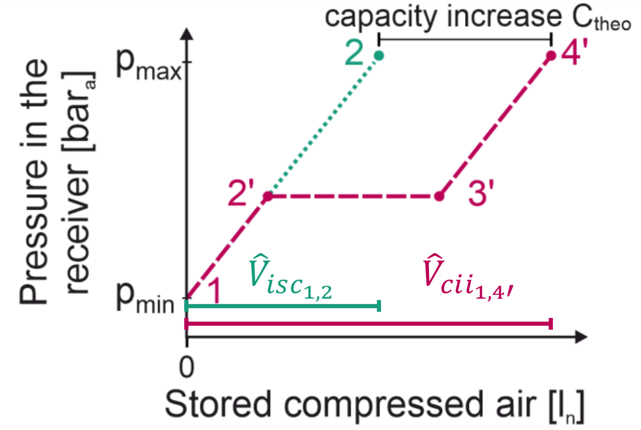
# Combined-isobaric-isochoric compressed air receiver

## Concept in *iso*STOR$^{Retrofit}$ - project

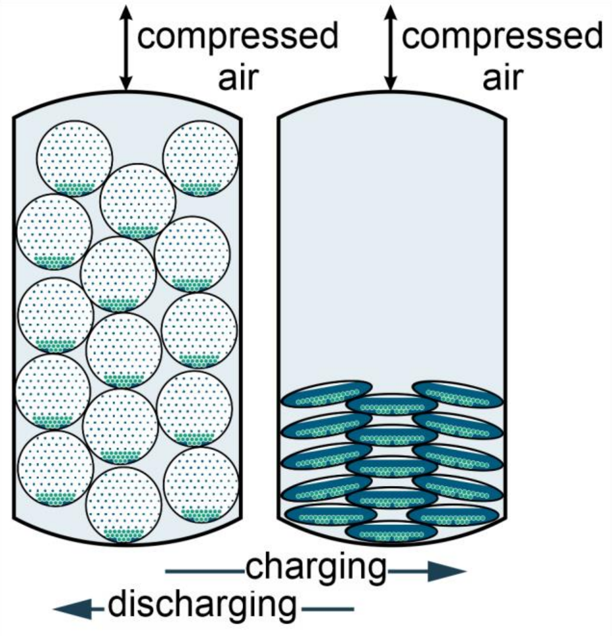
### Concept of isobaric storage with module-based concept

- Pressure equalizing modules (PEQM) contain $PCM_{l/g}$ and $PCM_{s/l}$ [1]
- No external equipment required, e. g. heat exchangers
- Retrofitting of existing receiver possible
- Isobaric storing is achieved through many PEQM




### Aim of the *iso*STOR$^{Retrofit}$ - project[a]

- Capacity increase of at least 600 % with PEQM
- Reducing the energy consumption by $> 20$ %




[a] Funded within the framework of the Fraunhofer Societies internal programs, funding number MEF 602 230, 07/2018 – 12/2021
[1] Budt et al.: Speichereinrichtung und Verfahren zur isobaren Speicherung eines Speicher-fluids, DE1020151120384A1, 2015

# Investigation within *iso*STOR$^{Retrofit}$ - project

## Investigation of PEQM

- Understanding of processes inside the PEQM
- Identifying suitable designs for PEQM
- Determining possible capacity increases

## Investigation of potential energy savings

- Determining possible capacity increases
- Investigating the influence of PEQM on energy consumption

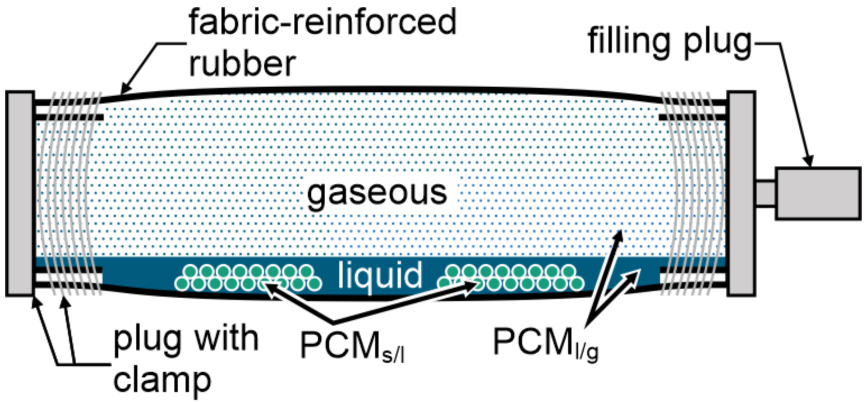
# Experimental investigation of pressure equalizing modules

## Method of investigation

### Requirements for PEQM

- Chemical resistance to R-1234ze(E) and oil-fumes
- Pressure resistant up to 10 $bar_a$
- Large volume change with little deflated volume
- Tightness to avoid leakages
- Easy handling in large quantities
- …

### Concept of hose module



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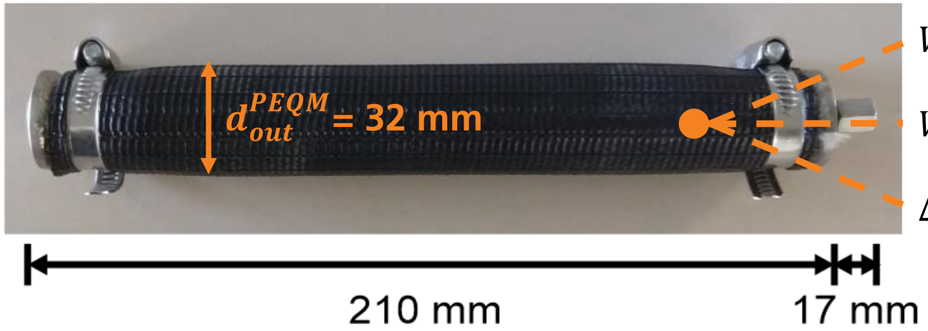
**Investigated hose module**




$V_{inflated}^{PEQM}$ = ~174 ml

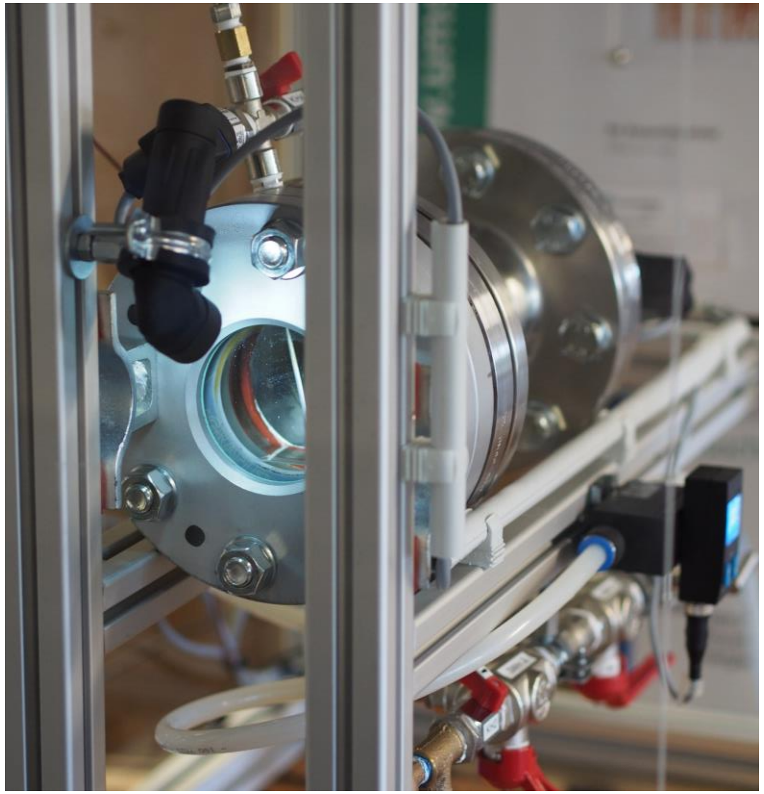
$V_{deflated}^{PEQM}$ = ~106 ml

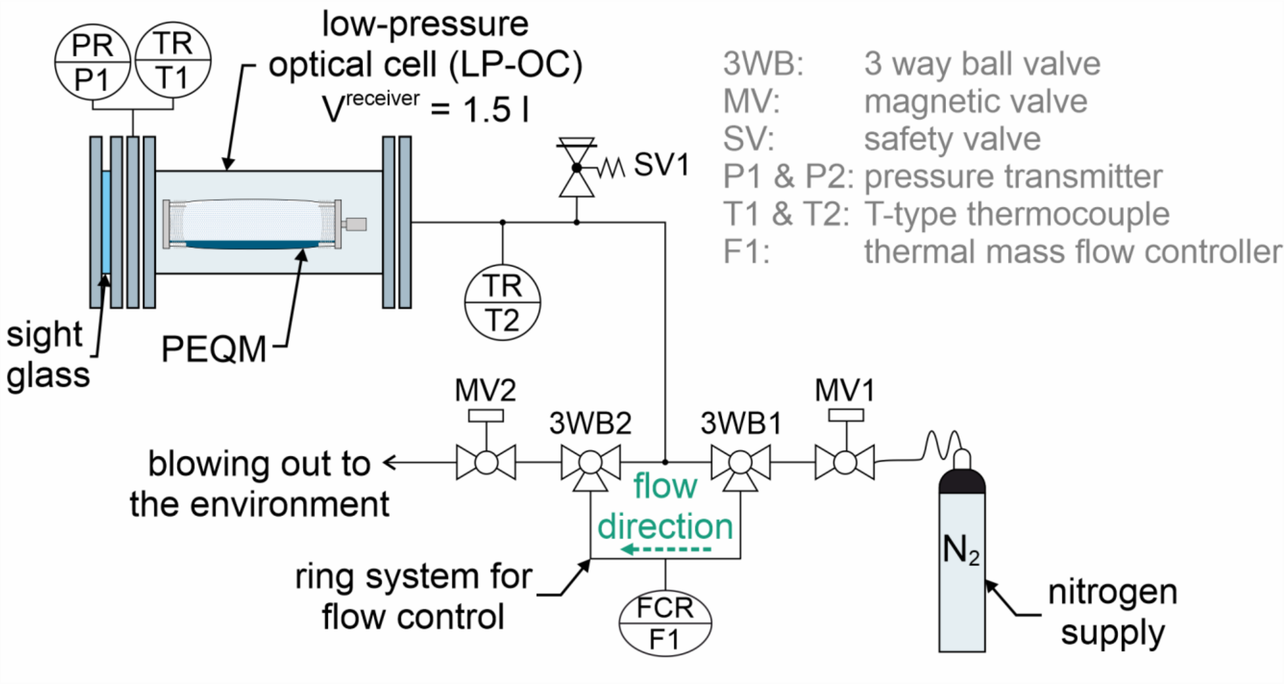
$\Delta V_{change}^{PEQM}$ = ~68 ml

# Experimental investigation of pressure equalizing modules

## Method of investigation



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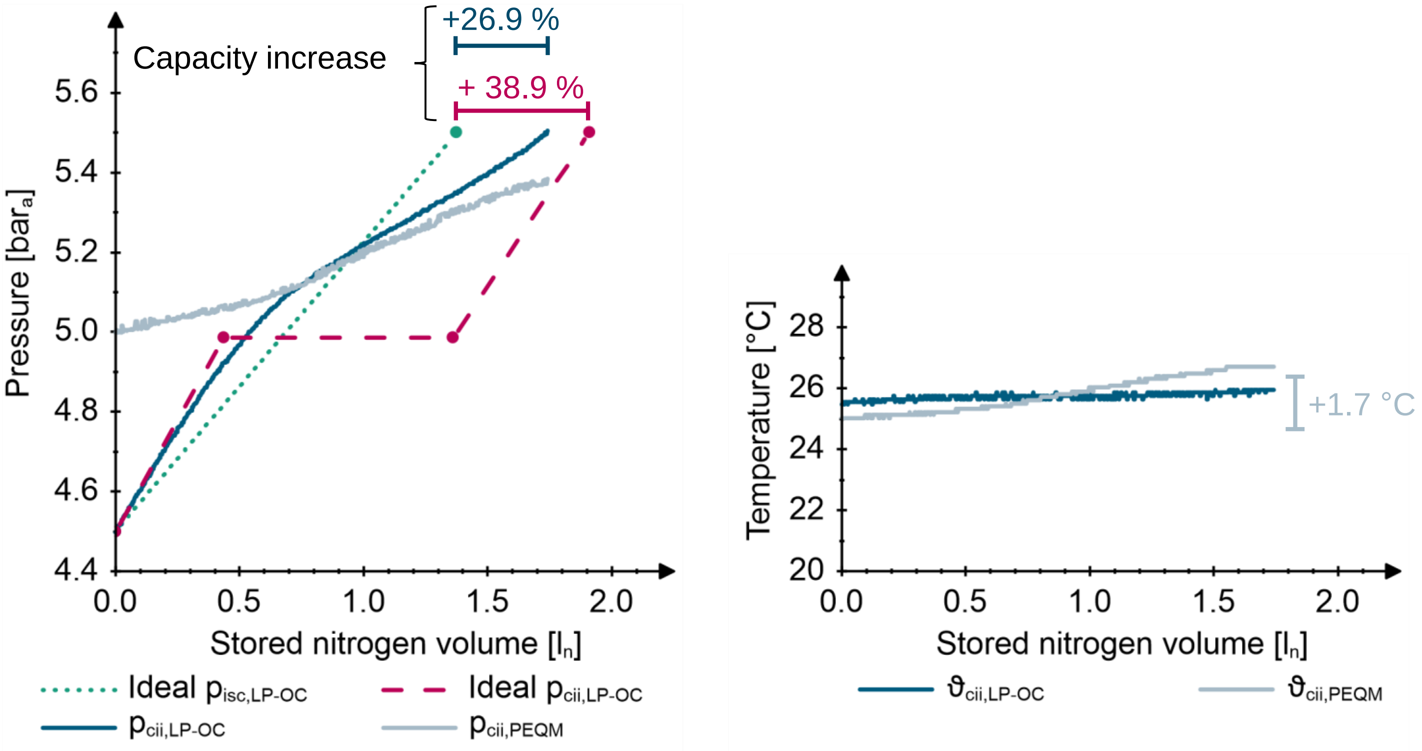
# Experimental investigation of PEQM

## Charging process with three PEQM




- Pressure range 4.5–5.5 bar$_a$
- Room temperature
- $N_2$ flow rate 0.27 l$_n$/min[a]
- Three PEQM without PCM$_{s/l}$

- Capacity of receiver can be increased
- Temperature change in PEQM causes shift of vapor pressure
- Volume of receiver is not fully utilized
- Decreasing pressure range
- Design changes are required to reduce deflated volume [1]

[a] Norm conditions $p_n$ = 1.01325 bar$_a$, $\vartheta_n$ = 0 °C

[1] Rolland et al.: Experimental Investigation of Pressure Equalizing Modules (PEQM) for Isobaric Storage of Compressed Air, submitted 2021

# Investigation within *iso*STOR$^{Retrofit}$ - project

## Investigation of PEQM

Understanding of processes inside PEQM

Identifying suitable designs for PEQM

Determining possible capacity increases

## Investigation of potential energy savings

Determining possible capacity increases

Investigating the influence of PEQM on energy consumption

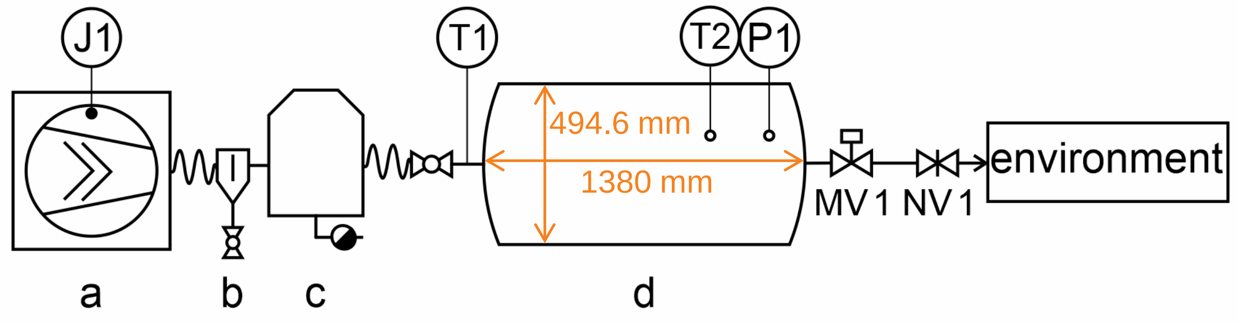
# Theoretical investigation of potential energy savings

## Method

**1**
- Measuring the energy consumption at a fixed air demand
- Determining storage capacity for isochoric process

**2**
- Determining theoretical number of PEQM
- Determining storage capacity for cii-process
- Determining new cycle frequency

**3**
- Determining the operation times for cii-process
- Determining the energy consumption for cii-process




a: rotary screw compressor
b: oil and water seperator
c: refrigerant dryer
d: compressed air receiver
MV: magnetic valve
NV: needle valve

- 4 kW rotary screw compressor
- Receiver volume: 250 l
- Storage volume: 253.2l
- Dew point: 3 °C
- Measurement frequency: 20 Hz

[1] Specht: The best known packings of equal circles in a circle (complete up to N = 2600), accessed 11/02/2022

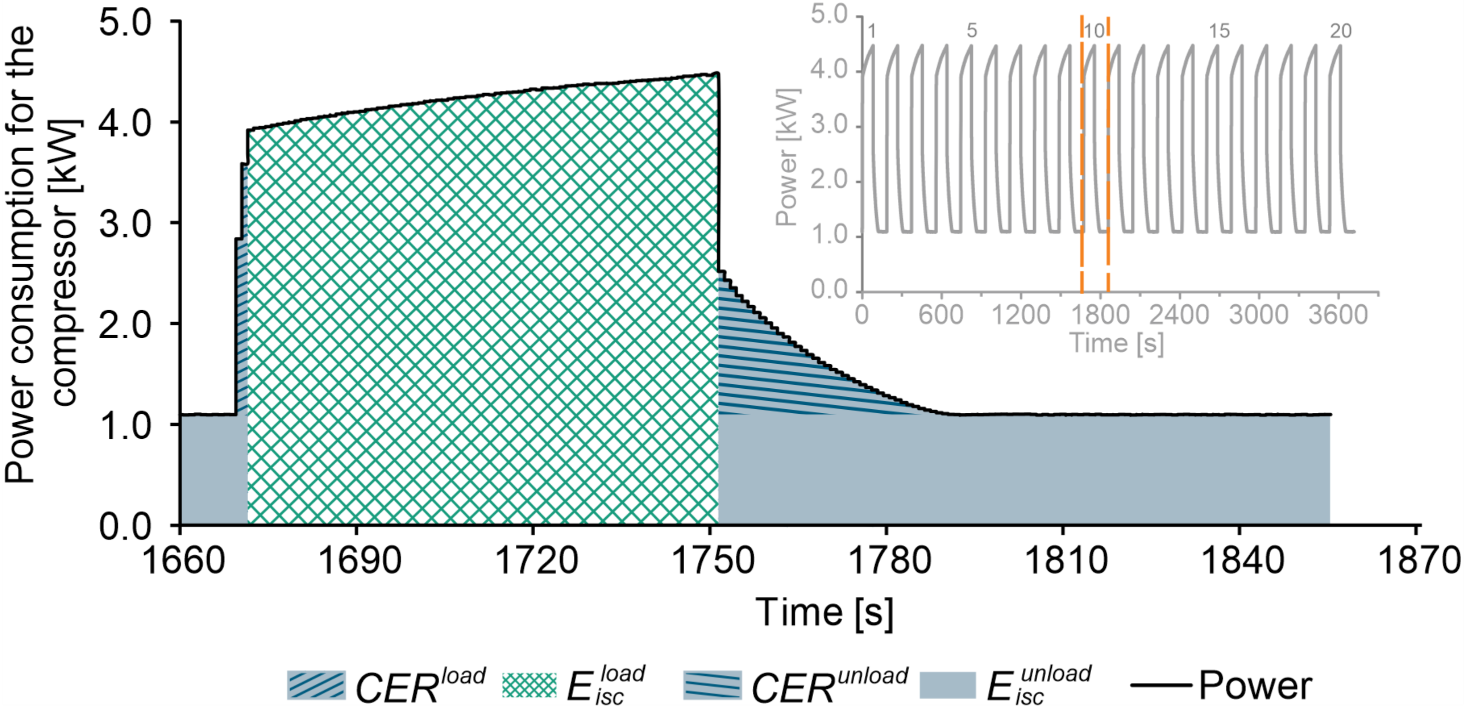
# Results of isochoric process

## Capacity and load ratio

1

- At the beginning of load mode:
  - Pressure: $\bar{p}_1 = 7.63\ bar_a,\ \sigma_{p1} \ll 0.01\ bar_a$
  - Temperature: $\bar{\vartheta}_1 = 23.58\ °C,\quad \sigma_{\vartheta 1} = 0.12\ °C$
- At the end of load mode
  - Pressure: $\bar{p}_2 = 9.53\ bar_a,\ \sigma_{p2} \ll 0.01\ bar_a$
  - Temperature: $\bar{\vartheta}_2 = 25.58\ °C,\quad \sigma_{\vartheta 2} = 0.14\ °C$

| | Isochoric process | cii-process | change |
|---|---|---|---|
| Capacity | 424 $l_n$ | | |
| No. of cycles | 20 | | |
| Load ratio | 42.2 % | | |

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# Theoretical investigation of potential energy savings

## Method

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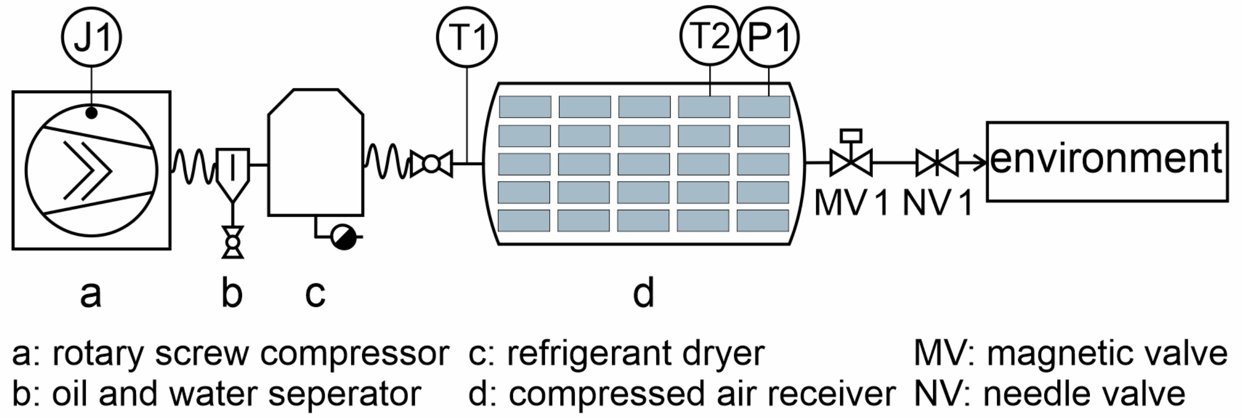
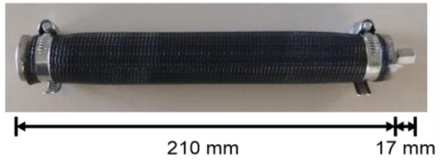
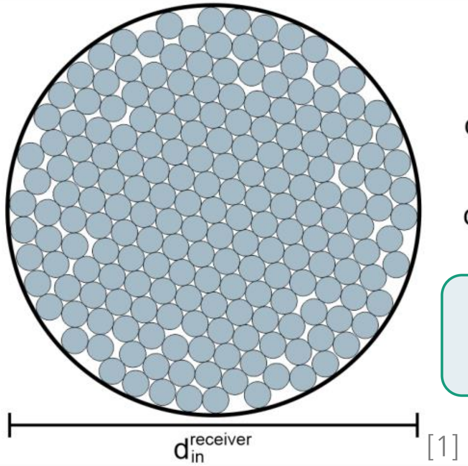



$d_{in}^{receiver}$ = 494,6 mm

$N_{small\ circles}$ = 199

$d_{small\ circle}$ = 32.1 mm

Theoretical no. of PEQM: 996

[1] Specht: The best known packings of equal circles in a circle (complete up to N = 2600), accessed 11/02/2022

# Isochoric and combined-isobaric-isochoric process

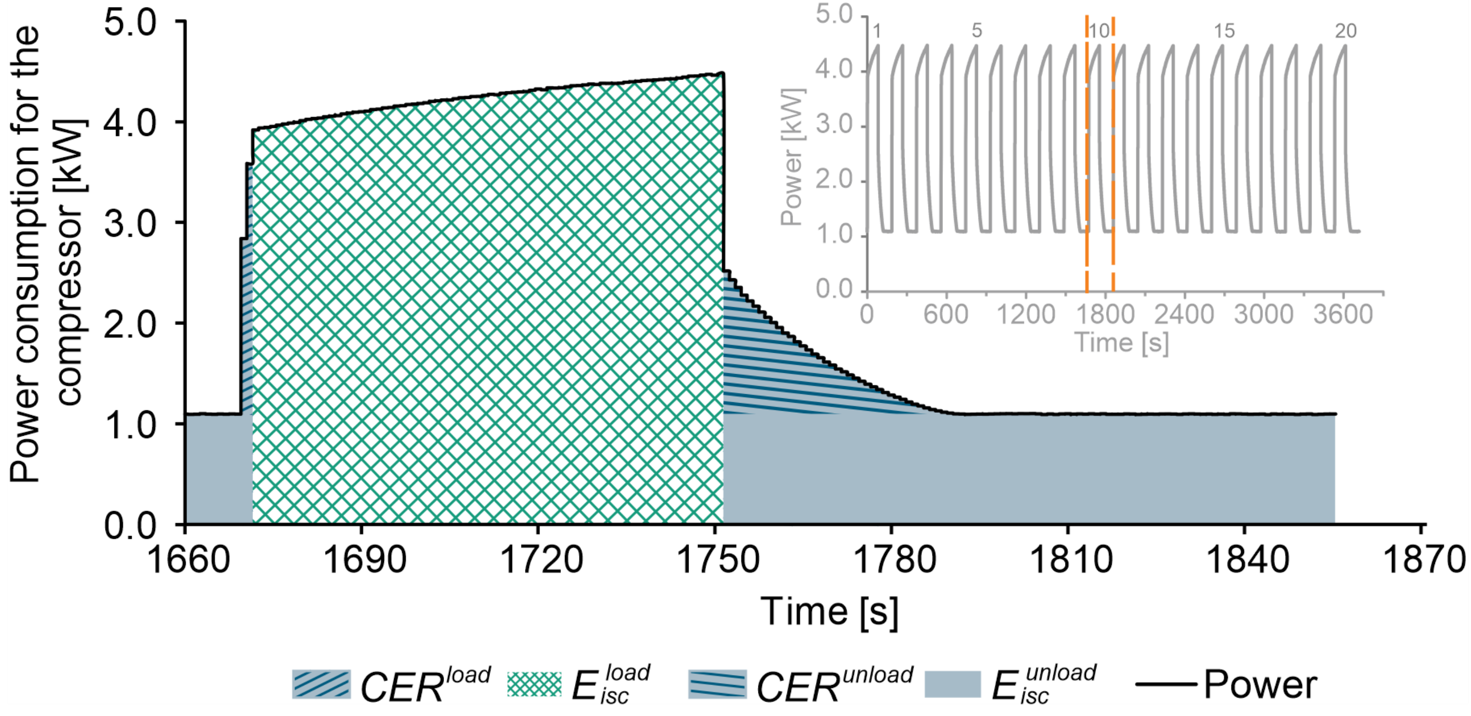
## Capacity and load ratio

2

- At the beginning of load mode:
  - Pressure: $\bar{p}_1 = 7.63\ bar_a,\ \sigma_{p1} \ll 0.01\ bar_a$
  - Temperature: $\bar{\vartheta}_1 = 23.58\ °C,\quad \sigma_{\vartheta 1} = 0.12\ °C$
- At the end of load mode
  - Pressure: $\bar{p}_2 = 9.53\ bar_a,\ \sigma_{p2} \ll 0.01\ bar_a$
  - Temperature: $\bar{\vartheta}_2 = 25.58\ °C,\quad \sigma_{\vartheta 2} = 0.14\ °C$

| | Isochoric process | cii-process | change |
|---|---|---|---|
| Capacity | 424 $l_n$ | 642 $l_n$ | + 58.5% |
| No. of cycles | 20 | 12.6 | - 37 % |
| Load ratio | 42.2 % | 50.6 % | |

**401 l isochoric receiver yields same capacity increase**

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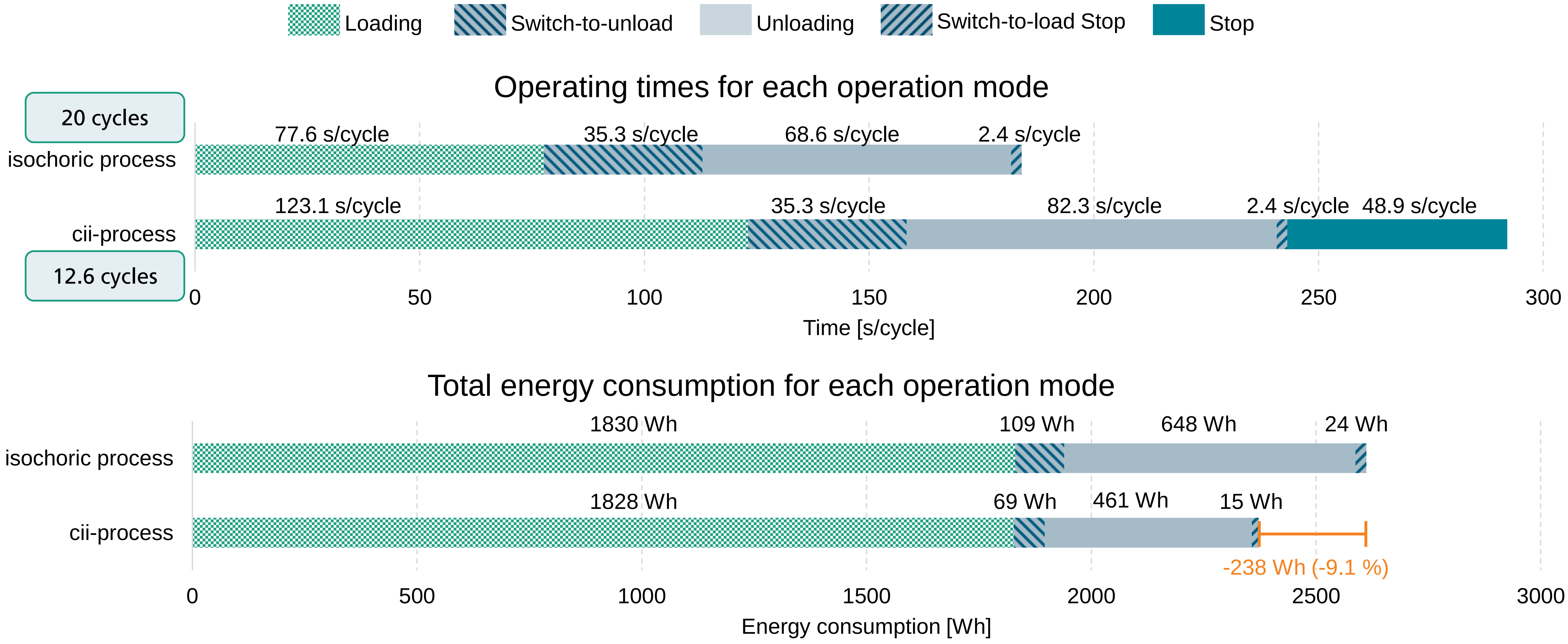
# Isochoric and combined-isobaric-isochoric process

## Operation time and energy consumption

3

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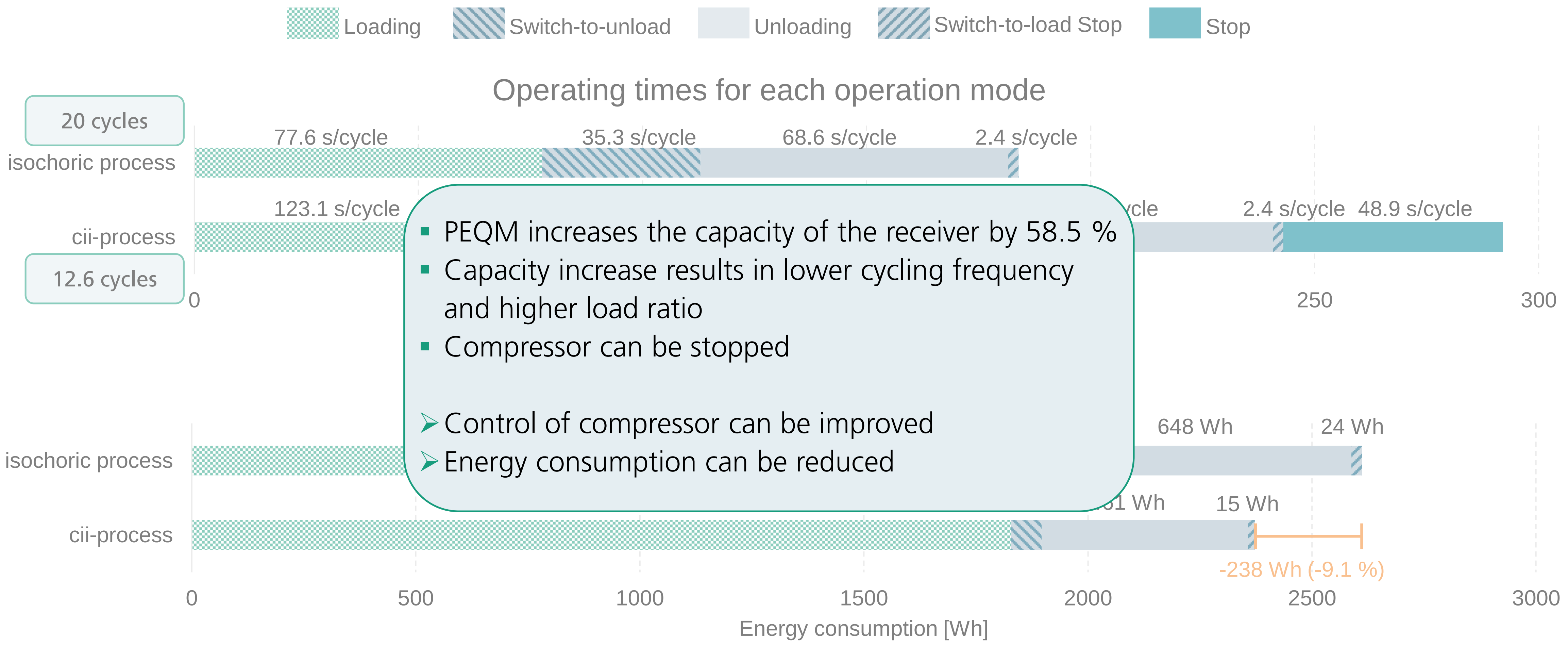


- PEQM increases the capacity of the receiver by 58.5 %
- Capacity increase results in lower cycling frequency and higher load ratio
- Compressor can be stopped

➢ Control of compressor can be improved
➢ Energy consumption can be reduced



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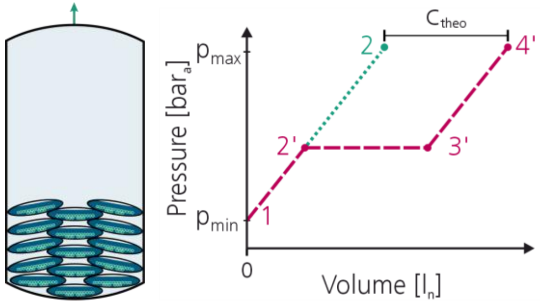
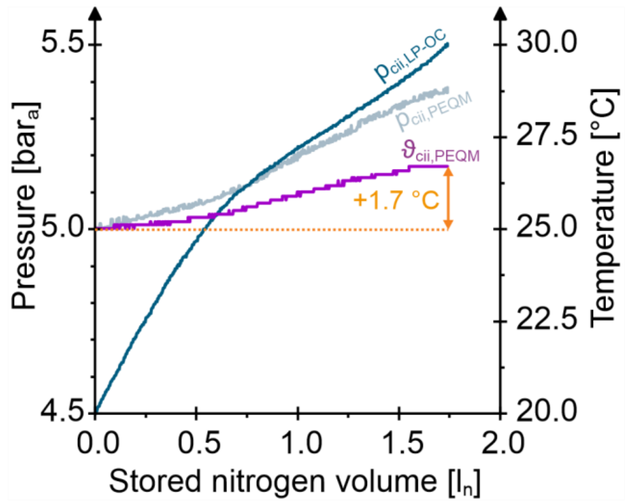
# Summary and future work

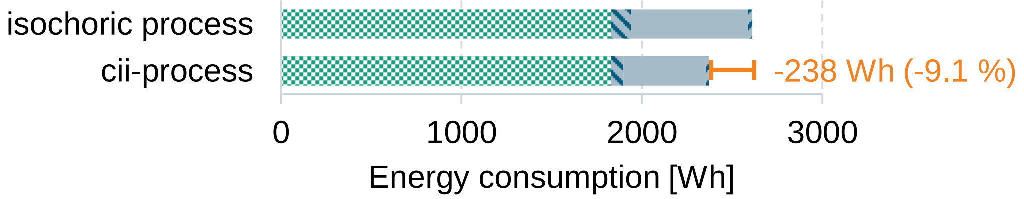
1 Concept of PEQM is suitable to increase the capacity of receiver

2 Heat management is essential for isobaric storage on a $PCM_{l/g}$-basis

3 PEQM improves control and energy consumption of compressor



# Summary and future work

1 Concept of PEQM is suitable to increase the capacity of receiver

2 Heat management is essential for isobaric storage on a $PCM_{l/g}$-basis

3 PEQM improves control and energy consumption of compressor

1 Investigation of the effects taking place inside the PEQM

2 Realizing a combined-isobar-isochoric compressed air receiver


# Contact

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