Center for Advanced Turbomachinery and Energy Research
Laboratory for Turbine Aerodynamics Heat Transfer and Durability

EXERGOECONOMIC ANALYSIS OF A HYBRID SCO2 BRAYTON POWER CYCLE

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PRESENTATION OUTLINE

- **Part 1: Introduction**
- **Part 2: System Description**
  - **A- CSP Cycle**
  - **B- Oxy-combustion Cycle**
- **Part 3: System Modeling & Results**
  - **A- Thermodynamic Analysis**
  - **B- Exergoeconomic Analysis**
  - **C- Parametric Study**
- **Part 4: Conclusion & Future Work**

INTRODUCTION

Energy & Environmental Outlook (What is going on?)

Globally

- Global **energy generation** & consumption is **rising** due to:
  a. Populations and economic growth
  b. Higher living standards

Impact

- Power generation is a **major sources of GHG** emission (e.g. CO_2)
- GHG leads to global warming

Solution

- Renewables: Utilize renewable technologies (Solar, wind …etc.)
- Efficiency: Increase the efficiency of existing tech. (sCO_2, Oxy-combustion)
- Hybridize: Combine different technologies.

Our Response

Solar Power Generation Cycle + Conventional Power Generation Cycle = Hybrid Power Generation Cycle

- Increases: Reliability

- Decreases: GHG, losses & cost [34]

INTRODUCTION

Objective & **Motivation**

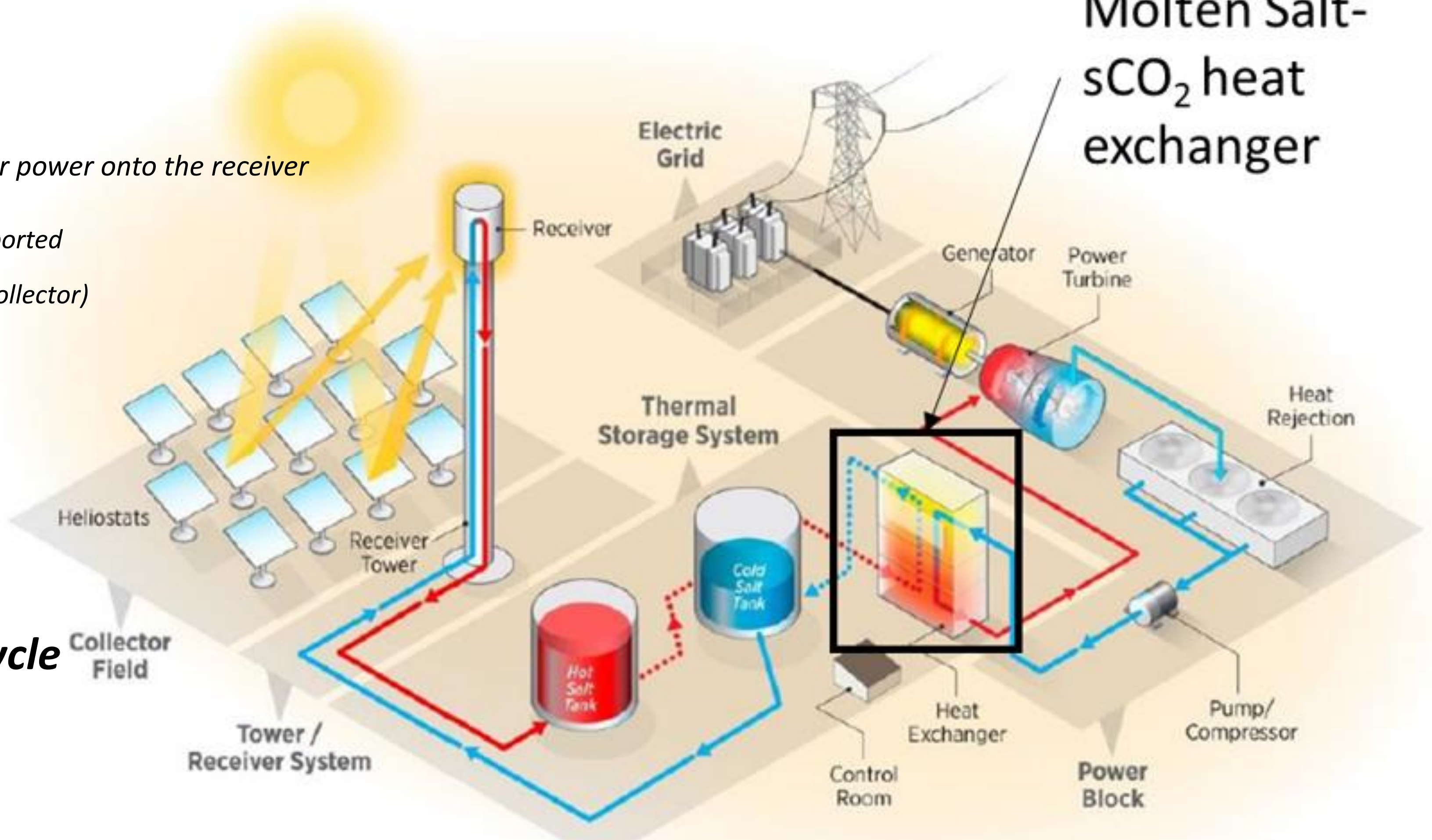
DEMAND	• Satisfy the increasing energy demand
ENVIRONMENT	• Fulfill environmental duty of care
ECONOMY	• Be economically viable
UNDERSTAND	• Leads to better cycle design & controls

INTRODUCTION

Solar Power Cycles: Concentrated Solar Power (CSP) Systems

- ***Consists of 4 main blocks**:*
  1. *Solar collector: Concentrates the solar power onto the receiver*
  2. *Solar receiver: Thermal energy is transported by heat transfer fluid (HTF) flowing through the collector)*
  3. *Thermal storage (hot & cold)*
  4. *Power block*

- *Blocks 1-3 are the **heat source***
- *Block 4 is the power **generation cycle***



Molten Salt-sCO_2 heat exchanger

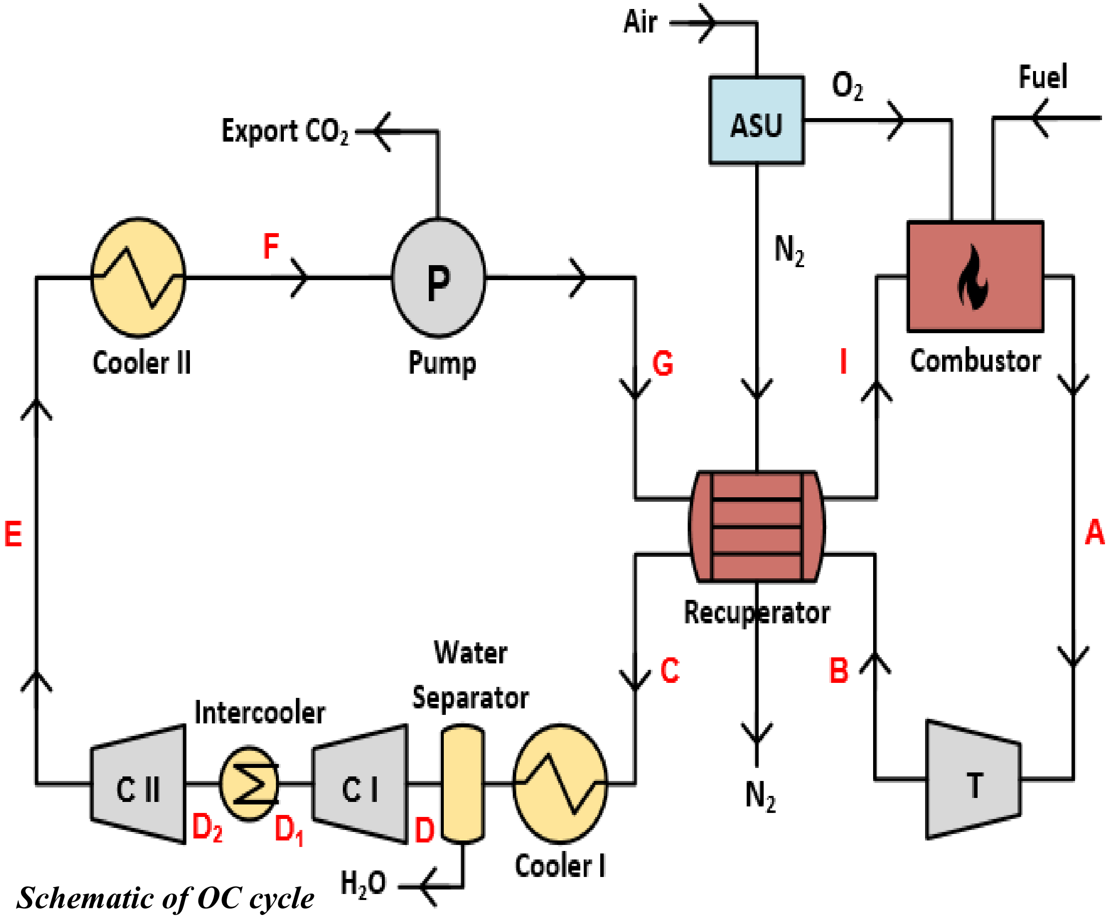
Schematic of CSP molten salt-based plant [18]

INTRODUCTION

Oxy-combustion Cycles (Allam Cycle)

Oxy-combustion cycles?

- They are cycles that utilize $\mathbf{O_2}$ **instead of air** for **combustion**
- Combustion reaction: $\boldsymbol{CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O}$
- Literature on Allam cycle claims η_{cycle} = 59 % [26]



Schematic of OC cycle

Advantages:

- OC is a clean energy tech. (carbon capture tech.)
- Main products: CO_2 & H_2O
- Resultant CO_2 is pure & at high pressure (ready for storage/export)
- Eliminates:
  - ✓ Air pollution resulting from the use of air (NO_x & SO_x)
  - ✓ Treatment processes (chem./phys.) for the combustion gases [24]

Disadvantages:

- ASU (cryogenic air separation) is energy intensive & have a parasitic effect on ηcycle [14]

  Solution: implement new air separation technology

- Combusting fuel in pure O2 → high temp. → negative on equipment structural integrity (safety)

  Solution: The CO_2 recycle stream 95% (O_2+ CH_4 = 5%) → dilutes O_2 & controls $T_{combustion}$

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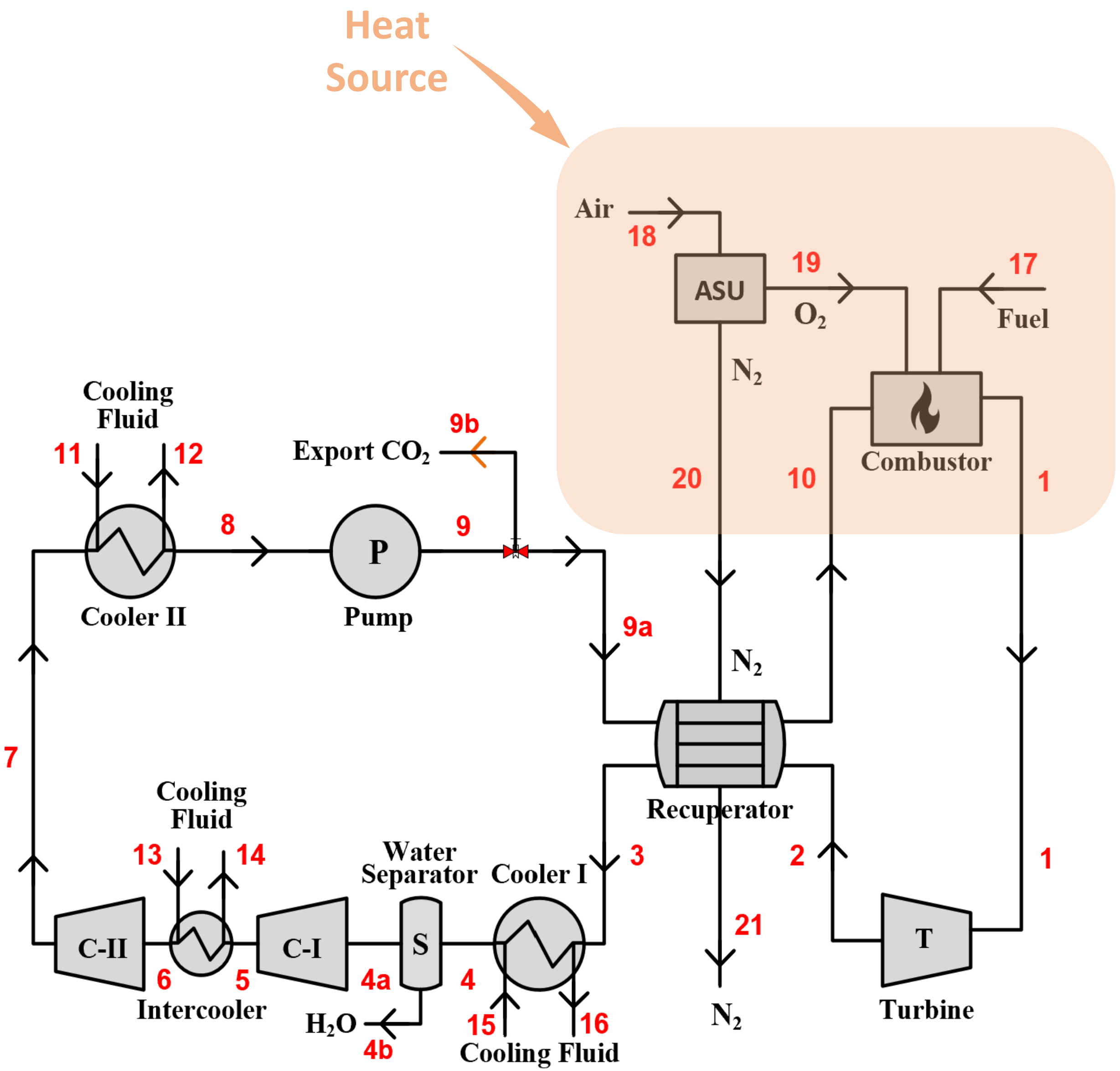
System Description

Proposed Hybrid Cycle

Item	*CSP Configuration*	*OC Configuration*
Cycle type	sCO_2 Brayton cycle	sCO_2 Brayton cycle
System type	Closed cycle	Semi- closed cycle
Working fluid	CO_2	CO_2 + H_2O
Cycle configuration	Simple recuperated	Simple recuperated
Heat source	Direct	Indirect
Heat input unit	CSP main HX	Combustor + ASU

Hybrid Cycle Unit	*Unique/Common*
Turbine	Common
Compressors I & II	Common
CO_2 export pumps	Common
Cooler I, Cooler II	Common
Recuperator	Common
CSP main heat exchanger	Unique to CSP configuration
Combustor	Unique to OC configuration
ASU	Unique to OC configuration
Water separator	Unique to OC configuration

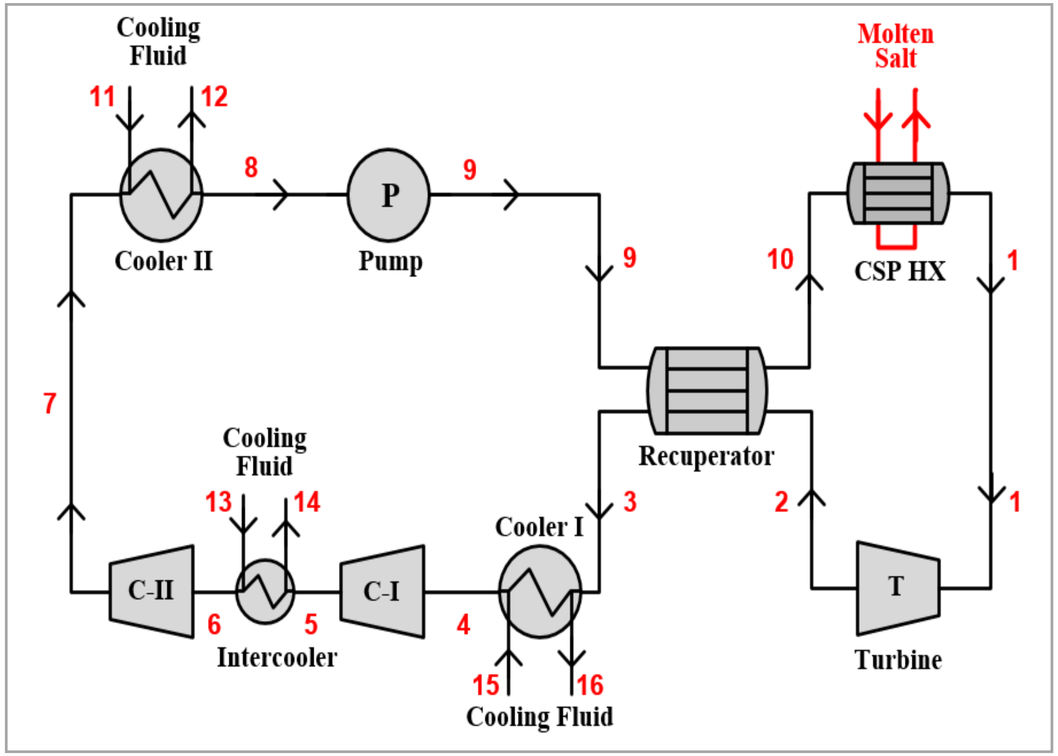


Process schematic of the hybrid cycle

System Description

A- CSP Standalone Configuration

- The CSP cycle is an RC configuration cycle also.
- The choice of the RC configuration is based on having the same equipment utilized for the NG Allam and CSP cycles.
- The CSP cycle is closed with no mass crossing its boundaries.
- The cycle consists of the main heat exchanger, a recuperator, coolers/heat exchangers, the compressor, the turbine and pumps.
- The heat into the cycle is gained at the main heat exchanger where the HTF with high thermal energy is heating up CO_2 stream before it is expanded in the turbine to produce work.
- Next, CO_2 is cooled down in a the recuperator while reheating the high-pressure CO_2 stream flowing back to the main heat exchanger.
- Then, CO_2 gas undergo intercooling compression (gas then liquid compression) in the same manner as in the NG Allam cycle where it goes into compression with intercooling as a gas then cooling at Cooler 2 to become liquid and finally boosted at the pump to a higher pressure.
- Finally, the high-pressure CO_2 stream flows back to the recuperator where it heats up before entering the main heat exchanger again.

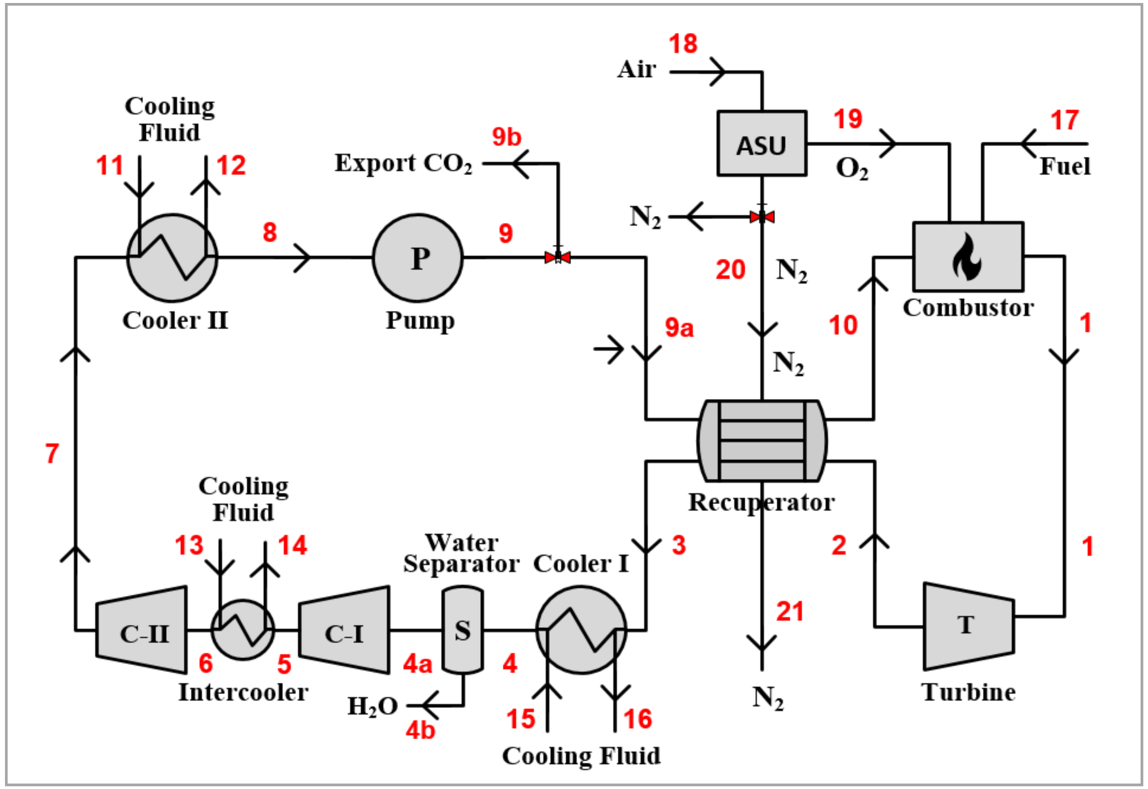


Process schematic of the standalone CSP Configuration

System Description

B- OC Standalone Configuration

- The hot CO_2 recycle stream coming from the recuperator, the fuel (CH_4) and pure O_2 stream from the ASU are burned at high-pressure at the combustor. CO_2 makes up to 95% of the mass flow rate in the combustor and the remaining 5% constitutes oxygen and fuel [16].
- To produce work, the combustion flue gases, mainly CO_2 and water (H_2O) are then expanded in the turbine where 90% of the flue gas entering the turbine is CO_2 [16].
- Flue gases are then cooled down in the recuperator while reheating the high-pressure CO_2 stream flowing back to the combustor.
- Then, the stream is cooled in cooler 1 and the water portion of the stream is separated and pumped out of the cycle before the remaining CO_2 gas undergoes intercooling compression (gas then liquid compression) in the compressor, cooler 2 and the pump.
- Gas compression is carried out in a two-stage compressor with intercooling while the pump is preceded with Cooler 2 to bring down the stream temperature.
- At this stage and after becoming a liquid, a portion of this high-pressure pure CO_2 is sent to export/storage whereas the rest of the stream flows back to the recuperator and then the combustor [15].



Process schematic of the standalone OC Configuration

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System Modeling & Results

Exergoeconomic Analysis Procedure

ENERGY & EXERGY ANALYSIS	• Assign all thermodynamic states • Assign exergy (Fuel + product + exergy destruction)
EXERGOECONOMIC ANALYSIS	• Assign Cost (Exergy + CAPEX + OPEX)
PERFORMANCE ECONOMIC ANALYSIS	• Assign base case cycle performance
PARAMETRIC STUDY	• Assign optimum values for single optimized variable

System Modeling & Results

Exergoeconomic Analysis Procedure

CONSERVATION (mass + energy)	Thermodynamic States	Inputs + outputs (MW)	Thermal efficiency
EXERGY	Exergy (process points) (MW)	Exergy (cycle units) (MW)	Exergy efficiency
EXERGOECONOMICS	(CAPEX + OPEX) cost rate ($/h)	Exergy cost rate ($/h)	Overall cost rate ($/h)

System Modeling & Results

Exergoeconomic Analysis: Assumptions & Input Parameters

The main system model assumptions

- All processes are under steady-state conditions.
- System heat losses to the environment are negligible.
- Potential and kinetic energy changes are negligible.
- The combustion process is complete.
- Combustion process flue gases are only H_2O and CO_2.
- Environmental ambient conditions are 25 ^{o}C and 1 atm.
- Turbine, compressors, and pumps assigned mean value isentropic efficiencies.
- Pressure drop is negligible for all equipment except for heat exchangers.
- The pressure drop for heat exchangers is 2%.
- A pinch point is assigned for all heat exchangers.
- Cooling water to coolers and intercooler is supplied at the dead state.

Model main input parameters

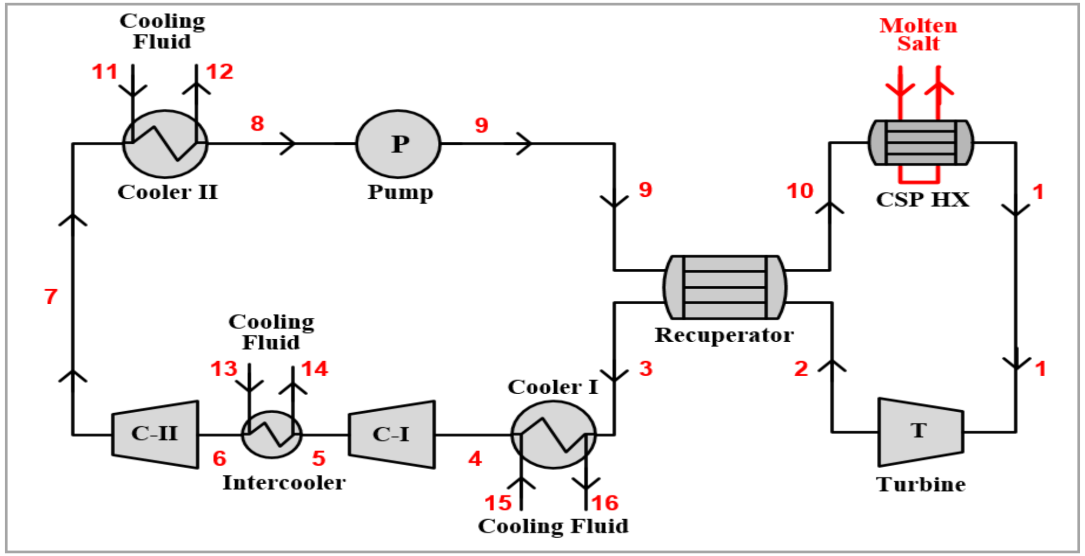
Parameter	**Value**
Dead state temperature (^{o}C)	25
Dead state pressure (bar)	1
Turbine isentropic efficiency (%)	90
Turbine inlet temperature (^{o}C)	700
Turbine inlet pressure (bar)	300
Turbine pressure ratio (--)	10
Turbine inlet mass flowrate (kg/s)	125
Minimum compressor inlet temperature (^{o}C)	20
Compressor inlet pressure (bar)	28.8
Compressor pressure ratio (--)	2.78
Compressor isentropic efficiency (%)	85
Pump isentropic efficiency (%)	80
Fractional pressure drop (%)	2
Cooler pinch point temperature (^{o}C)	5

System Modeling & Results

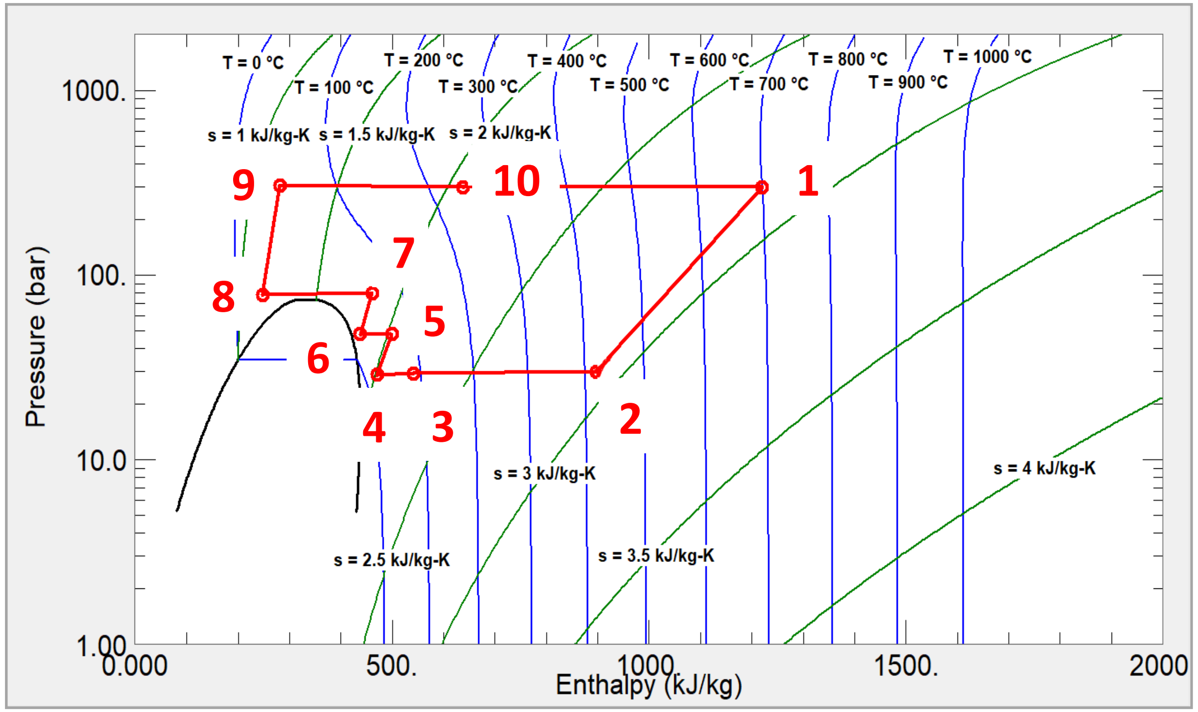
Part A: Thermodynamic Analysis (Results)

P, T & h of the main process points for CSP configuration

Process Point	CSP Standalone Configuration		
	P (bar)	T (K)	h (kJ/kg CO_2)
A	300	973.15	1223.5
B	30	692.27	897.57
C	29.4	359.06	541.58
D	28.81	293.15	470.87
E	80	334.45	462.15
F	78.4	293.00	247.51
G	306.12	318.98	282.10
I	300	519.55	637.47



CSP configuration standalone process schematic



CSP configuration standalone log P-h diagram

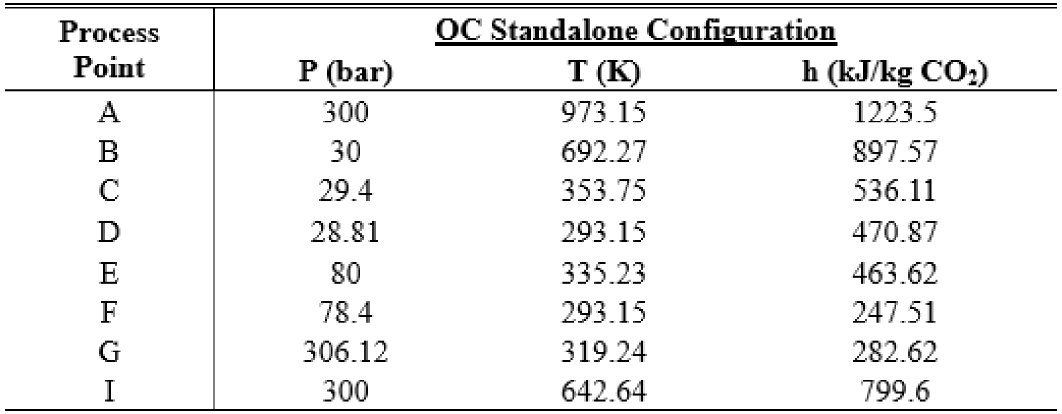
Model validation:

The model η_{cycle} = *61.64%* which is close to the number *(η_{cycle} = 59%)* reported by Allam et al [26]

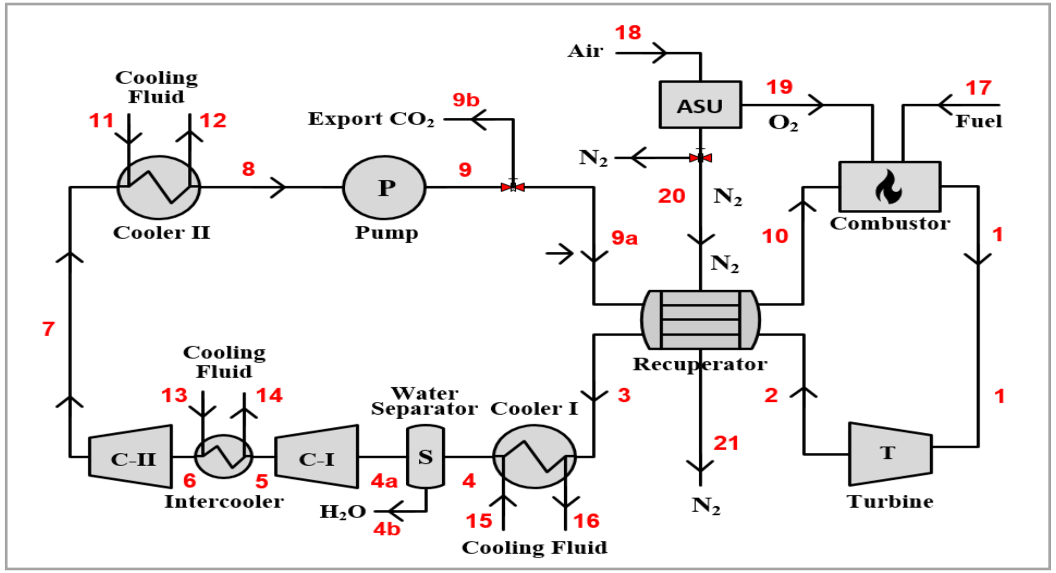
System Modeling & Results

Part A: Thermodynamic Analysis (Results)

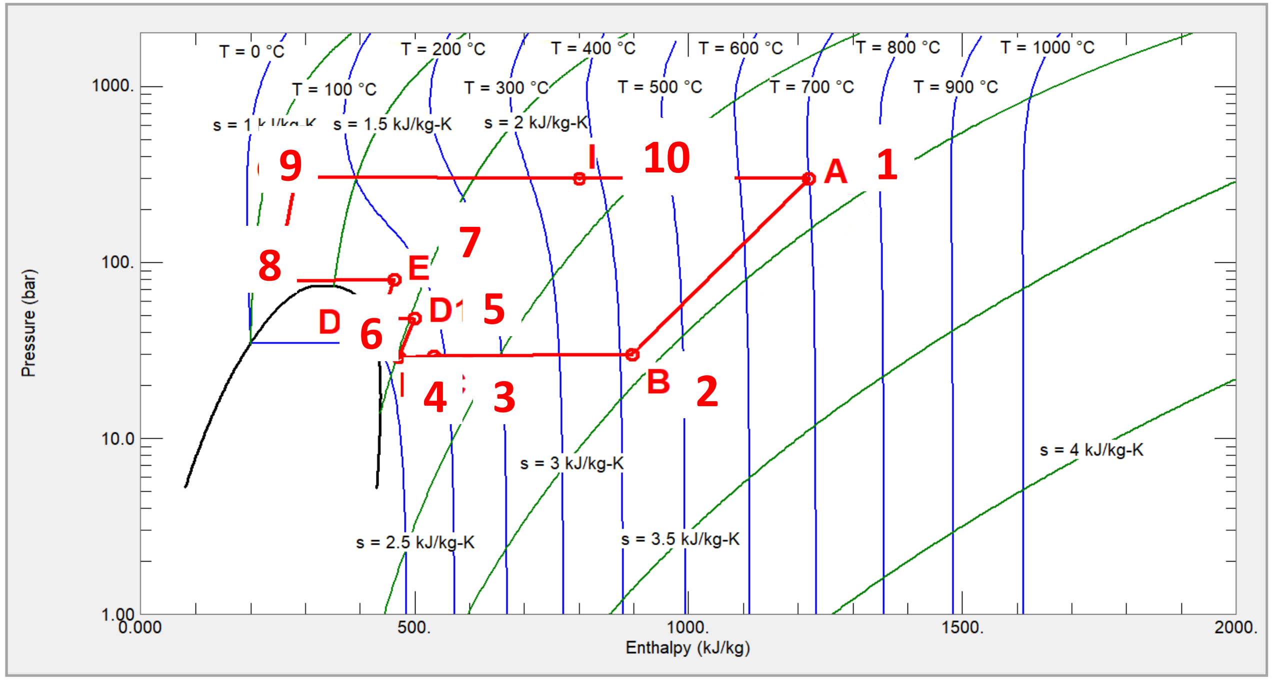
P, T & h of the main process points for OC configuration



Process Point	OC Standalone Configuration		
	P (bar)	T (K)	h (kJ/kg CO_2)
A	300	973.15	1223.5
B	30	692.27	897.57
C	29.4	353.75	536.11
D	28.81	293.15	470.87
E	80	335.23	463.62
F	78.4	293.15	247.51
G	306.12	319.24	282.62
I	300	642.64	799.6

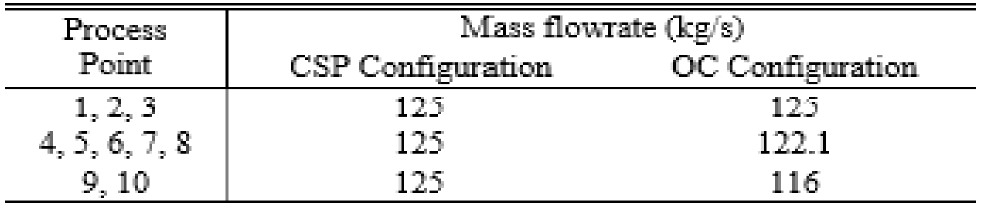


OC configuration schematic



OC standalone configuration log P-h diagram

Mass flow rates at the hybrid's main process points



Process Point	Mass flowrate (kg/s)	
	CSP Configuration	OC Configuration
1, 2, 3	125	125
4, 5, 6, 7, 8	125	122.1
9, 10	125	116

System Modeling & Results

Part B: Exergoeconomic Analysis (Results)

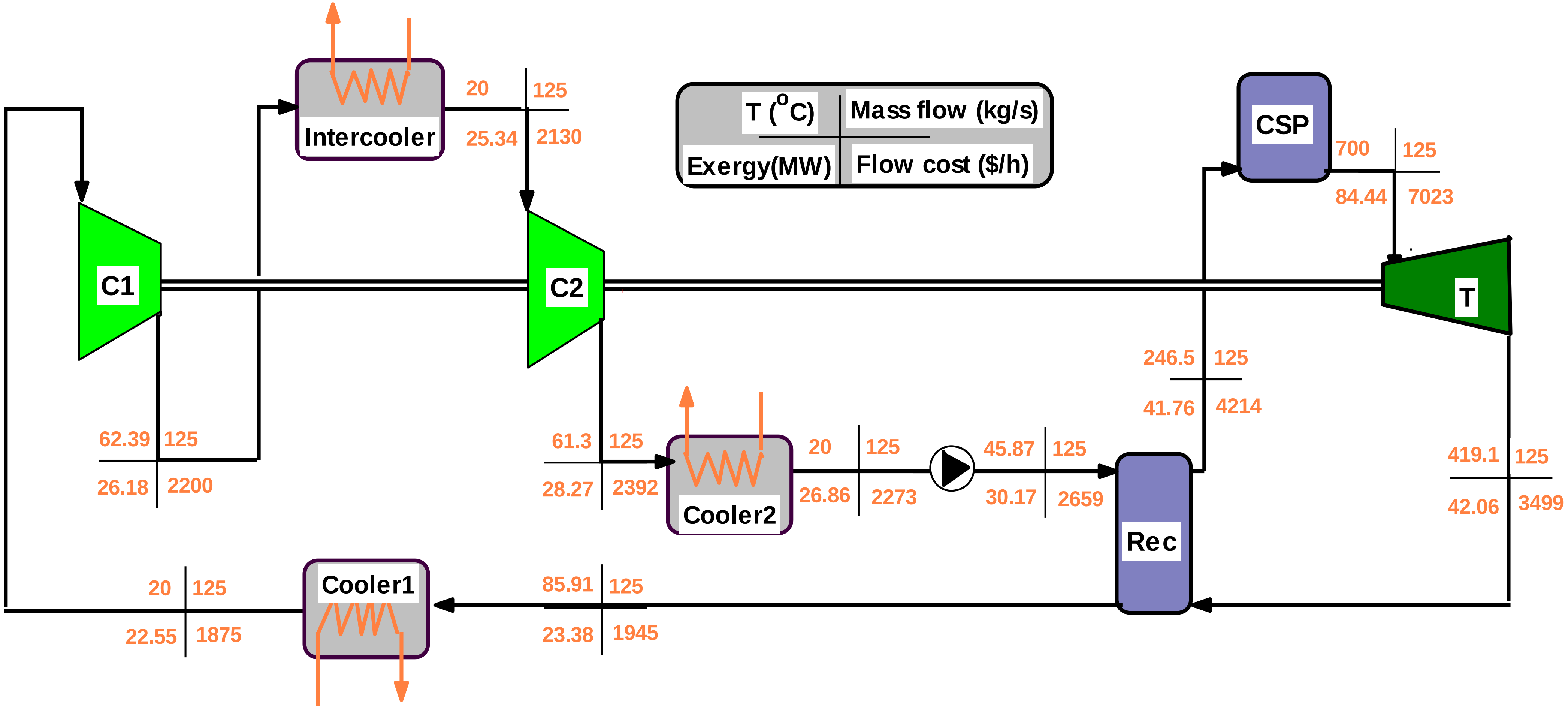
- Applying energy, exergy and economic equations result in a system of linear equations.
- The mathematical system is coded.
- **Software:** Engineering Equation Solver (EES)

Model main output parameters (The base case)

Parameter	CSP Configuration	OC Configuration
Net power (MW)	29.52	30.73
First law efficiency (%)	40.55	47.38
Second law efficiency (%)	56.92	54.72
Total unit cost of the product ($/GJ)	27.55	12.98
Unit cost of electricity (Cent/kWh)	9.8	6.1

System Modeling & Results

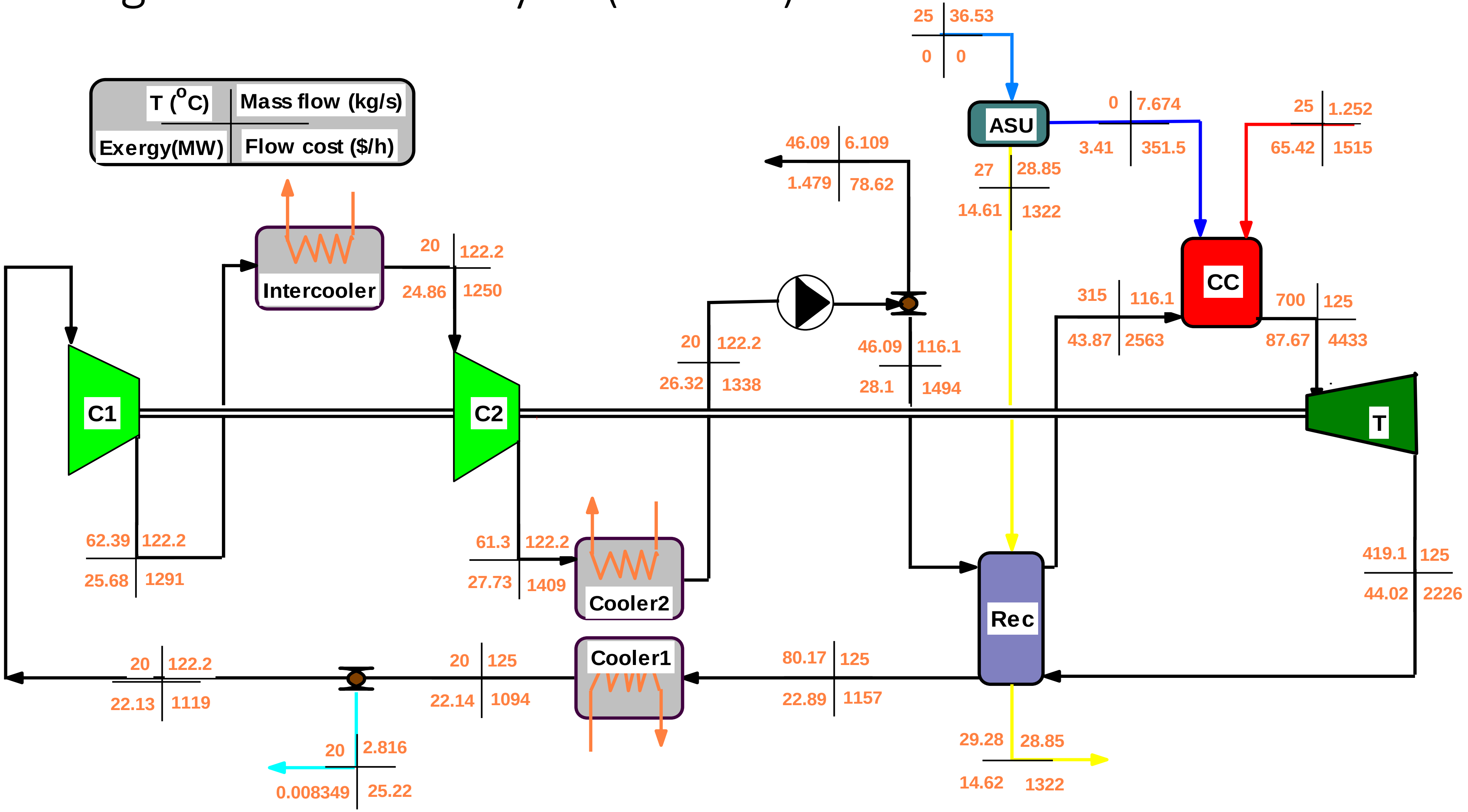
Part B: Exergoeconomic Analysis (Results)



Mass, exergy, and cost flowrates of the hybrid cycle CSP standalone configuration

System Modeling & Results

Part B: Exergoeconomic Analysis (Results)

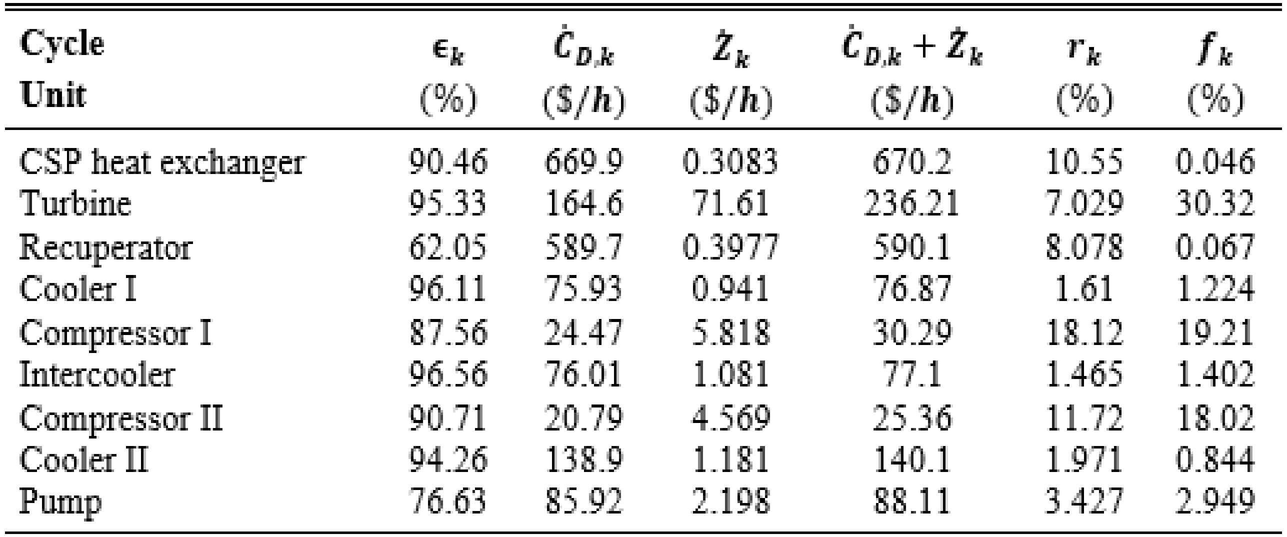


Mass, exergy, and cost flowrates of the hybrid cycle OC standalone configuration

System Modeling & Results

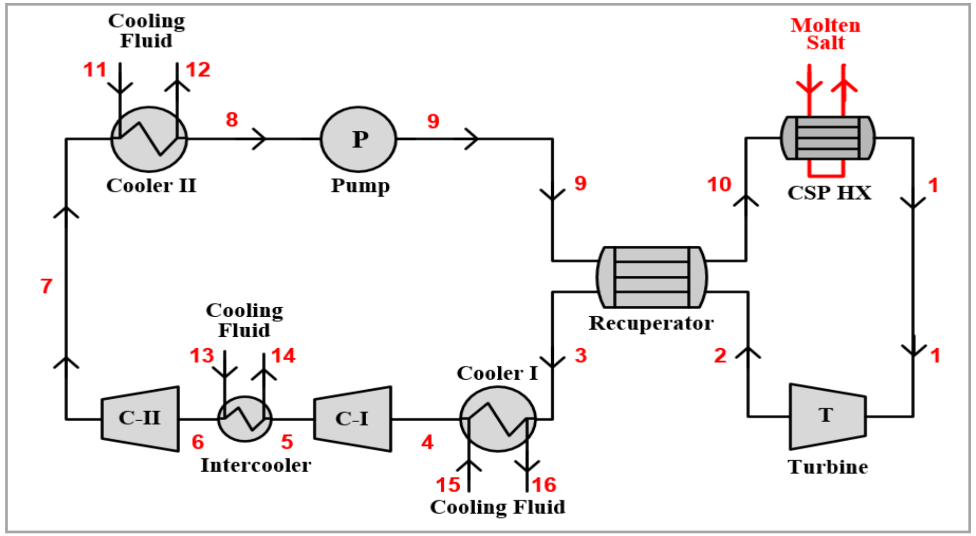
Part B: Exergoeconomic Analysis (Results)

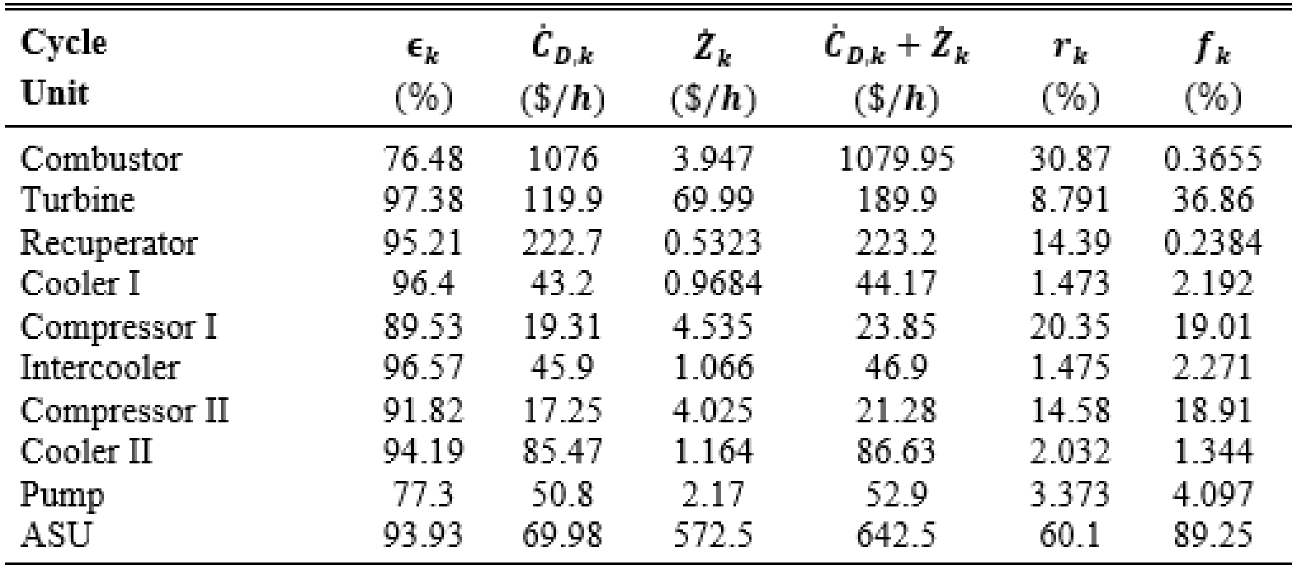
Base Case



Cycle Unit	ϵ_k (%)	$\dot{C}_{D,k}$ (\$/h)	$\dot{Z}_k$ (\$/h)	$\dot{C}_{D,k} + \dot{Z}_k$ (\$/h)	r_k (%)	f_k (%)
CSP heat exchanger	90.46	669.9	0.3083	670.2	10.55	0.046
Turbine	95.33	164.6	71.61	236.21	7.029	30.32
Recuperator	62.05	589.7	0.3977	590.1	8.078	0.067
Cooler I	96.11	75.93	0.941	76.87	1.61	1.224
Compressor I	87.56	24.47	5.818	30.29	18.12	19.21
Intercooler	96.56	76.01	1.081	77.1	1.465	1.402
Compressor II	90.71	20.79	4.569	25.36	11.72	18.02
Cooler II	94.26	138.9	1.181	140.1	1.971	0.844
Pump	76.63	85.92	2.198	88.11	3.427	2.949

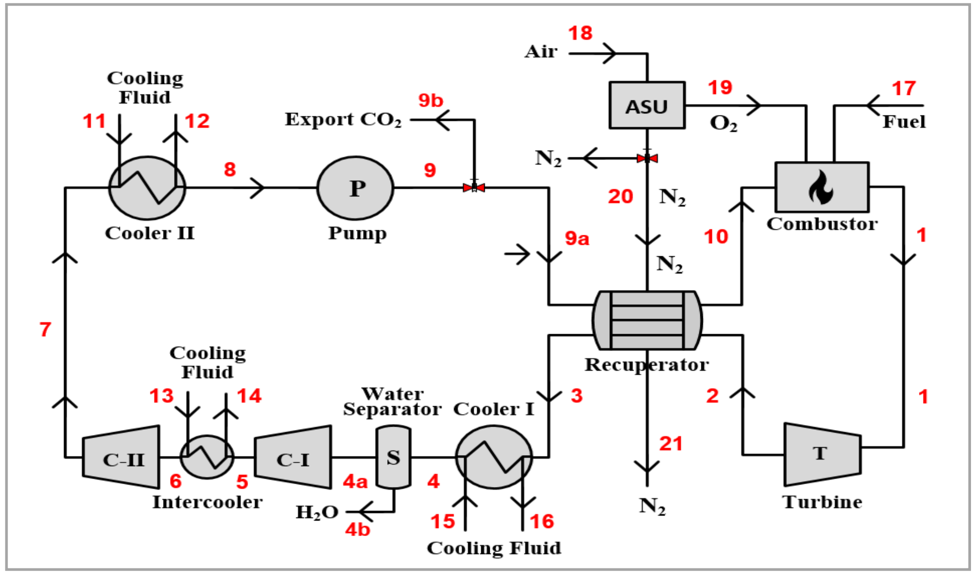
CSP





Cycle Unit	ϵ_k (%)	$\dot{C}_{D,k}$ (\$/h)	$\dot{Z}_k$ (\$/h)	$\dot{C}_{D,k} + \dot{Z}_k$ (\$/h)	r_k (%)	f_k (%)
Combustor	76.48	1076	3.947	1079.95	30.87	0.3655
Turbine	97.38	119.9	69.99	189.9	8.791	36.86
Recuperator	95.21	222.7	0.5323	223.2	14.39	0.2384
Cooler I	96.4	43.2	0.9684	44.17	1.473	2.192
Compressor I	89.53	19.31	4.535	23.85	20.35	19.01
Intercooler	96.57	45.9	1.066	46.9	1.475	2.271
Compressor II	91.82	17.25	4.025	21.28	14.58	18.91
Cooler II	94.19	85.47	1.164	86.63	2.032	1.344
Pump	77.3	50.8	2.17	52.9	3.373	4.097
ASU	93.93	69.98	572.5	642.5	60.1	89.25

OC



System Modeling & Results

Part C: Parametric study

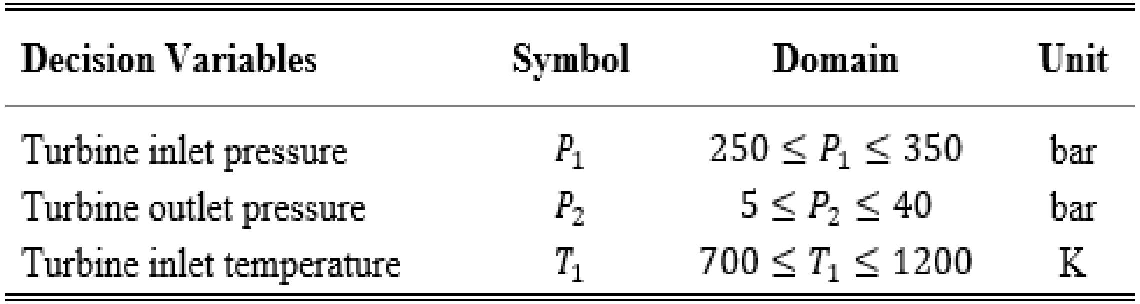
Decision variable:

- Utilized to evaluate the cycle's performance.
- Utilized for parametric & multi-objective optimization.
- Utilized to compute the dependent variables.
- Decision variables must be independent of each other.
- Carefully selected to arrive at meaningful conclusions

Dependent variables (performance indicators):

- Utilized to assess the studied systems.
- Dependent variables selected for this study are:
  a. Exergy efficiency (η_{ex}).
  b. Levelized cost of electricity (*LCOE*).

Decision variable for the parametric study

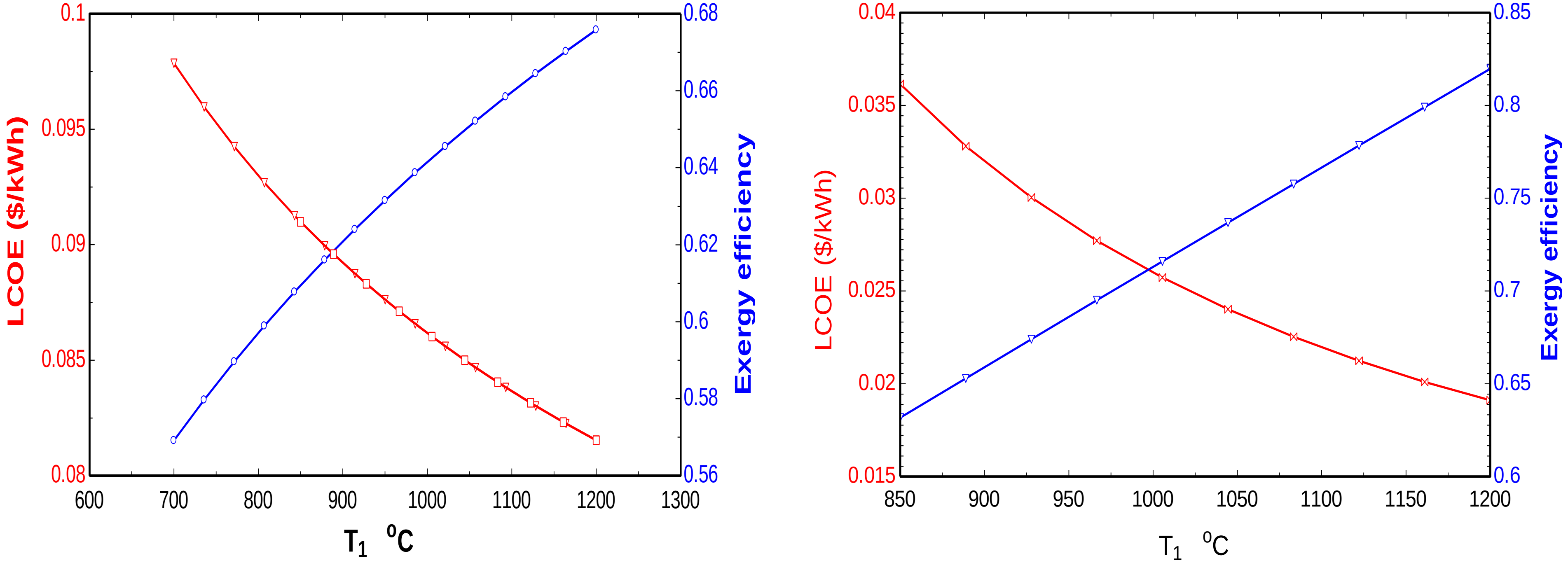


Decision Variables	Symbol	Domain	Unit
Turbine inlet pressure	P_1	$250 \leq P_1 \leq 350$	bar
Turbine outlet pressure	P_2	$5 \leq P_2 \leq 40$	bar
Turbine inlet temperature	T_1	$700 \leq T_1 \leq 1200$	K

System Modeling & Results

Part C: Parametric study (Results)

Conclusion: *Increasing $T_{turb,in}$ is conducive to improving the thermodynamic and exergoeconomic performances of both configurations.*



(a) CSP Configuration

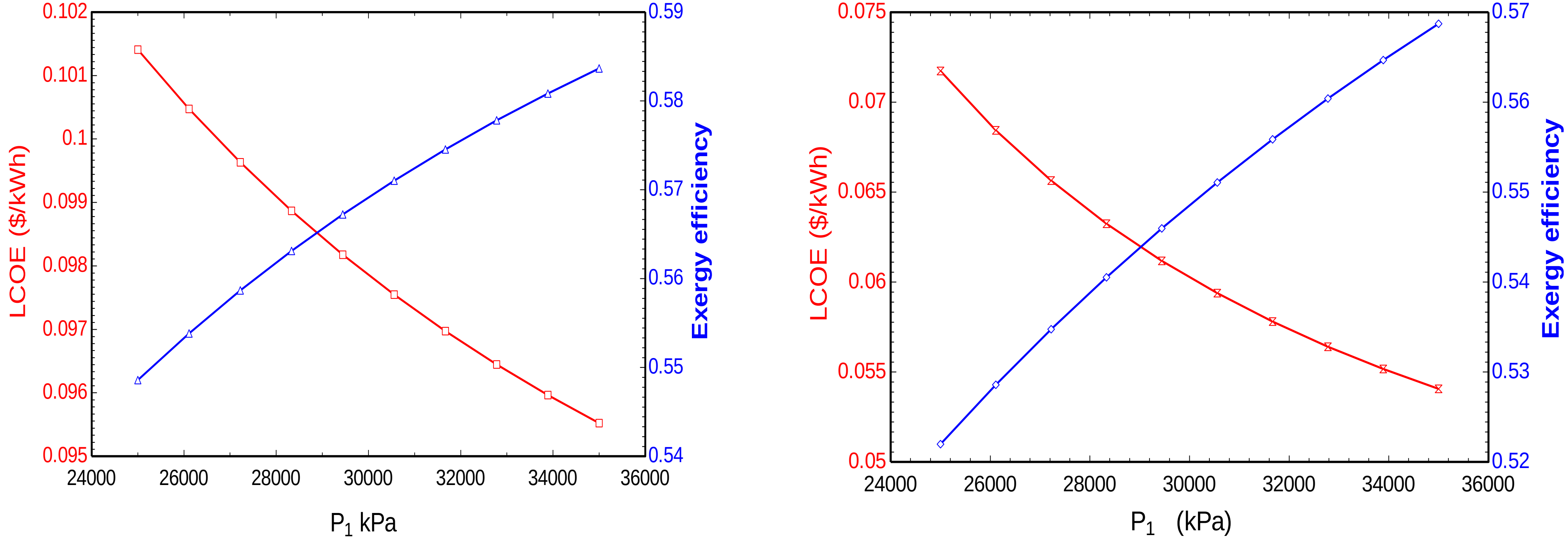
(b) OC Configuration

Variations of exergy efficiency and LCOE with turbine inlet temperature (T_1)

System Modeling & Results

Part C: Parametric study (Results)

Conclusion: *Increasing* $P_{turb,in}$ *is conducive to improving the thermodynamic and exergoeconomic performances of both configurations.*



(a) CSP Configuration

(b) OC Configuration

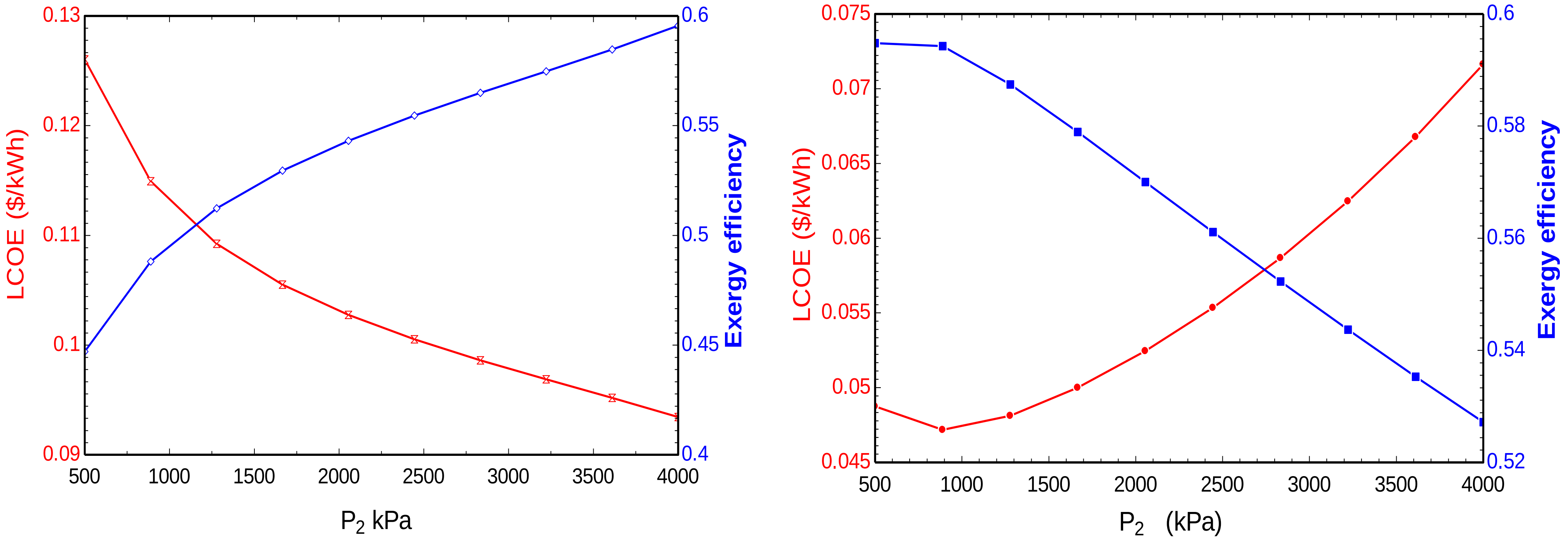
Variations of exergy efficiency and LCOE with turbine inlet pressure (P_1)

System Modeling & Results

Part C: Parametric study (Results)

Conclusion:

- ***CSP***: *The decrease in* $P_{turb,out}$ *decreases the turbine's produced power & compressor power consumption.*
- ***OC***: *The decrease in* $P_{turb,out}$ *results in a decrease in CAPEX and OPEX, which results in a decrease in LCOE as shown.*



(a) CSP Configuration

(b) OC Configuration

Variations of exergy efficiency and LCOE with turbine exit pressure (P_2)

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Conclusion
Exergoeconomic Analysis

In general:

- Both configurations obtained similar power output (30 MW) and second law efficiency (55%) .
- OC configuration’s thermal efficiency was higher (7%).
- The total product cost in ($/GJ) for the OC was half of that of the CSP.
- The unit cost of electricity in (Cent/kWh) for the CSP standalone configuration is 60% higher than OC configuration.

CSP Configuration:

- The main heat exchanger and recuperator are the most critical units to consider for savings.
- Reducing exergy destruction in main heat exchanger and recuperator is cost-effective for the entire cycle (even if it increases the component investment costs).
- Recommendation: Recuperator with higher efficiency will enhance exergoeconomic performance.

OC Configuration:

- The combustor and ASU are the most critical units for savings considerations.
- Replacement of ASU with a lower capital cost is recommended for overall exergoeconomic performance enhancement.

Conclusion

Exergoeconomic Analysis

Parametric Study:

$\boldsymbol{T}_{\mathbf{turb},\boldsymbol{in}}$:

- Increasing $T_{turb,in}$ improves the thermodynamic and exergoeconomic performances for both configurations.

$\boldsymbol{P}_{\boldsymbol{turb},\boldsymbol{in}}$:

- Similar trends for $P_{turb,in}$ for both configurations.

$\boldsymbol{P}_{\mathbf{turb},\boldsymbol{out}}$:

- The decrease in $P_{turb,out}$ decreases both turbine's produced power & compressor power consumption.
- CSP: The decrease in $P_{turb,out}$ results in a decrease in CAPEX and OPEX, which results in a decrease in LCOE.

Future Work

Conduct the following studies:

- An optimization study on the hybrid cycle.
- A dynamic simulation of the recuperator of the OC configuration.
- A dynamic simulation of the whole cycle.

THANK YOU

Questions?