TECHNISCHE UNIVERSITÄT DRESDEN

DRESDEN concept

The 4th European SCO_2 Conference for Energy Systems

TECHNO-ECONOMIC OPTIMIZATION METHOD AND ITS APPLICATION TO A SCO_2 GAS TURBINE BOTTOMING CYCLE

Dr. Thiago Gotelip[1], Prof. Dr.-Ing Uwe Gampe[1], Dr. Stephan Glos[2]

1 – Technical University Dresden, Chair of Thermal Power Machinery and Plants
2 – Siemens Energy AG, Mülheim, Germany

Agenda

1. Introduction
2. Optimization Structure
3. Cycle Architectures Comparison
4. Results
5. Conclusion

Introduction

The CARBOSOLA project is intended to represent the entry into SCO_2 technology development in Germany. For this reason, the project will first compare **SCO_2 technology with conventional technologies** in the areas of **waste heat recovery** (downstream processes for gas turbine plants) and solar thermal power plant technology (CSP) and subject them to a **technical and economic evaluation**.

For the entry into SCO_2 technology development for the target applications of a gas turbine process with SCO_2 downstream process (SCO_2-CC):

- Perform a technical and economic multi-objective optimization of the system architectures and the components for the considered applications based on process simulations.
- Determine the optimal SCO_2-CC configuration for the SCO_2 downstream process
- Determine the technology's application potential.

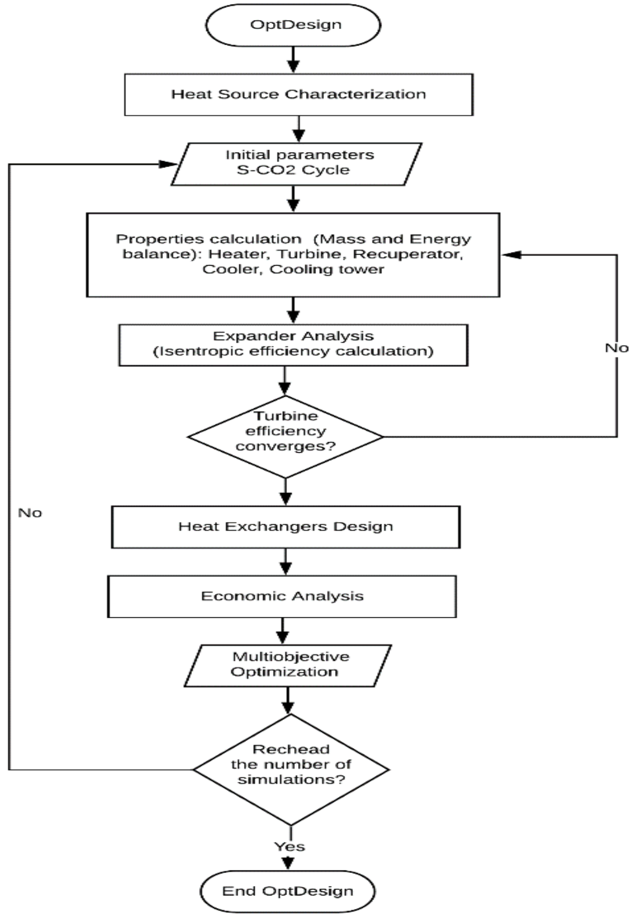
2-Optimization Structure

Optimization Tool

Computational tool developed to evaluate and investigate different configurations of CO_2 cycles.

The thermo-physical model is compiled in MATLAB® script.

Thermodynamic properties are determined from REFPROP® library.



Flow chart of OptDesign optimization program

Optimization Tool

Heat Source Characterization

- 2 aeroderivative gas turbines SGT-A65 (former Trent 60) + SCO_2 bottoming cycle

- SGT-A65 data:
  power output: 59 MW
  mass flow rate: 169 kg/s
  exhaust temperature: 432°C
  exhaust pressure: 1.040 bar
- Composition:
  - N2 72.0 %
  - O2 15.1 %
  - CO2 4.8 %
  - H2O 6.8 %
  - AR 1.2 %

- Boundary conditions of analysis:
  Ambient pressure 1.013 bar / Temperature: 15°C

Siemens

Optimization Tool
Input parameters

The discrete variables are the input data to the optimization program that will define all the cycles' operation properties.

	Discrete variable	Range	
Pressure Level [bar]	Pressure (HP)	200 – 300	
	Pressure (LP_{Sub})	57.2 - 65.8*	
	Pressure (LP_{Sup})	75 - 110	
Heater HX1	UTTD	> 10	$UTTD = T_{21} - T_{12}$
	Effectiveness	< 0.98	$\varepsilon_{Hx_1} = \frac{T_{21}-T_{22}}{T_{21}-T_{12}}$
Recup. HTR	UTTD	> 5	$UTTD = T_2 - T_{17}$
	Effectiveness	< 0.98	$\varepsilon_{Hx_1} = \frac{T_2 - T_3}{T_2 - T_{17}}$

Stack minimum temperature: 75°C

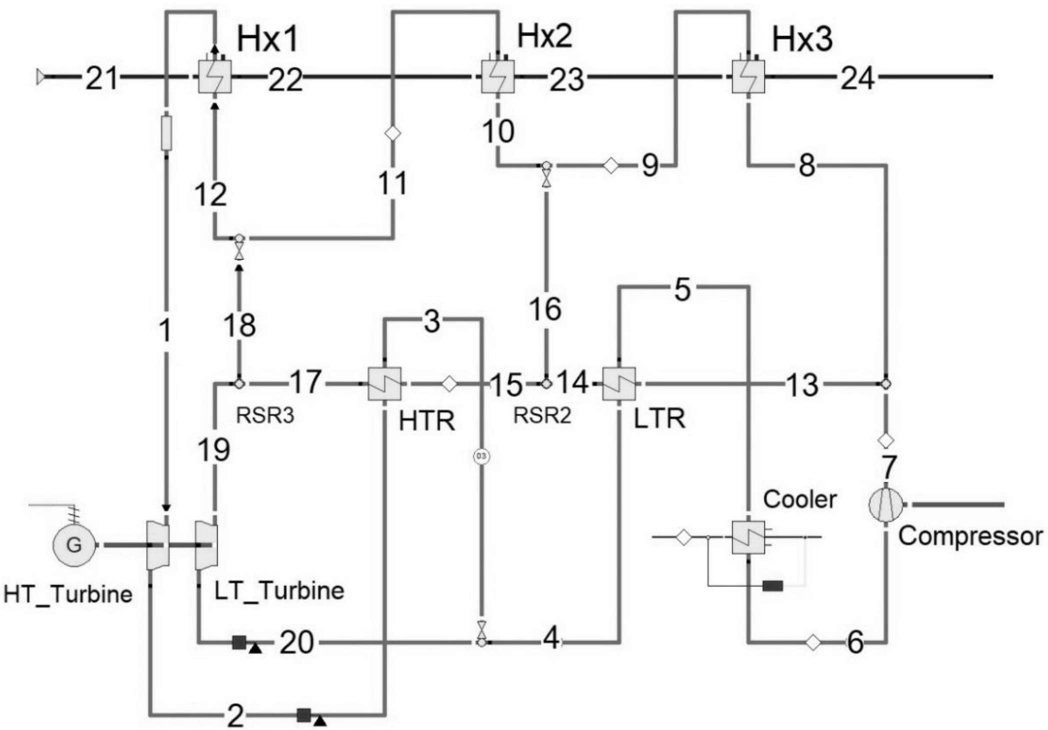


Figure: Representation of the Dual Rail architecture (3H2R).

Optimization Tool
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	Discrete variable	Range	
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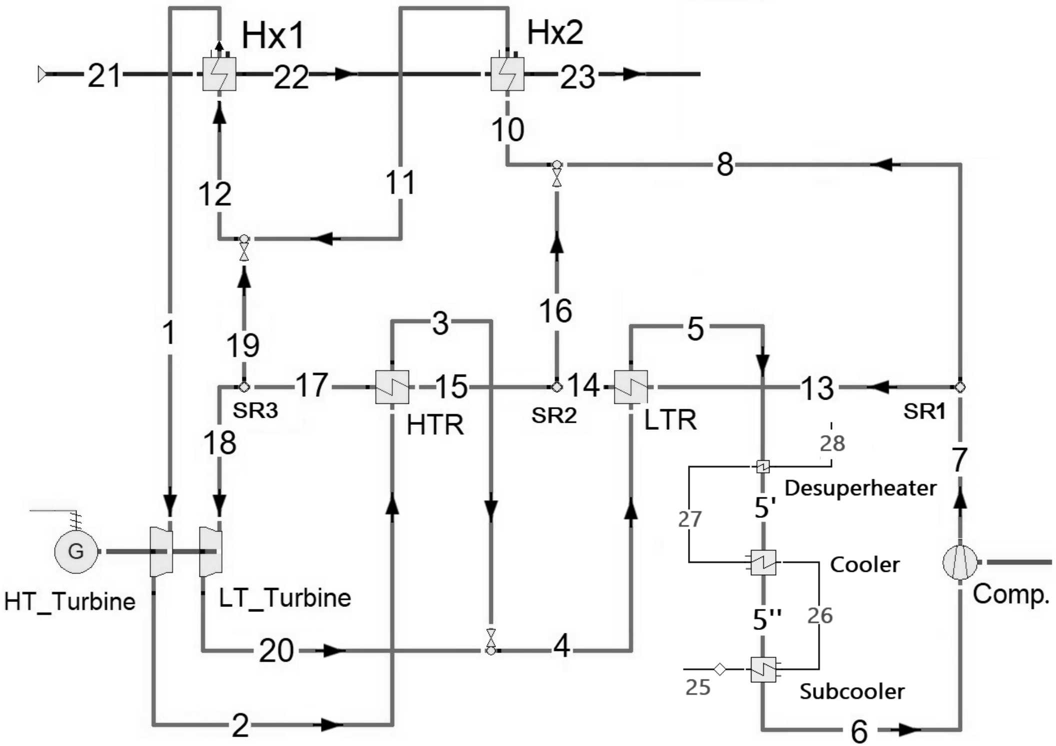

Figure: Representation of the Cascade architecture (2H2R).

Optimization Tool
Input parameters

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	Discrete variable	Range	
Pressure Level [bar]	Pressure (HP)	200 – 300	
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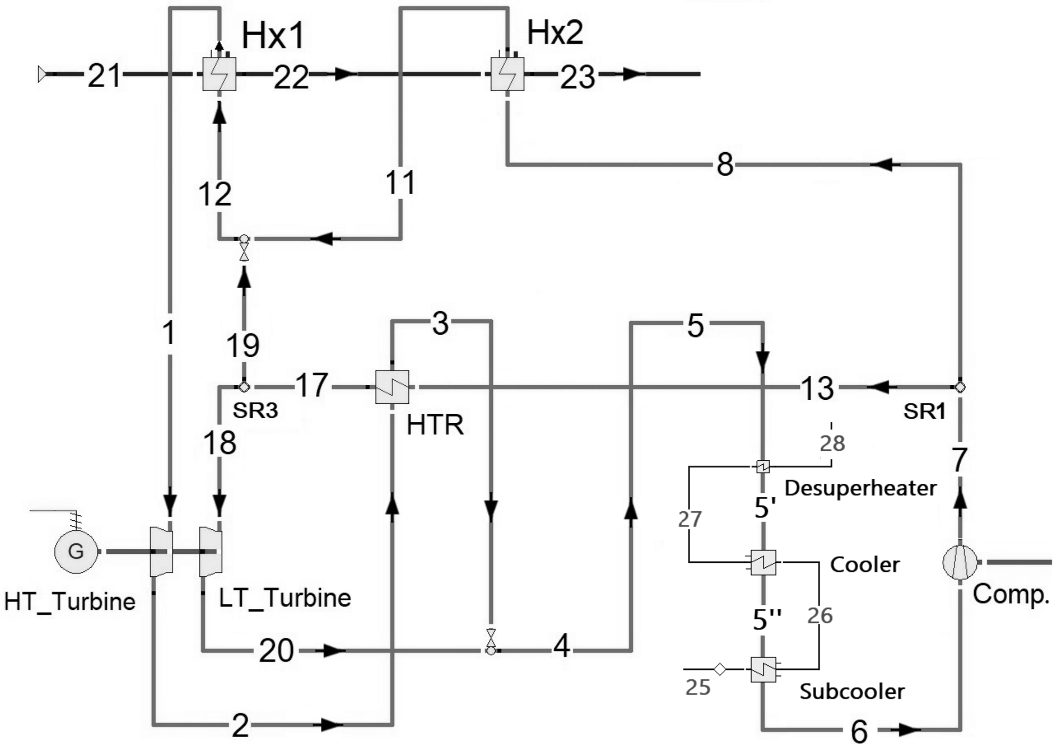

Figure: Representation of the 2H1R architecture.

Optimization Tool
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Pressure Level [bar]	Pressure (HP)	200 – 300	
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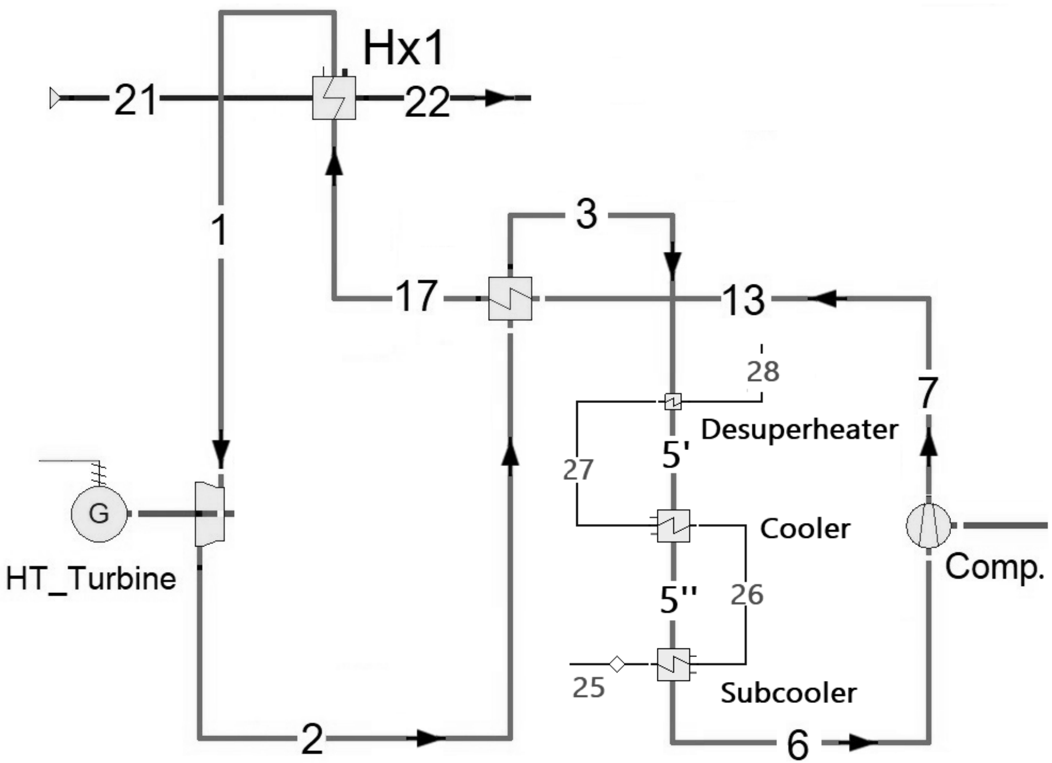

Figure: Representation of the Regenerative architecture.

Optimization Tool
Input parameters

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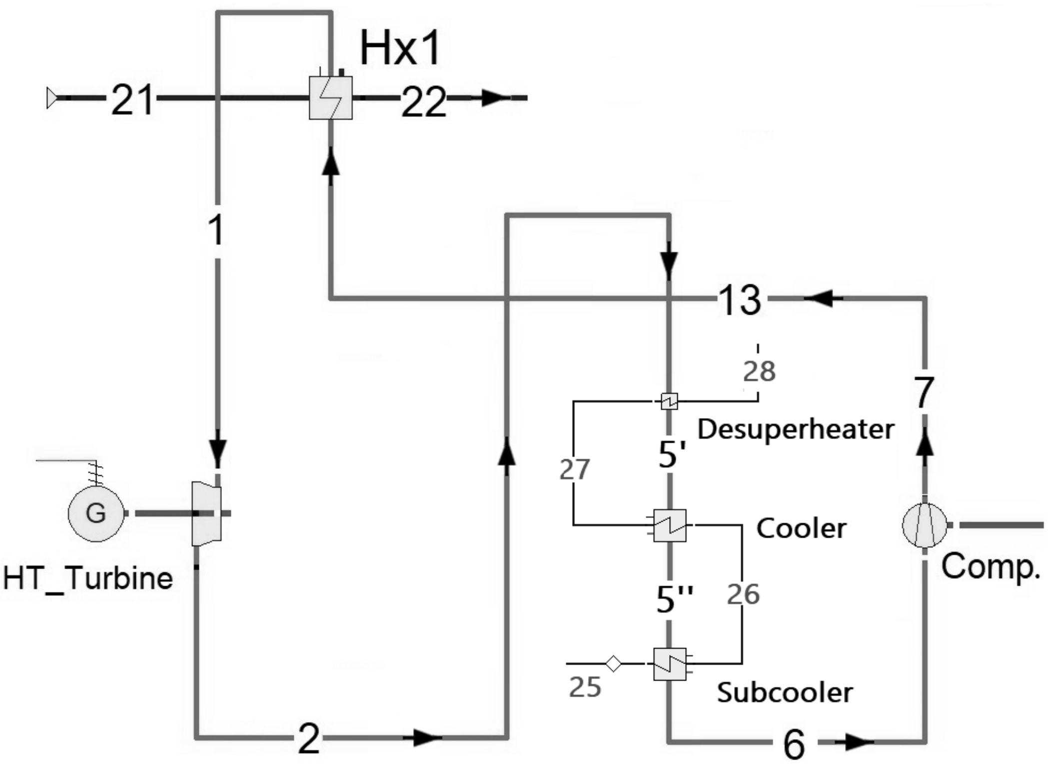

Figure: Representation of the Simple architecture.

Optimization Tool

With the initial parameters, the thermo-physical model will **perform the property calculations.**

For a starting point, the **isentropic efficiency** of the turbine is considered to be **90%** and the compressor is **80%**.

The turbine's efficiency is updated in the calculations iteration and is correlated with the volume flow in the equipment.

The optimization tool has subroutines with basic design models of the heat exchangers and the expander.

These tools can be updated with the project requirements for new cycle optimizations.

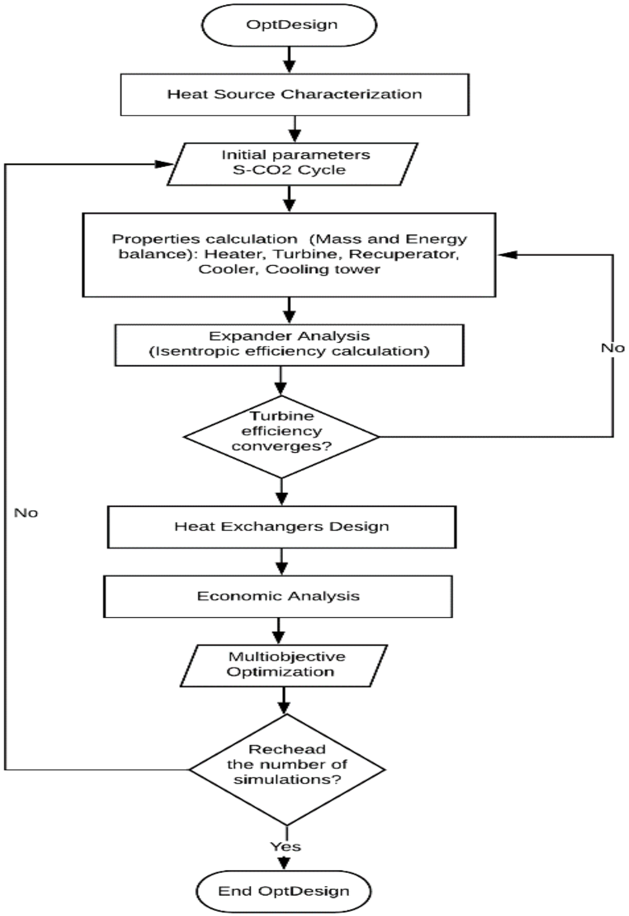

Figure: Flow chart of OptDesign optimization program

Variable Property Segmented Method

The variation of the CO_2 properties close to the critical point is a determining factor for the heat exchangers' design.

The optimization tool adopts the **variable property segmented calculation method** (VPSC) for calculating CO_2 properties in each heat exchanger.

VPSC is more suitable for **non-constant thermal capacities** process streams.

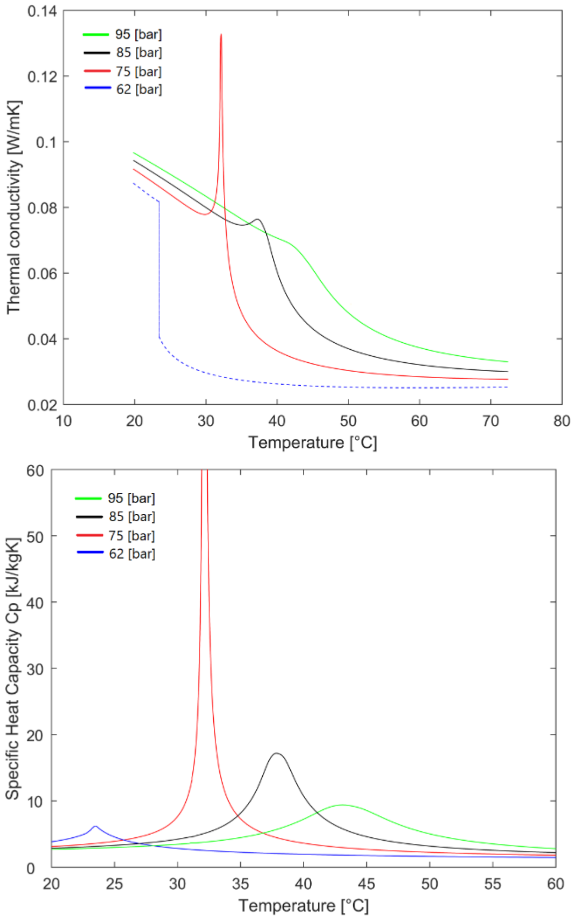

Figure: CO_2 properties near the critical point. (Elaborated with Refprop® data).

Variable Property Segmented Method

The VPSC method for property calculations consists of **dividing the heat exchangers** into several small blocks along the length.

This methodology determines the working fluid's physical properties according to each block's inlet and outlet pressures, and the temperature is calculated by the **LTMD method at each block**.

$$U \cdot A = \sum_{i=1}^{n} \left(\frac{\dot{Q}_i}{LM\dot{T}D_i} \right)$$

$$LMTD = \left[\frac{(\Delta T_{hot} - \Delta T_{cold})}{ln(\Delta T_{hot} / \Delta T_{cold})} \right]$$

i= number of segments for the heat exchanger.

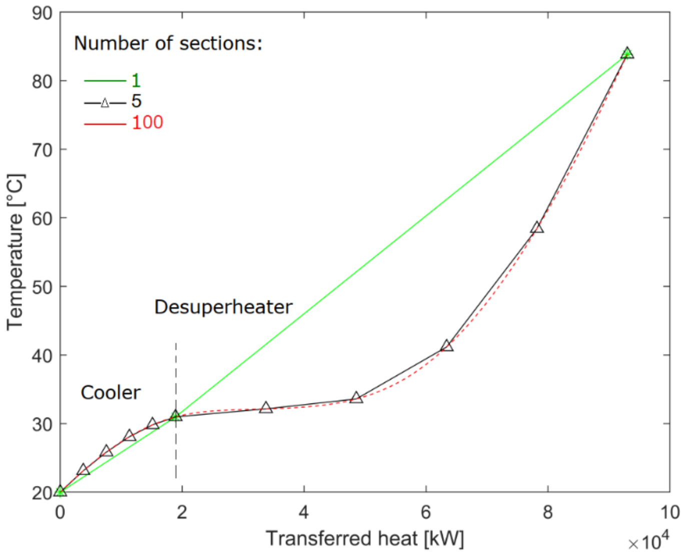

Figure: CO_2 properties calculated with VPSM. (Elaborated with Refprop® data).

		1 Section	5 Sections	Rel. Error
UA Hx1	[kW/K]	2201	2043	7.18%
UA Hx2	[kW/K]	1346	1192	11.49%
UA Hx3	[kW/K]	3.39	3	0.01%
UA HTR	[kW/K]	1866	1720	7.78%
UA LTR	[kW/K]	90	90	0.05%
UA Desuper.	[kW/K]	2266	3664	61.65%
UA Cooler	[kW/K]	2116	1918	9.35%
UA Cooler Total	[kW/K]	4382	5582	27.37%

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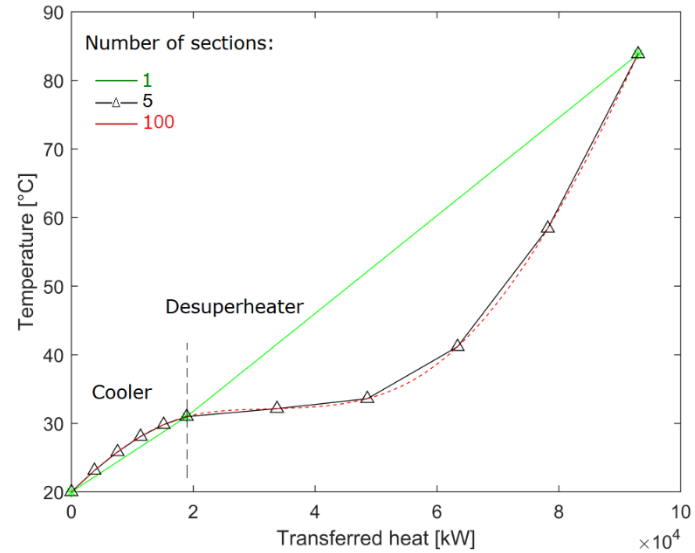

CO_2 properties in the cooler.
(Elaborated with Refprop® data).

		5 Section	100 Sections	Rel. Error
UA Hx1	[kW/K]	2043	2033	0.49%
UA Hx2	[kW/K]	1191	1185	0.49%
UA Hx3	[kW/K]	3	3	0.00%
UA HTR	[kW/K]	1720	1717	0.21%
UA LTR	[kW/K]	90	90	0.00%
UA Desuper.	[kW/K]	3664	3719	1.50%
UA Cooler	[kW/K]	1918	1910	0.40%
UA Cooler Total	[kW/K]	5582	5629	0.85%

Economic Evaluation

- General equation for equipment cost:

$$C = aSP^{b} \times f_{T}$$

- Net Present Value:

$$NPV = \sum_{n=1}^{n=20} \frac{Revenue - (Capex - Opex)}{(1 + interest\ rate)^{n}}$$

- Levelized Cost of Electricity:

$$LCOE = \frac{CAPEX \times f_{a} + OPEX}{P_{e} \times Hour_{year}}$$

$f_{a} = Capital\ recovery\ factor$

$P_{e} = electrical\ power\ output\ of\ the\ power\ plant$

Table: Summary of the scaling parameters for cost correlation. Weiland (2019).

Equipment	a	SP		b
Heater	49.45	UA_{Heater}	$[W_t/K]$	0.7544
Recuperator	49.45	UA_{Recu}	$[W_t/K]$	0.7544
Cooler	32.88	UA_{Cooler}	$[W_t/K]$	0.75
Axial Turbine	182600	P_{mec}	$[MW_t]$	0.5561
Generator	108900	P_e	$[MW_e]$	0.5463
Gearbox	177200	P_{mec}	$[MW_t]$	0.2434
Compressor (centrifugal)	1230000	P_{shaft}	$[MW_t]$	0.3992
Motor	399400	P_e	$[MW_e]$	0.6062

Table: Total investment decomposition Canepa (2014).

Fixed capital investment (FCI)	Direct costs (DC)	Onsite costs	Purchased Equipment Costs (PEC)	Calculated
			Others	%PEC
		Offsite costs	Civil work	%PEC
			Service	%PEC
	Indirect costs (IC)	Engineering		%DC
		Construction Costs		%DC
		Contingency		%

3- Cycle Architectures Comparison

Cycle Architectures Comparison

Simple cycle: Since the temperature at the evaporator's inlet is reduced, the amount of CO_2 mass flow is limited.

It limits the amount of power produced.

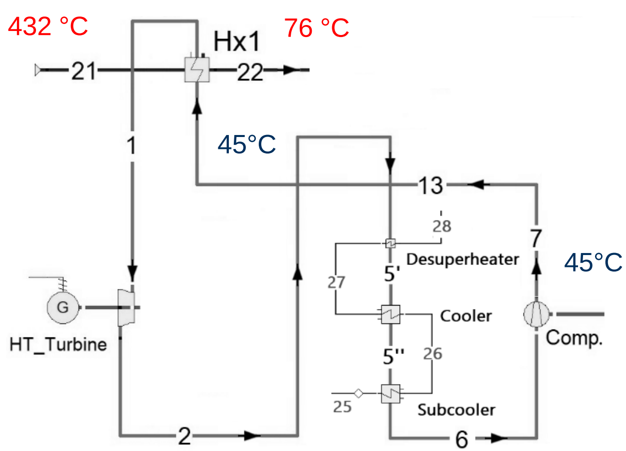

Figure: Representation of the Simple architecture.

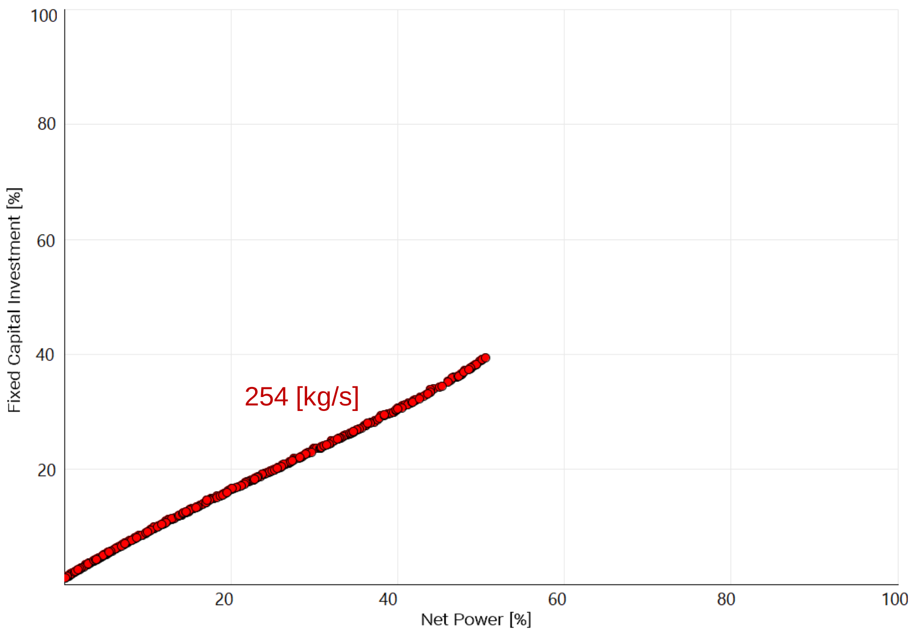

Figure: Cycle architectures optmization (↑ Net Power and ↓ Cost)

Cycle Architectures Comparison

Regenerative: The use of the recuperator increases the potential for heat recovery from the source.

The temperature difference in the evaporator limits cycle mass flow.

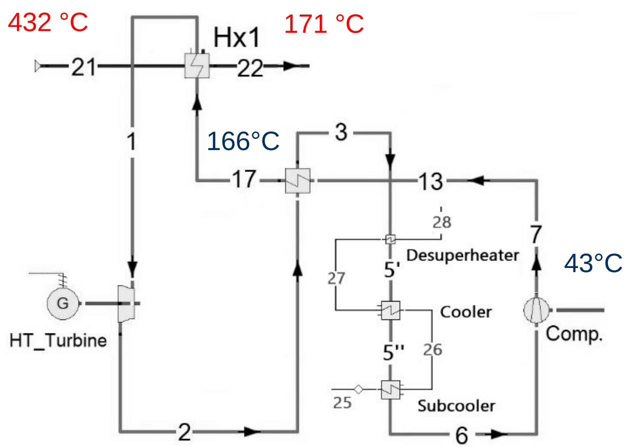

Figure: Representation of the Regenerative architecture.

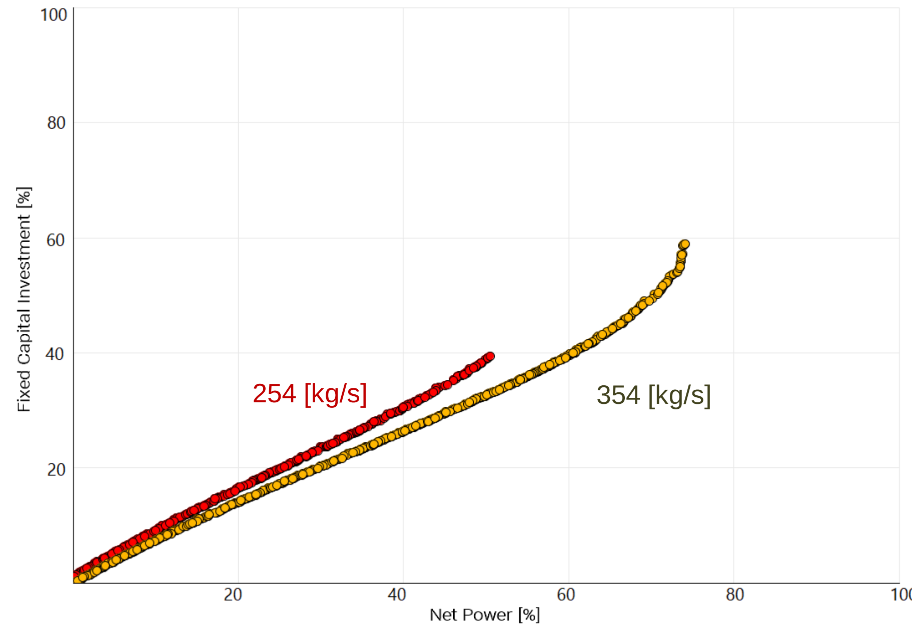

Figure: Cycle architectures optmization (↑ Net Power and ↓ Cost)

Cycle Architectures Comparison

2H1R: The use of a secondary heater allows a more significant amount of heat recovered from the exhaust gases after the main heater.

It increases the power generation of the cycle.

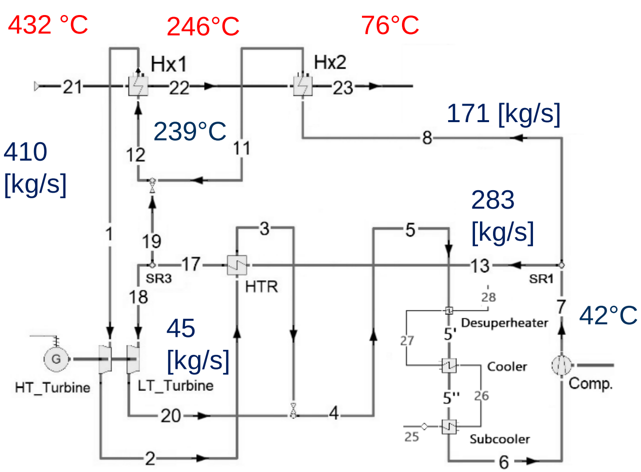

Figure: Representation of the 2H1R architecture.

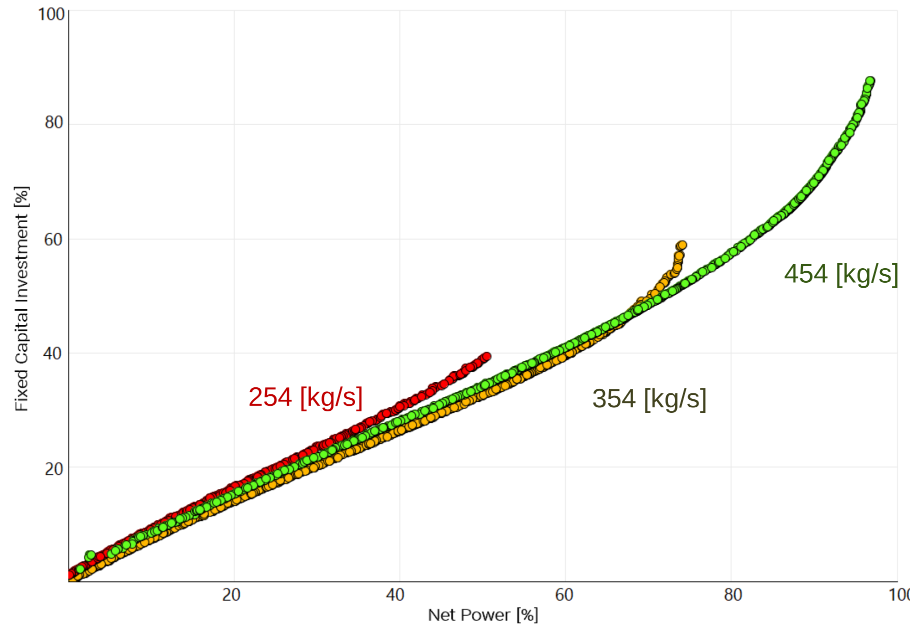

Figure: Cycle architectures optmization (↑ Net Power and ↓ Cost)

Cycle Architectures Comparison

2H2R: Addition of a low-temperature recuperator (LTR)

- More significant heat recovery from the source provides more efficient cycles and higher power generation.
- Economically penalized by the significant increase in equipment costs, not favoring NPV

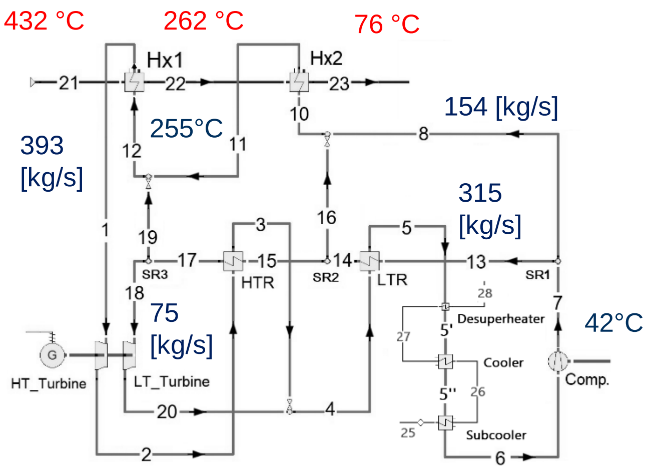

Figure: Representation of the 2H2R architecture.

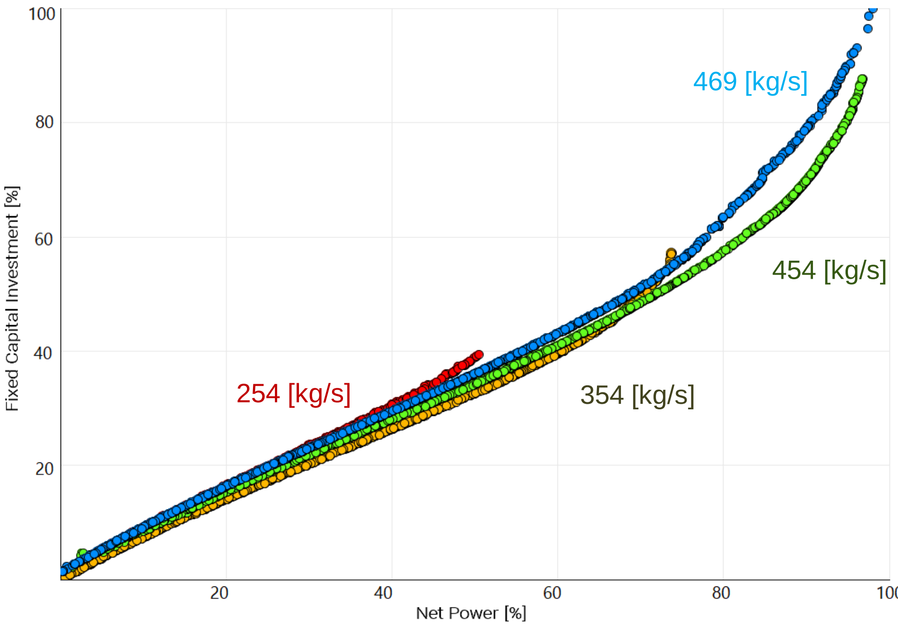

Figure: Cycle architectures optmization (↑ Net Power and ↓ Cost)

Cycle Architectures Comparison

3H2R : Addition of a third heater.

- More significant heat recovery from the source provides more efficient cycles and higher power generation.
- Economically penalized by the significant increase in equipment costs, not favoring NPV

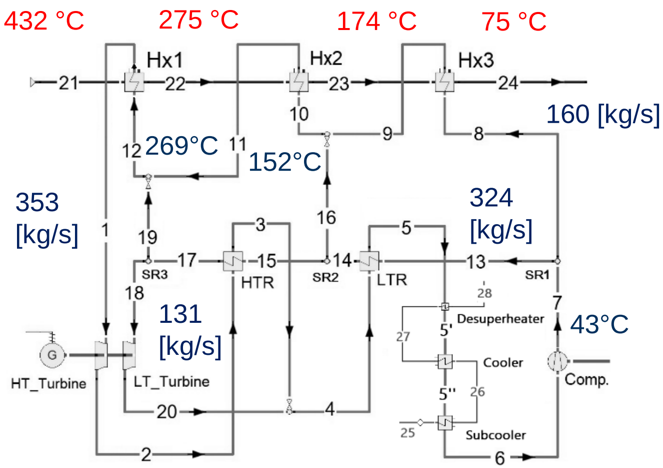

Figure: Representation of the 3H2R architecture.

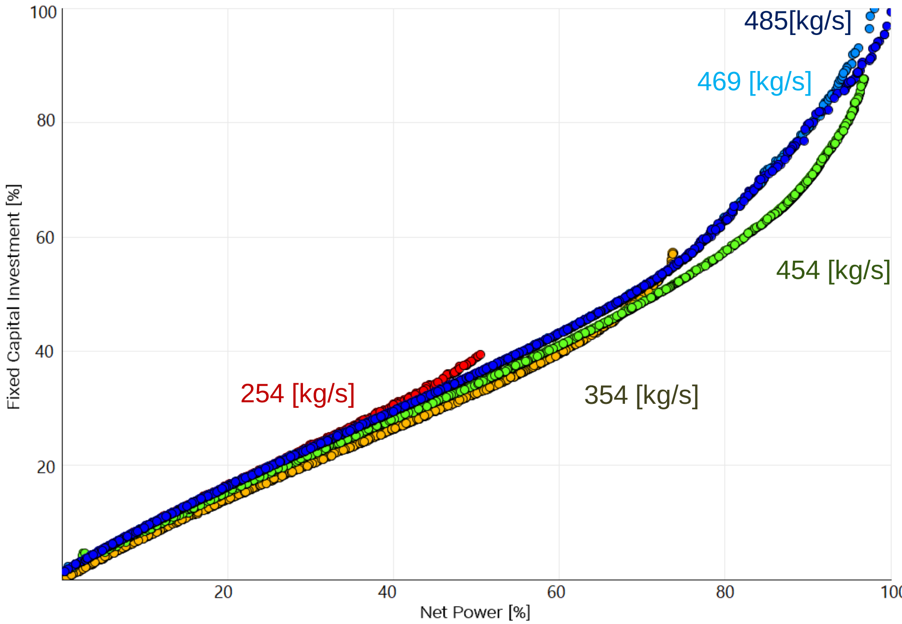

Figure: Cycle architectures optmization (↑ Net Power and ↓ Cost)

4- Results

Objective Function

Multi-objective means finding the **best operation conditions** considering predefined criteria from a set of feasible solutions**.**

Different multiobjective optimization scenarios were investigated, having as objective functions:

1) Maximization of **Net Power** and minimization of **Total Cost**.

2) Maximization of the **Net Present Value** and minimization of **Total Cost**.

3) Maximization of **Net Present Value** and minimization of the **Levelized Cost of Energy** (LCOE).

Objective Function: Net Power and Costs

The optimal results frontier represents different operating conditions that provide the lowest costs for the power generation range.

Each of the results that represent the optimal results frontier represents a specific operating condition of the cycle.

Each result brings with it the operating conditions of each equipment and the performance of the cycle.
The solutions present the direct relationship between net power and costs.

The range of **higher net power** comes with a more expressive **increase in costs**.

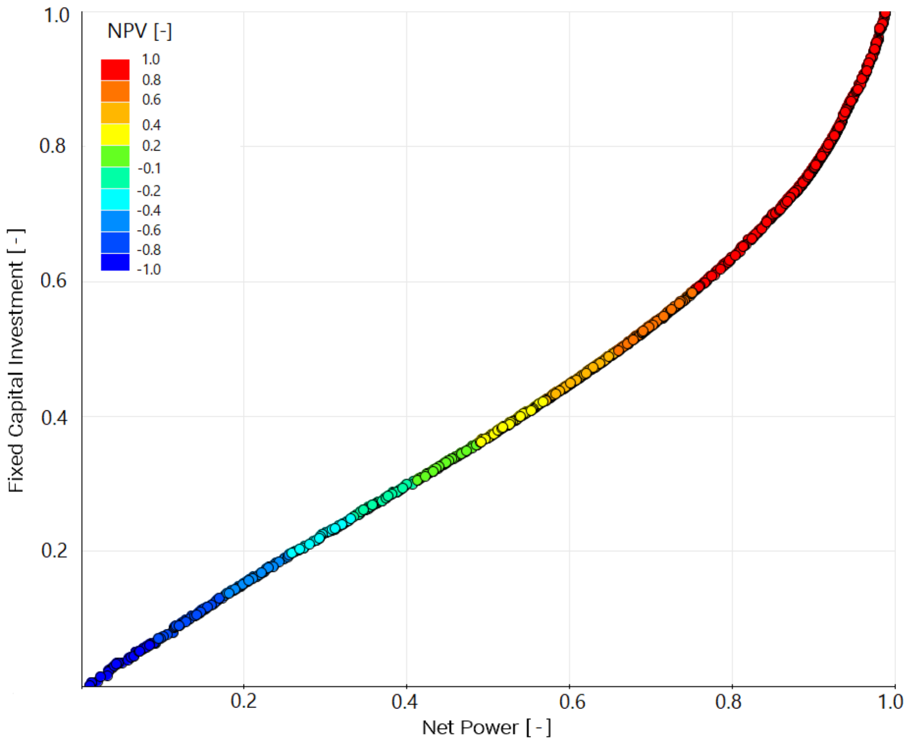

Figure: 2H1R optimization results (↑ Net Power and ↓Cost)

Objective Function: NPV and Costs

NPV evaluation provides the analysis with an auxiliary association between costs and power.

$$NPV = \sum_{n=1}^{n=20} \frac{Revenue - (Capex - Opex)}{(1 + interest\ rate)^n}$$

The color scale represents the Pareto frontier.

The optimal results frontier extends to the condition of 93% of maximum net power.

Higher power generations do not favor NPV and do not compose the Pareto frontier.

Net power conditions below 45% of maximum net power result in a negative NPV.

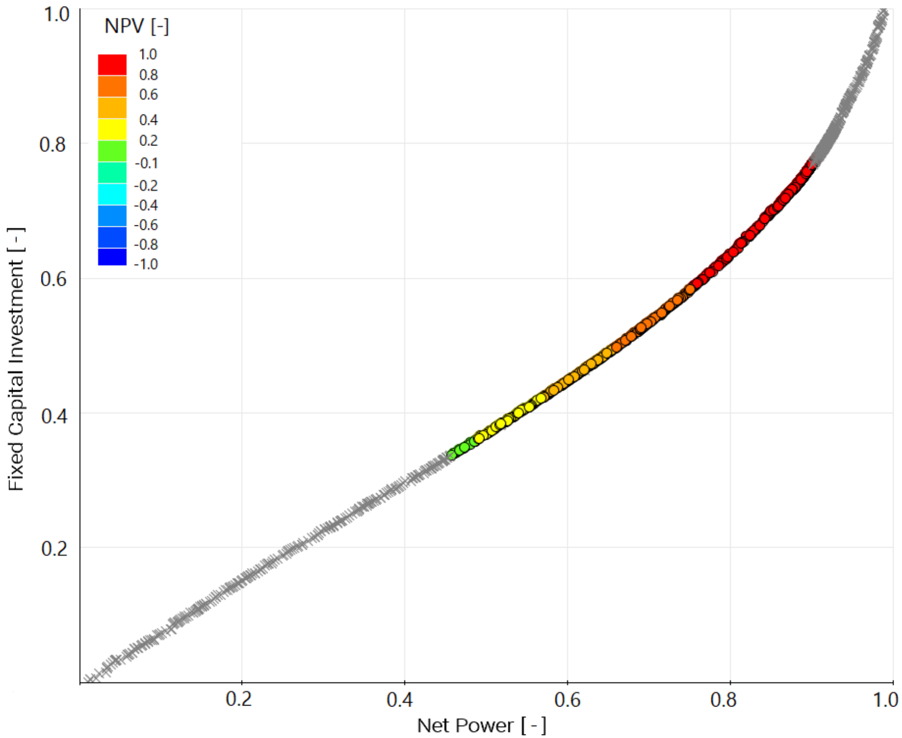

Figure: 2H1R optimization results (↑ NPV and ↓Cost)

Objective Function: Net Present Value and LCOE

LCOE can be viewed from an economic perspective as an **"average" electricity price** that must be earned by a specific generation source to **break even.**

LCOE minimization associates cost with net power generation

$$LCOE = \frac{CAPEX \times f_a + OPEX}{P_e \times Hour_{year}}$$

LCOE decreases with increasing net power until its minimum value in the region of optimal results.

After the frontier of optimal results, LCOE increases with increasing net power. This region also disfavors NPV.

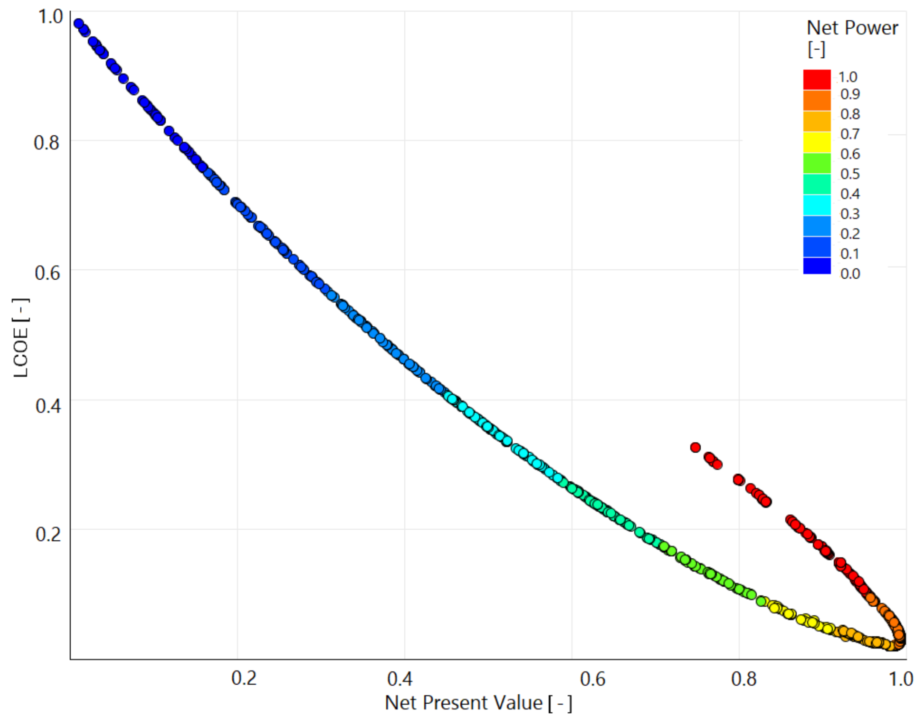

Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

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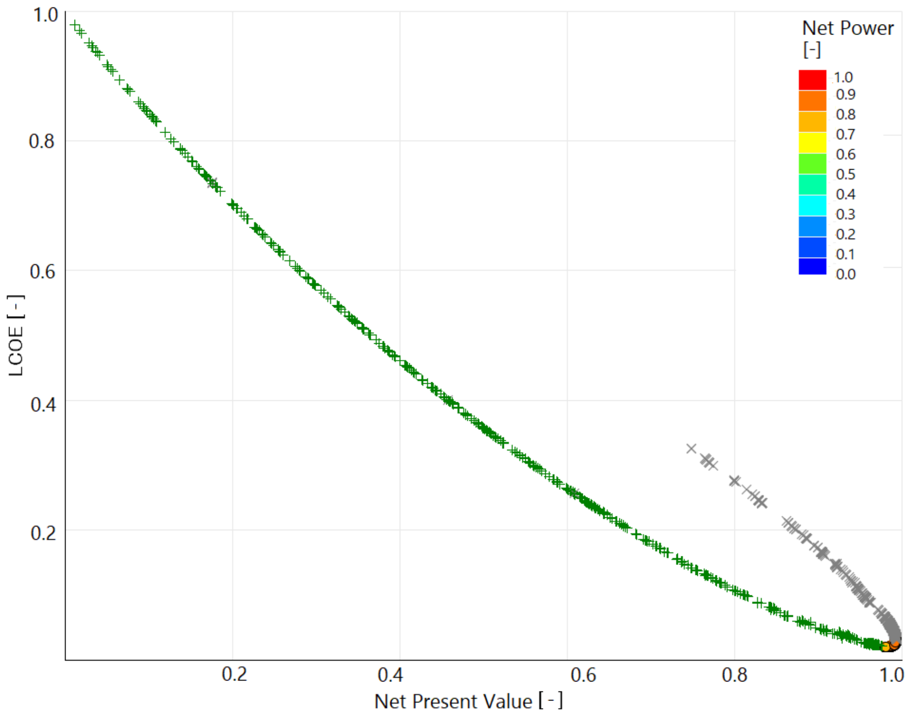


Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Objective Function: Net Present Value and LCOE

The optimal results of NPV maximization and minimization occur in a narrow range.

NPV values occur within 2% of the maximum value.

NPV values occur in a range of up to 1% greater than the minimum value.

The results represent 91% to 93% of the maximum net power value.

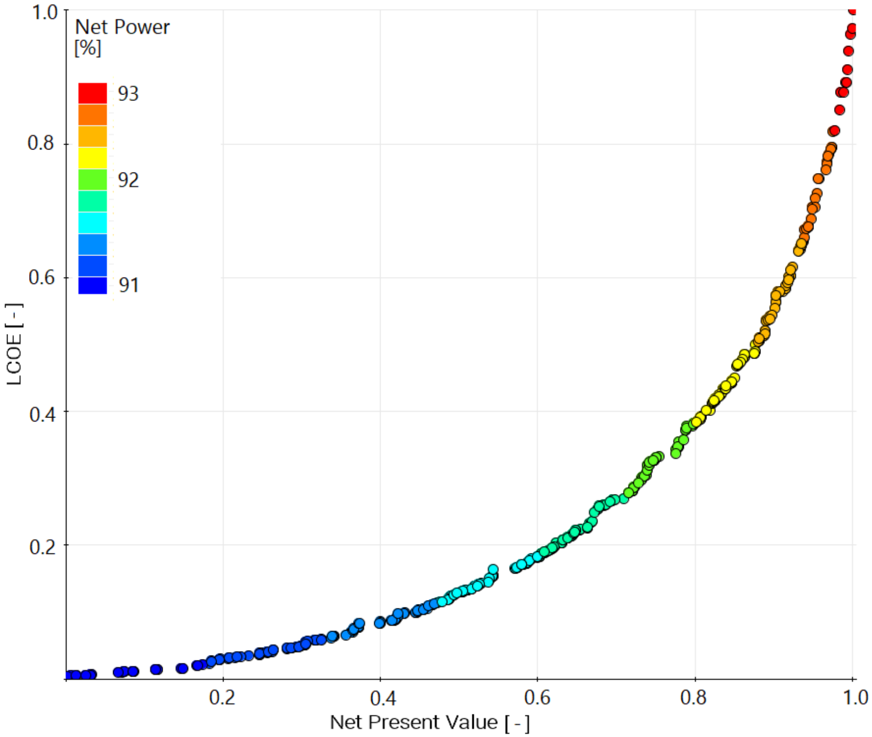


Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Objective Function: Net Present Value and LCOE

The 2H1R architecture is the most promising configuration by allowing larger NPV allied to smaller LCOE.

The 2H1R architecture provides the best net power and cost ratio among the others for the heat source evaluated.

This configuration allows lower specific costs than the 2H2R and 3H2R configurations.

Thus, at the frontier of optimal results, it presents higher power generation.

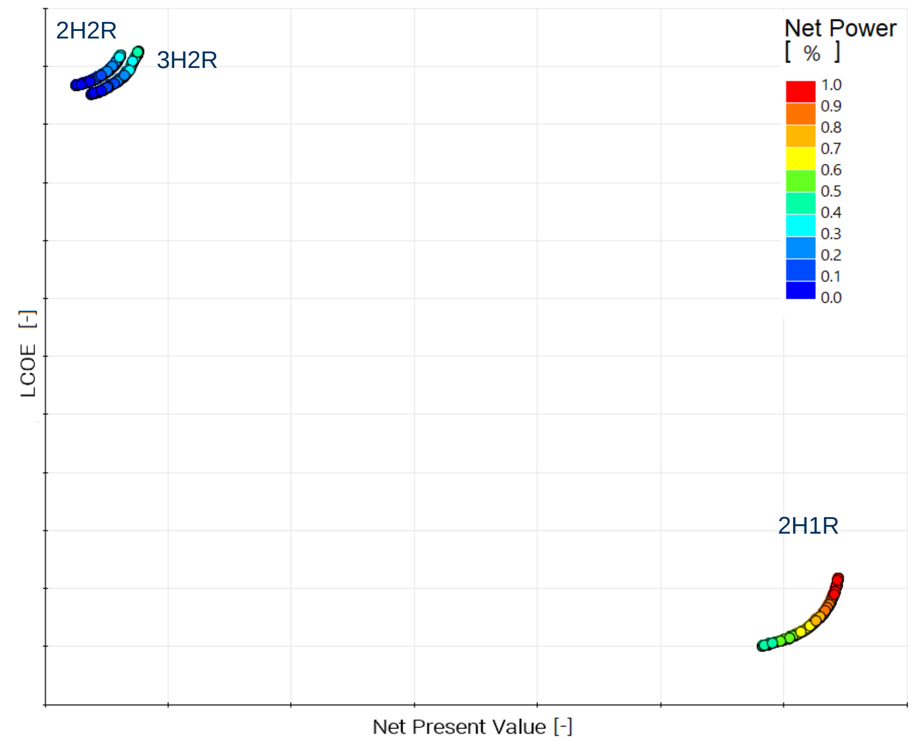


Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Sensitivity analysis of NPV and LCOE

In the optimization process, NPV and LCOE are variables dependent on net power and FCI.

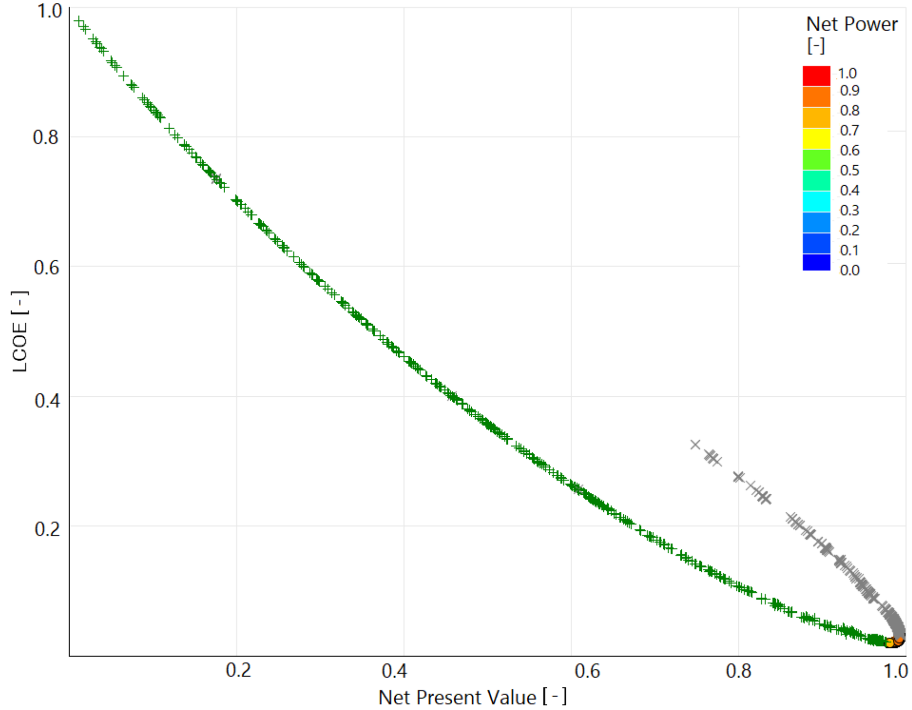
- Effect on NPV

	Region I NPV	Region II NPV	Region III NPV
Net Power [%]	60.3	52.9	39.6
FCI [%]	39.7	47.1	60.4

- Effect on LCOE

	Region I LCOE	Region II LCOE	Region III LCOE
Net Power [%]	55.7	47.5	35.7
FCI [%]	44.3	52.5	64.3

The optimal results region presents a balance between Net Power and FCI.



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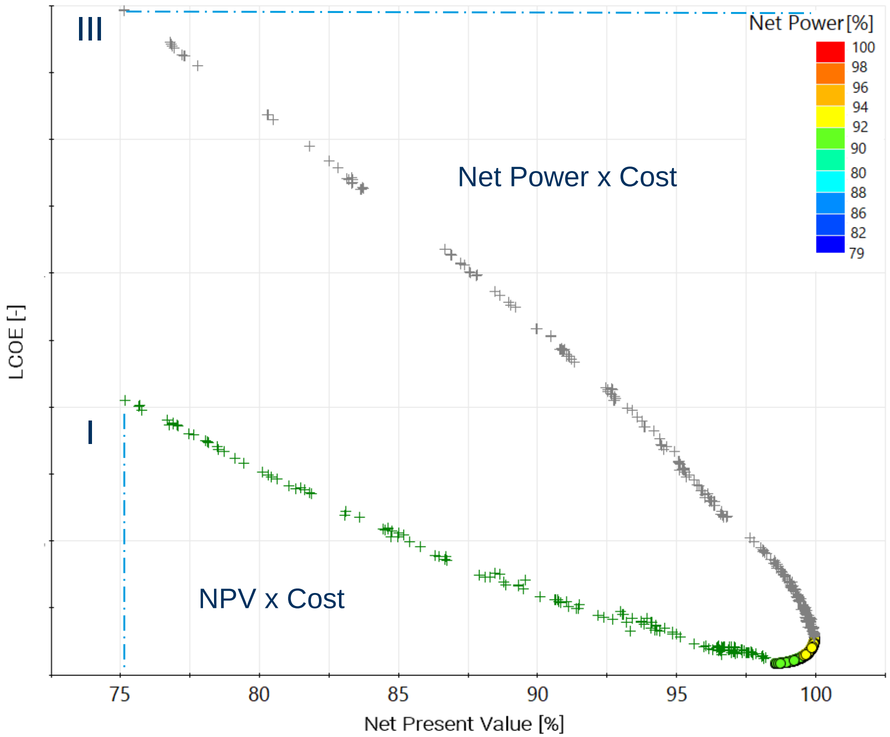

Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

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	Region I LCOE	Region II LCOE	Region III LCOE
Net Power [%]	55.7	47.5	35.7
FCI [%]	44.3	52.5	64.3

The optimal results region presents a balance between Net Power and FCI.

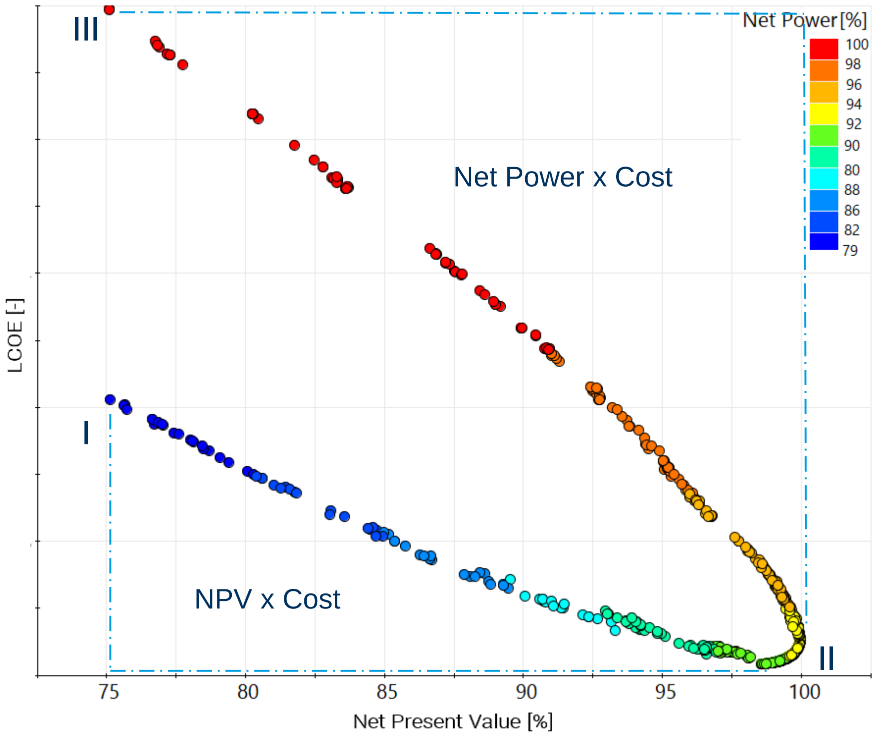

Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Objective Function: Net Present Value and LCOE

In region III, the influence of costs is predominant.

The significant increase of this parameter disfavors the results regarding NPV and LCOE.

Condition III:

- Net Power 7.6% higher
- Exergetic efficiency 9.8% higher

- Fixed Capital Investiment 17% superior.
- Especific cost increased by 8.8%

It reflects in a **25% decrease in NPV** performance.

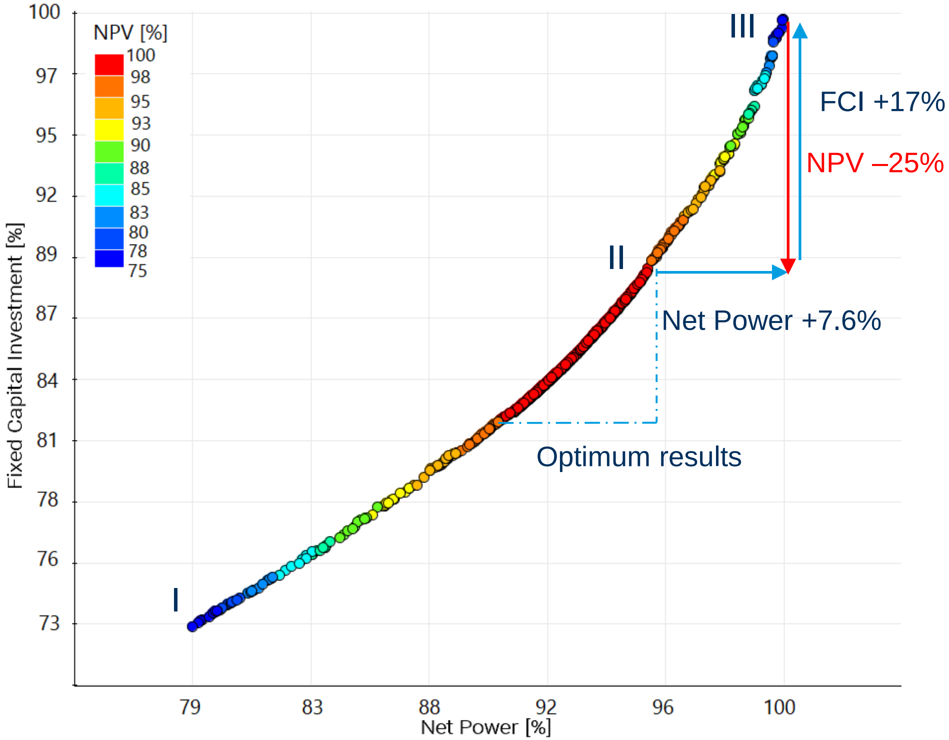

Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Objective Function: Net Present Value and LCOE

The cost increase in the higher net power region is strongly associated with the recuperator's higher effectiveness.

Until the limit of the optimal results frontier (condition II), the heater is the heat exchanger with the highest specific cost ($/MWt).

The recuperator overcomes the heater in region III related to higher specific cost ($/MWt).

The recuperator's cost at operating condition II is 50.6% less than the regenerator's price at the point I.

The increase in regenerator costs is 63% of the cost increase in the region I.

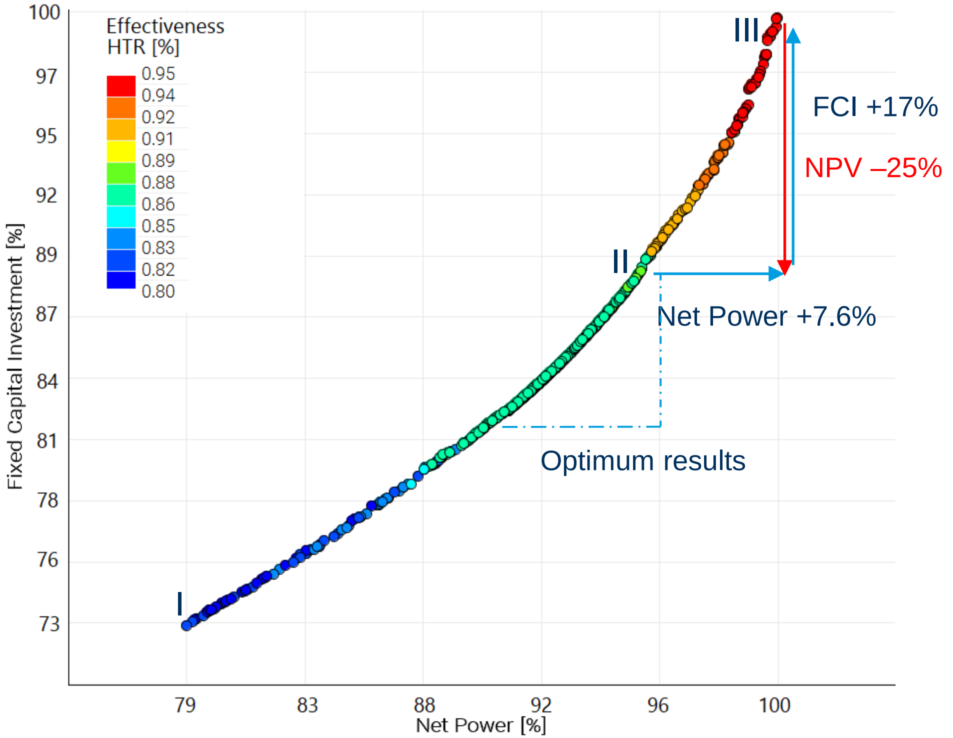

Figure: 2H1R optimization results (↑ NPV and ↓LCOE)

Net Present Value and LCOE

After the boundary of optimal results, there is a clear tendency to increase heat recovery at HTR significantly.

In the region of optimal results, the heat recovery of the source in Hx1 and Hx2 approaches the heat source's restrictions.

The increase in power generation comes from the higher heat recovery at HTR, providing an additional mass flow rate.

This mass flow increment is expanded in the LT turbine.

In the region of optimal results, the results tend to a simplified operation without using the LT turbine.

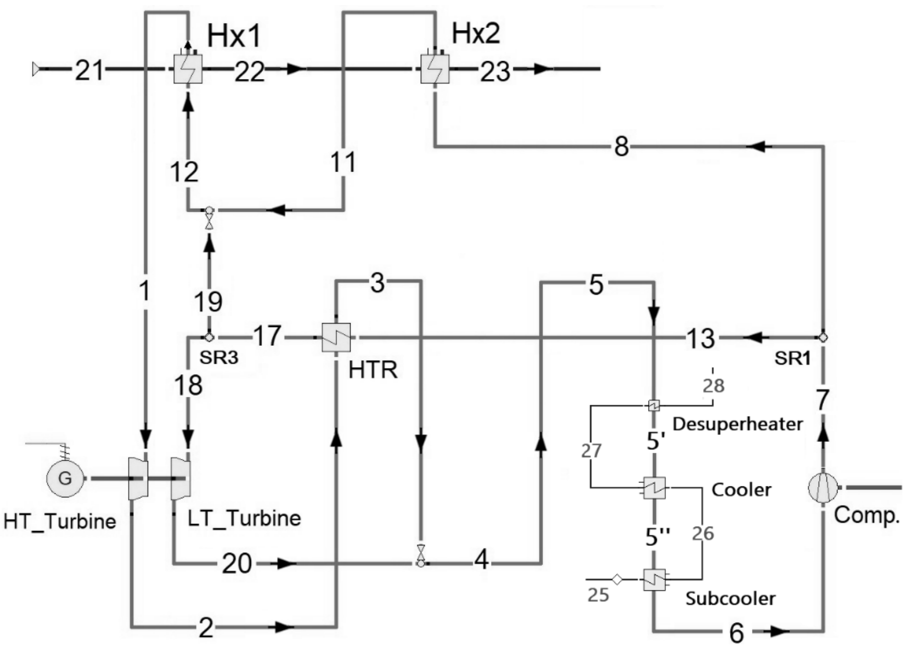

Figure: Representation of the 2H1R architecture.

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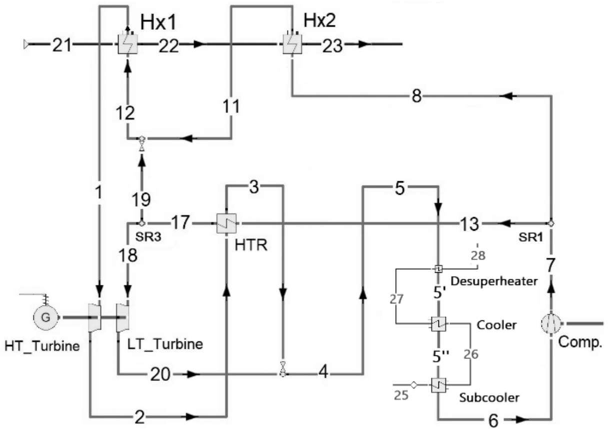

Figure: Representation of the 2H1R architecture.

Discrete Variable		2H1R Optimal	2H1R Net Power
Pressure (HP)	[bar]	268 – 290 *(273)	264 – 282
Pressure (LP)	[bar]	75	75
UTTD (Hx_1)	[-]	57 – 71	53 – 71
Effectiveness (Hx_1)	[-]	0.9 – 0.95	0.9 – 0.95
UTTD (HTR)	[-]	12 – 35	8 – 12
Effectiveness (HTR)	[-]	0.8 – 0.86	0.9 – 0.95
Results		2H1R Sub.	2H1R Sup.
Net Power	[MW]	30.1 – 33.9	32.1 – 35.3
Thermal Efficiency	[%]	26.1– 26.9	26.8 – 29.0
Exergetic efficiency	[%]	55.6 – 57.3	57.1 – 62.9

5- Conclusion

Conclusion

The optimization process allows optimal operation conditions, which are very sensitive to objective functions, cost models, economic evaluation, and equipment design and efficiency.

The 2H1R architecture configuration proposed in this study presents the most promising results.

Net power is the most relevant parameter for NPV maximization, while total costs are the main driver for LCOE analysis.

Sensitivity analyses point out the recuperator as the decisive equipment for the optimal operation of the cycle.

- The recuperator's operating conditions are determinant for the system's amount of mass flow, besides managing the heater and cooler operation.

- The equipment plays a decisive role in determining the correct equilibrium between power and costs for the optimal operation.

The results indicate a prominent potential for the proposed cycle configuration and operational conditions for exhaust heat recovery in a combined gas turbine SCO_2 cycle.

Thank you very much for your attention