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A comparative study of a geothermal double flash cycle equipped with a carbon dioxide transcritical cycle for different well inlet temperatures

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Abstract

This study investigates the integration of a transcritical carbon dioxide (CO_2) cycle with a conventional geothermal double-flash cycle to enhance energy and exergy efficiencies across varying inlet temperatures (225°C, 250°C, 275°C). Although the geothermal double-flash cycle and the CO_2 transcritical cycle are both recognized for their high efficiency and sustainability, comprehensive comparative analyses addressing their combined performance under different thermal conditions remain sparse. To bridge this research gap, a detailed computational model was developed to evaluate the thermodynamic behaviors of both the base and integrated systems under various operational scenarios. The results demonstrate that the integrated system yields significant improvements in energy efficiency, with values of 0.112, 0.1265, and 0.1383 at respective inlet temperatures, compared to 0.08436, 0.1038, and 0.1197 for the base cycle. Exergy analysis reveals potential thermal efficiency challenges at higher temperatures, necessitating further optimization. The study also explores the impact of separator pressure changes on system performance, suggesting that precise pressure management can substantially enhance power output. The findings advocate for the broader adoption of integrated geothermal systems, highlighting their potential to substantially increase the efficiency of renewable energy production and suggesting avenues for future research in system optimization and environmental impact assessment.

Keywords: CO_2 transcritical cycle, double flash geothermal cycle, energy efficiency, exergy efficiency, net power output.

1. Introduction

Geothermal energy is increasingly recognized as a viable alternative to traditional fossil fuels, due to its capacity to provide sustainable, renewable energy (Maddah, Goodarzi, & Safaei, 2020; Wang et al., 2022). Particularly, the double flash cycle and the carbon dioxide transcritical cycle are noteworthy for their high efficiency and sustainability. The former leverages high-pressure geothermal fluid, converting it to steam at lower pressures to drive turbines and generate electricity (Ozcelik, 2022). Conversely, the latter utilizes carbon dioxide's unique properties in a closed-loop system to produce power through the expansion and compression of the gas (Paulillo, Striolo, & Lettieri, 2019).

Despite extensive research on these two geothermal power generation technologies, there remains a gap in comprehensive comparative analyses, especially regarding their performance across various geothermal well inlet temperatures (Hernández Martínez, Avitia Carlos, Cisneros Solís, & Prieto Avalos, 2019). Addressing thisgap, this study examines the operational dynamics and efficiency of both cycles under different thermal conditions, which is crucial for optimizing the functionality of geothermal power plants and improving their overall output. Unlike previous studies, this article provides a detailed comparison between the geothermal double flash cycle and the carbon dioxide transcritical cycle, focusing particularly on their efficacy at varied geothermal well inlet temperatures (Shamoushaki, Aliehyaei, & Rosen, 2021).

This study builds upon the extensive body of research presented at previous SESDE conferences. Notable examples include the work by Kefer et al. (2023) on machine learning and heuristic optimization for building simulation models and Saad et al. (2023) on eco-friendly initiatives for urban delivery systems. These studies highlight the innovative approaches being developed for energy and sustainability applications, which align with our focus on enhancing geothermal energy efficiency through the integration of CO_2 transcritical cycles (Kefer et al., 2023; Saad et al., 2023). Our methodological approach is further informed by recent advances in simulation techniques presented at SESDE, such as the optimization of complex thermally electrically coupled buildings using genetic programming (Kefer et al., 2021) and the simulation of smart energy tools for investment scenarios (Badicu et al., 2021). The significance of our findings is supported by similar studies presented at SESDE, including the optimization of logistics operations through big data in solar panel companies (Rivas Pellicer et al., 2023) and the simulation of power plant safety enhancements using neural networks (Yousif et al., 2023). By incorporating these references, we align our work with the broader research community focused on simulation for energy and sustainability, highlighting the relevance and applicability of our study within this established framework.

The integration of the CO_2 transcritical cycle with a double flash geothermal cycle is a novel approach that leverages the distinctive properties of each system to enhance overall energy efficiency and sustainability. By reutilizing waste heat and optimizing geothermal resource exploitation, this hybrid system demonstrates significant improvements in both energy and exergy efficiencies, thus offering a promising pathway for advancing geothermal power generation technologies (Colorado-Garrido, Alcalá-Perea, Alaffita-Hernández, & Escobedo-Trujillo, 2021; J. Liu, Yu, Lin, Su, & Ou, 2021).

An intricate computational model, grounded in thermodynamic principles and empirical data, was developed to facilitate this comparative analysis. This model assesses the thermodynamic behaviors of the geothermal double-flash cycle and the carbon dioxide transcritical cycle under varying inlet temperatures. The findings from this study will elucidate the performance disparities, strengths, and limitations of these technologies, thereby guiding decision-making in the design and operation of geothermal power facilities (Ambriz-Díaz et al., 2022). The role of modeling and simulation in this study is paramount, as it allows for a comprehensive analysis of the thermodynamic behaviors and efficiencies of both the geothermal double flash cycle and the CO_2 transcritical cycle under varying operational conditions. By utilizing advanced computational techniques, the study accurately predicts the performance outcomes and identifies potential optimization strategies, which would be challenging to achieve through empirical methods alone.

Furthermore, the integration of a CO_2 transcritical cycle with a double flash geothermal cycle represents a novel strategy for maximizing geothermal energy utilization (J. Liu et al., 2021). The CO_2 transcritical cycle, which employs carbon dioxide as a working fluid, achieves high efficiency in its supercritical state, exhibiting both liquid and gaseous characteristics (Martínez et al., 2019). Meanwhile, the double-flash geothermal cycle, a tried-and-tested method, harnesses subterranean geothermal energy by converting extracted hot water or steam into steam through a separator. This steam powers turbines, and the residual fluid undergoes a second flash to further harvest thermal energy before being re-injected into the reservoir (Venomhata, Oketch, Gathitu, & Chisale, 2023).

Integration of the double flash and carbon dioxide transcritical cycles leverages the distinctive properties of each system to enhance efficiency. The process involves using the hot water or steam generated by the double-flash geothermal cycle to warm the CO_2 in the transcritical cycle, thus facilitating efficient energy production (Ionita, Bucsa, Serban, Dobre, & Dobrovicescu, 2022). This heat transfer enables the CO_2 cycle to operate more effectively by utilizing the high-temperature geothermal fluid as a source for the supercritical heat exchanger. Consequently, the transcritical cycle boosts the overall efficiency of the geothermal setup, achieving greater thermal effectiveness than the traditional organic Rankine cycles typically found in geothermal power plants (Hasan, Rai, & Arora, 2014). Moreover, the CO_2 transcritical cycle's high-pressure exhaust serves as a thermal source for the secondary flash process within the geothermal system. This application of waste heat recovery facilitates the extraction of additional energy from the geothermal fluid, substantially improving system efficiency (G. Liu, Wang, Xu, & Miao, 2020).

This study explores a system configuration that includes both a geothermal double flash cycle and a transcritical carbon dioxide cycle, analyzing their performance from both energy and exergy perspectives. The geothermal well inlet temperatures were set at 225°C, 250°C, and 275°C for the comparative analysis. The research also delves into how changes in separator pressure affect the system's key output parameters, such as energy efficiency, exergy efficiency, and total output work, presenting these findings through illustrative diagrams.

The remainder of this paper is organized as follows: Section 2 details the materials and methods used in this study, including the operational layout and initial data for modeling the geothermal power systems. Section 3 presents the results and discussion, providing a comprehensive analysis of the thermodynamic data, performance metrics, and the impact of varying separator pressures. Section 4 addresses the research limitations, highlighting the constraints that could affect the generalizability of the findings. Section 5 offers suggestions for future research to advance the understanding and application of geothermal power generation technologies. Finally, Section 6 concludes the paper, summarizing the key findings and their implications for the broader adoption of integrated geothermal systems.

2. Materials and methods

The operational layout of the basic double-flash geothermal system (DFGC) is depicted in Fig. 1(a). Initially, at point 1, high-pressure, high-temperature geothermal fluid enters the system as a liquid. This fluid undergoes a pressure reduction at valve 1, transitioning into a two-phase state. At point 2, this two-phase fluid feeds into separator 1, where it is divided: the liquid accumulates at the bottom, and vapor collects at the top. Vapor departs from point 3 towards the steam turbine, while the liquid phase exits from point 4 of separator 1, progressing to valve 2. Here, the fluid again experiences a pressure drop while maintaining constant enthalpy, entering the second separator in a two-phase state.

Within separator 2, arranged similarly to separator 1, the liquid resides at the bottom and vapor at the top. The vapor stream exits from point 6, joining the steam turbine. The liquid component exits separator 2 at point 10. Combining the vapor outputs from points 3 and 6, the steam turbine generates energy and expels it at point 7.

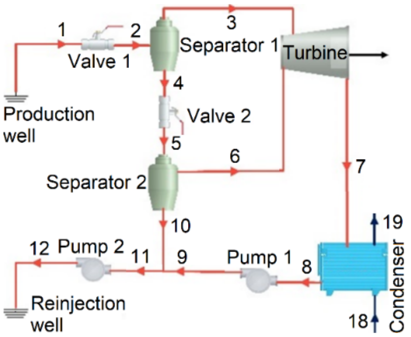
The turbine's vapor output is then converted back to liquid in the condenser under constant pressure. The liquid from the condenser, increased in pressure by pump 1 at point 9, merges with the liquid from point 10. This combined flow, further pressurized by pump 2 at point 11, is reinjected into the subsurface.

The enhanced system configuration, depicted in Figure 1(b), introduces a carbon dioxide transcritical cycle (DFGC-CO_2) to the standard geothermal double-flash cycle for waste heat recovery. In this setup, a portion of the liquid geothermal fluid exiting separator 2 at point 10 is diverted to the vapor generator, contributing heat to the transcritical CO_2 cycle. At point 14, CO_2 enters the vapor generator at high pressure and temperature, which is heated under constant pressure to further elevate its temperature. The heated CO_2 then powers a gas turbine, generating electricity. The turbine's exhaust, at point 16, enters the condenser where it is condensed under constant pressure, and the cycle concludes with the condensed CO_2 being pumped out at point 17.

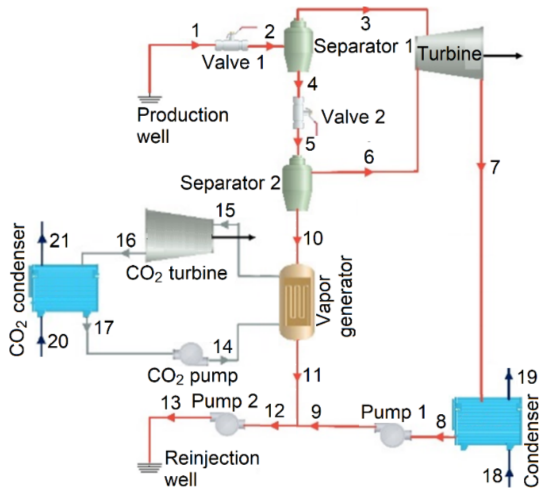
In thermodynamic analysis, the quality refers to the fraction of a fluid in the vapor phase in a two-phase mixture (liquid-vapor). It is a crucial parameter in geothermal systems because it directly affects the efficiency and performance of the turbines and other system components. A quality of 0 indicates a fully liquid state, while a quality of 1 indicates a fully vapor state. Intermediate values represent the proportion of vapor present in the mixture, which is critical for accurately modeling and optimizing the thermodynamic processes within the geothermal cycle.

An intricate computational model, grounded in thermodynamic principles and empirical data, was developed using advanced simulation software to facilitate this comparative analysis. The model incorporates detailed parameters and operational scenarios to evaluate the thermodynamic performance and efficiency metrics of both the base and integrated systems. This approach ensures a high level of precision and reliability in predicting system behaviors under different inlet temperatures and separator pressures. Table 1 provides essential data necessary for simulating the system in a software environment. Understanding data types is fundamental in programming; accurate knowledge facilitates more efficient and effective application development.

Utilizing simulation tools, it could be conducted sensitivity analyses and explored a wide range of operational parameters, thereby providing a deeper understanding of the system's response to changes in key variables. This methodology not only enhances the robustness of the study's findings but also offers valuable insights for future research and practical applications in geothermal energy optimization.



(a)



(b)

Fig 1. Schematic of (a) basic double-flash geothermal cycle (DFGC) (b) trans-critical CO_2 cycle powered by a double-flash geothermal cycle (DFGC-CO_2).

Table 1. Initial data for modeling (Aryanfar & Alcaraz, 2023; El Haj Assad et al., 2021; Huang, Abed, Eldin, Aryanfar, & García Alcaraz, 2023)

Parameter Definition	Symbol	Value
Dead state temperature	T_0	25 °C
Dead state Pressure	P_0	101 kPa
Geothermal fluid inlet temperature	T_1	300 °C
Geo-fluid mass flow	$\dot{m}_1$	70 kg/s
Geo-fluid inlet pressure	P_1	Saturated Steam
Separator 1 pressure	P_2	1000 kPa
Separator 2 pressure	P_5	500 kPa
Steam turbine output pressure	P_7	20 kPa
Pump 1 output pressure	P_9	500 kPa
Pump 2 output pressure	P_{12}	2000 kPa
CO_2 turbine inlet pressure	P_{15}	15000 kPa
CO_2 condenser temperature	T_{cond}	30 °C
Steam turbine isentropic efficiency	η_{tur}	85 %
CO_2 turbine isentropic efficiency	$\eta_{tur,\,CO2}$	85 %
Pump 1 isentropic efficiency	η_{pump1}	85 %
Pump 2 isentropic efficiency	η_{pump2}	85 %
CO_2 Pump isentropic efficiency	$\eta_{pump,\,CO2}$	75%
Evaporator inlet-outlet difference temperature	ΔT_{TTD}	20 °C
Vapor generator pinch point	ΔT_{PP}	5 °C

3. Results and discussion

The application of the previously outlined methodology yielded detailed thermodynamic data, as systematically recorded in Tables 2 and 3. These tables delineate the thermodynamic properties observed at various critical points throughout both the fundamental geothermal cycle and the integrated recovery system following the simulations. In Tables 2 and 3, each measurement's location within the cycle is detailed in the first column, while the second column clarifies the type of fluid at each stage. Subsequent columns present a comprehensive breakdown of key thermodynamic parameters: temperature, pressure, enthalpy, entropy, mass flow rate, fluid quality, and exergy.

Furthermore, Table 4 outlines the performance metrics for two geothermal power systems: the Double Flash Geothermal Cycle (DFGC) and the enhanced DFGC with a Carbon Dioxide Transcritical Cycle (DFGC-CO_2). It presents the data for various operational parameters across three different inlet temperatures (225°C, 250°C, and 275°C). The parameters evaluated include the power output of turbines (both steam and CO_2), power consumption of different pumps, net power output, and efficiency metrics (energy and exergy efficiencies), as well as total exergy destruction.

In Table 4 for both systems, the steam turbine output (Wtur, steam) increases with rising inlet temperatures from 5228 kW at 225°C to 9405 kW at 275°C. The CO_2 turbine in the DFGC-CO_2 system, however, shows a decrease in output from 3069 kW at 225°C to 2828 kW at 275°C, indicating a potential thermal efficiency issue at higher temperatures.

The power consumed by Pump 1 and Pump 2 in both systems shows a consistent increase with higher temperatures. Notably, Pump 2 consumes less power in the DFGC-CO_2 system than in DFGC, possibly due to improved system integration. The CO_2 pump in DFGC-CO_2 shows decreasing power consumption with increasing temperatures, suggesting better performance at higher temperatures. The net power output significantly increases in the DFGC-CO_2 system compared to DFGC across all temperatures, ranging from a 33% increase at 225°C to a 16% increase at 275°C. This highlights the added benefit of incorporating the CO_2 transcritical cycle.

Energy efficiency and exergy efficiency both generally increase with temperature in both cycles. The DFGC-CO_2 system shows a

Table 2. Properties of different points of the basic cycle (DFGC) after modeling

Point	Working Fluid	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Mass flow rate (kg/s)	Quality (-)	Exergy (kW)
1	Geo-Fluid	250	3974	1085	2.793	70	0	18008
2	Geo-Fluid	179.9	1000	1085	2.851	70	0.16	16799
3	Geo-Fluid	179.9	1000	2778	6.586	11.2	1	9171
4	Geo-Fluid	179.9	1000	762.9	2.139	58.8	0	7628
5	Geo-Fluid	151.9	500	762.9	2.149	58.8	0.0581	7446
6	Geo-Fluid	151.9	500	2749	6.821	3.416	1	2458

7	Geo-Fluid	60.07	20	2275	6.904	14.62	-	3229
8	Geo-Fluid	60.07	20	251.5	0.8321	14.62	-	115.8
9	Geo-Fluid	60.11	500	252	0.8324	14.62	-	123.1
10	Geo-Fluid	151.9	500	640.4	1.861	55.38	0	4988
11	Geo-Fluid	133	500	559.3	1.666	70	-	4702
12	Geo-Fluid	133.2	2000	561.2	1.667	70	0	4819

Table 3. Properties of different points of the recovery system (DFGC-CO_2) after modeling

Point	Working Fluid	Temperature (°C)	Pressure (kPa)	Enthalpy (kJ/kg)	Entropy (kJ/kg.K)	Mass flow rate (kg/s)	Quality (-)	Exergy (kW)
1	Geo-Fluid	250	3974	1085	2.793	70	0	18008
2	Geo-Fluid	179.9	1000	1085	2.851	70	0.16	16799
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8	Geo-Fluid	60.07	20	251.5	0.8321	14.62	-	115.8
9	Geo-Fluid	60.11	500	252	0.8324	14.62	-	123.1
10	Geo-Fluid	151.9	500	640.4	1.861	55.38	0	4988
11	Geo-Fluid	72.1	500	302.2	0.9802	55.38	-	802.7
12	Geo-Fluid	69.6	500	291.7	0.9498	70	0	916.9
13	Geo-Fluid	69.74	2000	293.5	0.9506	70	-	1027
14	CO_2	52.1	15000	-186.3	-1.383	94.21	-	20729
15	CO_2	131.9	15000	12.53	-0.8275	94.21	-	24118
16	CO_2	71.43	7214	-19.94	-0.8107	94.21	-	20598
17	CO_2	30	7214	-202.2	-1.395	94.21	0	19567

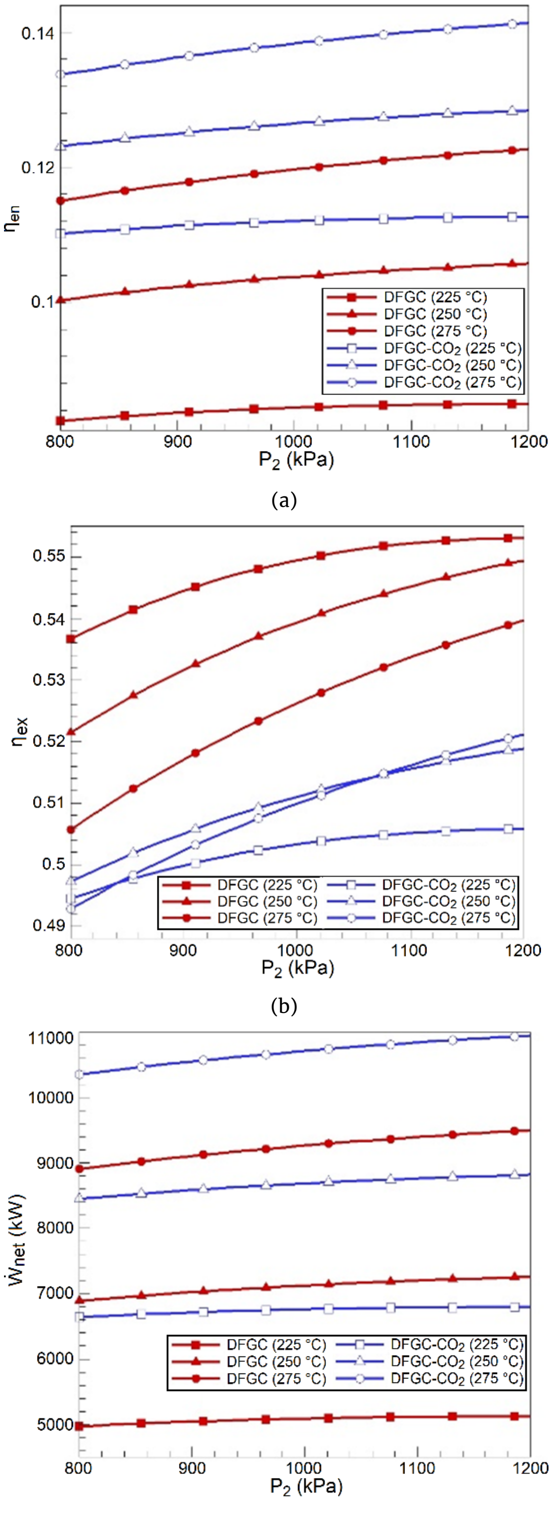
Table 4. Output design parameters of DFGC and DFGC-CO_2

Parameters	Definition	DFGC			DFGC-CO_2			Unit
		225°C	250°C	275°C	225°C	250°C	275°C	
$W_{tur,\ steam}$	The power output of the steam turbine	5228	7264	9405	5228	7264	9405	kW
$W_{tur,CO2}$	The power output of the CO_2 turbine	-	-	-	3069	3054	2828	kW
W_{pump1}	Power consumption of pump 1	6.175	8.41	10.76	6.175	8.41	10.76	kW
W_{pump2}	Power consumption of pump 2	133.1	132.5	131.8	126.3	126.3	126.2	kW
$W_{pump,\ CO2}$	Power consumption of CO_2 pump	-	-	-	1605	1500	1389	kW
W_{net}	Net power output	5089	7123	9263	6760	8684	10708	kW
η_{en}	Energy efficiency	0.08436	0.1038	0.1197	0.112	0.1265	0.1383	-
η_{ex}	Exergy efficiency	0.5495	0.5394	0.5262	0.5033	0.5111	0.5099	-
$Ex_{destruction,total}$	Total exergy destruction	1558	2557	3869	4066	4899	6038	kW

superior energy efficiency at all points, which supports its integration despite slightly lower exergy efficiency at higher temperatures. The total exergy destruction is higher in the DFGC-CO_2 system across all temperatures, indicating greater irreversibilities possibly due to the additional complexity of integrating the CO_2 cycle.

Figures 2(a), 2(b), and 2(c) present an in-depth analysis of how variations in separator pressure, ranging from 800 kPa to 1200 kPa, impact key performance metrics of the geothermal power generation system at geothermal well inlet temperatures of 225°C, 250°C, and 275°C. The graphs illustrate the shifts in energy efficiency, exergy efficiency, and net power output, respectively, across these temperatures. Notably, these figures highlight two distinct operational modes within the proposed system. In Figure 2(a), the relationship between separator pressure and energy efficiency is explored, revealing how adjustments in pressure can optimize the thermal conversion processes within the system. Higher pressures generally correlate with improved energy capture from the geothermal fluid, enhancing the overall efficiency of the cycle.

Figure 2(b) examines the effect of varying separator pressures on exergy efficiency. This analysis is crucial as it provides insights into the degree of irreversibility within the system under different operational conditions. Understanding these dynamics allows for the refinement of process parameters to minimize energy loss and maximize sustainable energy production. Lastly, Figure 2(c) quantifies changes in net power output as a function of separator pressure at the specified inlet temperatures. This figure is particularly informative as it demonstrates the potential for increased power generation with optimized pressure settings, underscoring the critical role of pressure management in enhancing the overall output of geothermal power systems.



(a)

(b)

(c)

Fig. 2. Effect of pressure changes in separator 1 on (a) energy efficiency, (b) exergy efficiency, and (c) net power output for the basic cycle (DFGC) and recovery system (DFGC-CO2) at three different input temperatures.

Together, these figures substantiate the dual functional modes of the system, each mode offering distinct advantages under different pressure and temperature conditions. This dual-mode operation enables the system to adapt to varying geothermal conditions, thereby optimizing performance and enhancing the efficiency of power generation. The analysis provided by these figures is essential for designing more effective geothermal energy systems that can dynamically adjust to changing environmental and operational conditions.

4. Research limitations

This study, while offering a detailed comparison of geothermal double flash cycles and carbon dioxide transcritical cycles under varying well inlet temperatures, encounters several limitations that could impact the generalizability and applicability of its findings:

- Model Dependence: The results presented rely heavily on the computational models used for simulation. These models are based on specific assumptions and parameters that may not perfectly replicate real-world operational conditions. Variations in actual geothermal plant operations could lead to different outcomes than those predicted by our simulations.
- Scope of Technology: The focus on only two types of geothermal power generation technologies—double flash cycles and carbon dioxide transcritical cycles—excludes other potentially viable and emerging geothermal technologies. Future studies should explore a broader range of geothermal systems to provide a more comprehensive understanding of the field.
- Data Constraints: The accuracy of the data used, particularly concerning the thermodynamic properties and operational parameters of the geothermal systems, is crucial. The unavailability of extensive real-world operational data for these specific technologies limits the depth of analysis possible and may introduce biases in the model outcomes.
- Simplifications in Simulation: To manage the complexity of the simulation, certain simplifications were necessary. These include assuming constant properties for materials and ignoring potential losses or variations in performance due to external factors. Such simplifications, while necessary, could detract from the accuracy of the simulation results.
- Environmental and Economic Factors: This study does not extensively address the environmental impact and economic feasibility of integrating carbon dioxide transcritical cycles into existing geothermal setups. These factors are critical for

practical implementation and should be addressed in further research.

- Temporal Aspects: The study's cross-sectional approach does not consider the long-term performance and sustainability of the technologies under study. Geothermal systems often undergo changes in efficiency and operational capacity over time due to geological and mechanical factors, which were not accounted for in this study.

By acknowledging these limitations, this study aims to pave the way for future research that could address these gaps, enhancing the robustness and applicability of the findings to real-world scenarios. Further studies should aim to incorporate a broader set of data, consider a wider range of technologies, and include long-term operational analysis to fully assess the potential of geothermal power generation technologies.

5. Future research suggestions

To build on the findings of this study and address the identified limitations, several areas of further research are recommended to advance our understanding of geothermal power generation technologies:

- Broader Technological Evaluation: Future studies should expand the scope of research to include a wider array of geothermal technologies, such as binary cycle systems, enhanced geothermal systems (EGS), and hybrid systems combining multiple renewable energy sources. Comparing a broader range of technologies will help identify the most efficient and sustainable options for different geothermal conditions.
- Longitudinal Studies: To better understand the long-term performance and viability of geothermal power systems, longitudinal studies are necessary. These studies should focus on the durability, maintenance needs, and operational stability of geothermal power plants over extended periods.
- Real-World Data Collection: Enhanced data collection efforts are needed to obtain more accurate and comprehensive operational data from existing geothermal power plants. This includes detailed performance metrics under various environmental and geological conditions, which would help refine simulation models and predictions.
- Environmental Impact Analysis: Comprehensive studies on the environmental impacts of different geothermal technologies are crucial. This includes assessing lifecycle carbon emissions, land use impacts, and potential ecological disruptions, which will inform sustainable development practices in the geothermal industry.
- Economic Analysis: Further research should also incorporate detailed economic analyses of geothermal technologies, considering both initial capital costs and long-term operational expenses. This will provide valuable insights into the economic feasibility and cost-effectiveness of deploying different geothermal systems.
- Integration Strategies: Exploring the integration of geothermal systems with other renewable energy sources, such as solar and wind, could enhance overall system efficiency and reliability. Studies could investigate optimal integration strategies and hybrid system designs that capitalize on the strengths of each energy source.
- Advanced Simulation Models: Developing more sophisticated simulation models that can more accurately mimic real-world conditions is essential. These models should account for variable geological conditions, material properties, and operational uncertainties to better predict system performance.
- Policy and Regulatory Frameworks: Research into the policy and regulatory environments that support the expansion of geothermal energy is also needed. This includes identifying barriers to adoption and proposing policy instruments that could encourage the uptake of geothermal technology.

By pursuing these suggested research avenues, the scientific community can significantly contribute to the advancement of geothermal energy technology, ensuring its role as a cornerstone of the global renewable energy portfolio.

7. Conclusions

This study has conducted a comprehensive examination of the operational efficiencies of the geothermal double flash cycle (DFGC) and the carbon dioxide transcritical cycle (DFGC-CO_2), with a specific focus on their performance across a range of geothermal well inlet temperatures. By integrating advanced computational models grounded in thermodynamic principles, the research has provided a nuanced understanding of how these two cycles perform under different thermal conditions, and how their integration can optimize the energy output and sustainability of geothermal power systems. The findings reveal significant enhancements in both the energy and exergy efficiencies when the CO_2 transcritical cycle is paired with the conventional double flash cycle. This hybrid system not only utilizes the thermal properties of CO_2 to boost power generation efficiency but also effectively leverages waste heat, which is typically lost in conventional systems. The analysis shows that with increasing geothermal well inlet temperatures, there are notable improvements in net power output and energy efficiency, particularly in the integrated DFGC-CO_2 system. Moreover, the study has highlighted the critical role of separator pressures in optimizing the thermal conversion processes. Adjusting these pressures can significantly affect the overall system efficiency, pointing to a potential area for further refinement in geothermal power plant operations. Future research should focus on exploring other innovative cycle configurations and their potential for integration. It is also recommended that further studies consider the environmental impacts of such systems in greater depth, particularly in terms of their long-term sustainability and potential contributions to reducing carbon emissions in the energy sector. Overall, this research underscores the viability of integrating the CO_2 transcritical cycle with traditional geothermal technologies as a means to enhance the efficiency and environmental friendliness of geothermal power generation. Such advancements could play a crucial role in transitioning towards more sustainable energy systems worldwide.

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