Article

Modeling of Combined Lead Fast Reactor and Concentrating Solar Power Supercritical Carbon Dioxide Cycles to Demonstrate Feasibility, Efficiency Gains, and Cost Reductions

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Abstract: Separate cycles for solar concentrating power and lead fast reactors, which innately have issues with weather, grid demand, and time of day, have potential to benefit when coupled together in a supercritical CO2 Brayton cycle. Combining these cycles could allow for the lead fast reactor cycle to thermally charge the salt storage in the solar concentrating power cycle during low demand periods and be utilized when grid demand increases. The implementation of the independent cycles into one cycle is modeled to find the preferred location of the lead fast reactor heat exchanger, concentrating solar power heat exchanger, salt charging heat exchanger, turbines, and recuperators within the supercritical CO2 Brayton cycle. Three cycle configurations have been studied: a two-cycle configuration which uses CSP and LFR heat for dedicated turbocompressors, combined cycle with two high temperature recuperators for both the CSP and LFR, and a combined cycle with CSP and LFR heat sources in parallel. [CONCLUSION]

Keywords: Supercritical carbon dioxide Brayton Cycle; Concentrating Solar Power (CSP); Lead Fast Reactor (LFR), Cogeneration, Combined Cycle, Thermal Energy Storage (TES)

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1. Introduction

2. Materials and Methods

2.1. Cycle Component Modeling

2.1.1. Heat Exchangers

2.1.2. Turbines

2.1.3. Compressors

2.1.4. Concentrating Solar Power Cycle

2.2. Cycle Models

3. Results

3.1. Cycle Configurations

Table 1. Constant cycle parameters with definition, variable and set value. The variables with (*) have changing labels depending on the specific cycle diagram.

Parameter	Variable	Design Point Value
Efficiencies		
Main Compressor	η_{MC}	0.91 (-)
Re-Compressor	η_{RC}	0.89 (-)
Turbine	η_T	0.90 (-)
Pump	η_P	0.90 (-)
Approach Temperatures		
Low Temperature Recuperator	δ_{LTR}	10 (K)
High Temperature Recuperator	δ_{HTR}	10 (K)
Concentrating Solar Power Heat Exchanger	δ_{CSPHX}	10 (K)
Pressures		
Pressure Ratio	PR	3.27 (-)
High Side Pressure	(*)	2.88e7 (Pa)
Heat Into System		
Lead-Fast Reactor Heat Transfer	$\dot{Q}_{LFRHX}$	9.5e8 (W)
Concentrating Solar Power Heat Transfer	$\dot{Q}_{CSP}$	7.5e8 (W)
Temperature		
Main Compressor Inlet	(*)	313.2 (K)
Lead-Fast Reactor Low Temperature	(*)	673.2 (K)
Pumps		
Pressure Rise Across Pump	Δ_P	3.726e6 (Pa)
Pump Low Side Pressure	(*)	3.0e6 (Pa)

3.1.1. C-LFR-ON

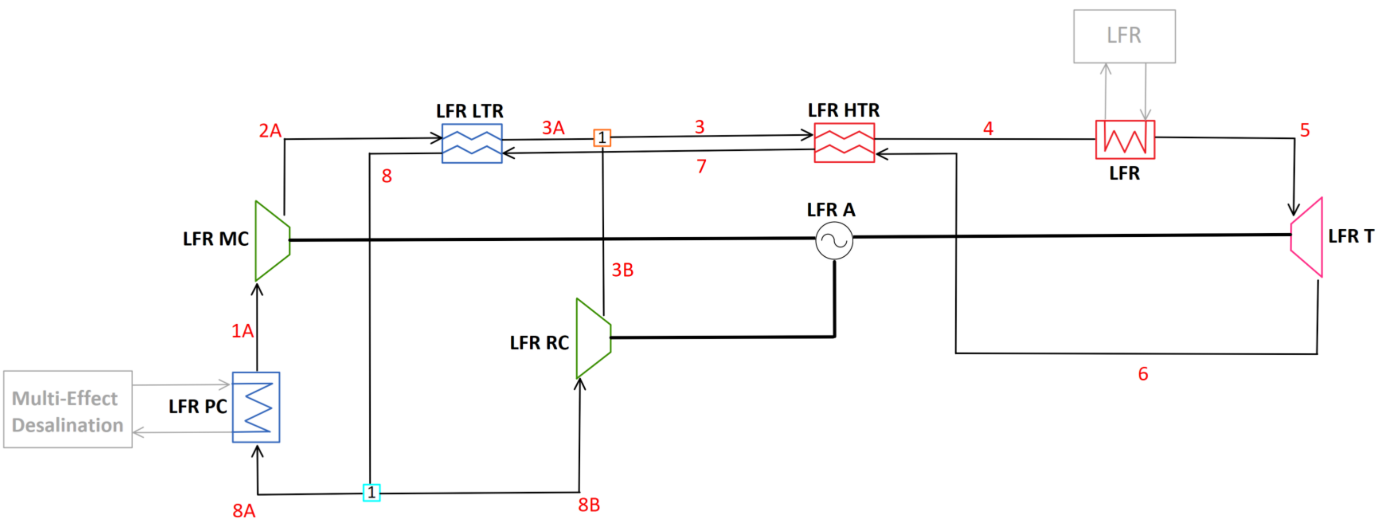


Figure 1. Diagram for C-LFR-ON with focus on electricity generation

Table 2. State points calculated at steady state operation and LFR low temperature constrained to 673.2 K for C-LFR-ON cycle.

Diagram Label	Temperature (K)	Pressure (Pa)	Mass Flow (kg/s)	Enthalpy (J/kg)
1a-A	313.2	8.807e6	3029	-149660
1b-A	313.2	8.807e6	3029	-149660
2a-A	374.2	2.88e7	3029	-110393
2b-A	374.2	2.88e7	3029	-110393
3a-A	438.2	2.88e7	3029	10618
3a-B	506.4	2.88e7	832.4	114847
3b	451.9	2.88e7	3861	33089
3b-A	451.9	2.88e7	3861	33089
4a-A	673.2	2.88e7	3861	333669
4b	673.2	2.88e7	3861	333669
5a	868.2	2.88e7	3861	579720
5b	868.2	2.88e7	3861	579720
6a	722.8	8.807e6	3861	417482
6b	722.8	8.807e6	3861	417482
7a	722.8	8.807e6	3861	417482
7b	722.8	8.807e6	3861	417482
8a	461.9	8.807e6	3861	116902
8b	461.9	8.807e6	3861	116902
9a	384.2	8.807e6	3861	21981
9b-A	384.2	8.807e6	3029	21981
9b-B	384.2	8.807e6	834.2	21981

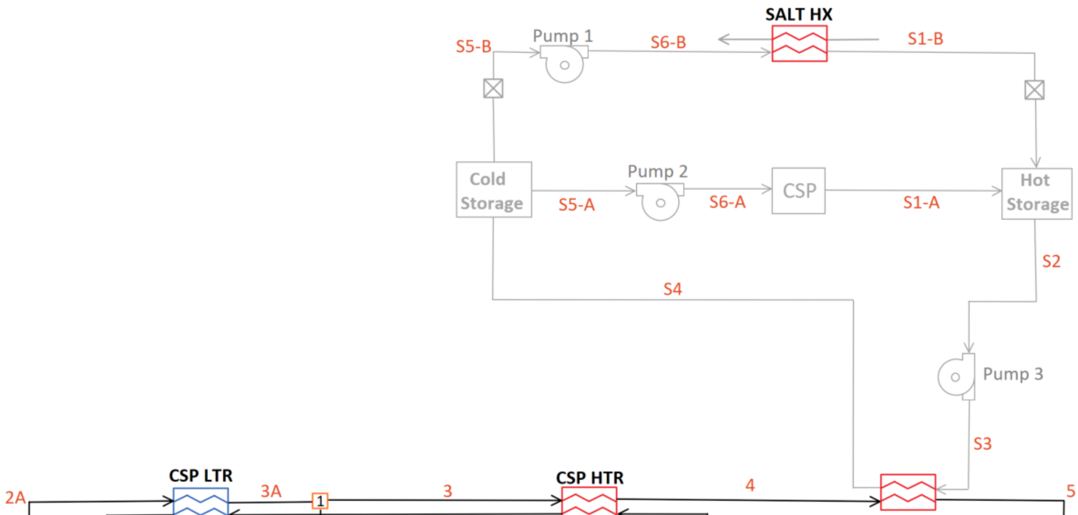
Definition	Variable	Calculated Value
Cycle Efficiency (%)	η_{cycle}	45.28
Alternator Power (W)	$\dot{W}_A$	4.302e8
PreCooler Heat Transfer (W)	$\dot{Q}_{PC}$	5.198e8
Main Compressor Power (W)	$\dot{W}_{MC}$	1.189e8
ReCompressor Power (W)	$\dot{W}_{RC}$	7.730e7
Turbine Power (W)	$\dot{W}_T$	6.264e8
Main Compressor Mass Flow Fraction (-)	y_1	0.7844
LTR UA Value (W/K)	UA_{LTR}	2.284e7
LTR Capacitance Ratio (-)	CR_{LTR}	0.8473
LTR Heat Transfer Rate (W)	$\dot{Q}_{LTR}$	3.665e8
LTR Effectiveness (-)	ε_{LTR}	0.8742
HTR UA Value (W/K)	UA_{HTR}	4.271e7
HTR Capacitance Ratio (-)	CR_{HTR}	0.9627
HTR Heat Transfer Rate (W)	$\dot{Q}_{HTR}$	1.161e9
HTR Effectiveness (-)	ε_{HTR}	0.9627

Table 3. State points calculated at steady state operation with LFR low temperature unconstrained and cycle efficiency maximized for C-LFR-ON cycle.

Diagram Label	Temperature (K)	Pressure (Pa)	Mass Flow (kg/s)	Enthalpy (J/kg)
1a-A	313.2	8.807e6	2929	-149660
1b-A	313.2	8.807e6	2929	-149660
2a-A	374.2	2.88e7	2929	-110393
2b-A	374.2	2.88e7	2929	-110393
3a-A	505.7	2.88e7	2929	113832
3a-B	506.4	2.88e7	1255	114847
3b	505.9	2.88e7	4184	114137
3b-A	505.9	2.88e7	4184	114137
4a-A	688.3	2.88e7	4184	352679
4b	688.3	2.88e7	4184	352679
5a	868.2	2.88e7	4184	579720
5b	868.2	2.88e7	4184	579720
6a	722.8	8.807e6	4184	417482
6b	722.8	8.807e6	4184	417482
7a	722.8	8.807e6	4184	417482
7b	722.8	8.807e6	4184	417482
8a	515.9	8.807e6	4184	178939
8b	515.9	8.807e6	4184	178939
9a	384.2	8.807e6	4184	21981
9b-A	384.2	8.807e6	2929	21981
9b-B	384.2	8.807e6	1255	21981

Definition	Variable	Calculated Value
Cycle Efficiency (%)	η_{cycle}	47.08
Alternator Power (W)	$\dot{W}_A$	4.473e8
PreCooler Heat Transfer (W)	$\dot{Q}_{PC}$	5.027e8
Main Compressor Power (W)	$\dot{W}_{MC}$	1.150e8
ReCompressor Power (W)	$\dot{W}_{RC}$	1.166e8
Turbine Power (W)	$\dot{W}_T$	6.789e8
Main Compressor Mass Flow Fraction (-)	y_1	0.7000
LTR UA Value (W/K)	UA_{LTR}	5.468e7
LTR Capacitance Ratio (-)	CR_{LTR}	0.9867
LTR Heat Transfer Rate (W)	$\dot{Q}_{LTR}$	6.568e8
LTR Effectiveness (-)	ε_{LTR}	0.92
HTR UA Value (W/K)	UA_{HTR}	4.829e7
HTR Capacitance Ratio (-)	CR_{HTR}	0.8657
HTR Heat Transfer Rate (W)	$\dot{Q}_{HTR}$	9.981e8
HTR Effectiveness (-)	ε_{HTR}	0.9544

3.1.2. C-CSP-ON



3.1.3. C-1HTR1T-ON

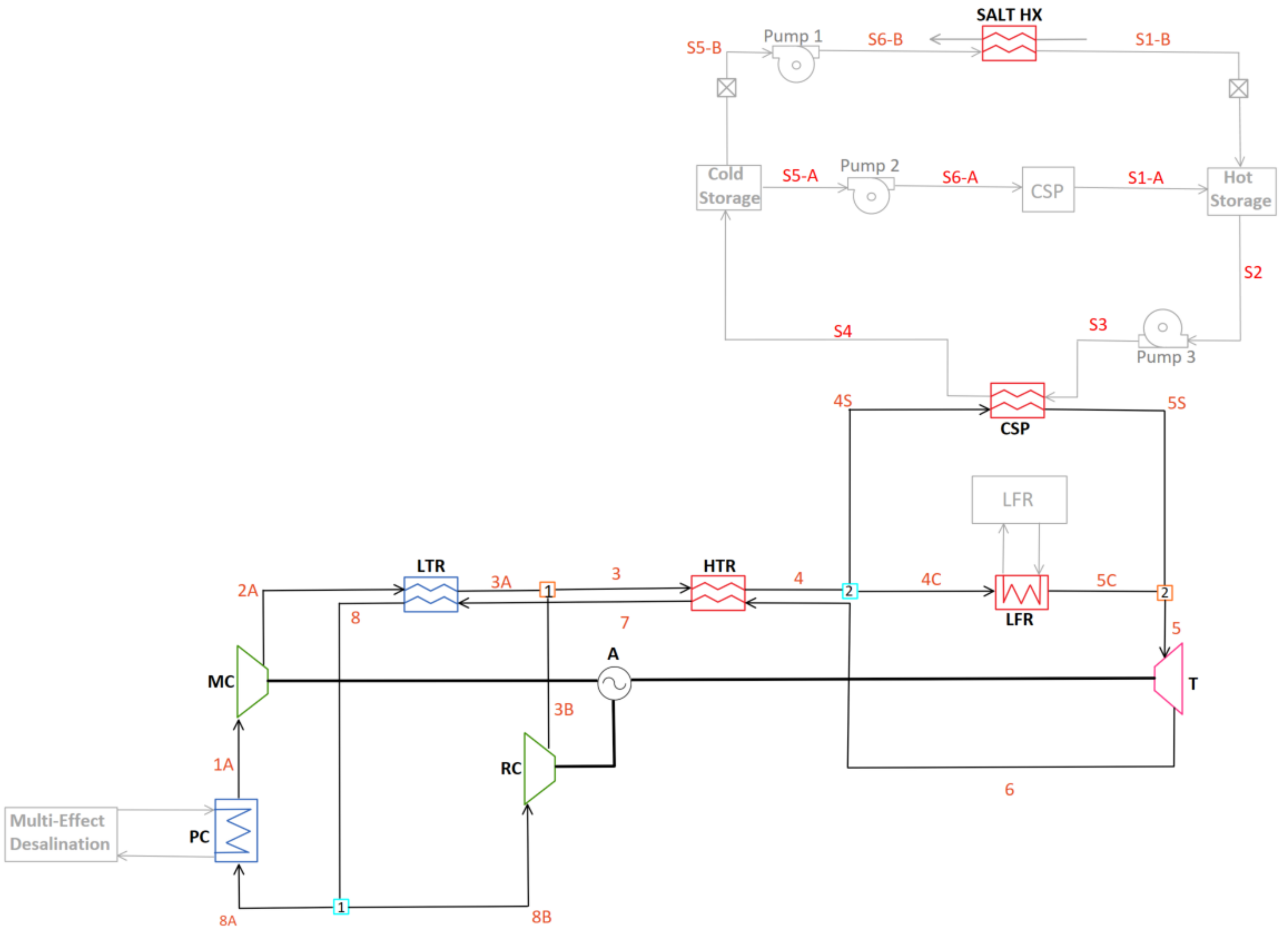


Figure 3. Diagram for C-1HTR1T-ON with focus on electricity generation

3.1.4. C-2HTR3T-ON

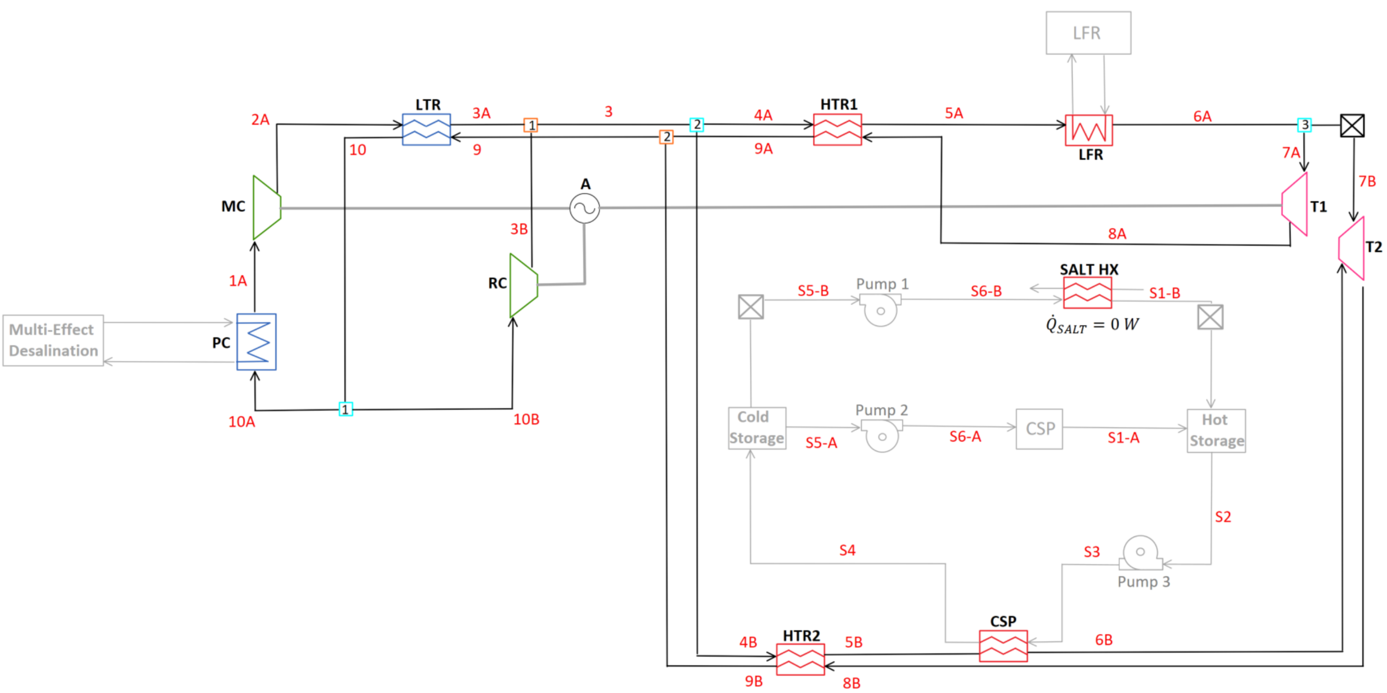


Figure 4. Diagram for C-2HTR3T-ON with focus on electricity generation

3.2. Thermal Energy Storage Charging Techniques

3.2.1. C-LFR-PRE

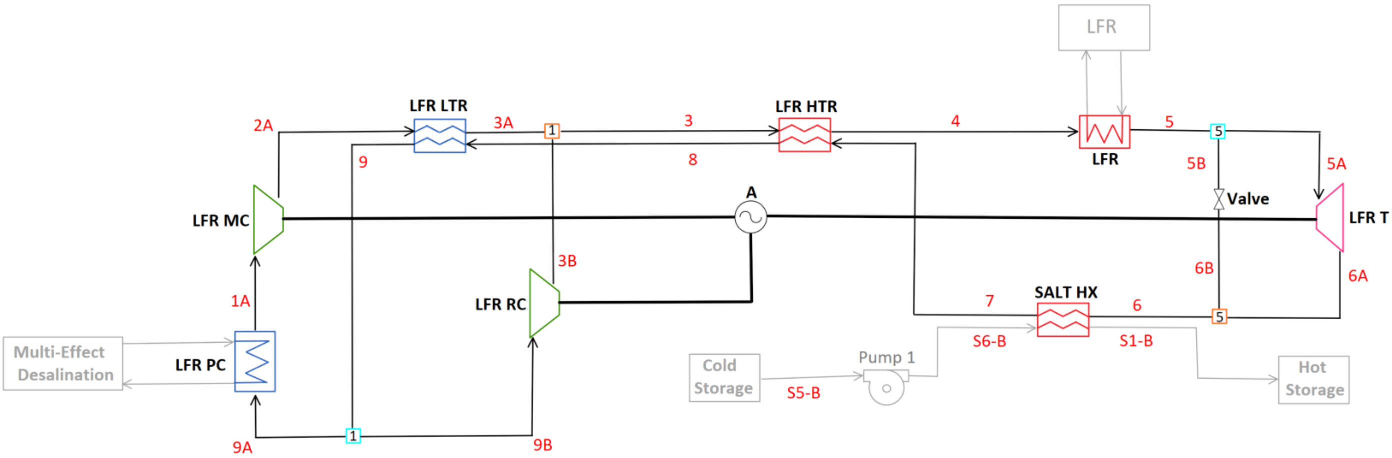


Figure 5. Diagram for C-LFR-PRE thermal energy storage charging orientation

3.2.2. C-LFR-POST

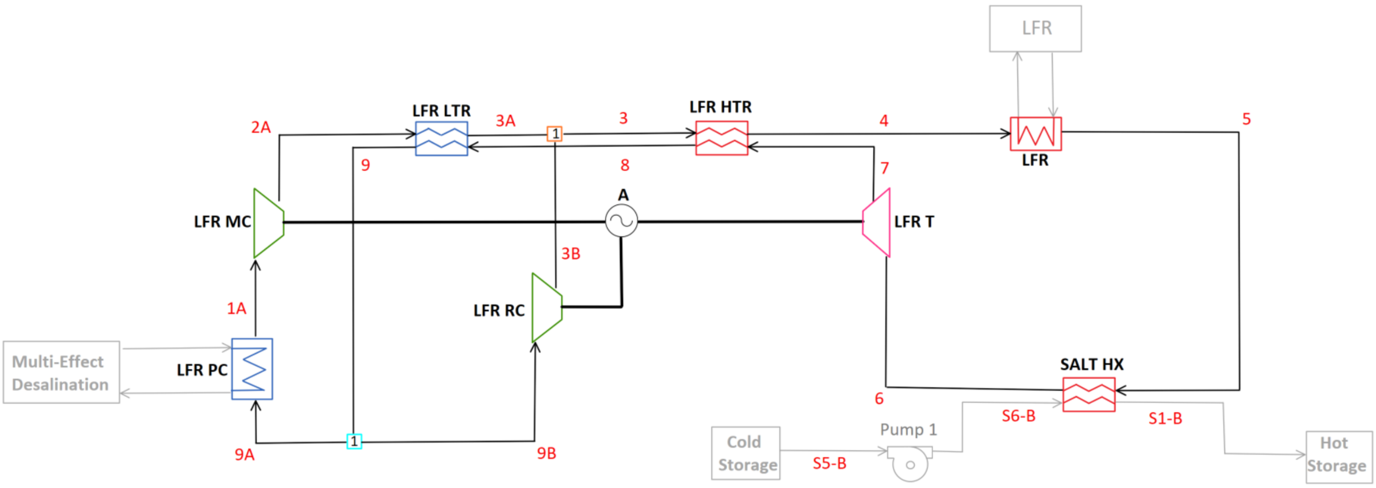


Figure 6. Diagram for C-LFR-POST thermal energy storage charging orientation

3.2.3. C-LFR-PAR

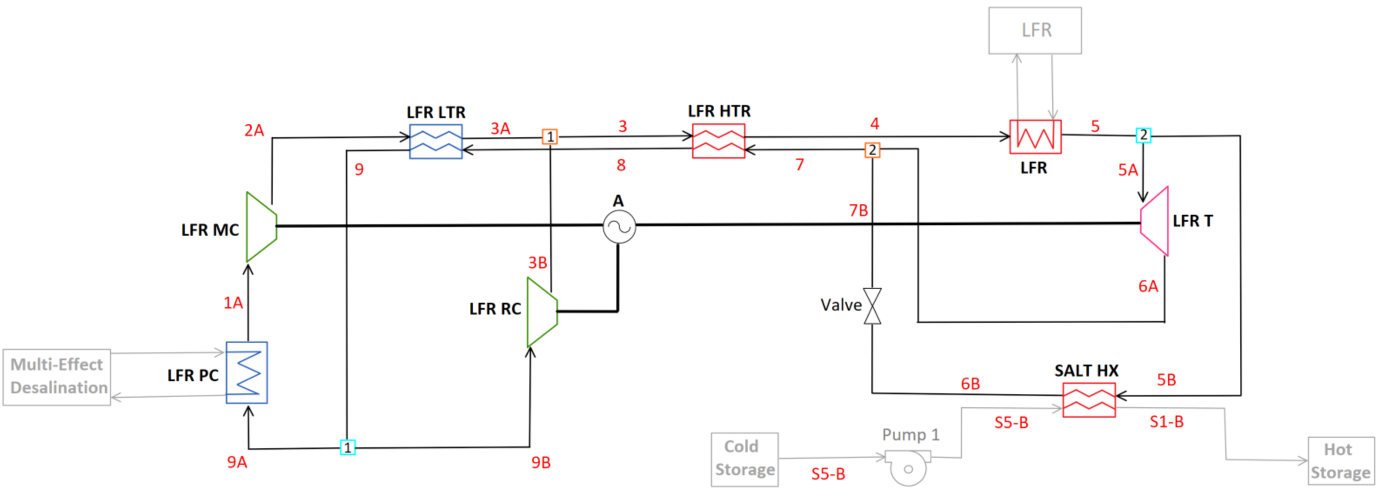


Figure 7. Diagram for C-LFR-PAR thermal energy storage charging orientation

3.2.4. C-LFR-CIRC

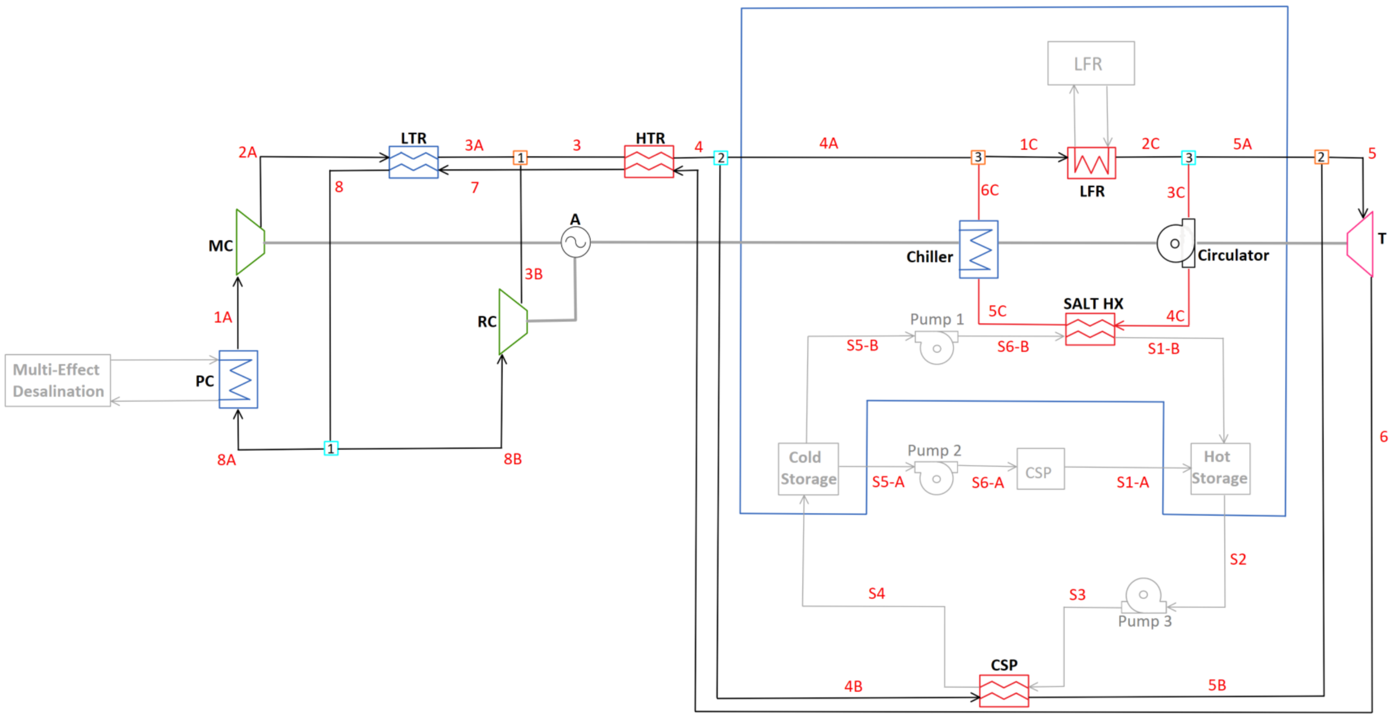


Figure 8. Full diagram for C-LFR-CIRC thermal energy storage charging orientation

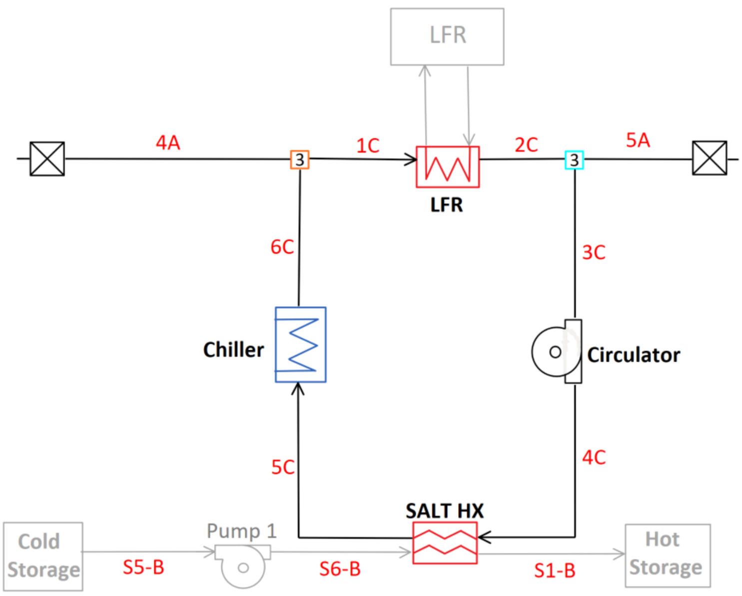


Figure 9. Diagram for C-LFR-CIRC subcycle thermal energy storage charging orientation

4. Discussion

Authors should discuss the results and how they can be interpreted from the perspective of previous studies and of the working hypotheses. The findings and their implications should be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Conclusions

This section is not mandatory, but can be added to the manuscript if the discussion is unusually long or complex.

6. how to use

6.1. Subsection

Citing a journal paper [1] . Now citing a book reference [2] or other reference types [3]. [4]

6.1.1. Subsubsection

Bulleted lists look like this:

- First bullet;
- Second bullet;
- Third bullet.

Numbered lists can be added as follows:

1. First item;
2. Second item;
3. Third item.

The text continues here.

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All figures and tables should be cited in the main text as Figure 10, Table 4, etc.

Figure 10. This is a figure. Schemes follow the same formatting. If there are multiple panels, they should be listed as: (**a**) Description of what is contained in the first panel. (**b**) Description of what is contained in the second panel. Figures should be placed in the main text near to the first time they are cited. A caption on a single line should be centered.

Table 4. This is a table caption. Tables should be placed in the main text near to the first time they are cited.

Title 1	**Title 2**	**Title 3**
Entry 1	Data	Data
Entry 2	Data	Data

Text.
Text.

6.3. Formatting of Mathematical Components

This is the example 1 of equation:

$$a = 1, \tag{1}$$

the text following an equation need not be a new paragraph. Please punctuate equations as regular text.

This is the example 2 of equation:

$$\begin{aligned} a &= b + c + d + e + f + g + h + i + j + k + l \\ &+ m + n + o + p + q + r + s + t + u + v + w + x + y + z \end{aligned} \tag{2}$$

Please punctuate equations as regular text. Theorem-type environments (including propositions, lemmas, corollaries etc.) can be formatted as follows:

Theorem 1. *Example text of a theorem.*

The text continues here. Proofs must be formatted as follows:

Proof of Theorem 1. Text of the proof. Note that the phrase "of Theorem 1" is optional if it is clear which theorem is being referred to. □

The text continues here.

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Funding: Please add: "This research received no external funding" or "This research was funded by NAME OF FUNDER grant number XXX." and and "The APC was funded by XXX". Check carefully that the details given are accurate and use the standard spelling of funding agency names at https://search.crossref.org/funding, any errors may affect your future funding.

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Nomenclature

The following abbreviations and variables are used in this manuscript:

Abbreviations:

A	Alternator
CSP	Concentrating solar power
EES	Engineering Equation Solver
HTR	High temperature recuperator
HX	Heat exchanger
LFR	Lead-fast reactor
LTR	Low temperature recuperator
MC	Main compressor
NREL	National Renewable Energy Laboratory
P	Pump
PC	Pre-cooler
RC	Re-compressor
sCO_2	supercritical carbon dioxide
T	Turbine
TES	Thermal energy storage

Variables [Units]:

CR	Capacitance Ratio [-]
$\dot{C}$	Capacitance Rate [W/K]
Δ	Temperature difference [K]
δ	Approach temperature of heat exchanger [K]
ε	Effectiveness of heat exchanger [-]
η	Isentropic efficiency [-]
h	Enthalpy [J/kg]
$\dot{m}$	Mass flow rate [kg/s]
NTU	Number of transfer units [-]
P	Pressure [Pa]
$\dot{Q}$	Heat transfer rate [W]
T	Temperature [K]
UA	Conductivity of heat exchanger [W/K]
v	Volumetric flow rate [m^3/kg]
$\dot{W}$	Power [W]
y	Splitter Fraction [-]

```
#My ees file
def myfunc():
    return x
x = y

f = 8*y^2
```

$$a^2 + b^2 = c^2 \tag{3}$$

References

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