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Feasibility Study of Supercritical CO_2 Rankine Cycle for Waste Heat Recovery

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Background

- Introduction
- Objective
- Assumption
- Cycle Analysis
- Results Comparison
- Conclusion

Introduction

What is Waste Heat ?

Waste heat is the heat which is generated in a process by way of fuel combustion or chemical reaction.

India has large quantity of hot flue gases generated from the Boilers, Kilns, Ovens and Furnaces.

Introduction

Waste Heat Source Classification

High Temperature Heat source (700-1000 °C)	Medium Temp. Heat Source (300 – 700 °C)	Low Temp. Heat Source (50-300 °C)
➢ Cement Kiln ➢ Nickel Refining Furnace ➢ Aluminium Refining Furnace ➢ Steel Heating	➢ Steam Boiler Exhaust ➢ Gas Turbine Exhaust ➢ Annealing Furnace	➢ Furnace Doors ➢ Welding Machines ➢ Air Compressor

Introduction

Consensus of Waste heat in cement industries in India

- In 2012, India has **146** cement plants which has production capacity of **346.2 MiTPA** and per capita cement use is **191 kg**.

- Cement industries consumes 9.10% of total 163.7 Million toe in India.

- Nearly 35% heat is lost primarily in preheater and cooler in Cement industry.

Objective

- ❖ The objective of this study is to find best possible thermodynamic power cycle that suits the medium range waste heat recovery.
- ❖ We have considered 1.18 MW of waste Heat source at 873 K temperature for Analysis.
- ❖ We performed the first law and second law analysis of these three power cycles using Engineering equation solver to do comparison study.

1) Steam Rankine Cycle
2) Transcritical CO_2 Cycle
3) Combined CO_2 and steam power Cycle

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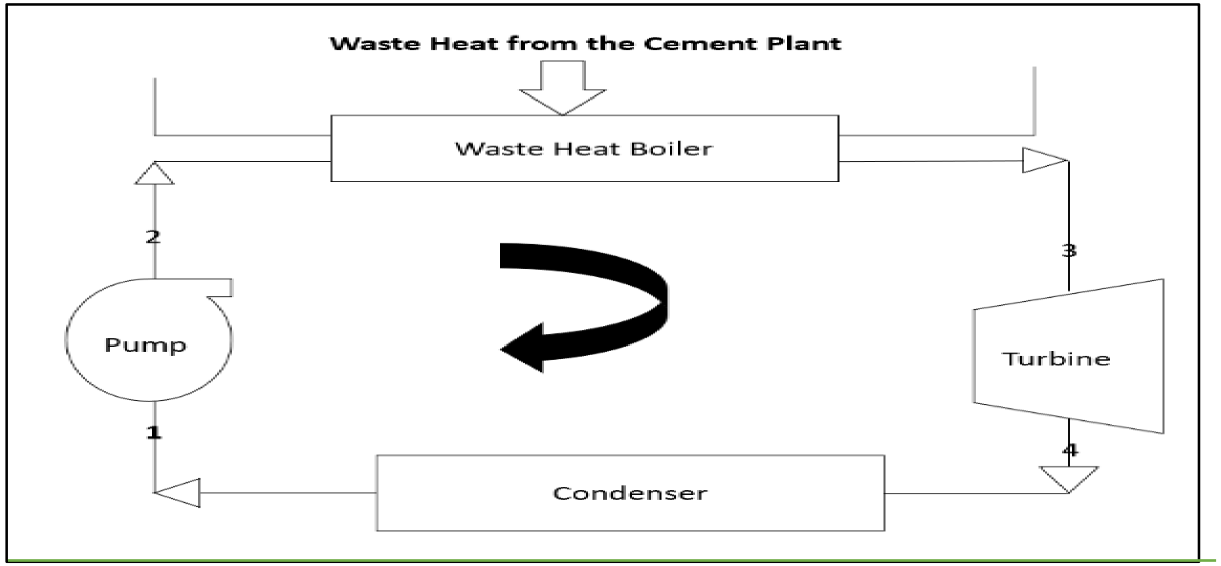
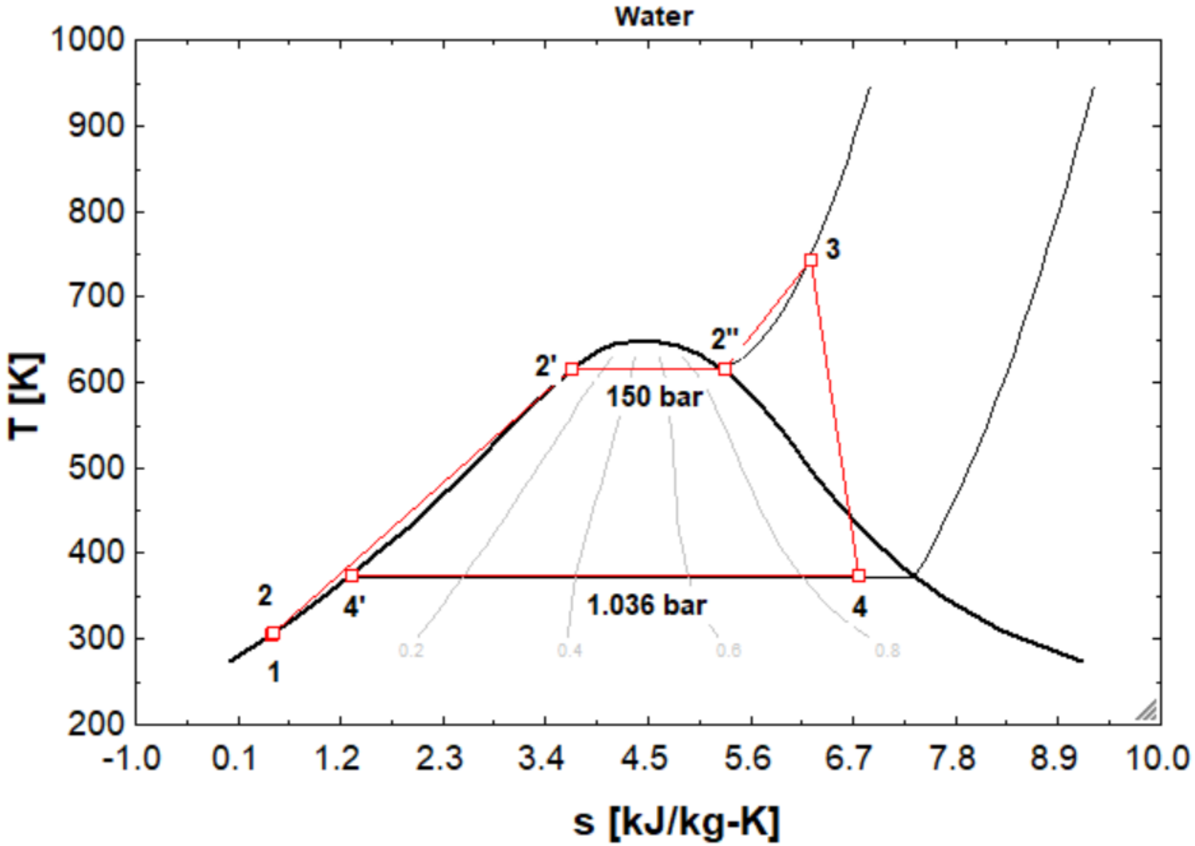
Assumption

- Steam Turbine and pump both have 80% isentropic efficiencies.
- A minimum temperature difference of 20 K is required at the end between warm and cold streams in any heat-exchanger.
- A pressure drops of 3.5% of entry pressure occurs in each stream during the heat addition and heat rejection processes.
- The same entropy generation at the both ends of boiler to find inlet temperature of working fluid.

Steam Rankine Cycle





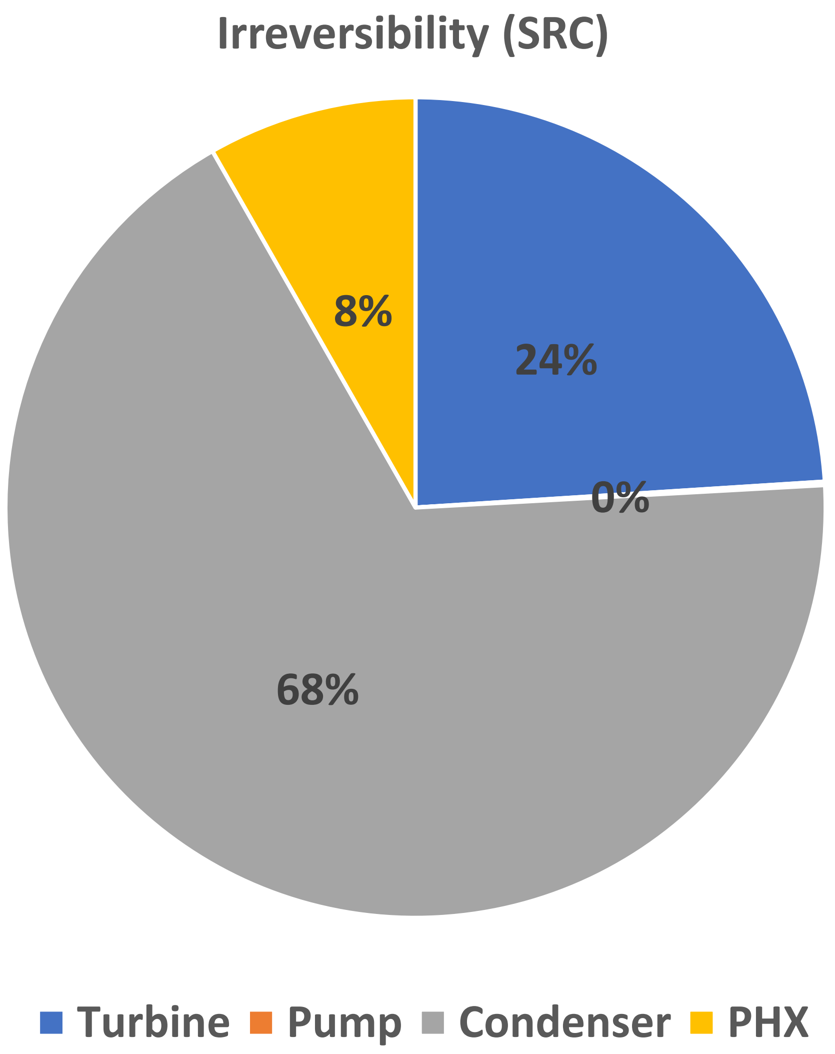
Operating parameters

Operating Pressure	150 bara
Condensation Pressure	1 bara
Turbine inlet Temperature	743.1 K
Cooling Water Temperature	290 K
Mass flow rate of steam	0.3662 kg/s
Mass flow rate of flue gas	2 kg/s

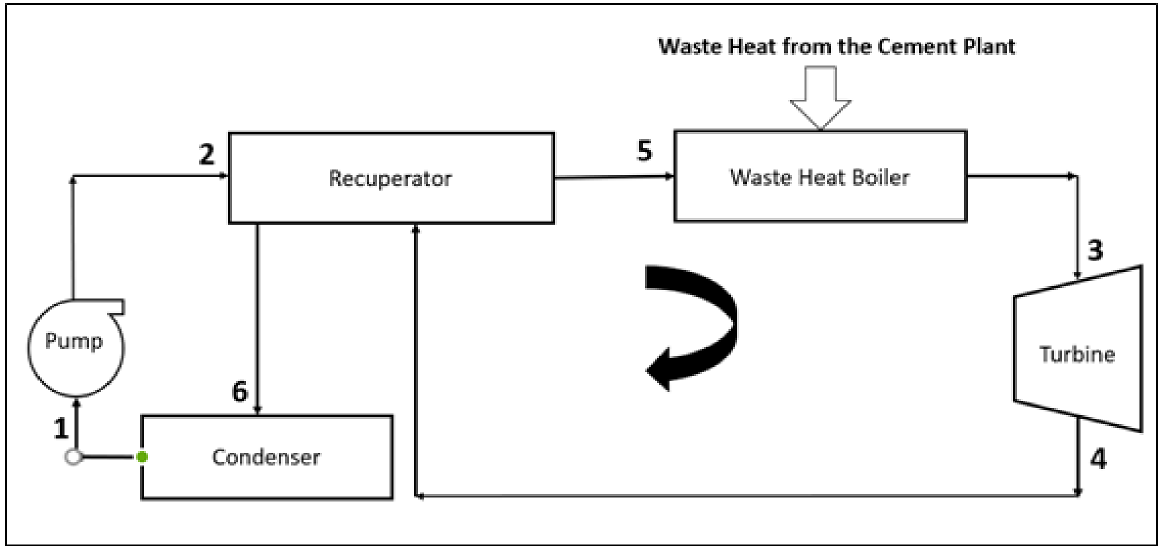
Steam Rankine Cycle-Results

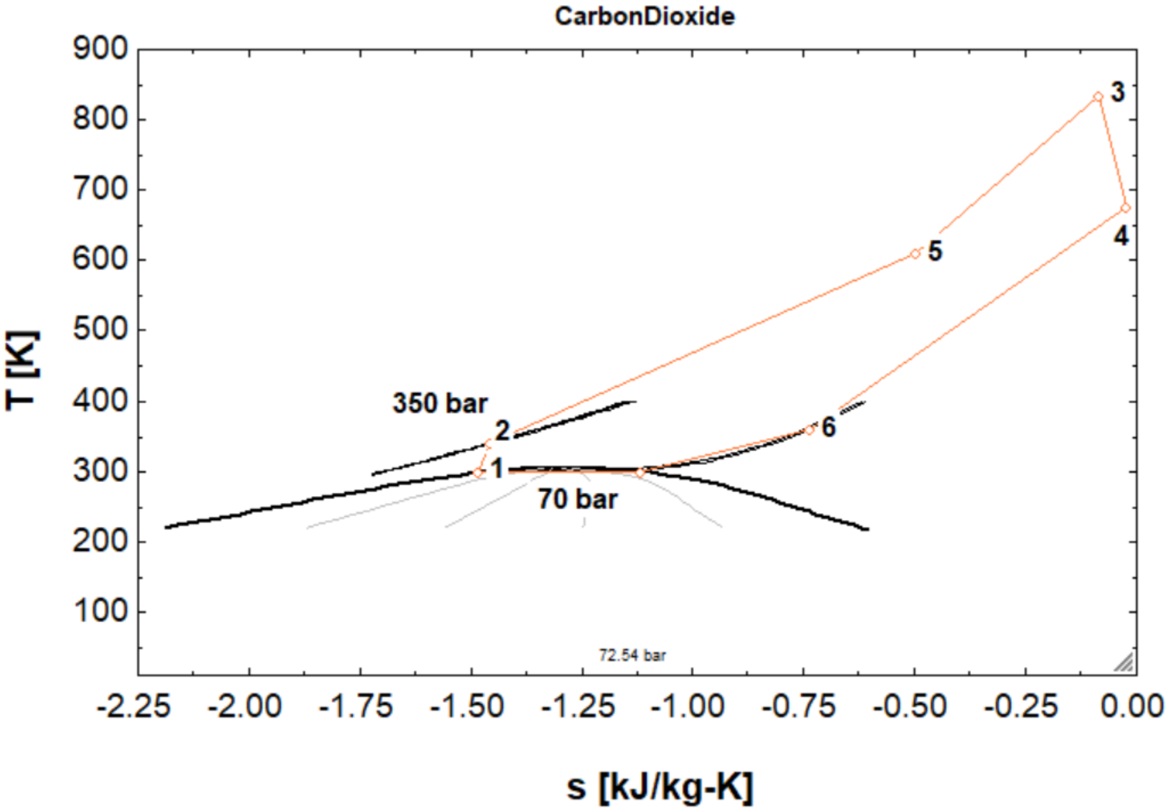
Results	
Power Output	274.59 kW
Thermal Efficiency	24.38 %
Exergy Efficiency	68.02 %

- Maximum exergy is destroyed in condenser due to latent energy of condensation.
- Irreversibility in turbine is high due to limitation of isentropic efficiency.
- In boiler, exergy is destroyed around 8% of total exergy , due to latent heat for vaporization.



Transcritical CO_2 Rankine Cycle





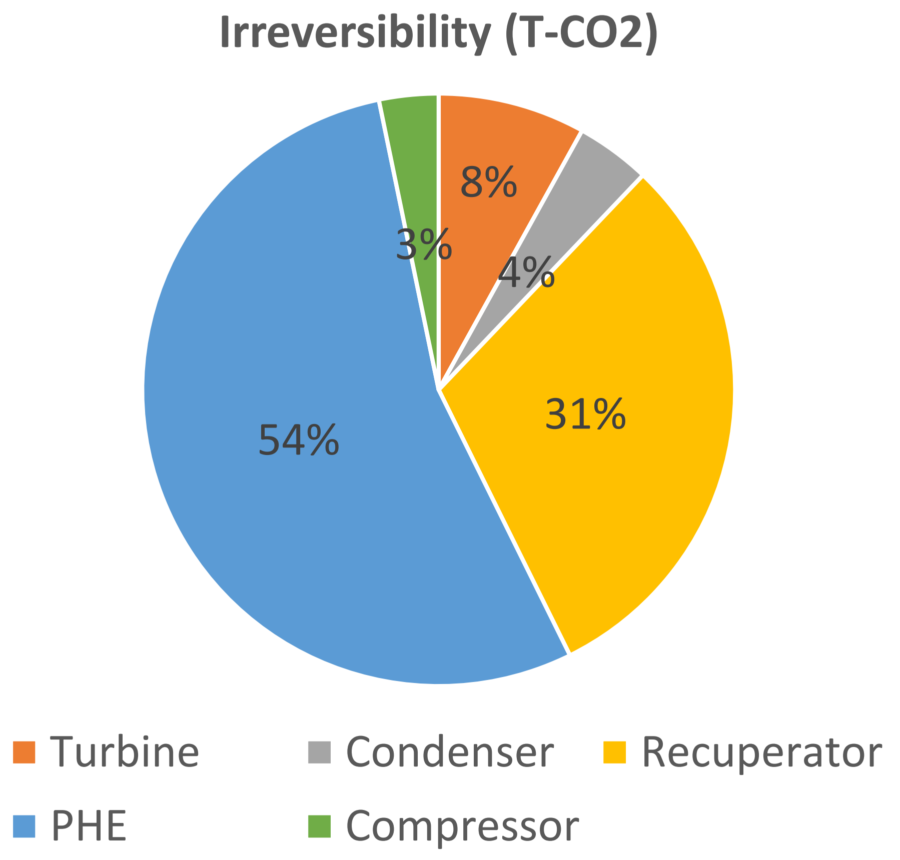
Operating parameters

Operating Pressure	350 bara
Condensation Pressure	70 bara
Turbine inlet Temperature	835 K
Cooling Water Temperature	290 K
Mass flow rate of CO_2	1.732 kg/s
Mass flow rate of flue gas	2 kg/s

Transcritical CO_2 Rankine Cycle - Results

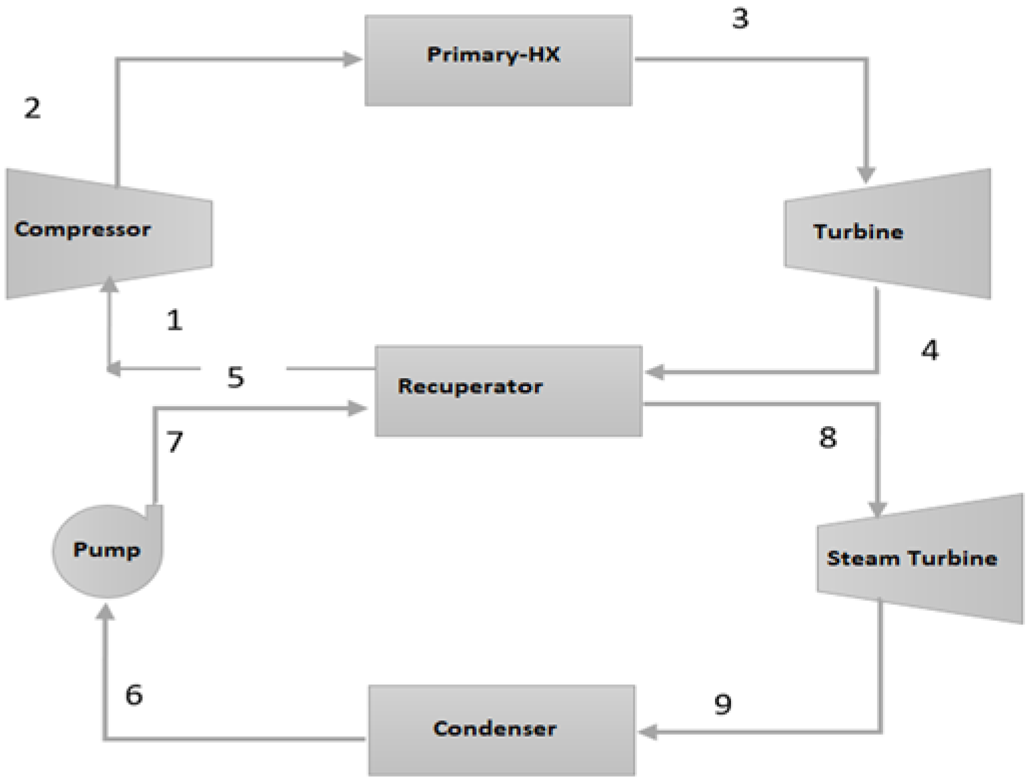
Results	
Power Output	217.87 kW
Thermal Efficiency	18.46 %
Exergy Efficiency	46.14 %

- In T-CO_2 cycle, the maximum exergy destruction is in the primary heat exchanger (PHE).
- Use of Recuperator, reduces the temperature difference between S-CO_2 and flue gas in main heat exchanger, which leads to ineffective heat exchange and continuous heat loss



Combined Power Cycle System

- In the combined cycle, Supercritical CO_2 brayton as the topping cycle and steam Rankine as the bottoming cycle.



Operating parameters	
high Pressure (S-CO_2 cycle)	350 bara
Lowest Pressure (S-CO_2 cycle)	72.54 bara
S-CO_2Turbine inlet Temperature	764.7 K
Steam Turbine inlet Temperature	544.4 K
High pressure (SRC)	45 bara
Lowest Pressure (SRC)	1.036 bara
Cooling Water Temperature	290 K
Mass flow rate of CO_2	1.673 kg/s
Mass flow rate of steam	0.2086 kg/s

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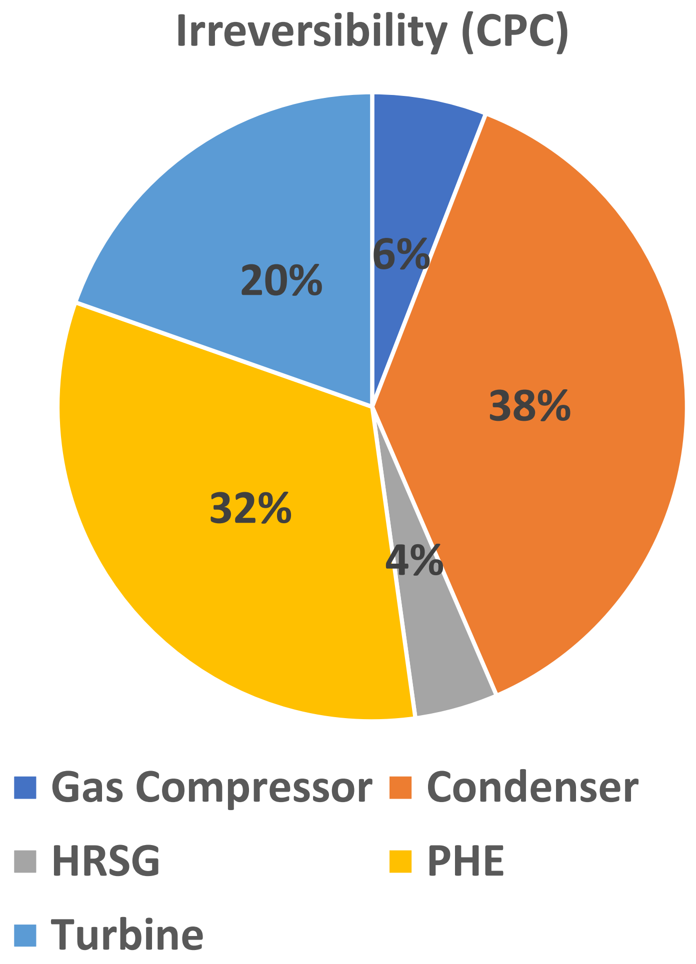
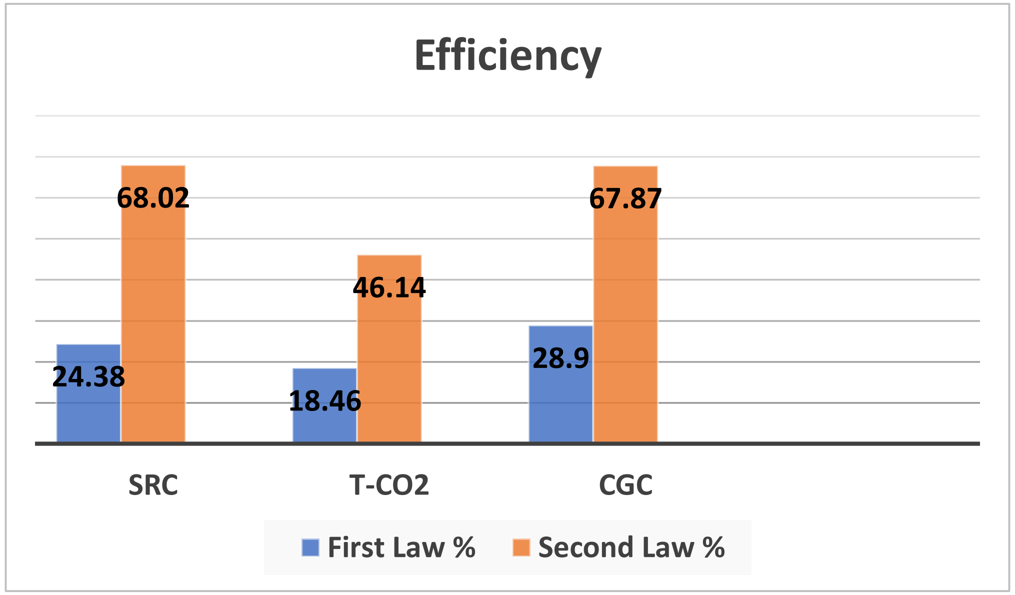
Combined Power Cycle- Results

Results	
Power Output	304.44 kW
Thermal Efficiency	28.88 %
Exergy Efficiency	67.87 %

- Major part of exergy loss is in boiler and condenser. For that, the main reason is latent heat requirement for the phase change.
- Exergy loss in the CO_2 turbine is higher as compare to steam turbine because of very high inlet temperature and law expansion ratio.



Cycles Comparison



- First law efficiency is maximum for combined cycle which is 28.9%
- No latent heat as well as complete utilization of waste heat source by adding SRC in bottoming cycle leads to maximum efficiency.
- Exergetic efficiency is almost equal for combined power cycle and steam rankine cycle.

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Conclusion

- From the first law analysis, results shows that combined power cycle is 28.9 % efficiency, which is greater than S-CO_2 rankine cycle (18.46 %) and SRC (24.48 %) cycle for medium waste heat source.
- S-CO_2 rankine cycle is not feasible for waste heat recovery because maximum exergy destroyed during the heat exchange in primary heat exchanger and exergy efficiency is 46% only.

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