sCO2 WASTE HEAT RECOVERY SYSTEM EVALUATION FOR STEELMAKING PROCESS

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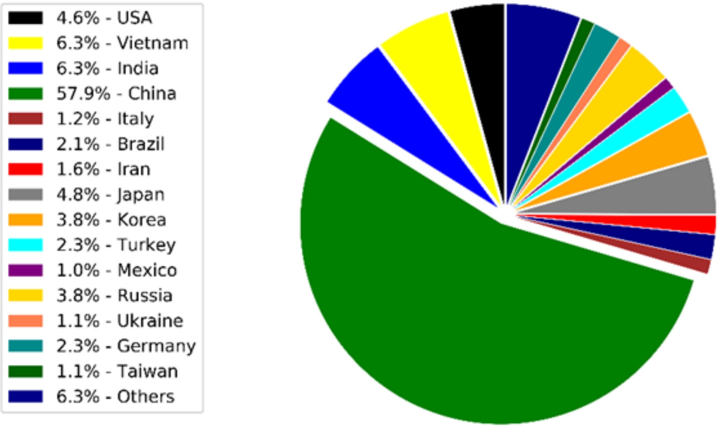
Background

Steel and Iron Industry

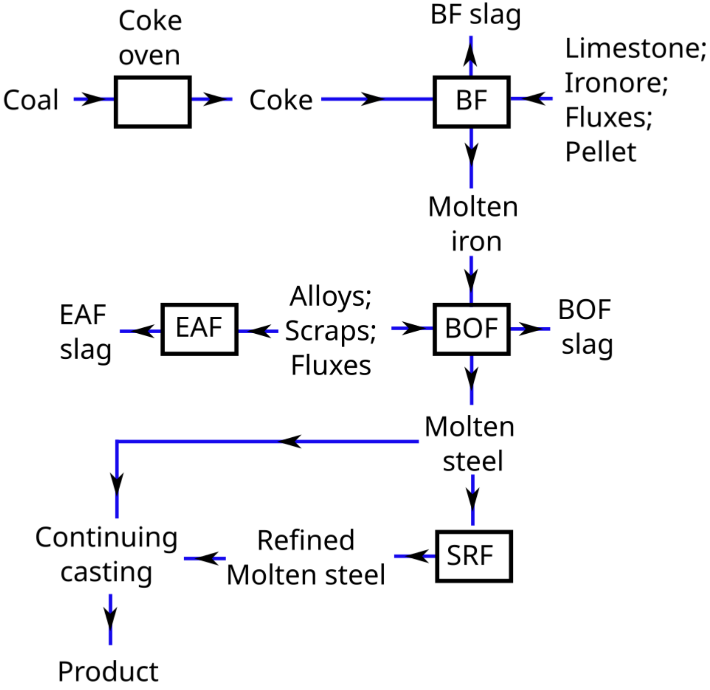
- Iron and Steel production is an energy-intensive process.
  - Iron and Steel production requires raw materials to be heated to >1973 K.
  - Exhaust gases can reach up to 1573 K, depending on the process.
- Improving the energy efficiency of a plant will dramatically improve its bottom line & reduce emissions.
- Waste heat recovery (WHR) systems are the key for transition current iron and steel plants to greening cement plants

Raw steel production

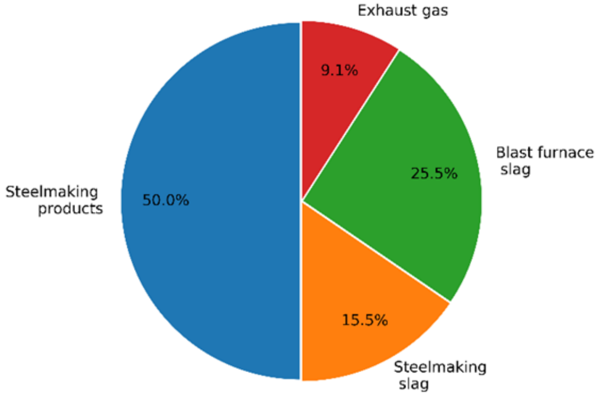


	Aluminum	Iron and Steel	Cement	
Production	0.86	86 (steel); 22 (iron)	93	million tons per year
Capacity	1.69	-	100	

Iron and Steel Industry - Process description



Distribution of waste heat in the iron and steel industry



Available waste heat from steel industry and estimation temperature

Process	Temperature
Electric arc furnace	1273 – 1573 K
Electric arc furnace with recovery	473 – 573 K
Blast and cupola furnace	723 K

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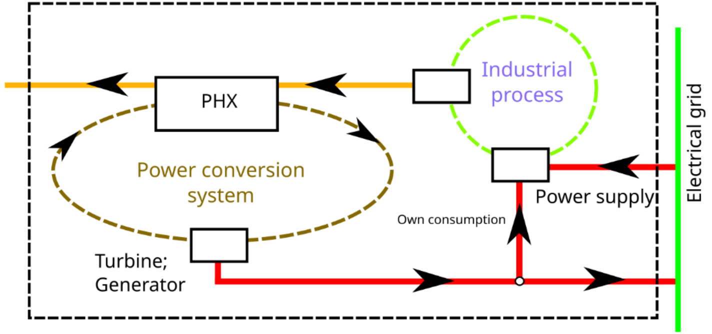
Iron and Steel Industry Decarbonization

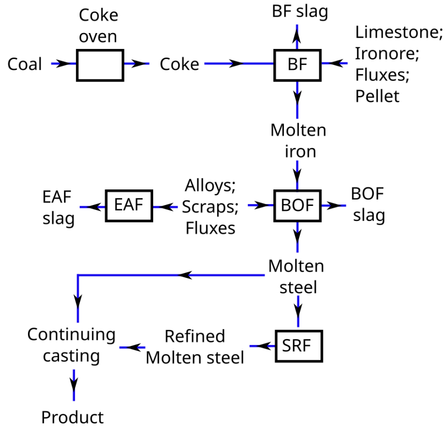
- Different approaches to Decarbonization in each sector:
  - Use an alternative fuel or energy source – direct approach:
    - Alternative fuel - H_2
    - Energy generated from renewable energy sources (e.g., solar, wind, geothermal plants) or nuclear (e.g., fission and fusion)
  - Carbon capture systems (CCS) – direct approach:
    - CCS can help reduce CO_2 emissions if it is not possible to replace the heat source or the emissions are a product of a chemical process in the plant.
  - Utilization of waste heat – indirect approach:
    - Waste heat can be re-input to the process for additional added heat
    - Waste heat contains a large amount of energy – can be recovered and converted into electricity
    - By-product of the system – potentially a secondary source to reduce plant consumption

System Description

WHR systems – principle and heat source

- Iron and Steel production requires raw materials to be heated to >1973 K.
- Exhaust gases can reach up to 1573 K (Depends on the process).
  - Potential heat source for WHR systems.



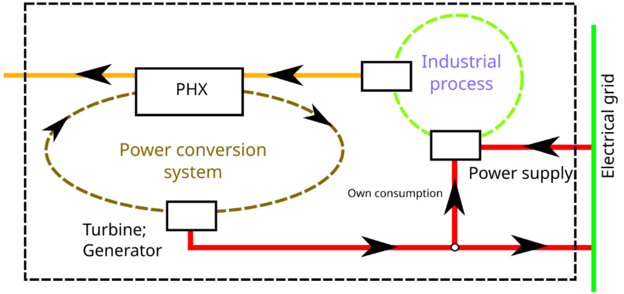


Iron and steelmaking process – two sources of the waste heat in three different steps:

- solid streams (molten slag)
- exhaust gas streams

	Exhaust temperature range		H_2	CO	CO_2	N_2	CH_4	C_2H_6	H_2O
	K		%						
Coke oven	1253.15	473.15	52	4	2 {8}	{70}	37	5	{22}
Blast furnace	703.15	403.15	3	26	21 {26}	50 {68}			{5}
Basic oxygen furnace	1973.15			73	16	8			
Electric arc furnace	1473.15	477.15	11	18	14	57			

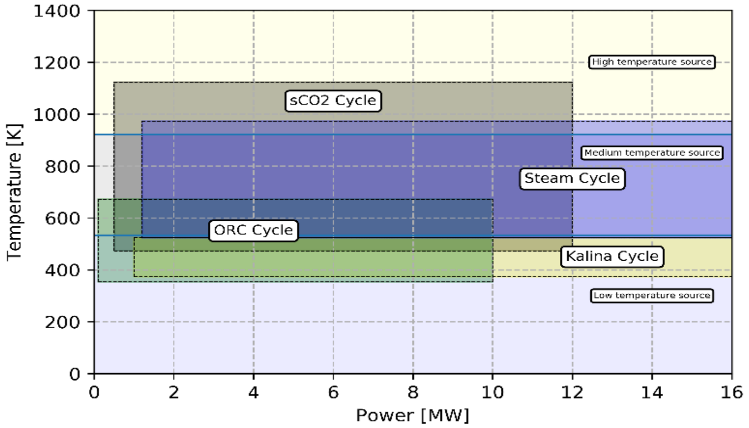
WHR systems comparison



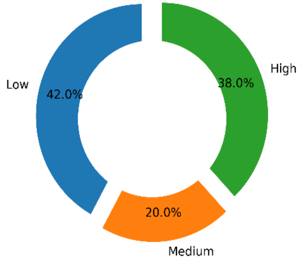
Advantages	Disadvantages
ORC	
Current use; Footprint; Size; Retrofitting	Max. operating temperature 400 °C; Working medium; Price
SRC	
Current use; Working medium; Price	Water requirement; Footprint; Size; Retrofitting
sCO_2	
High efficiency; Footprint; Size; No water requirement; Turbomachinery; Retrofitting	Under development; Price; Material; HEX

Proposed cycles:

- Organic Rankine cycle (ORC)
- Steam cycle (SRC)
- sCO_2 cycle

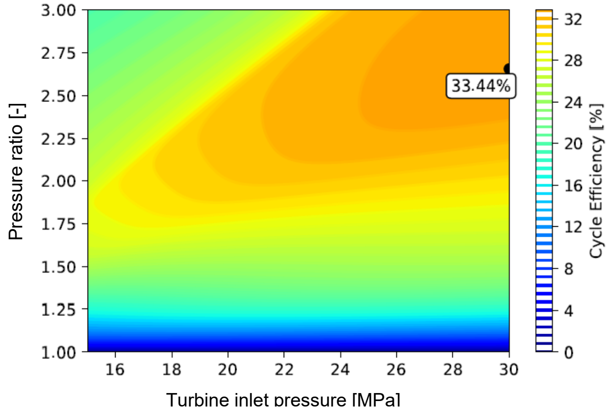


Temperature range of waste heat

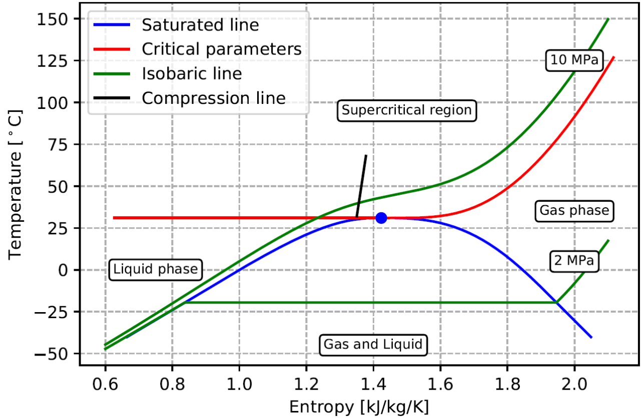


Waste heat power cycles - sCO_2 power cycle

- Theoretical and practical promise of compactness, high efficiency, and wide-range-applicability
- Can be used for the majority of heat sources in energy conversion systems
- Main applications:
  - waste heat recovery systems
  - solar power plants
  - geothermal power plants
  - fossil power plants
  - nuclear power plants

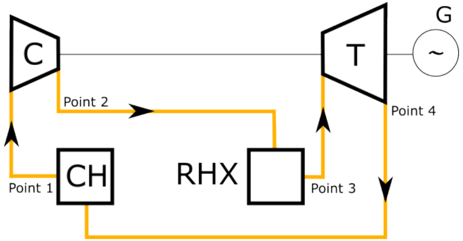


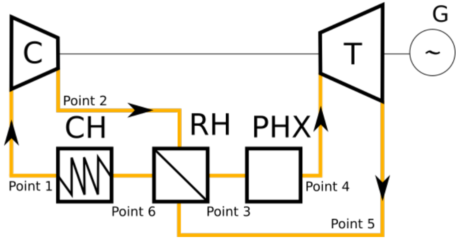
Application	Power	Operation Temperature	Operation Pressure
	[MWe]	[K]	[MPa]
Nuclear	10 - 300	623 - 973	20 - 35
Fossil fuel (syngas, natural gas, coal)	300 - 600	823 - 1773	15 - 35
Geothermal	10 - 50	1373 - 573	15
Concentrating solar power	10 - 100	773 - 1273	35
Waste heat recovery	1 - 10	573 - 923	15 - 35

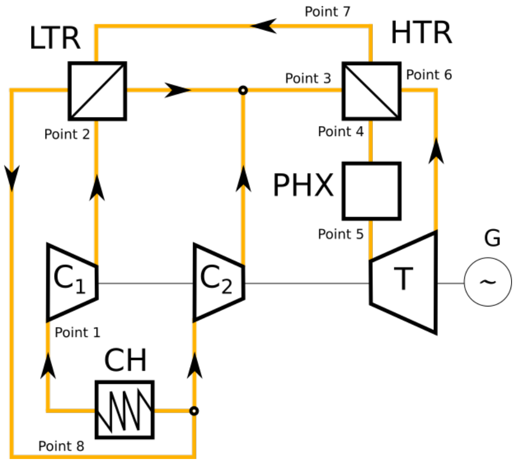


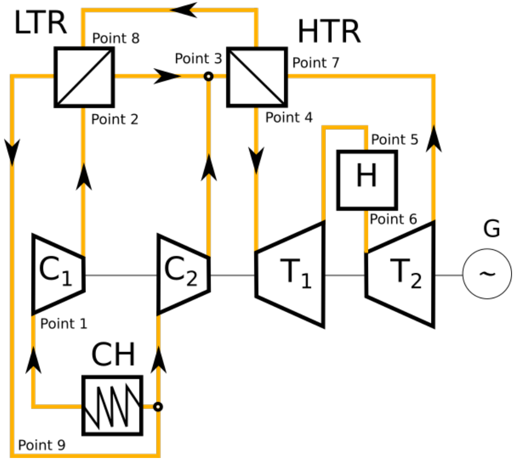
sCO_2 Cycle layouts

- Cycle configuration:
  - Simple Brayton
  - Recuperated
  - Re-compression
  - Split expansion









System Analysis

sCO_2 Cycle layouts - Input and boundary conditions

- Waste heat parameters
  - Exhaust and cooling stream:
    - Waste heat stream temperature is 1473 K
    - Exhaust gas flow is uniform and pressure drops are not considered
    - Average ambient air temperature is defined as 300 K
  - sCO_2 stream:
    - Minimal temperature difference between air and CO_2 streams is 5 K
    - The pressure drops are not considered in the calculation for all cases
- The system is designed for 4 MWe net power

<table>
<tr><th>Parameter</th><th>Lower</th><th>Upper</th><th></th></tr>
<tr><td>Pressure ratio</td><td>2.6</td><td>4.0</td><td>-</td></tr>
<tr><td>Turbine inlet pressure</td><td>20</td><td>30</td><td>MPa</td></tr>
<tr><td>Turbine inlet temperature</td><td colspan="2">823.15</td><td rowspan="2">K</td></tr>
<tr><td>Compressor inlet temperature</td><td colspan="2">306</td></tr>
<tr><td>Turbine efficiency</td><td colspan="2">90</td><td rowspan="3">%</td></tr>
<tr><td>Compressor efficiency</td><td colspan="2">69</td></tr>
<tr><td>Recuperator effectiveness</td><td colspan="2">90</td></tr>
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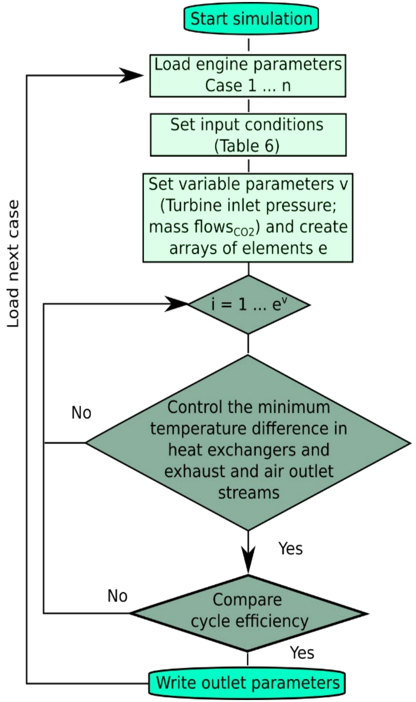
The generator efficiency is 96 %, clutch efficiency is 95 %, and gearbox efficiency is 93 %.

sCO_2 Cycle layouts – Simulation procedure

- In-house computer code based on the Python programing language
- sCO_2 properties table (sCO_2 and exhaust gas)
  - NIST Reference Fluid Thermodynamic and Transport Properties database, Version 9.1
  - CoolProp - open-source Thermo-physical Property Library
- The optimized parameters:
  - Cycle efficiency

Parameter	Lower	Upper	
Pressure ratio	2.6	4.0	-
Turbine inlet pressure	20	30	MPa
Turbine inlet temperature	823.15		K
Compressor inlet temperature	306		
Turbine efficiency	90		%
Compressor efficiency	69		
Recuperator effectiveness	90		



Results and Discussion

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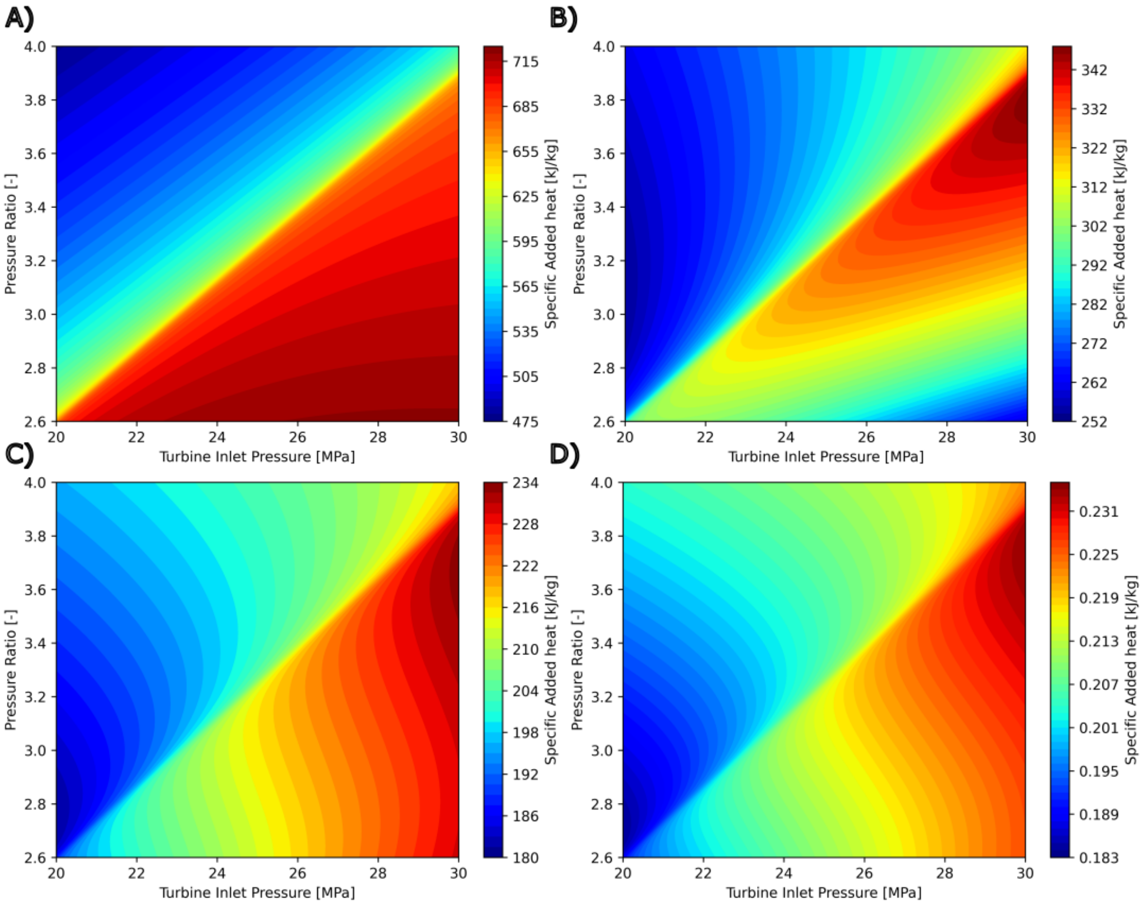

Specific added heat :

A) Simple Brayton
B) Recuperated
C) Re-compression
D) Split expansion

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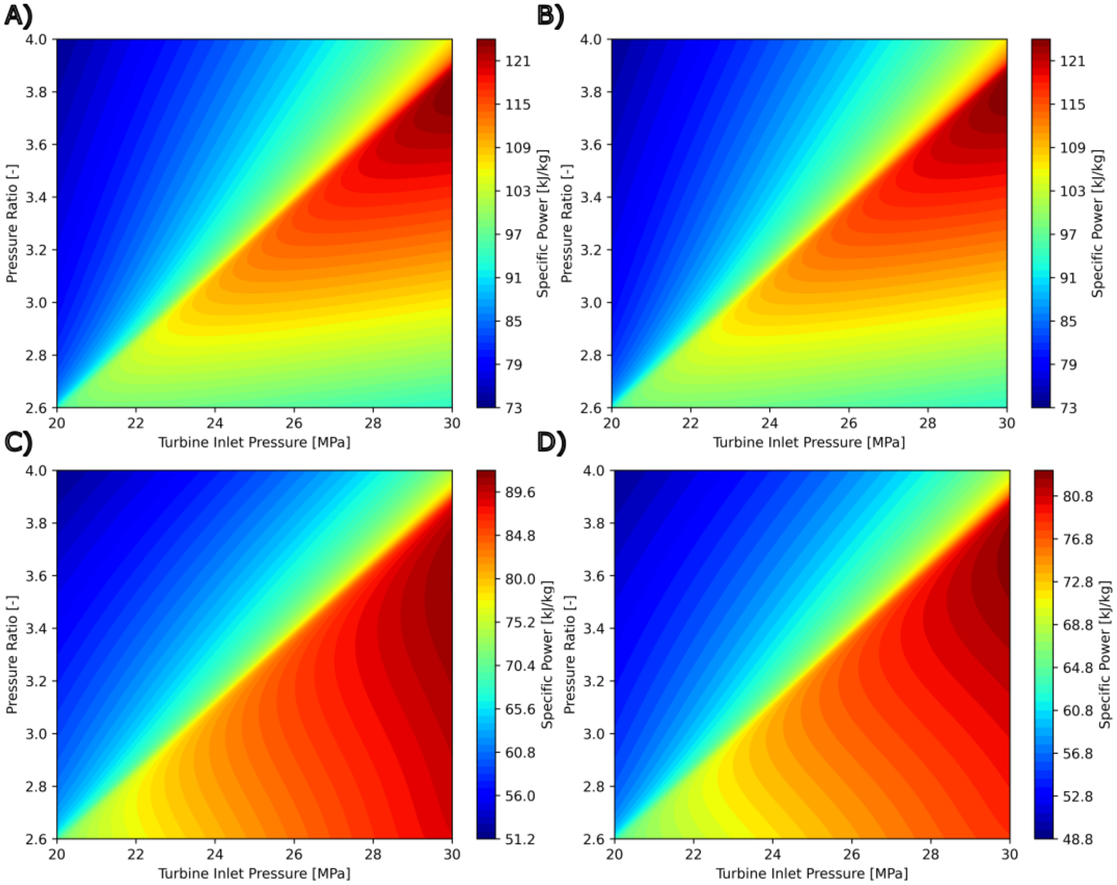
Results and Discussion



Specific Net power:
A) Simple Brayton
B) Recuperated
C) Re-compression
D) Split expansion

Results and Discussion

- Optimization results for the cycle efficiency

	Simple Brayton	Recuperated	Re-compression	Split Expansion	
η_{th}	18.35	35.68	**39.15**	35.38	%
W_t	6.59	6.59	6.03	6.2	MW
W_c	1.75	1.75	1.22	1.35	
Q_{in}	26.34	13.5	**8.62**	9.09	
Q_{out}	21.5	8.7	3.34	3.76	
Q_{reg}	0	12.76	12.84	17.39	
W_{gross}	4.8				
W_{net}	4				
m_{sCO2}	39	39	37	39	kg/s
π	3.8		3.6	3.7	

- The turbine inlet pressure = 30 MPa
- The compressor inlet temperature = 306 K

Conclusion

Conclusion

- The work presented:
  - Evaluation of potential sCO_2 power conversion cycle layouts to utilize waste heat from steel process exhaust gas streams
    - Simple Brayton
    - Recuperated
    - Re-compression
    - Split expansion
- The results show the potential to use the sCO_2 power cycle
  - High temperature range waste heat source
  - The re-compression cycle has the greatest cycle efficiency (39.15 %); added heat 8.62 MW for 4 MWe output

- Future work:
  - Techno-economic analysis for cycle layouts
  - Detailed design and optimization of the PHX

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Thank you for your attention.

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