INNOVATIVE SOLUTIONS FOR HEAT EXCHANGE AND HEAT RECOVERY IN ADVANCED CYCLES

“A TECHNICAL ANALYSIS OF THE ALLAM CYCLE”

Ph.D IN ENERGY, SYSTEMS, TERRITORY AND CONSTRUCTION ENGINEERING
XXXVII° CYCLE
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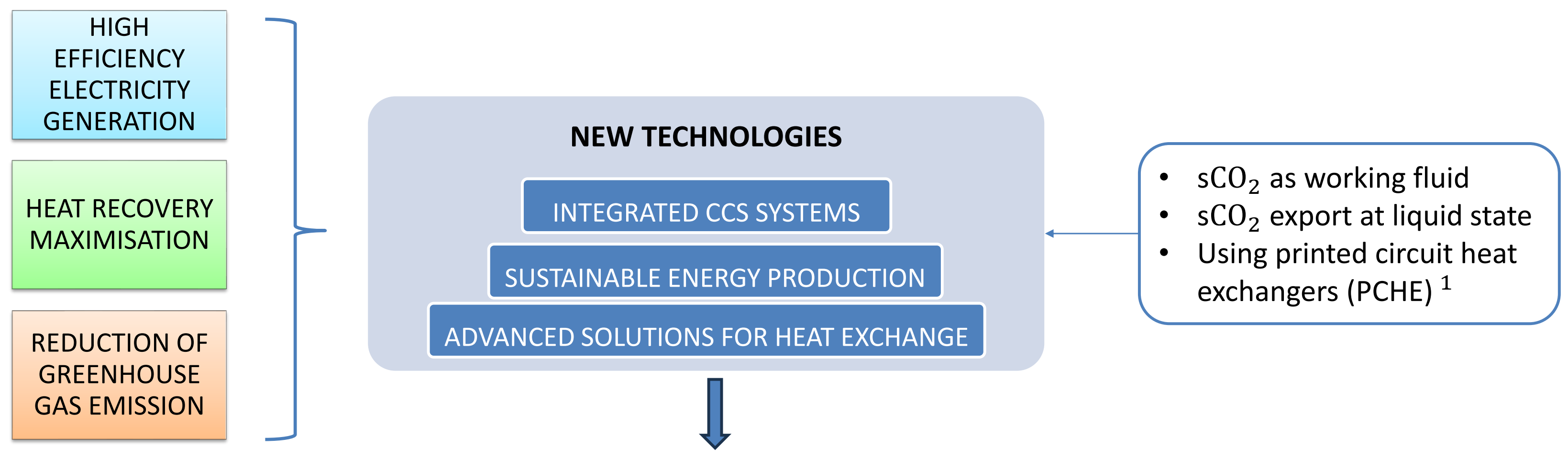
PhD student:
Dago Gnandjuet Gaston Brice

Supervisors:
Desideri Umberto; Ferrari Lorenzo

I) Research Interests and Objectives



HIGH EFFICIENCY ELECTRICITY GENERATION

HEAT RECOVERY MAXIMISATION

REDUCTION OF GREENHOUSE GAS EMISSION

NEW TECHNOLOGIES

INTEGRATED CCS SYSTEMS

SUSTAINABLE ENERGY PRODUCTION

ADVANCED SOLUTIONS FOR HEAT EXCHANGE

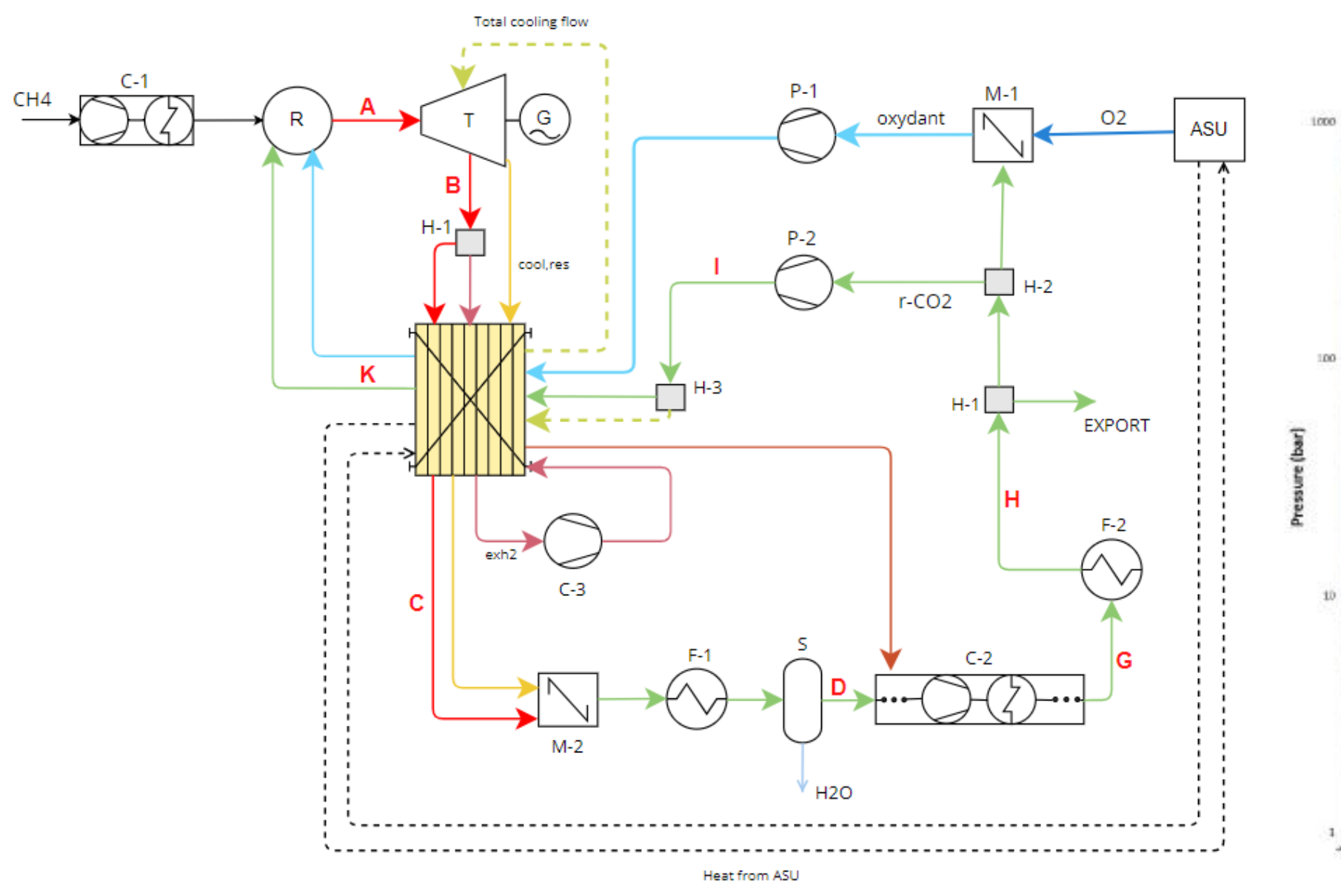
- sCO_2 as working fluid
- sCO_2 export at liquid state
- Using printed circuit heat exchangers (PCHE) [1]

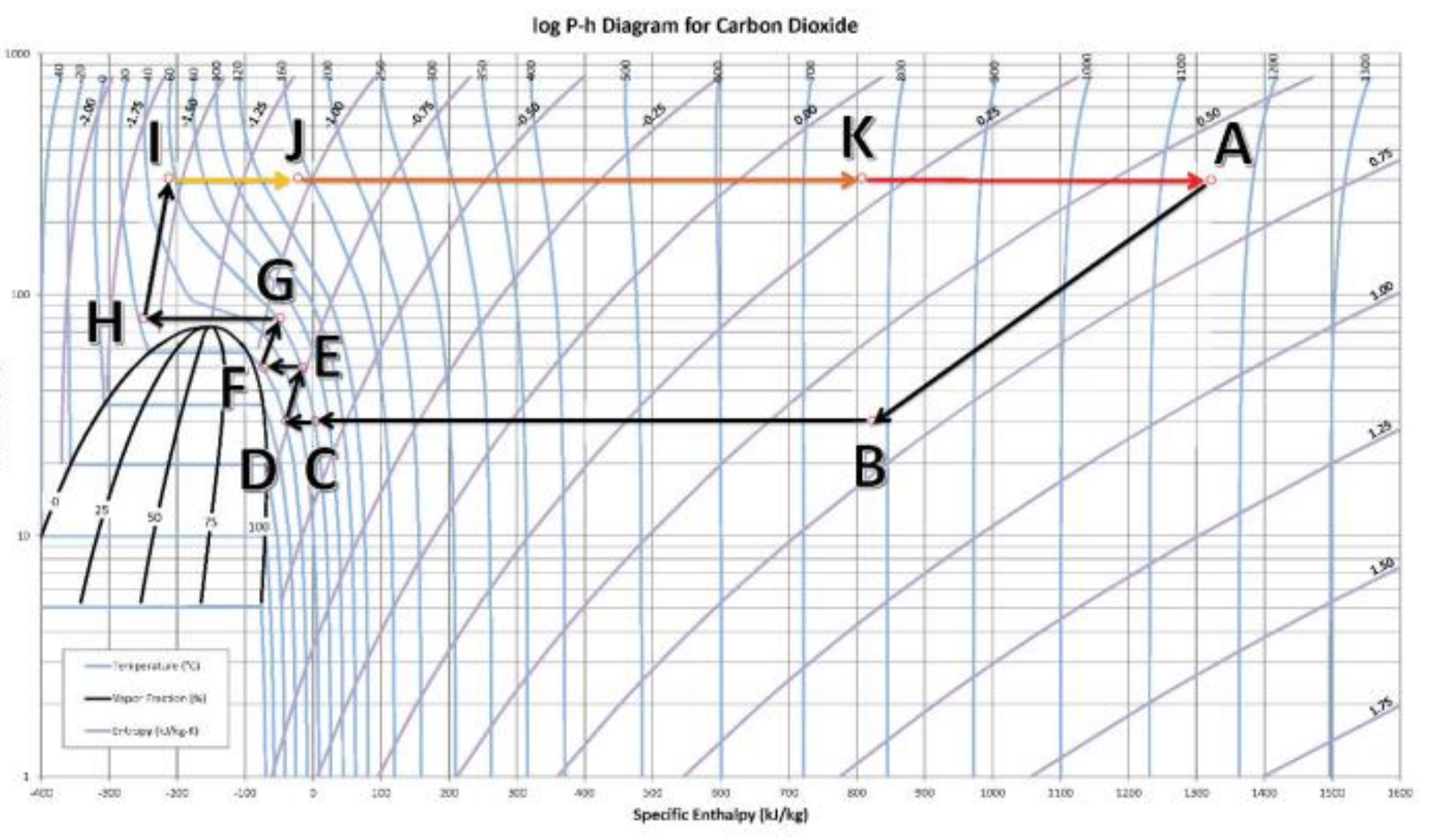
ALLAM CYCLE

Research activities focus on metodology for ALLAM cycle critical iusses finding and technicques for cycle efficency improvement

II) Introduction

ALLAM is a novel **oxy-combustion cycle** that employs high-pressure supercritical CO_2 as working fluid to reduce emissions and allow the CO_2 capture. Pure methane is considered as fuel.



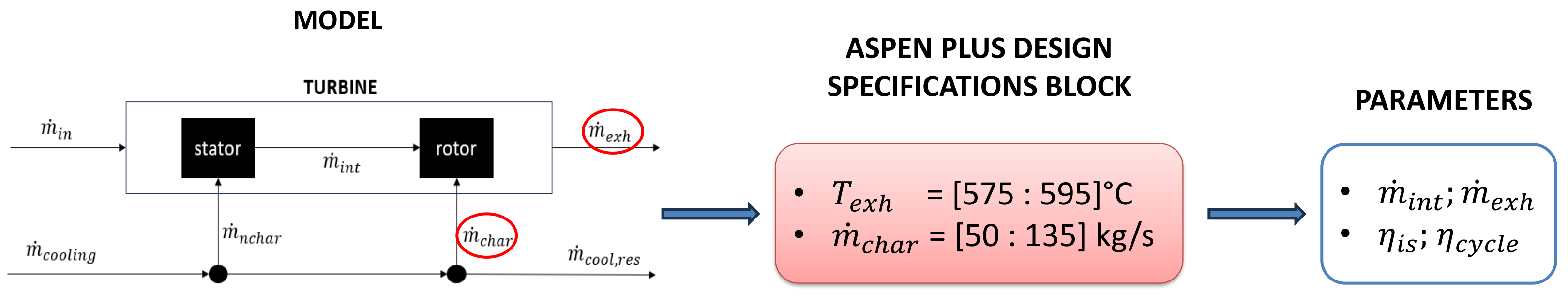


Cycle complexity and critical issues have been addressed by means of the following studies :

- Preliminary sensitivity analysis of the turbine cooling flows and outlet temperature is needed to pinpoint how the system reacts to their variation. Both analyses have been performed for a fixed turbine inlet temperature due to restriction on material maximum allowable stress;
- A recuperator design to determine the dimensions that allow the best trade-off between the maximum recoverable heat and the cycle efficiency;
- An exergy analysis to identify the sources of the cycle’s thermodynamic inefficiencies at the component level.

III) Methods and Materials

☐ PART 1: SENSITIVITY ANALYSIS



ASPEN PLUS DESIGN SPECIFICATIONS BLOCK

- T_{exh} = [575 : 595]°C
- $\dot m_{char}$ = [50 : 135] kg/s

PARAMETERS

- $\dot m_{int}$; $\dot m_{exh}$
- η_{is}; η_{cycle}

☐ PART 2: RECUPERATOR DESIGN

The recuperator design has been computed considering two turbine inlet temperature

VARIABLES

T_{fire} 925 °C 1025 °C

$T_{oxy,out}$ [560 : 600] °C

$T_{CO_2,out}$ [530 : 600] °C

ASPEN PLUS DESIGN SPECIFICATIONS BLOCK

UA
[15 : 75]· 10^3 kW/K

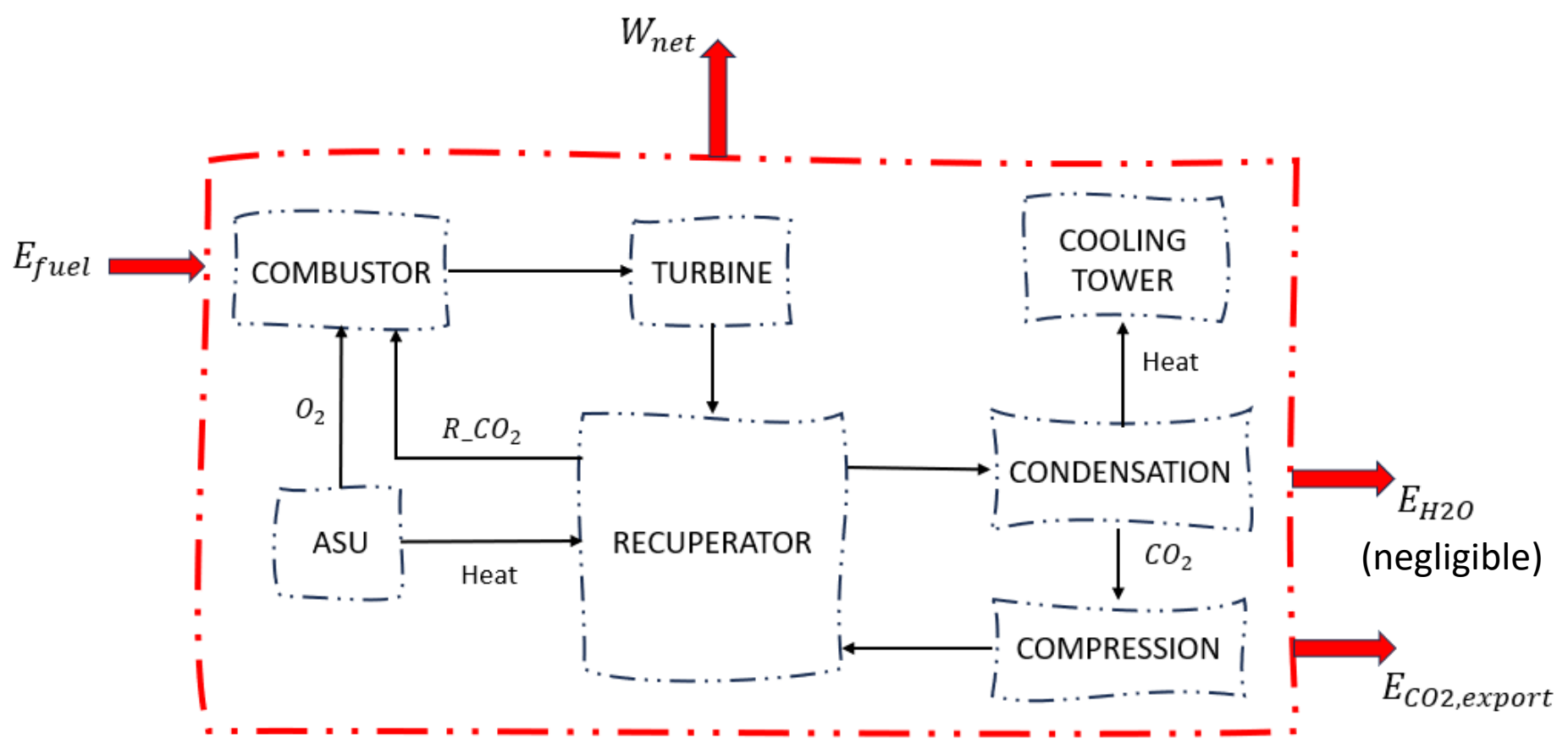
PARAMETERS

- NTU
- η_{cycle}

☐ PART3: EXERGY ANALYSIS

Exergy analysis was performed for the two temperature cases studied in the second part, with their corresponding optimal recuperator dimensions.

Control region



COMPONENT	E_D	ε
TURBINE	$(E_i$-$E_e)$-W_t	$W_t/(E_{in}$-$E_{out})$
COMPRESSOR/ PUMP	$W_{c/p}$-$(E_e$–$E_i)$	$(E_{out}$-$E_{in})/W_{c/p}$
COMBUSTOR	$(E_i$+$E_{fuel})$-E_e	$E_e/(E_i$+$E_{fuel})$
HEAT EXCHANGER	$\sum E_i$-$\sum E_e$	$\sum E_e/\sum E_i$

- From the first and second law of thermodynamic

$$\dot{E}_x = \sum_j \left(1-\frac{T_0}{T_j}\right)\dot{Q}_j + \dot{W} + \sum_i \dot{m}_i\, e_i - \sum_e \dot{m}_e\, e_e$$

$$\Downarrow$$

$$E_i^{tot} - E_e^{tot} - E_D = E_{S,k} - E_{P,k} - E_D = 0$$

- k-th component exergy efficiency

$$\varepsilon_k = \frac{E_{P,k}}{E_{S,k}}$$

- Overall exergy efficiency

$$\psi = \frac{W_{net} + E_{CO_2,export}}{E_{fuel}}$$

where E_{CO_2} and E_{fuel} are given by their physical and chemical parts

- Chemical exergy

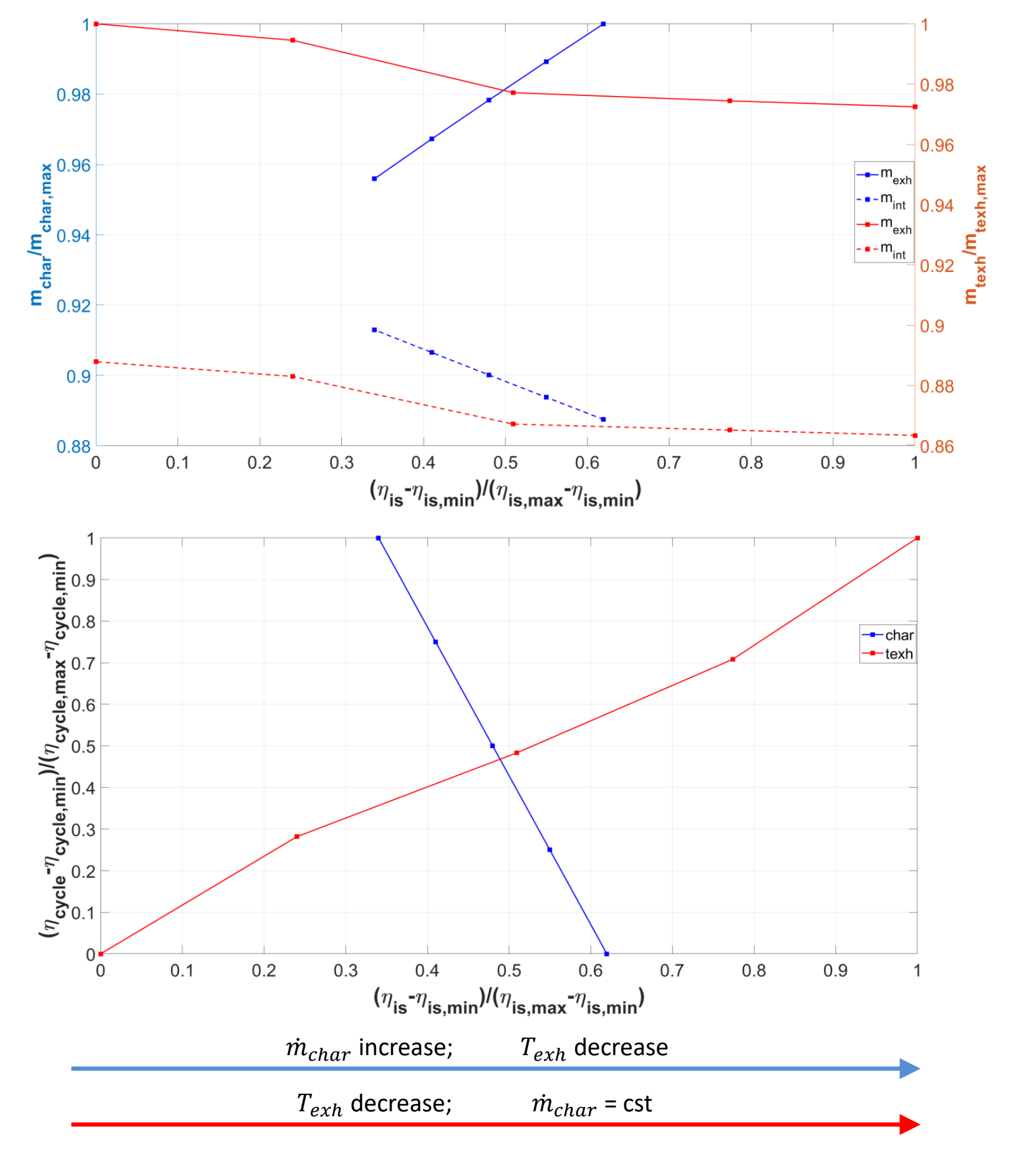
standard chemical exergy[2]

$$E_x^{CH} = \dot{m}\left(\frac{\chi}{MW}\right)\boxed{e_{0,x}^{ch}}$$

i = inlet; e = outlet; D = destroyed; S = supplied; P = producted

IV) Results and Discussions

✓ Sensitivity results



Results demonstrate that:

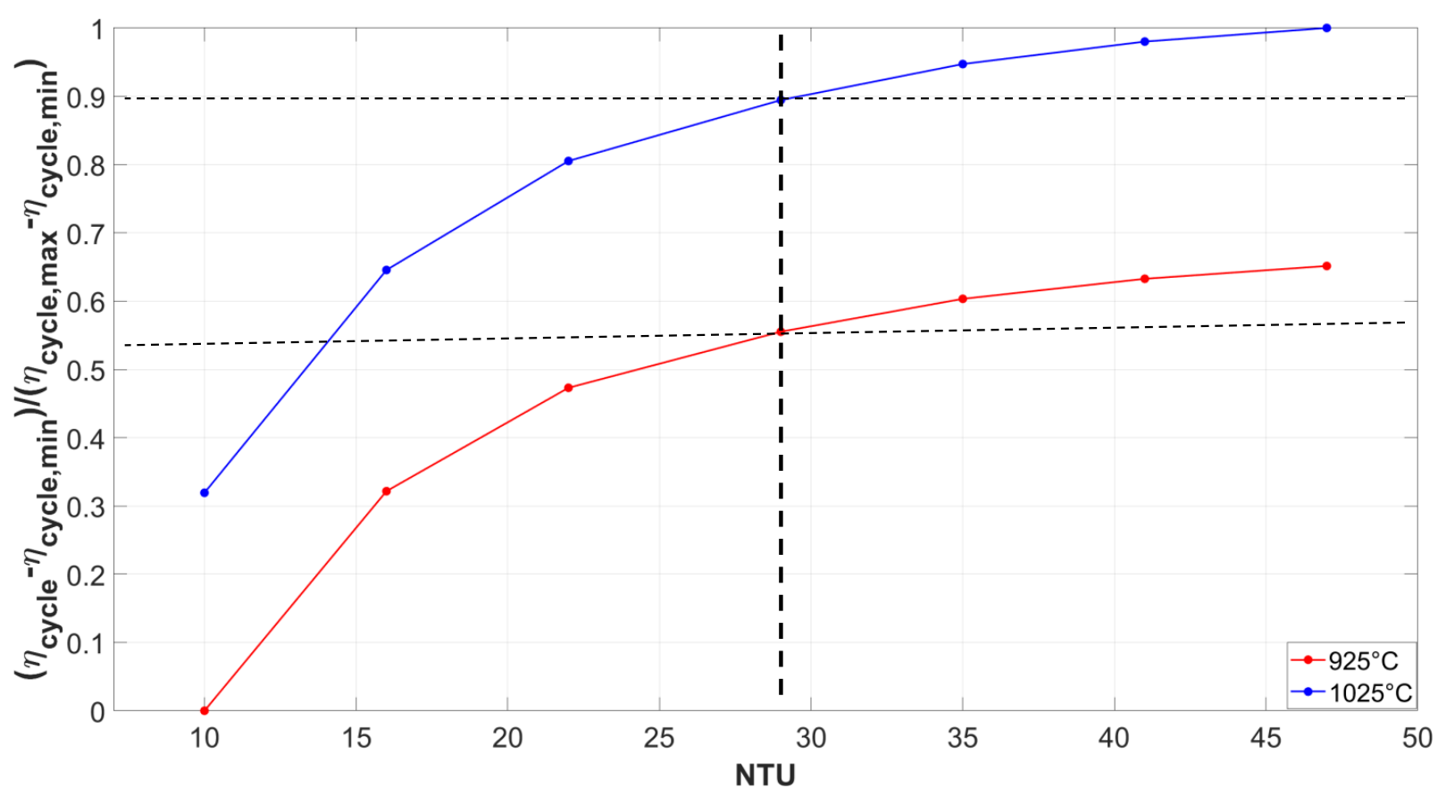
Chargeable cooling Flow Sensitivity

- Turbine cooling flow ($\dot m_{char}$) and turbine exit temperature (T_{exh}) are inversely proportional;
- $\dot m_{char}$ increase causes a turbine isentropic efficiency to increase while the cycle efficiency decreases;
- The cycle efficiency decrases due to the **lower delivered power** caused by the lower flow rate ($\dot m_{int}$) recirculated into the system given constant turbine inlet temperature and fuel flow rate.

Turbine Exhaust Temperature Sensitivity

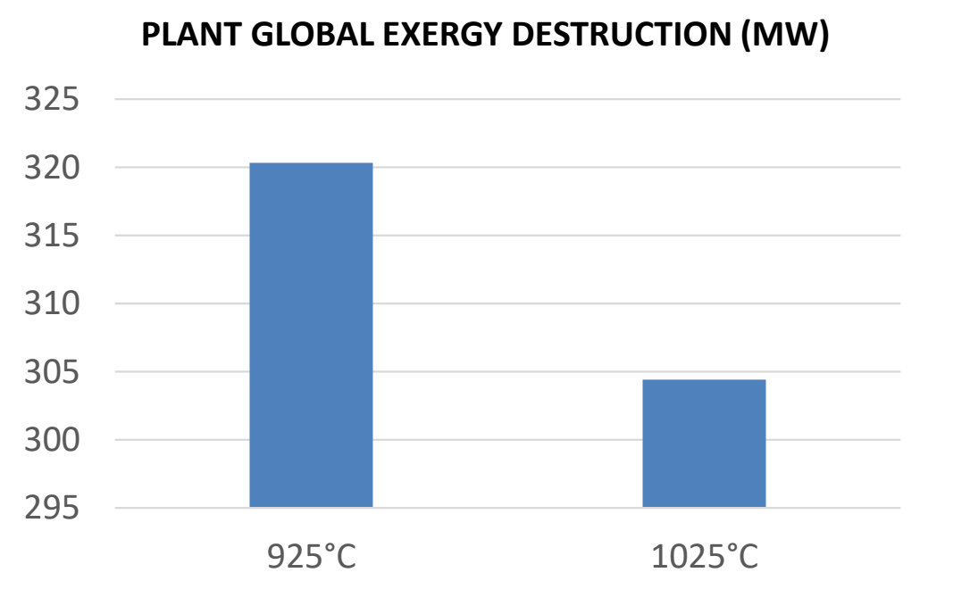
- Similar effect on the recirculated mass flow rate ($\dot m_{int}$) to that obtained in the first part is observed;
- Contrary to the chargeable cooling flow sensitivity, Low T_{exh} values corrispond to high cycle efficiency values ;
- The difference is due to the fact that T_{exh} decrement is generated by a larger turbine isentropic efficiency than that obtained with the $\dot m_{char}$ variation.

✓ HE design results

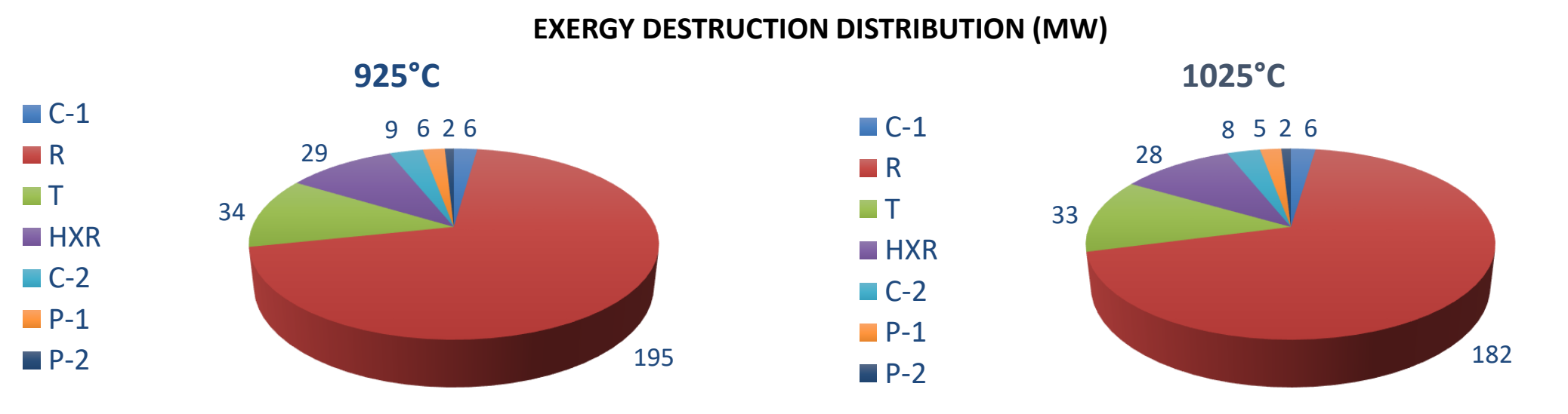


- Cycle efficiency trend is the same for both cases;
- As expected, the higher the turbine inlet temperature, the higher the cycle efficiency;
- A recuperator with **NTU = 27** is set to be the best trade-off between the global cycle efficiency and the recuperator dimensions (costs).

✓ Exergy Results



	925°C	1025°C
COMPONENT	ε (%)	
C-1	0.52	0.52
R	0.88	0.89
T	0.93	0.93
HXR	0.96	0.97
C-2	0.73	0.73
P-1	0.73	0.73
P-2	0.80	0.80
OVERALL	**0.44**	**0.47**



- Graphs show that the lower the turbine inlet temperature, the higher the global exergy destruction;
- According to the exergy destruction distribution, the **combustor is the main source of irreversibilities of the system**, within which more than **30%** of the supplied exergy is destroyed;
- **Turbine and recuperator rank second and third**, respectively, in terms of exergy destruction, even though their exergy efficiencies are relatively high.

V) Findings

- ✓ Cooling flow usage improves the turbine performance but needs to be moderated to avoid negative effects on the overall cycle efficiency;
- ✓ Large recuperator dimensions are required to enhance the maximum power elaborated by the cycle;
- ✓ Aside from the combustor, the turbine and recuperator are the main sources of the Allam cycle inefficiencies.

VI) Plan Continuation

The topic deserves further study:

- ✓ Different Allam cycle layout evaluation for reducing key components losses;
- ✓ A rigorous recuperator design: either hydraulic or mechanical.

Contacts

Dago Gnandjuet Gaston Brice
DESTeC, University of Pisa, L.go Lucio Lazzarino 1, 56122, PI
gnandjuet.dago@phd.unipi.it
+39 3512010945

References

1. D. Shiferaw, J. M. Carrero, and R. Le Pierres, “Economic analysis of SCO2 cycles with PCHE recuperator design optimisation,” *5th Int. Symp. - Supercrit. CO2 Power Cycles*, pp. 1–13, 2016.

2. T. J. Kotas, *The exergy method of thermal plant analysis*, vol. 16, no. 1. 1988.

3. R. Allam *et al.*, “Demonstration of the Allam Cycle: An Update on the Development Status of a High Efficiency Supercritical Carbon Dioxide Power Process Employing Full Carbon Capture,” *Energy Procedia*, vol. 114, no. November 2016, pp. 5948–5966, 2017, doi:

4. M. Penkuhn and G. Tsatsaronis, “Exergy Analysis of the Allam Cycle,” *5th Int. Symp. - Supercrit. CO2 Power Cycles*, pp. 1–18, 2016.