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Comment

Comment on Rogalev et al. Structural and Parametric Optimization of S-CO_2 Thermal Power Plants with a Pulverized Coal-Fired Boiler Operating in Russia. *Energies* 2021, *14*, 7136

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Abstract: The reconstruction of ageing thermal power plants with the possibility of their increased efficiency, prolonged service and decreased environmental impact is an intensely debated and researched topic nowadays. Among various concepts, the replacement of the steam cycle by a supercritical CO_2 cycle is proposed with the prospect of reaching higher efficiencies at the same working fluid inlet parameters as the ultra-supercritical steam cycles. A paper published previously by Rogalev et al. (2021) analyzed the variants of supercritical coal power plant reconstruction to a supercritical CO_2 cycle and ranked them according to the cycle efficiency. This contribution comments on the scope and applied method in that paper aiming to provide additional input relevant to the decision-making process on thermal power plant reconstruction to such a cycle.

Keywords: thermal power plant; supercritical CO_2 cycle; boiler reconstruction; investment; environmental impact

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Citation: Varіny, M. Comment on Rogalev et al. Structural and Parametric Optimization of S-CO_2 Thermal Power Plants with a Pulverized Coal-Fired Boiler Operating in Russia. *Energies* 2021, *14*, 7136. *Energies* **2022**, *15*, 1640. https://doi.org/10.3390/en15051640

Academic Editor: Eduard Petlenkov

Received: 13 January 2022
Accepted: 15 February 2022
Published: 23 February 2022

1. Introduction

The issue of ageing conventional thermal power plants and the optimal solution of this problem are both intensely researched topics. These power plants have served for decades as traditional and reliable power sources with sufficient flexibility to balance the power transmission system [1,2]. With increasing awareness of the environmental impact of power production technologies in light of ongoing climate change, their operation became less feasible and socially accepted [3,4]. As a result, many coal power plants in Europe were decommissioned or refitted to other fuels in the last decade, and several other are to follow shortly [5,6]. Using the basic infrastructure of decommissioned plants, several modern and cleaner plants were erected, mostly firing natural gas, which, being a cleaner fuel, is deemed as transition fuel [7,8].

Research concepts still considering coal as a future fuel include modern supercritical power plants with projected net efficiencies close to 50% [9,10] or coal gasification and the use of syngas in combined cycle plants with expected similar net efficiencies [11]. The carbon capture and sequestration option is frequently applied both to the optimization of existing plants as well as to new plant layouts [12,13]. The inclusion of gas turbines in the existing steam cycles as a viable option has also been studied with combustion air, serving as a working medium in an open cycle before being sent to a coal boiler [14]; a modest power production increase is expected with reasonable investment costs. The conversion of conventional steam cycles to supercritical CO_2 cycles (S-CO_2) is yet another option that has received attention in recent years [15,16].

Rogalev et al. work in this research field very intensely, providing alternative reconstruction and refit solutions for the power production sector [17,18]. Their research, relevant to this comment paper, is devoted to the inclusion of S-CO_2 cycle to both nuclear [19] and thermal power plants [20]. Their present paper [21] published in *Energies* provides and analyzes alternatives increasing the thermal efficiency of conventional coal-fired power plants, confronting the commonly proposed increase in steam parameters with steam cycle replacement by a supercritical CO_2 cycle. In order to contribute to the scientific debate and to strengthen the basis for the decision-making process regarding the reconstruction of thermal power plants, a few remarks pertaining to the scope of the presented analysis and the underlying calculations are presented here.

2. Comments

In the case of obsolete thermal power plants, their reconstruction or replacement by other power sources is necessary to maintain the desired production capacity. Even in such a case, decision-making on any related investment follows pre-set priorities that include economic and environmental impact evaluation and ranking [22–24]. Environmental evaluation can be based on the CO_2 (or CO_2 equivalent) emission factor, which varies for conventional sub- and supercritical coal-fired power plants in the range from 0.7 to 0.85 tCO_2/MWh [25,26]. Increasing the plant's efficiency is only one of several options to decrease this value:

- Plant refit (with comparatively small investment required) to co-firing or full firing of carbon-neutral fuels, such as biomass, while employing the steam cycle [27–29];
- Partial or full repowering with highly efficient cogeneration technologies (gas turbines, internal combustion engines) [30–32] utilizing a part or most of the existing infrastructure;
- Replacement with a highly efficient (currently above 60% efficiency for several hundred mw-sized plants) natural-gas-fired combined cycle power plant utilizing basic plant infrastructure [8].

All the proposed alternatives benefit from the use of a cleaner fuel and the latter two also from increased efficiency beyond that reached by steam cycle replacement with a S-CO_2 cycle. The economics of the use of cleaner fuels (natural gas) instead of coal is determined by their price, including carbon tax and its expected future trend [33], on one hand, and the gain in net efficiency on the other one, including the necessary investment costs for the plant's renovation in these calculations.

However, the authors offer alternatives to steam thermal power plant reconstruction to S-CO_2 cycle and evaluate them based solely on the cycle's efficiency. It is expected that an economic assessment favors a different alternative than the thermodynamic one. As the authors rightly point out, the price of the construction material for equipment intended for high-temperature and high-pressure applications increases every year. By switching from the steam cycle to the S-CO_2 cycle, the turbine cost is expected to be reduced significantly (see page 1, Introduction in [21]). That can hardly be argued. In addition, certain savings can also be expected due to the absence of the vacuum part of the plant and the makeup water system, including its deaeration, while stepwise feedwater preheat can also be omitted in the S-CO_2 plant. However, the costs of other major components can present a substantial contribution to total capital costs of the S-CO_2 plant. A few arguments are presented:

- To reach a similar power output, the mass flow of the working fluid is several times higher compared to that of water steam in the conventional plant. This has significant consequences, starting with the need of a larger pipeline diameter, leading to significant costs increase in not only the pipes but in the whole metering and regulation equipment as well as the need for more robust supports, which might lead to problems with the necessary space constraints. In addition, differences in working fluid mass flows in the considered cycle layout alternatives can be significant due to different degrees of heat recuperation.
- The construction of conventional steam boilers is known to include the so-called "thermal shield"—the hottest flue gas gives away a portion of heat in the evaporator before it proceeds to further boiler parts. The steam superheater is placed further in the flue gas path to reduce the tubes' outer skin temperature compared to the superheater being placed first. As a result, steel with lower heat resistance can be used for the

evaporator. On the contrary, the authors propose to place the CO_2 superheater directly in the hottest flue gas path. It can be expected that even more costly materials will be needed for boiler reconstruction than in current steam boilers to avoid boiler failure due to higher tube skin temperatures. In addition, corrosion under S-CO_2 conditions has to be considered as well [34].

- The heat exchange area needed for individual heat exchangers placed in the flue gas path can be larger than in conventional steam boilers. The resistance to heat transfer in supercritical CO_2 is most probably higher than in boiling water, which results in decreased heat transfer intensity and a larger (and thus more costly) heat exchanger. As the authors point out, a "rational layout of boiler heat exchange surfaces" (see Conclusions) is the key to economic feasibility. A very recent paper devoted to S-CO_2 boiler design and cost optimization stated that the costs of such a boiler is several % higher than that of traditional steam boilers [16], which supports this comment.
- It can be expected that the heat exchange surface of a water cooler is significantly higher than that for an exhaust steam condenser in a conventional power plant as the phase change does not occur. This equipment, along with intercoolers and heat recuperators, considered in various alternatives significantly contributes to the overall reconstruction costs.

In addition, the comparison of a water and steam working cycle was most probably not performed on the same calculation/modeling basis, which again lowers the relevance of the resulting recommendations for power plant reconstruction as:

- Modeling the CO_2 cycle omits the very important fact of working fluid pressure losses. Thus, the CO_2 cycle efficiency is significantly higher, and the CO_2 cycle gains an unfair advantage if compared with the existing steam cycle comprising steam pressure losses. To demonstrate, let us choose 25 MPa/540 °C at the CO_2 expander inlet and assume a 3% CO_2 pressure loss in the superheater, decreasing the CO_2 expander inlet pressure from 25 to 24.25 MPa. With a fixed expander outlet pressure of 7.5 MPa, the expander's output decreases by approximately 2%. Otherwise, to maintain the expander's inlet pressure of 25 MPa, the CO_2 compressor outlet pressure needs to increase from 25 to 25.8 MPa, which leads to an adequate consumed compression power increase. For the plant's layouts comprising extensive heat recuperation, the related net power loss amplifies, and the cycle's efficiency decrease becomes more visible. The authors are recommended to include reasonable process-side pressure losses in any future analyses devoted to the analysis of working cycle efficiency.
- It is unclear whether the steam cycle performance, as depicted in Figure 9 in [21], was obtained by modeling or adopted from literature, as neither option is referred to. In such situations, the authors should be really careful when comparing the performance of the cycles. Apart from the above-mentioned process-side pressure losses, a correct comparison requires other aspects to be considered, for example: type of fuel, fuel burnout, boiler efficiency, ambient air temperature, steam condenser pressure, etc. It is very important since the recommendations for power plant reconstruction are stated based on this comparison.
- Internal power consumption of the S-CO_2 cycle related to cooling water considers the water cooler's hydraulic resistance as the only input to calculate the cooling water pump power input, which is an oversimplification. The question of cooling water origin remains unanswered. Most modern power plants operated semi-closed cooling water circuits, including water pumping to the cooling towers, which increases the required deltap of the water pump. Another important contribution to internal power consumption is the operation of cooling tower fans.

However, another problem is the possibility of low-temperature corrosion [35] as a part of sulfur is released to flue gas in the form of SO_2, and a small portion of it converts to SO_3, as it is also the case during the combustion of other fuels containing sulfur and its compounds. The authors assume the combustion of coal with comparatively low sulfur content (0.3 wt.%), and the reconstructed boiler will certainly be equipped with additives to entrap most of the sulfur in ash [36,37]; however, even a few ppms of SO_x present in the flue gas are known to increase the flue gas dewpoint significantly [35]. Given this situation, flue gas to stack should not come into contact with surfaces colder than 100 to 120 °C; otherwise, diluted sulfuric acid might condense on the surfaces and cause their corrosion. As it results from model assumptions and results, the air heater is operated with inlet air temperature of 15 °C, and the flue gas to stack temperature is around 130 °C. By neglecting heat transfer resistance of the air heater itself and assuming similar heat transfer resistances of inlet air and exhaust flue gas, the wall temperature of the air heater can be as low as 75 to 80 °C, which is too low to avoid corrosion. In similar situations, it is the best practice to preheat combustion air in a separate heater (using steam or hot water) to 50 to 100 °C before sending it to the air heater heated by flue gas [38].

3. Conclusions

This contribution analyzed the previous paper by Rogalev et al. (2021) [21] considering the applied method of evaluating individual layouts of coal power plant reconstruction alternatives. As it has been pointed out, such evaluation and ranking can provide irrelevant results if based solely on the cycle efficiency. Instead, combined economic and environmental assessment is proposed, and new equipment is reviewed in terms of its dimensions and possible operational problems. When modeling working cycle operation, the authors are recommended to include reasonable process-side pressure losses in their models to reduce the net power output and net efficiency of any cycle. Additionally, the authors should consider the risk of low-temperature corrosion and include the necessary temperature constraints in their boiler models. I hope the presented comments provide relevant input to any future studies devoted to the reconstruction of thermal power plants.

Funding: This study was supported by the Slovak Research and Development Agency under the contracts no. APVV-15-0148 and APVV-18-0134.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data are listed directly in this study.

Conflicts of Interest: The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

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