Referee responses, Paper # sustainability-1425053:

Modeling Complimentary Lead-cooled Fast Reactor and Concentrating Solar Power Supercritical Carbon Dioxide Cycles to Compare Efficiency Gains and Feasibility

Brian T. White

Mike J. Wagner

Ben Lindley

Done

The authors of this paper want to thank the editor and reviewers for critiquing the paper. We hope that the following edits based on the review reports improved the paper to the standards of MDPI. The paper has been thoroughly proofread with the reviewers’ comments in black font while the responses of the authors are in blue.

Edits in the paper follow the standard form of:

Edited sentence. ~~Unedited sentence.~~ [x] Author comment. [Reviewer Number, Comment Number]

**Reviewer #1:**

**Report Form**

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| --- | --- | --- | --- | --- | --- |
| English Language and Style | ( ) Extensive editing of English language and style required  ( ) Moderate English changes required  (x) English language and style are fine/minor spell check required  ( ) I don’t feel qualified to judge about the English language and stye | | | | |
|  | | Yes | Can be improved | Must be improved | Not applicable |
| Is the content succinctly described and contextualized with respect to previous and present theoretical background and empirical research (if applicable) on the topic? | | (x) | ( ) | ( ) | ( ) |
| Are the research design, questions, hypotheses, and methods clearly stated? | | (x) | ( ) | ( ) | ( ) |
| Are the arguments and discussion of findings coherent, balanced, and compelling? | | (x) | ( ) | ( ) | ( ) |
| For empirical research are the results clearly presented? | | ( ) | ( ) | ( ) | (x) |
| Is the article adequately referenced? | | (x) | ( ) | ( ) | ( ) |
| Are the conclusions thoroughly supported by the results presented in the article or referenced in secondary literature? | | ( ) | ( ) | ( ) | ( ) |

**Comments to the Author**

1. It is not clear how the pinch point issue in the recuperators was dealt with. Eps-NTU method can capture this only if heat exchanger is divided into multiple calculation domains as cp varies significantly. From the resulting efficiencies I would concur that pinch point was taken into account as the results appears to be correct. However, for the less educated reader it might be misleading. Please improve the description of sCO2 cycle recuperators modelling.

Edits done for clarity of approach temperature to the sentence in the third paragraph of Section 2.1.2. The sentences ‘The temperatures of the hot and cold flows on either side of the heat exchanger have a temperature difference known as an approach temperature.’ was changed to ‘The smallest temperature difference of the hot and cold flows on either the low or high end of the heat exchanger is defined as the approach temperature of the counter-flow heat exchanger and a calculation is performed to identify whether the hot end or cold end is limiting.’ Additional explanation of the capacitance ratios explained in the last paragraph of section 2.1.2 with the sentence ‘Specific heat is found using library correlations.’ Changed to two sentences with a source ‘Specific heat is found using library correlations, with the average capacitance rate assumed to be constant during the analysis. Assuming constant average capacitance rate is suitable for most engineering purposes, especially when there is uncertainty associated with other parameters [25].’

Plots with the y axis being specific heat capacity at constant pressure (cp in kJ/kg-K) and x axis being dimensionless position throughout the heat exchanger are plotted. Additionally, another set of plots with the y axis being temperature (oC) and x axis being dimensionless position are plotted. These plots use the extreme cases of both mass flow rate and hot and cold temperatures experienced by the low temperature recuperator and high temperature recuperator. The following section was added to the paper in the final two paragraphs of section 2.1.2 with supplementary graphs provided in a two-by-two layout:

‘Assuming constant average capacitance rate is suitable for most engineering purposes, especially when there is uncertainty associated with other design parameters [25]. To justify the assumption of constant average capacitance rate, two graphs for the LTR and HTR are plotted. To ensure that there is no internal pinch point, the temperatures of the hot and cold streams as a function of dimensionless length in the LTR and HTR are shown in Figure 2b and Figure 2d respectively. Additionally, to confirm approximate linearity of specific heats at differential steps throughout the counter-flow heat exchanger, the specific heat as a function of dimensionless length of the hot and cold streams in the LTR and HTR are plotted in Figure 2a and Figure 2c respectively.

Chart, line chart

Description automatically generated

The calculations used to discretize the counter-flow heat exchangers into a sub-heat exchanger model, shown in Figure 2 is from JJ Dyreby's (2014) PhD thesis [26]. The series of figures are constructed using extreme values experienced by the recuperators; the cold inlet temperature is lowest recorded value, and the hot inlet temperature is the highest recorded value. As seen in the presented graphs, the capacitance ratio determines the approach temperature, not an internal pinch point in the recuperator. All pinch points recorded are on the high end.’

1. Check if sentence on the line 446-447 is correct. It does not make a sense to me.

This sentence seems to be correct except for the additional conjuncture ‘and’ that was overlooked in the proofreading. This sentence has been corrected to ‘Cycles that do not contain the listed component omit the associated values.’

**Reviewer #2:**

**Report Form**

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| English Language and Style | ( ) Extensive editing of English language and style required  ( ) Moderate English changes required  (x) English language and style are fine/minor spell check required  ( ) I don’t feel qualified to judge about the English language and stye | | | | |
|  | | Yes | Can be improved | Must be improved | Not applicable |
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| Are the arguments and discussion of findings coherent, balanced, and compelling? | | ( ) | (x) | ( ) | ( ) |
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**Comments to the Author**

This paper discusses different configurations to couple lead fast reactor and concentrating solar power through supercritical carbon dioxide cycles to improve efficiency and reduce cost. In general, this work is well written, but the authors are suggested to consider the following comments when revise the manuscript:

1. In the abstract, “Nuclear reactors, including lead-cooled fast reactors (LFRs), can load follow, but have high fixed and low operating costs which can make this economically unattractive.” This sentence needs to be revised.

Revised this sentence for readability to ‘Nuclear reactors, including lead-cooled fast reactors (LFRs), can adjust power output according to demand, but with high fixed costs and low operating costs there may not be sufficient economic incentive to make this worthwhile.’ Changing ‘load following’ to ‘adjust power output according to demand’ reduces the requirement of knowing what ‘load following’ is. Additionally changing ‘high fixed’ to ‘high fixed costs’ distinguishes the two discussed costs from each other increasing readability.

1. Page 2, “Utilizing complementary technologies, specifically solar concentrating power and lead-cooled fast reactors, can offset the drawbacks of each”. Can authors explain in more detail what are the drawbacks of LFR and CSP?

Additional explanation of drawbacks added after this sentence. The supplementary sentence reads ‘These drawbacks include CSP dependency on weather conditions and time of day, while the LFR in isolation does not incorporate thermal energy storage for meeting peak demand.’

1. Page 5, “Restricting the lead ﬂow velocity, and therefore lead mass ﬂow rate, leads to a higher LFR power output when the inlet sCO2 temperature is reduced.” The logic behind this sentence is unclear.

Edited the sentence to exemplify that reducing the lead flow rate in the LFR while reducing the sCO2 inlet temperature increases the power output of the LFR. This sentence is important when explaining the benefits of decreasing the sCO2 inlet temperature in the parametric studies. The new sentence reads ‘At constant lead velocity (and hence mass flow rate), reducing the sCO2 inlet temperature allows for a higher lead delta T in the LFR core and hence higher thermal power output.’

1. Page 7, “As grid demand diminishes, CSP HX ramps down heat extraction until no power is being dispatched through the salt and the hot TES begins charging. During this process, the LFR gradually adds a larger fraction of heat input to the TES through C2S. This process continues until no electrical production is occurring in the cycle and all heat is stored in TES for later use.” Why cannot we keep using CSP to charge hot TES when grid demand diminishes?

This section was edited for clarity, the cycle uses the CSP to charge the hot TES when grid demand diminishes. The sentences now read ‘As grid demand diminishes, CSP HX ramps down heat extraction until no power is being dispatched through the salt and the hot TES begins charging. During this process, the LFR gradually adds a larger fraction of heat input to the TES through C2S, **supplementing the heat produced by the CSP which is also used to charge the TES**. This process continues until no electrical production is occurring in the cycle and all heat is stored in TES for later use.’

1. Page 7, Table 1, P2A, T1A, T5, T2C, T6A, T5C need to be explained.

A supplementary sentence was added to explain the variable names in Table 1. The sentence reads ‘In Table 1, variable names require further explanation. The high side pressure with the variable label P2A, is the constant pressure outlet on the compressors and inlet to the turbines. In all models the value is set by the outlet of the main compressor and held constant with the assumption that there is no pressure drop across heat exchangers. In addition to this pressure, temperatures are also set. The inlet temperature of the main compressor, T1A, is set to a value of 40oC in all models. The temperature of the sCO2 on the outlet of the LFR HX has different variable names, T5, T2C, T6A, and T5C, according to the associated cycle configuration diagram.’

**Reviewer #3:**

**Report Form**

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| For empirical research are the results clearly presented? | | (x) | ( ) | ( ) | ( ) |
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**Comments to the Author**

In this paper, the authors study the possible synergies between CSP and LFR technologies. They compare different configurations of SCO2 cycles with these technologies as heat sources. The topic and conclusions are interesting. Also, the paper is well written, and the methods are correct. I recommend accepting after minor revision.

1. The CSP technology is not clearly explained, and I suppose that is a Solar tower. It is necessary to include some details (efficiency, heliostat area, receiver area) about the CSP.

Introduction was changed to further explain the details of the CSP technology. The sentence before edits read ‘A CSP has an array of mirrors concentrating solar rays towards a receiver to generate thermal energy therefore causing a dependency on weather conditions and time of day.’ After edits this sentence reads ‘A CSP has an array of mirrors concentrating solar rays towards a tower receiver, transferring the energy into a solar salt, and storing the solar salt in tanks. CSP systems require direct sunlight to operate at full power therefore causing variability based on weather conditions and time of day.’ Additional details into the operating temperatures and solar salt with a full diagram of the CSP system is explained further in Section 2.1.4. The efficiency, heliostat area, and receiver area are not within the scope of the paper with the receiver being described as a ‘black box’ heat input, meaning that these specific values are simplified down to a single heat input.

1. It is necessary to include an analysis of the discharging process. When the TES is discharging, the operational conditions of the cycle change, especially the turbine inlet temperature.

Brian T. White The authors agree that there are different operational conditions that change when the cycle is receiving varying heat inputs from a variety of factors. The scenario where cycles are discharging is set to a specific value to draw a direct comparison to other cycles, running cycles with off-design parameters with partial discharge of the TES is out of the scope of this current paper. Future work will investigate the effect of varying power fractions between the CSP and LFR, varying ambient weather conditions, component downtime, and pressure drop across components to further analyze the design point. Currently the separate and combined cycles offer efficiencies with a reasonable assumption made that the performance of the design point case will fall somewhere intermediate to the studied cases.

1. The scenario of C-LFR-ON and C-CSP-ON is not a suitable alternative. In this scenario, the two power plants could operate alone. They are reference cases. The configuration with synergies should be compared with them.

We agree that in isolation these are reference cases for the discharging mode. **A clarification is made in the paper to this effect.** The scenario of C-LFR-ON and C-CSP-ON operating in conjunction is discussed in section 3.1.1 with the final paragraph. Analyzing the separate configuration efficiencies in the prior paragraphs build to an explanation of the two cycles being combined and having ‘combined efficiencies’ which consist of a ‘highest efficiency’ case while the other is a ‘favorable LFR and CSP characteristic’ case. Additionally, in discharging mode, the cycles are coupled through the sCO2 to Salt HX and hence a combined power plant may use C-LFR-ON and C-CSP-ON but nonetheless substantial synergies between cycles.

**Reviewer #4:**

**Report Form**

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| For empirical research are the results clearly presented? | | (x) | ( ) | ( ) | ( ) |
| Is the article adequately referenced? | | (x) | ( ) | ( ) | ( ) |
| Are the conclusions thoroughly supported by the results presented in the article or referenced in secondary literature? | | ( ) | ( ) | ( ) | ( ) |

**Comments to the Author**

I find your manuscript very interesting and well written. I have just three suggestions:

1. There is a list of abbreviations at the end. You define some of the abbreviations in the text, but definitions of some are missing making it harder to read the text. I suggest you to define all the acronyms the first time they are mentioned in the text. For example: line 27 sCO2, line 40 CSP and TES, line 52 LFR, line 142 EES, line 163 UA and NTU, line 261 PC, line 262 MC, RC.

For clarity, the following abbreviations have been defined after the first time that they are mentioned within the article, if they were defined later in the paper the abbreviation was deleted:

* supercritical carbon dioxide (sCO2)
* concentrating solar power (CSP)
* thermal energy storage (TES)
* lead-cooled fast reactor (LFR)
* Engineering Equation Solver (EES)
* effectiveness (ε)
* capacitance ratio (CR)
* conductivity (UA)
* number of transfer units (NTU)
* precooler (PC)
* low temperature recuperator (LTR)
* main compressor (MC)
* recompressor (RC)
* high temperature recuperator (HTR)
* heat exchanger (HX)

1. In the description of Figure 2, lines 236-263 you also mention the LFR role. Perhaps you could add LFR to Figure 2 and change the subsection title to “Concentrating Solar Power Cycle with Added Lead Fast Reactor” or add a new subsection indicating the addition of LFR.

We agree with the sentiment that there is a coupling with the LFR. However, our intent with Figure 2 is to display the components of the CSP with cold and hot thermal energy storage, pumps, and receiver. This is a component that is part of the full cycles and is never directly connected to the LFR. This comment is addressed throughout Section 2.3.1 – 2.4.4 with explanations of where the C2S is drawing heat around the cycle. Additionally, the cycle diagrams in these sections display where the CSP HX is positioned.

1. I suppose that all the calculations have been made using EES? Perhaps you could clearly indicate that ate the beginning of Section 3.

Edited a sentence in the Section 3 introduction paragraph to signify that all calculations were made using Engineering Equation Solver. The sentence now reads ‘All calculations were carried out using EES, with the results obtained using standardized values found in Table 2 for a more direct comparison between cycles.’

**References**

25. Nellis, G.; Klein, S. *Heat Transfer;* Cambridge University Press, 2008. doi:10.1017/CBO9780511841606

26. Dyreby, J.J. Modeling the Supercritical Carbon Dioxide Brayton Cycle with Recompression. PhD thesis, 2014. Copyright-Database copyright ProQuest LLC; ProQuest does not claim copyright in the individual underlying works; Last updated – 2021-10-26.