



Technische Universität Berlin

Institute for Energy Engineering



ADVANCED EXERGETIC ANALYSIS AS A TOOL FOR THE THERMODYNAMIC EVALUATION OF SUPERCRITICAL CO₂ POWER CYCLES

T. Morosuk and G. Tsatsaronis

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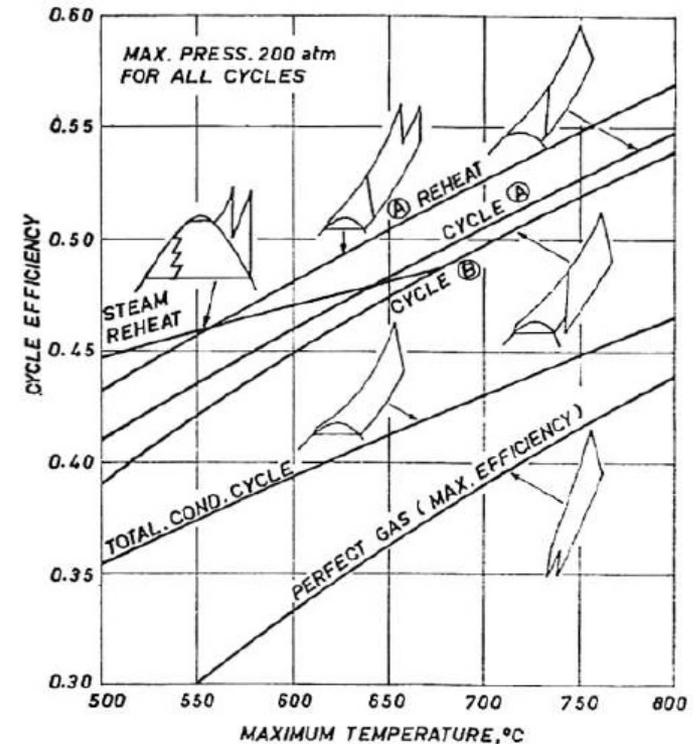
*morozyuk@iet.tu-berlin.de
www.ebr.tu-berlin.de*

*tsatsaronis@iet.tu-berlin.de
www.energietechnik.tu-berlin.de*

Introduction

The idea of developing supercritical CO₂ power cycles and applying them to industrial processes became increasingly popular in the last decade.

The potential for the application of supercritical CO₂ cycles is high for both *power generation systems* (Angelino, 1968) and *refrigeration systems* (Lorentzen, 1994) .



Significant research has been done in this field, including

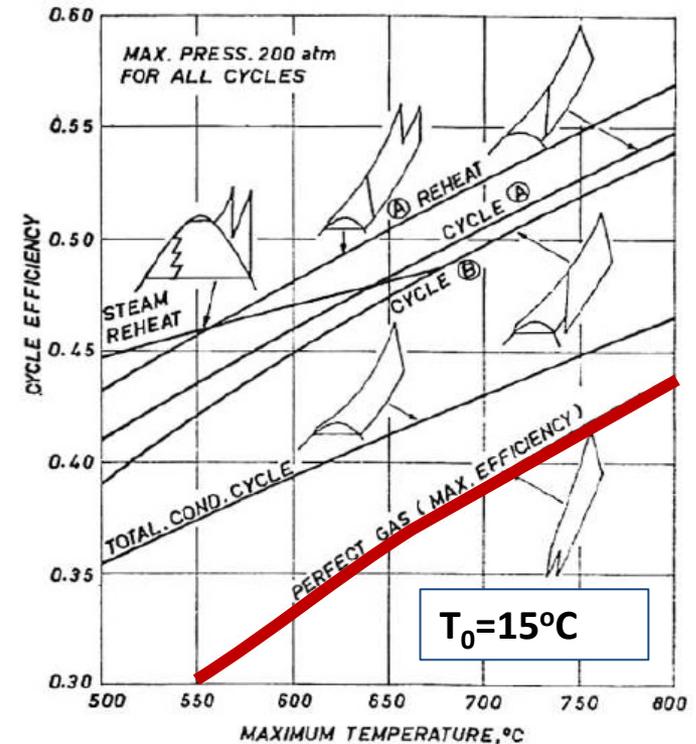
- the development of new thermodynamic cycles,
- investigation of specific equipment, and
- parametric optimization of power systems.

Purpose of the paper

The present paper deals with the demonstration of the **application of advanced exergy-based methods** to supercritical CO₂ power cycles.

The examples used here assume power generation *when the temperature of the environment is high enough, so that a simple CO₂ cycle must operate above the critical temperature of CO₂ (i.e., >31.1 °C).*

Then none of the known condensation cycles can be applied.



Why Exergy-Based Methods? - 1

The objective evaluation and the improvement of an energy conversion system from the viewpoints of *thermodynamics*, *economics*, and *environmental impact* require a deep understanding of

- the *real thermodynamic inefficiencies* and the processes that cause them,
- the *costs associated with equipment and thermodynamic inefficiencies* as well as the connection between these two important factors,
- the *environmental impact associated with equipment and thermodynamic inefficiencies* as well as the connection between these two sources of environmental impact, and
- the *interconnections among efficiency, investment cost and component-related environmental impact* associated with the selection of specific system components

Why Exergy-Based Methods? - 2

Energy-based methods do not provide this understanding because the only thermodynamic inefficiencies identified by energy-based methods are the transfer of energy to the environment. However, ***the inefficiencies caused by the irreversibilities within the system*** being considered are, in general, by far the most important thermodynamic inefficiencies and are identifiable with the aid of an exergetic analysis.

If we want to successfully reduce thermodynamic inefficiencies, cost and environmental impacts in a system we must first understand how these are formed. *Exergy-based methods* reveal the location, the magnitude and the sources of inefficiencies, costs and environmental impact and allow us to study the interconnections between them.

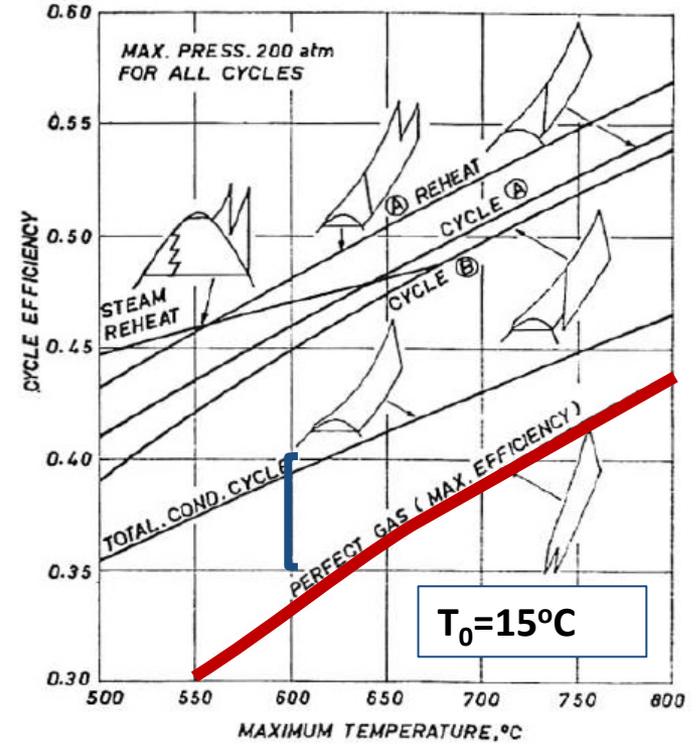
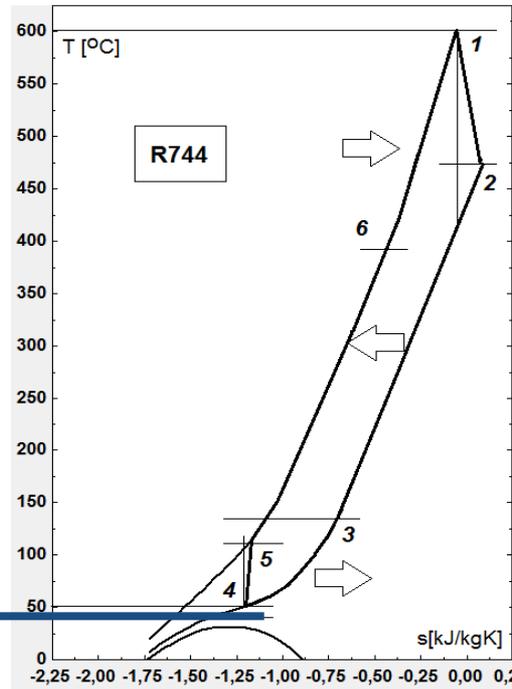
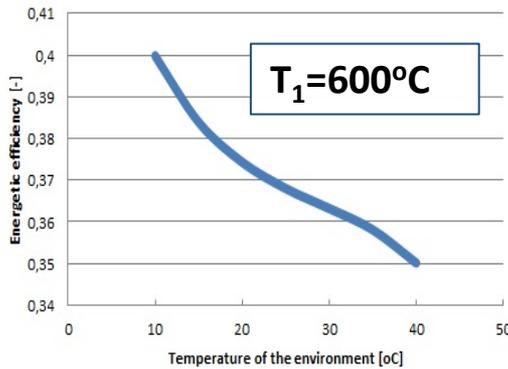
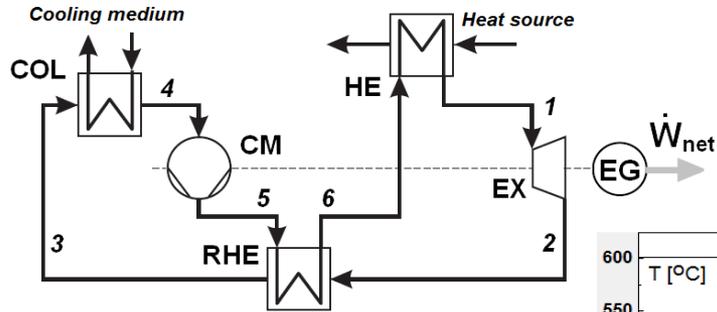
Exergy-Based Methods

Exergy-based methods is a general term that includes the conventional and advanced *exergetic*, *exergoeconomic*, and *exergoenvironmental analyses* and evaluations.

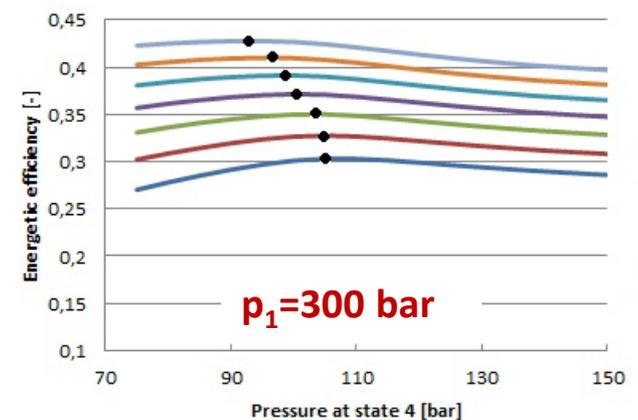
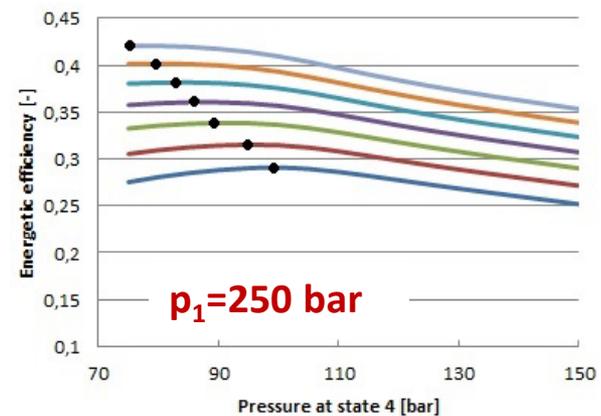
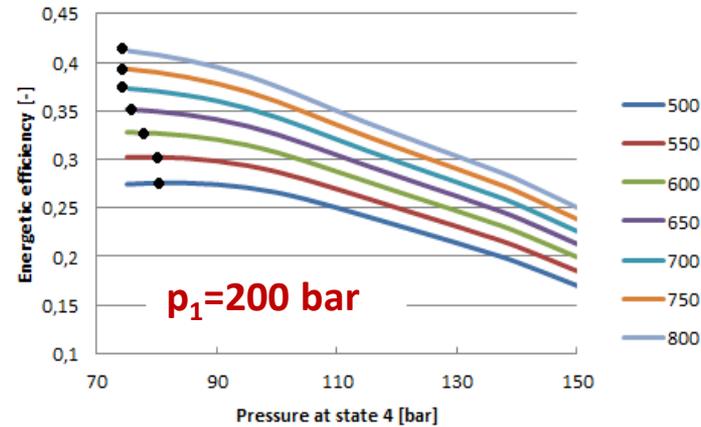
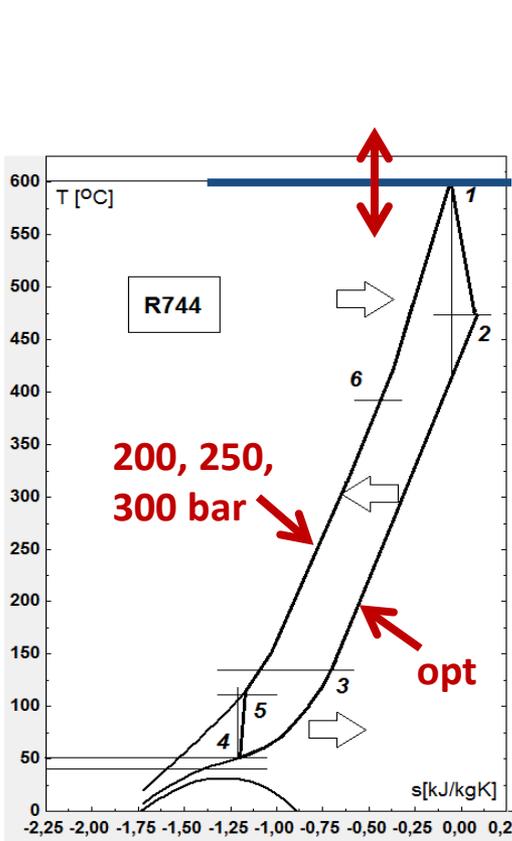
The *concept of exergy* complements and enhances an energetic analysis by calculating

- (a) the true thermodynamic value of an energy carrier,
- (b) the real thermodynamic inefficiencies in a system, and
- (c) variables that unambiguously characterize the performance of a system (or one of its components) from the thermodynamic viewpoint.

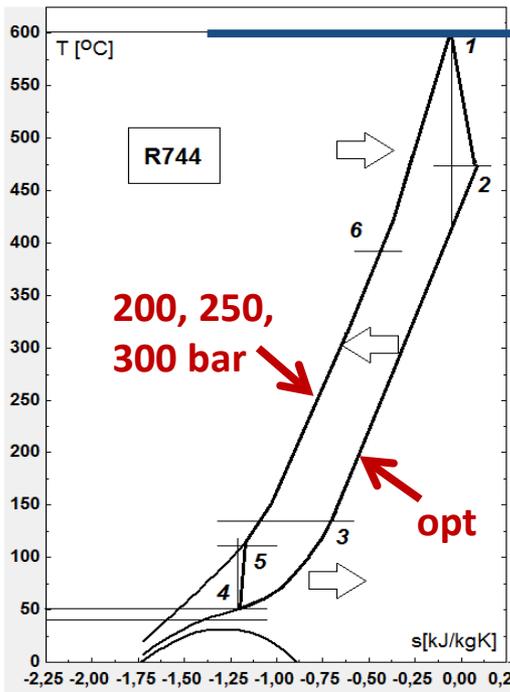
Case Study



Case Study: Sensitivity Analysis



Case Study: Base Case



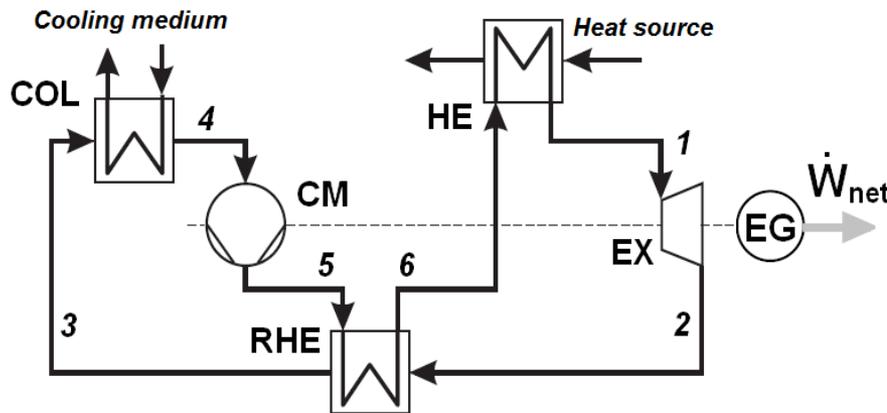
p_1 [bar]	p_4^{opt} [bar]	η [-]	w_{net} [kJ/kg]	\dot{m}_{cycle} [kJ/kg]
200	75	0.33	73.15	136.7
250	90	0.34	83.95	119.1
300	105	0.35	94.97	105.3

Conventional Exergy Analysis

Exergy of a system

$$E_{sys} = \quad + E_{sys}^{PH}$$

physical



Physical exergy
associated with a material
stream

$$\dot{E}_{ms}^{PH} = (\dot{H} - \dot{H}_0) - T_0(\dot{S} - \dot{S}_0)$$

Exergetic Variables: E_P and E_F

Exergy of product: \dot{E}_P

The desired result, expressed in exergy terms, achieved by the system (the k -th component) being considered.

Exergy of fuel: \dot{E}_F

The exergetic resources expended to generate the exergy of the product.

The concepts of product and fuel are used in a consistent way not only in *exergetic analyses* but also in the *exergoeconomic* and *exergoenvironmental* analyses.

Exergetic Variables: E_D and E_L

Exergy destruction: \dot{E}_D

Exergy destroyed due to irreversibilities within a system (the k -th component).

Exergy loss: \dot{E}_L

Exergy transfer to the system surroundings. This exergy transfer is not further used in the installation being considered or in another one.

Exergy balance:

$$\dot{E}_F = \dot{E}_P + \dot{E}_D (+ \dot{E}_L)$$

\dot{E}_D and \dot{E}_L are **absolute** measures of

the thermodynamic inefficiencies.

Exergetic Variables: ε and $y_{D,k}$

Relative measures of the thermodynamic inefficiencies:

Exergetic efficiency: The ratio between exergy of product and exergy of fuel

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}}$$

Exergy destruction ratio for the k -th component

$$y_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$$

Cost Sources

The real cost sources (identifiable only by an exergoeconomic analysis) in an energy conversion system are the:

- capital investment for each component
- operating and maintenance expenses
- ***cost of exergy destruction***
- ***cost of exergy loss***

Advanced Analyses

Advanced Exergetic Analysis

The *conventional exergetic* analysis do not evaluate the mutual interdependencies among the system components nor the potential for improving a component.

These issues are considered in the *advanced analysis*, in which the exergy destruction in each component is split into:

- *Endogenous* and *exogenous* parts,
- *Unavoidable* and *avoidable* parts, and
- The resulting combined parts.

Definition of $\dot{E}_{D,k}^{EN}$ and $\dot{E}_{D,k}^{EX}$

The *endogenous* exergy destruction in a component ($\dot{E}_{D,k}^{EN}$) refers to the irreversibility occurring within this component when all other components operate in an ideal way and the component being considered operates with its current efficiency.

The *exogenous* exergy destruction ($\dot{E}_{D,k}^{EX}$) is caused in the k -th component by the irreversibilities that occur in the remaining components.

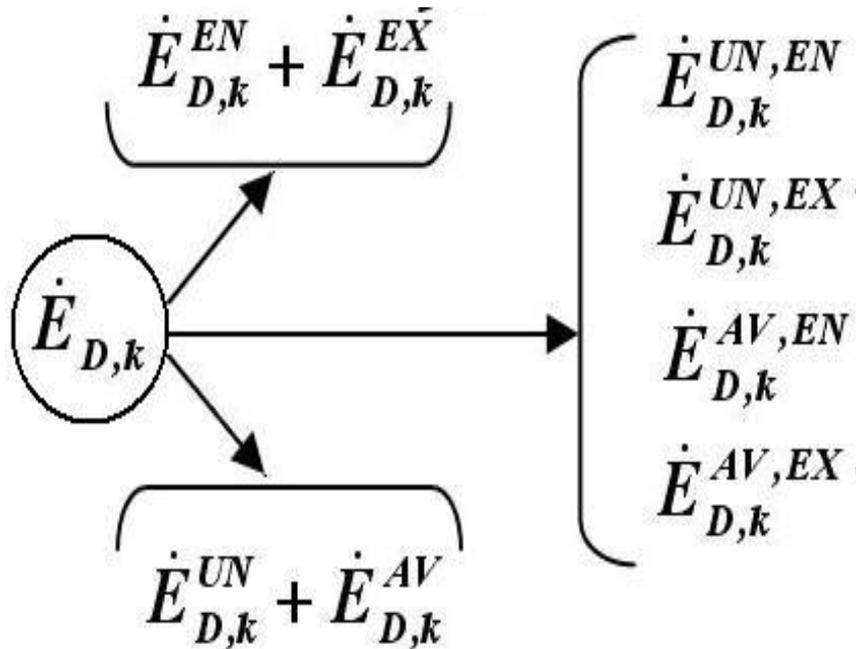
$$\dot{E}_{D,k} = \dot{E}_{D,k}^{EN} + \dot{E}_{D,k}^{EX}$$

Definition of $\dot{E}_{D,k}^{UN}$ and $\dot{E}_{D,k}^{AV}$

Unavoidable ($\dot{E}_{D,k}^{UN}$) is the exergy destruction in a component that will always be there as long as this component is being used in the system, i.e. the unavoidable exergy destruction cannot be reduced because of technological limitations such as availability and cost of materials and manufacturing methods.

The **avoidable** exergy destruction ($\dot{E}_{D,k}^{AV}$) can be varied during efforts to improve the cost effectiveness of the component and the overall system.

Advanced Exergetic Analysis



The *endogenous unavoidable* part cannot be reduced because of technological limitations for the k -th component.

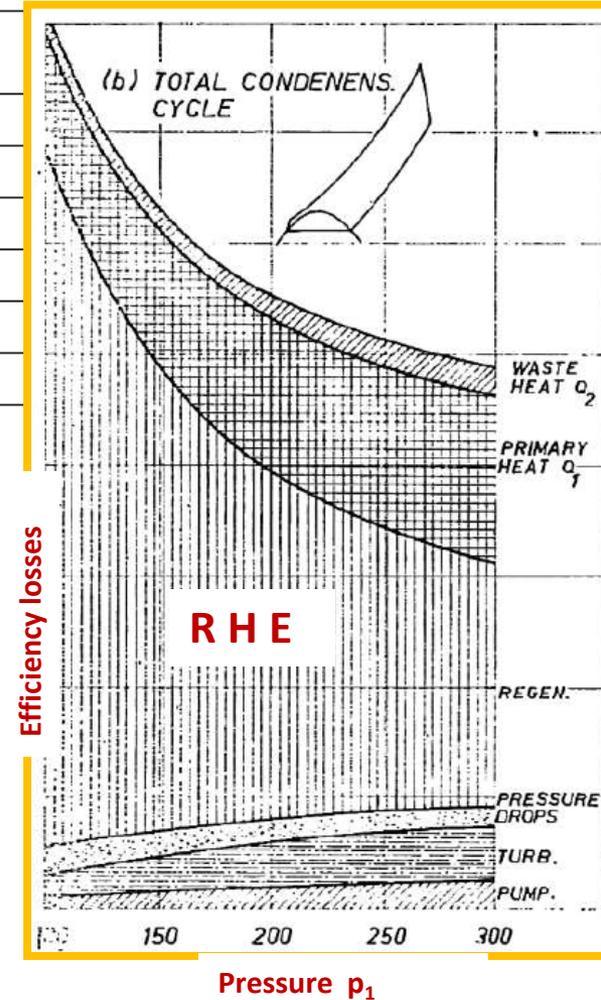
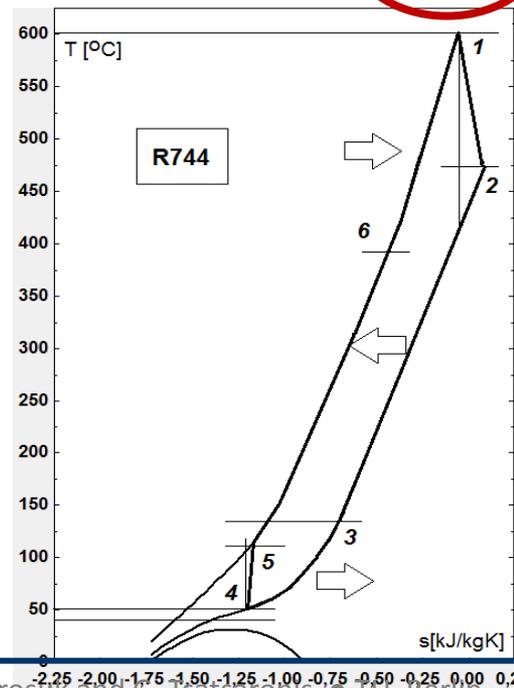
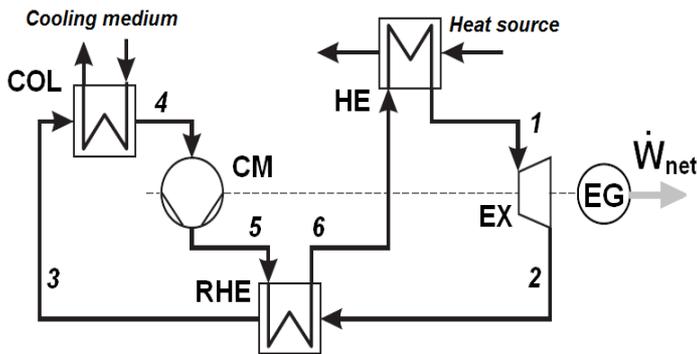
The *exogenous unavoidable* part cannot be reduced because of technological limitations in the other components of the overall system for its given structure.

The *endogenous avoidable* part can be reduced by improving the efficiency of the k -th component.

The *exogenous avoidable* part can be reduced by an improvement in the structure of the overall system, or by improving the efficiency of the remaining system components, and of course by improving the efficiency in the k -th component.

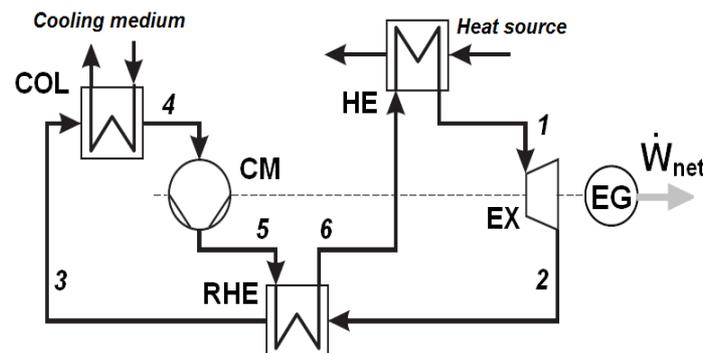
Conventional Exergetic analysis: Results

Component	$\dot{E}_{F,k}$ [kW]	$\dot{E}_{P,k}$ [kW]	$\dot{E}_{D,k}$ [kW]
CM	4,688	4,114	574
COL	2,215	1,249	966
EX	15,377	14,689	688
HE	16,939	16,623	316
RHE	19,036	15,891	3,145
Overall system	16,939	10,000	5,689



Advanced Exergetic analysis: Results

Component	$\dot{E}_{D,k}^{EN}$ [kW]	$\dot{E}_{D,k}^{EX}$ [kW]	$\dot{E}_{D,k}^{UN}$ [kW]	$\dot{E}_{D,k}^{AV}$ [kW]	Splitting $\dot{E}_{D,k}^{real}$ [kW]			
					$\dot{E}_{D,k}^{UN}$		$\dot{E}_{D,k}^{AV}$	
					$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$
CM	324	250	313	261	157	156	167	94
COL	739	257	505	490	386	119	353	137
EX	578	110	330	358	274	56	304	54
HE	258	58	198	118	142	56	116	2
RHE	2,297	148	1,985	1160	1,913	72	1,084	76



Conclusions

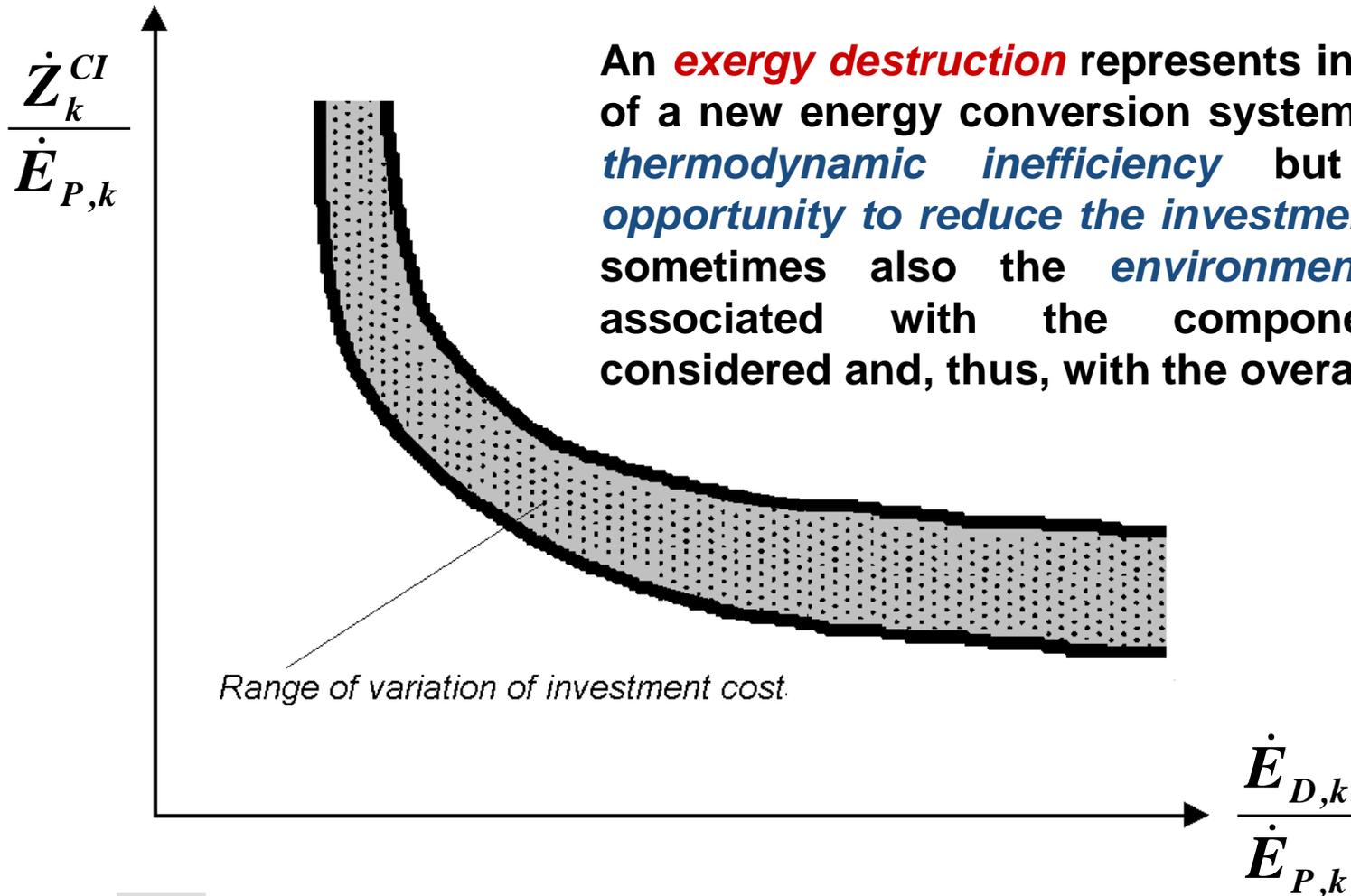
The application of an advanced exergetic analysis to a simple supercritical CO₂ cycle was demonstrated. This system can be improved by improving the components in isolation, because the *avoidable* inefficiencies caused by the components interconnections are relatively low.

The most important component from the thermodynamic viewpoint is the regenerative heat exchanger. System designers should focus on this component.

Future investigations will include the evaluation of more complex configurations and the application of advanced exergoeconomics to identify the configurations and the system parameters that will lead to lower cost of electricity.

Thank you
for your attention

Basic Principle of Exergoeconomics



Graphical Presentation

