

9th International Supercritical CO₂ Energy Technologies Symposium
March 2 – 5, 2026, Pittsburgh, PA



**Development of a reversible heating and cooling system using
CO₂ as a refrigerant for industrial customers and residential
areas with heating and cooling requirements**

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Agenda



- I. Introduction
- II. Objectives
- III. CO₂ WP
- IV. Project Results
- V. Summary and Conclusion

I. Introduction

1. ZIM Cooperation project CO₂ WP

Project partners:



BKW Kälte- Wärme-
Versorgungstechnik GmbH
[Prototyp]



Reutlingen University
(Hochschule Reutlingen)
[Simulation]

With Subcontractor:



enisyst GmbH
[Control engineering]

Project period: Q2 2021 – Q2 2024

Financial support :

Federal Ministry for Economic Affairs and Energy
(Bundesministerium für Wirtschaft und Energie *BMWE*)

Target:

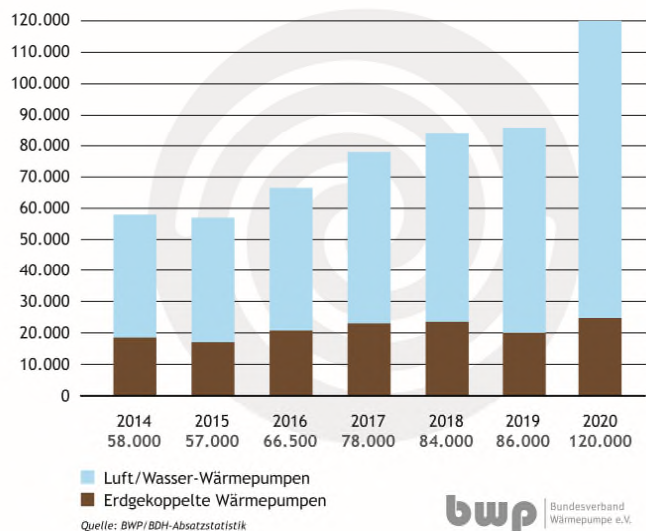
- Development of a reversible CO₂ refrigeration unit / CO₂ heat pump) with a power output of approximately 20-50 kW for heat and cold generation.
- Optimising of work operations through intelligent control with connection with the digital twin.
- Achieving a COP value higher than 4.38 in Heating Mode, according to the Federal Office for Economic Affairs and Export Control (BAFA)

Main Focus of the project:

- CO₂ as refrigerant for heating and cooling technology
- Digital Twin for optimized control

I. Introduction

2. Market situation



Heat pump sales figures in Germany 2014 to 2020

[1]

1. BWP/BDH-Absatzstatistik [Online](#)

2. Waterkotte: Industrial Line EcoTouch 5110T. [Online](#)

3. VERORDNUNG (EU) Nr. 517/2014 DES EUROPÄISCHEN PARLAMENTS UND DES RATES vom 16. April 2014 über fluorierte Treibhausgase und zur Aufhebung der Verordnung (EG) Nr. 842/2006. 2014

Significantly increasing market share of heat pumps [1]

The market offers a range of products that are powered by a fluorinated hydrocarbon [2]

Reduction of fluorochlorohydrocarbons by 2030 [3]

CO₂ Application area in Germany:

- Refrigeration supply in the supermarket area,
- Bus air conditioning,
- Container and transport refrigeration systems

Higher efficiency of CO₂ refrigerant in hot water preparation and at higher heating flow Temperatures

I. Introduction

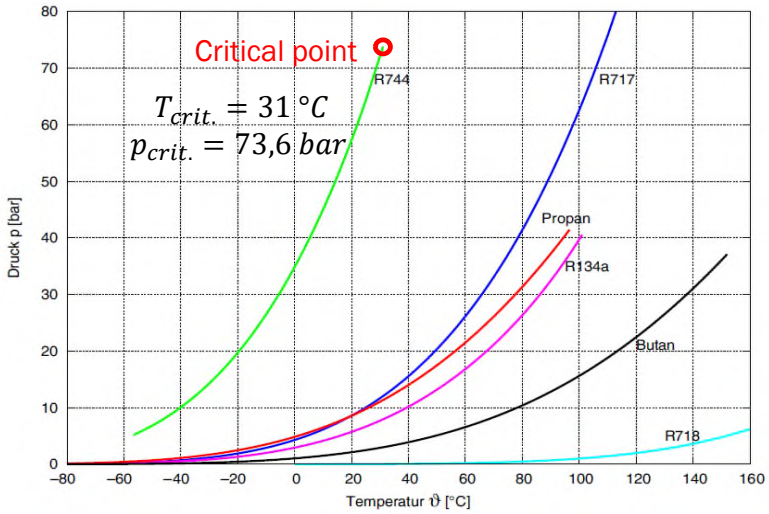


3. CO₂ as Refrigerant (R744)

- The effect of a substance as a greenhouse gas is assessed using the GWP (Global Warming Potential)

Refrigerant	GWP
Freon (R23)	14 800
Fluorcarbon (R134a)	1 430
Propan (R290)	3
Carbon dioxide CO ₂ (R744)	1

- New EU Fluorinated Gas (F-Gas) regulation 2024/573 [4]
 - from 1st January 2025, F-Gases with GWP ≥ 2.500 won't be allowed
 - from 1st January 2030: Extension to include F-Gases with GWP ≥ 150



Dampfdruck verschiedener Kältemittel [5].

CO₂ Characteristics

- High pressures of up to 120 bar occur in transcritical operations
- Possibility of reaching extremely high and low temperatures

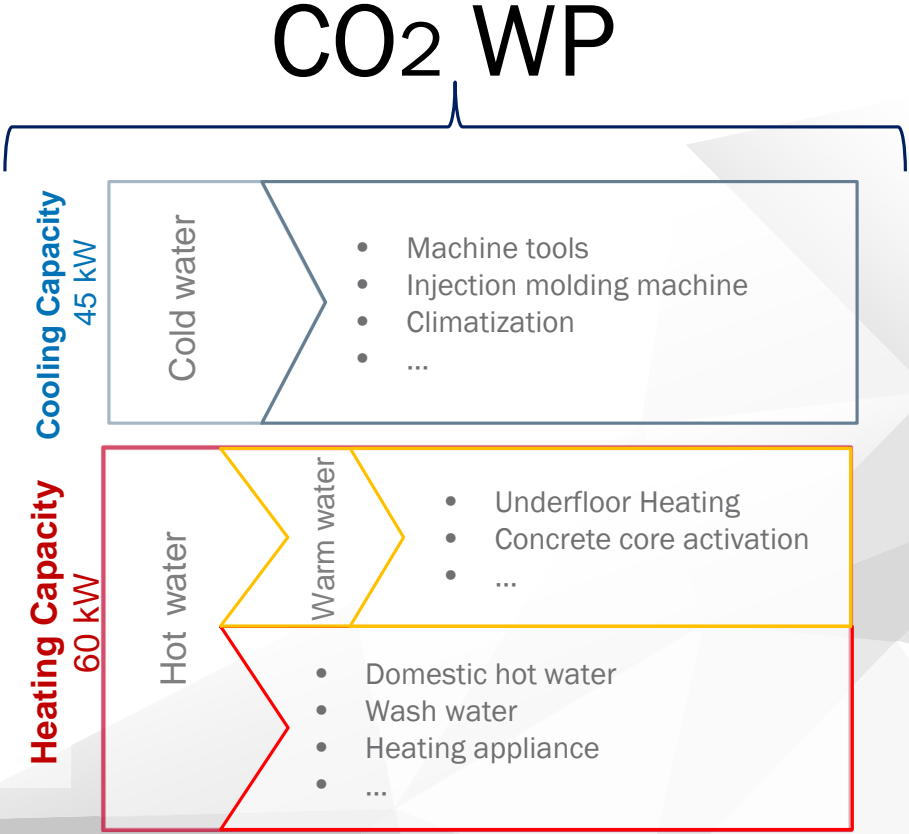
4. Verordnung (EU) 2024/573 des europäischen Parlaments und des Rates 07.02.2024
 5. Thermodynamik der Kälteanlagen und Wärmepumpen pp 62

II. Objectives

1. Capacity and characteristics of prototype CO₂ WP

As part of this project, the prototype of the CO₂ WP was tested. This allows:

- The cooling and heating capacities to be determined empirically and numerically.
- Define the application areas.



III. CO₂ WP

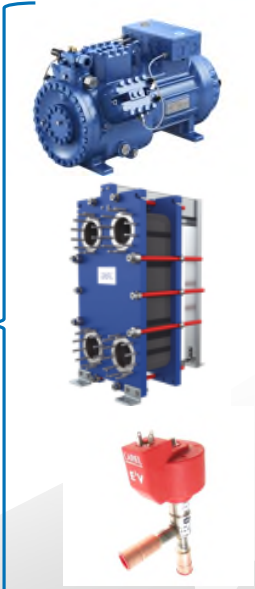
1. Construction of the prototype CO₂ WP



→ During operation of the CO₂ WP, the working pressure on the high-pressure side was regulated to between 75 - 95 bar.



Therefore, special components that were specifically developed for CO₂-refrigeration applications are used.



Reciprocating compressor - Co. *BOCK*

- High pressure 70 - 120 bar
- Low pressure min 12 bar
- Frequency converter 20 - 70 Hz

3 Plate heat exchangers - Co. *Alfa Laval*

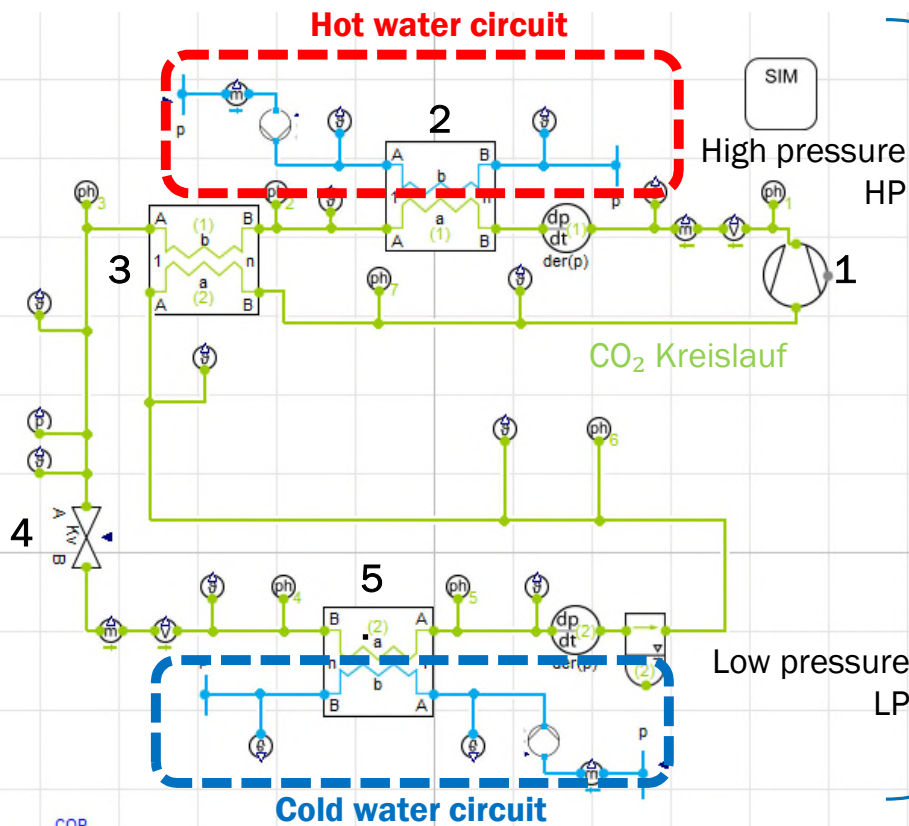
- Evaporator \dot{Q}_o bis 50 kW
 \dot{m}_{Wasser} bis 3,96 kg/s
- Gas cooler \dot{Q}_c bis 63 kW
 \dot{m}_{Wasser} bis 3 kg/s
- Internal heat exchanger
 \dot{Q} bis 8,5 kW - \dot{m}_{CO_2} bis 0,33 kg/s

Expansion valve - Fa. *Carel*

- pressure. max. 140 bar
- T Refrigerant -40° C / 70° C
- T Refrigerant -30° C / 70° C

III. CO₂ WP

2. Digital Twin DT



Simulation environment:

Software: *Dymola* (Dynamic Modeling Laboratory) (e.g. aerospace, automotive, process engineering)

Programming language: *Modelica* + *TIL-Tools* (TLK-Thermo-GmbH) for modeling and simulation of thermal processes

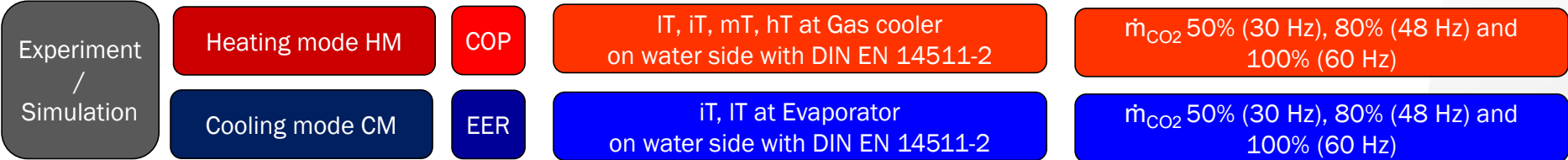
Simulation model with main components

1. Compressor
2. Gas cooler
3. Internal heat exchanger
4. Expansion valve
5. Evaporator
6. Water pumps (secondary sides)

IV. Project Results

1. Project results – Experiment / Simulation

The efficiency of the CO₂ WP is determined through experiments and simulations in heating and cooling modes (HM and CM) with different CO₂ refrigerant mass flows \dot{m}_{CO_2} and different water temperature on gas cooler / evaporator.



$$COP = \epsilon_{wp} = \frac{\dot{Q}_{GC}}{P_{el}} = \frac{\text{Heating capacity}}{\text{Electrical power}}$$

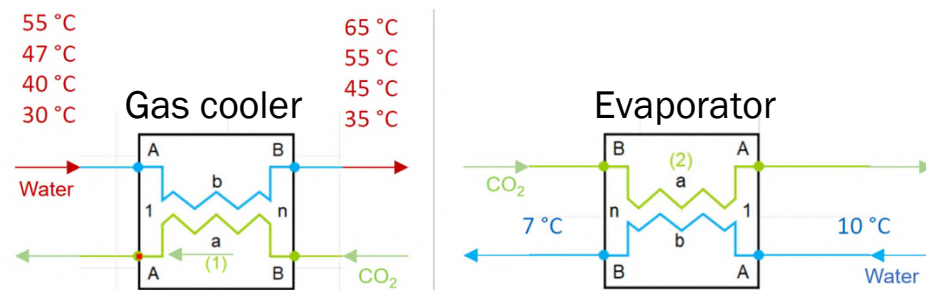
$$EER = \epsilon_K = \frac{\dot{Q}_{EV}}{P_{el}} = \frac{\text{Cooling capacity}}{\text{Electrical power}}$$

IV. Project Results

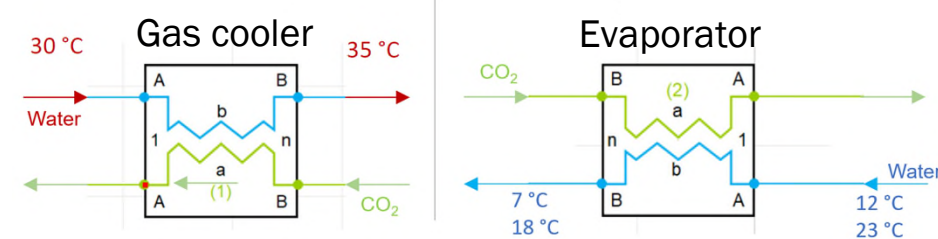
2. Project results - Heating mode COP / Cooling mode EER

Compressor frequency [Hz]			Evaporator		Gas cooler		Operating mode HM / CM
			Inlet temperature $T_{EV,in}$ [°C]	Outlet temperature $T_{EV,out}$ [°C]	Inlet temperature $T_{GC,in}$ [°C]	Outlet temperature $T_{GC,out}$ [°C]	
30	48	60	10	7	30	35	HM - low temperature IT
30	48	60	10	7	40	45	HM - intermediate temperature IT
30	48	60	10	7	47	55	HM - midle temperature mT
30	48	60	10	7	55	65	HM - high temperature hT
30	48	60	12	7	30	35	HM - intermediate temperature IT
30	48	60	23	18	30	35	CM - low temperature IT

Heating mode HM, Values for simulations and experiments on gas cooler and evaporator in accordance with DIN EN 14511-2

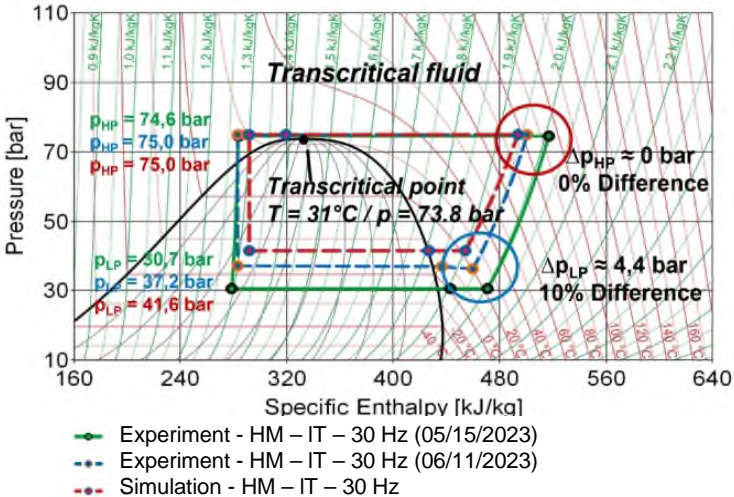


Values for Experiments and Simulations HM



Values for Experiments and Simulations CM

IV. Project Results – COP / EER



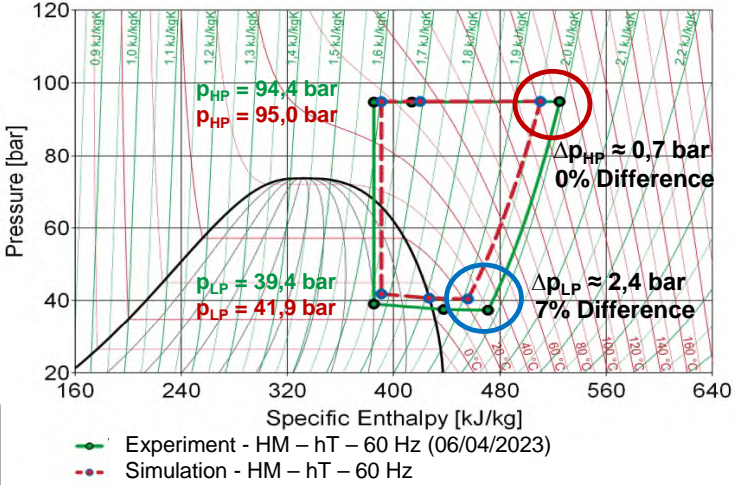
Heating mode HM, low temperature IT, 30Hz, experiment and simulation results with pressure limitation HP to 75 bar

max COP **3.77** (HM, IT)
max EER **3.40** (CM, iT)

- There is no discrepancy ΔP_{HP} between the simulation and the test results for the gas cooler HP.
- significant deviation ΔP_{LP} at the evaporator when CO₂ is low compared to sufficient CO₂.
- High Pressure in transcritical area leads to leakage on the system and loss of Refrigerant

→ This has negative effect on COP and EER

This concerns **HM – (IT) + CM – (iT, IT)**



Heating mode HM, high temperature hT, 60Hz, experiment and simulation results with pressure limitation HP to 95 bar

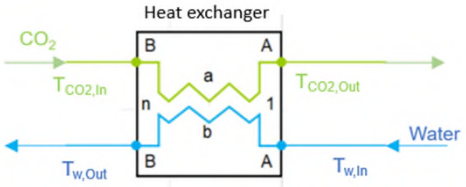
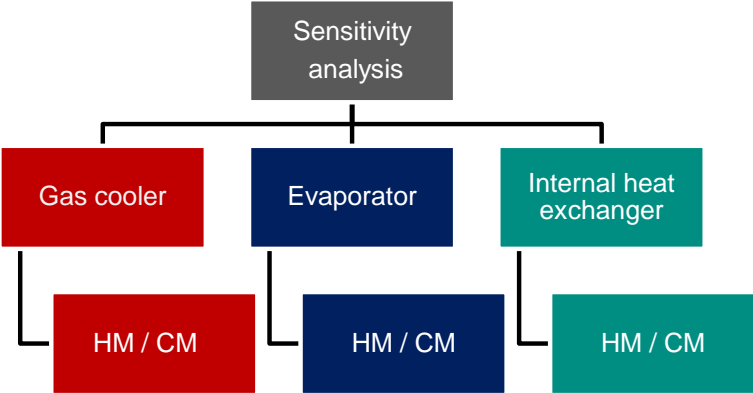
- Minimal (negligible $\approx 0\%$) pressure deviation ΔP_{HP} has been detected at the gas cooler.
- Medium to large pressure deviations ΔP_{LP} have been detected at the evaporator (CO₂ insufficient in the system).
- High Pressure in the transcritical area leads to leakage on the system and loss of Refrigerant

→ This has negative effect on COP

This concerns **HM – (iT, mT, hT)**

IV. Project Results - Sensitivity analysis

3. Project results – Sensitivity analysis



Temperatures of fluids at the heat exchanger

- Sensitivity analysis using variation of the number of plates in all the heat exchangers (Impact on COP / EER)
- The number of plates is a critical factor in designing heat exchangers. This variable is equivalent to the heat exchanger's heat transfer area (A).
- The design of each heat exchanger is described by the specific thermal output $\dot{Q} \approx k \cdot A \cdot \text{LMTD}$ ($\text{Ln}\Delta T$ at the inlet and outlet).

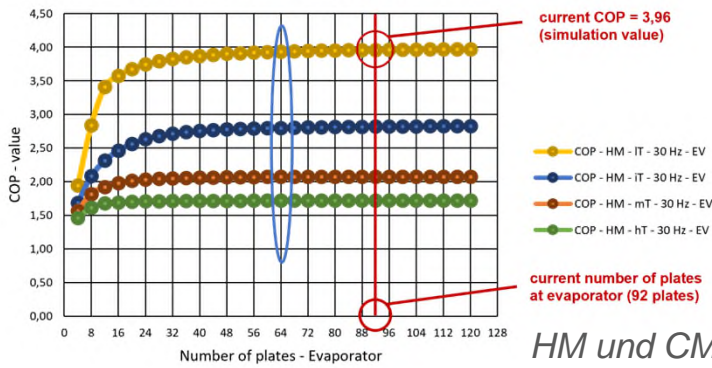
$$\dot{Q} = K \times A \times \text{Ln}\Delta T k \qquad \Delta T_1 = T_{w,in} - T_{CO_2,out}$$

$$\text{Ln}\Delta T = \frac{\Delta T_1 - \Delta T_2}{\ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad \Delta T_2 = T_{w,out} - T_{CO_2,in}$$

IV. Project Results - Sensitivity analysis

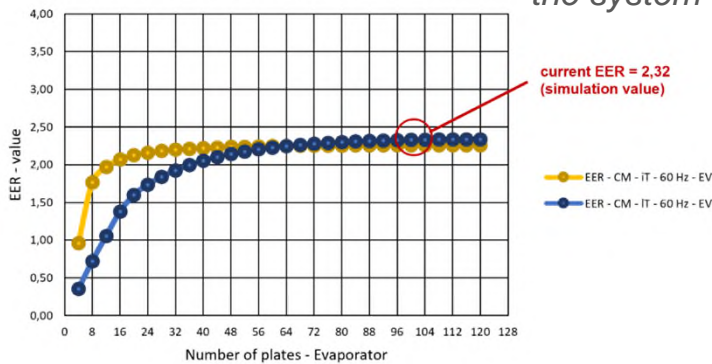
Evaporator

COP at different Temperatures at 30 Hz

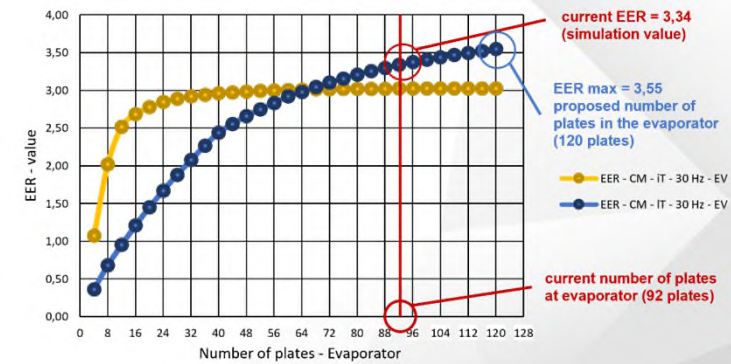


HM und CM - iT: The number of plates can be reduced (from 92 to 64) → no impact on the system

EER at different temperatures at 60 Hz



EER at different temperatures at 30 Hz

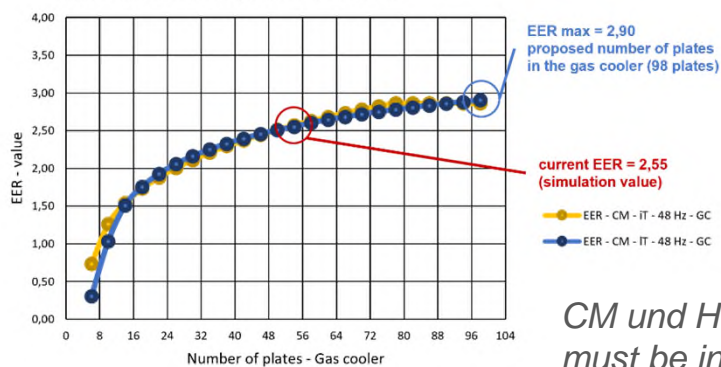


CM - IT: The number of plates must be increased to obtain higher EER values.

IV. Project Results - Sensitivity analysis

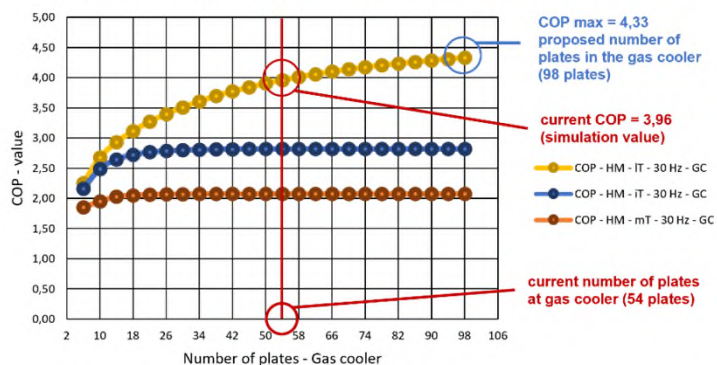
Gas cooler

EER at different temperatures at 48 Hz

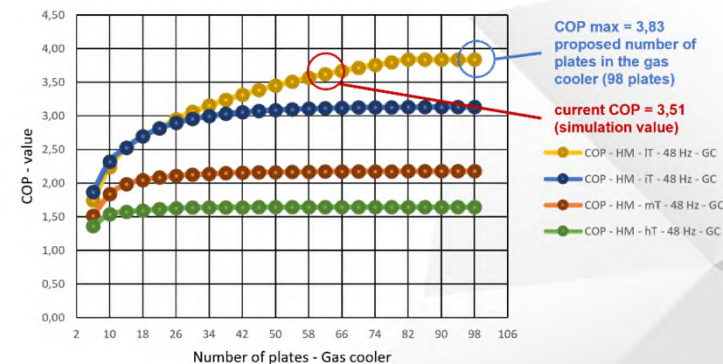


CM und HM - IT: The number of plates must be increased werden (from 54 to 98) → higher EER and COP

COP at different temperatures at 30 Hz



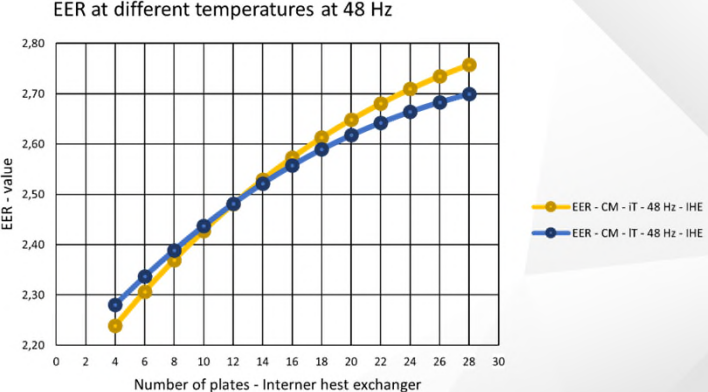
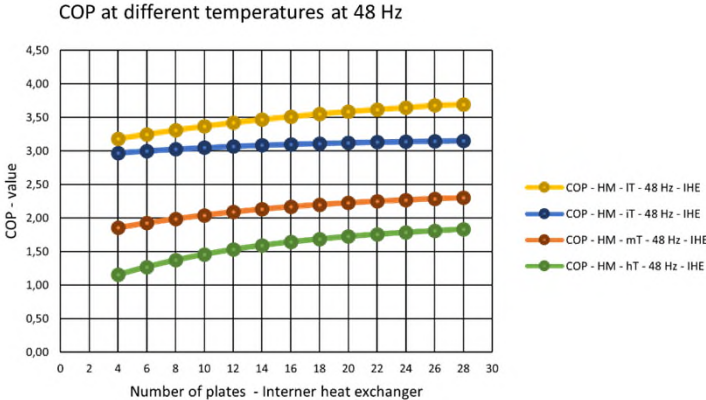
COP at different temperatures at 48 Hz



HM - iT, mT, hT: The number of plates can be reduced (from 54 to 42) → no impact on the system

IV. Project Results - Sensitivity analysis

Internal heat Exchanger

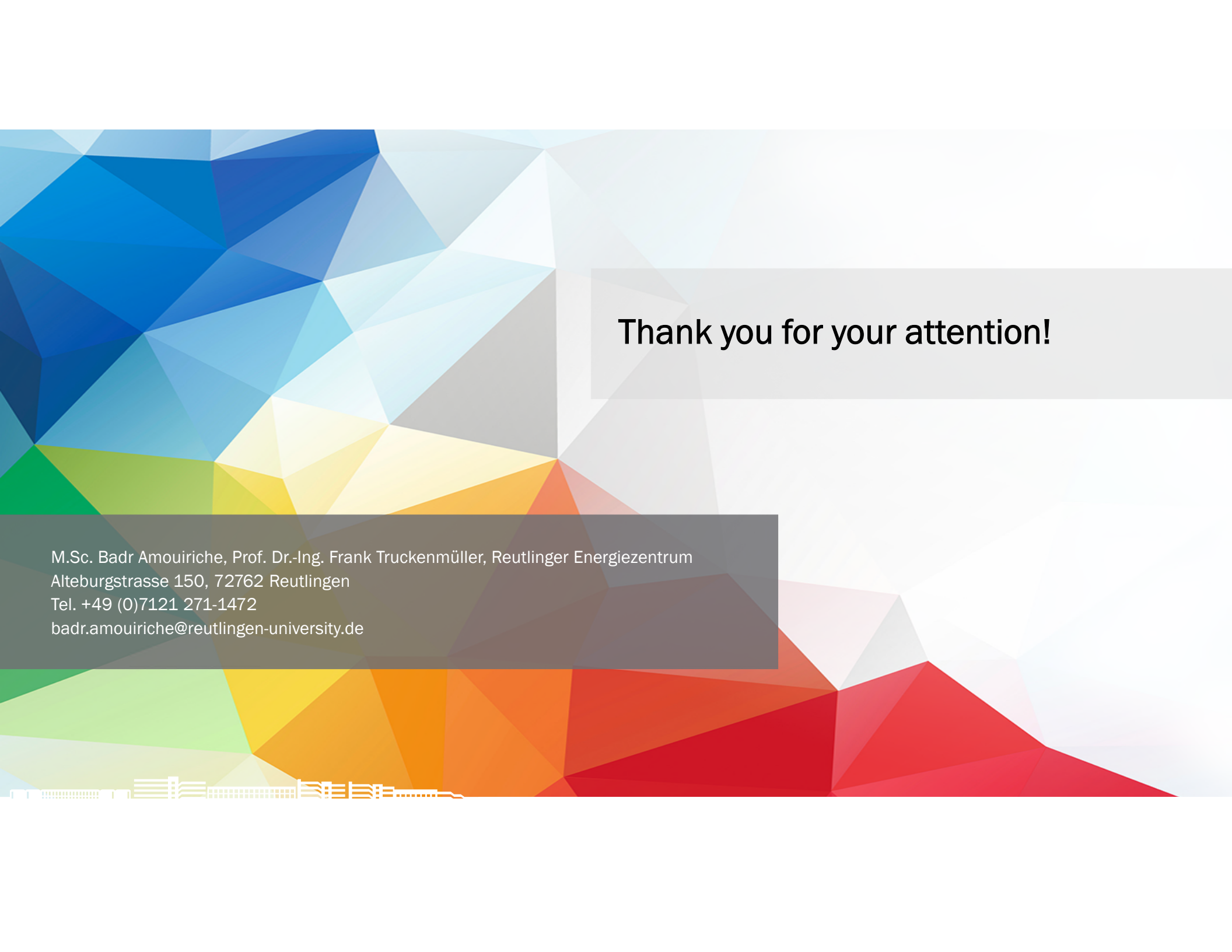


Increasing the number of plates in the internal heat exchanger leads to better COP and EER

V. Summary and Conclusion

- The targeted COP value of 4.38, set by the *Federal Office for Economic Affairs and Export Control* (Bundesamt für Wirtschaft und Ausfuhrkontrolle) BAFA, was unfortunately not achieved by the CO₂ WP (achieved COP = 3.77)
- The COP value decreases continuously when using the CO₂ WP in HM at high temperatures. The same applies to the EER during CM at low Temperatures.
- The high pressures lead to leaks within the CO₂ WP. This reduces the refrigerant charge in the system.
- The efficiency of the CO₂ WP is strongly influenced by the fill quantity. **(The COP / EER values improve with sufficient CO₂ refrigerant in the System).**
- Number of Plates (Evaporator): can be reduced to a specific number **(in this case from 92 to 64)** during HM and at iT during CM **(no effect on COP and EER)**. It must, be increased during CM at IT, to achieve a **better EER**.
- Number of Plate (Gas cooler): can be increased in HM at IT and in CM on a certain number of plates **(in this case from 54 to 98) (for better COP and EER)**. It may be reduced (in this cas to 42) in HM at iT, mT and hT **(COP remains the same)**.
- Number of Plates IHE: must not be reduced **(COP and EER will suffer)**. Increasing the number of plates **improves the efficiency of CO₂ WP**.
- The fill quantity was an important factor in the CO₂ WP. It needs to be optimized (e.g., by installing a CO₂ level sensor).
- Measures to improve the tightness between components, e.g. through optimized connection and assembly quality as well as through the use of electronic leak detection systems and regular leak tests for leak detection.

	Temperature	Simulation	Experiment
COP	nT	3,96	3,77
	iT	3,06	2,69
	mT	2,12	1,96
	hT	1,57	1,5
EER	nT	-	2,4
	iT	-	3,4



Thank you for your attention!

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