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Energy Recovery Strategies in CO_2 Compression Using an Integrated Supercritical Rankine Cycle

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One of the leading technologies for reducing industrial CO_2 emissions is Carbon Capture and Storage (CCS). Existing publications address the high energy requirements of the capture process while overlooking the subsequent compression process required for CO_2 transportation, which also exhibits intense energy needs. This work aims to investigate and compare the energy requirements of two alternative methods to the conventional process for pressurising captured CO_2 to 150 bar. After the capture process, CO_2 is typically at near atmospheric pressure, requiring multi-stage compression due to compressor limitations. After each compression stage, cooling is required to maintain the fluid close to the optimal temperature for further compression. The proposed alternative methods utilise the compressed CO_2, which is in a supercritical state (sCO2), as the working fluid to recover heat that is available among the compression stages. One of the alternative methods uses sCO_2 in an integrated open supercritical Rankine cycle (sRC) at each cooling stage. The other method, apart from the sRC, heats the CO_2-rich liquid stream before the regeneration column of the capture process at the final compression stage. The compression processes are designed for a CO_2 stream of 2,779 t/d, representing the typical captured CO_2 mass flow from a 400 MW power plant. Results suggest that the case of combining sRC and the CO_2-rich stream heating is the most energy-efficient among the tested cases, requiring 5.11 MW less than the sRC-only case and 4.31 MW less than the conventional compression case without intercooling.

1. Introduction

One of the main greenhouse gases contributing to climate change is CO_2. The accumulation of CO_2 in the atmosphere has been identified as a significant driver of global warming, necessitating urgent measures to mitigate its emissions. To address this challenge, Carbon Capture and Storage (CCS) has emerged as a pivotal technology. CCS involves capturing CO_2 from industrial sources, transporting the captured CO_2 to a storage site or utilising it. Due to its potential to significantly reduce greenhouse gas emissions, CCS has become a popular topic in current scientific literature.

Various technologies exist for CO_2 capture, with amine-based CO_2 capture being particularly promising. This method utilises chemical solvents to selectively absorb CO_2 from flue gases. One of the key advantages of amine-based systems is their ability to be retrofitted onto existing plants, making them a versatile option for industries looking to reduce their carbon footprint (Nessi et al., 2021).

A major challenge associated with CCS is the high energy consumption required for the CO_2 compression process. Compressing CO_2 to the necessary pressure for transportation, typically around 150 bar, demands substantial energy, impacting the overall efficiency and feasibility of CCS technologies in industrial applications (Aminu et al., 2017). Detailed energy consumption data from traditional CO_2 compression processes highlight this issue, with conventional multi-stage compression systems requiring significant power input (Shavalieva et al., 2019). According to Muhammad et al. (2020), CO_2 compression can result in a significant energy penalty, reducing the overall efficiency of a power plant by up to 12 %. Addressing this energy demand is crucial for improving the overall efficiency and feasibility of CCS technologies in industrial applications. In the literature,

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the process of CO_2 compression has been extensively studied by many researchers, emphasising the need for innovative solutions to reduce energy consumption (Shogenova et al., 2022).
One such process improvement is suggested by Witkowski et al. (2013), who proposed a compression chain strategy that implements CO_2 liquefaction and pumping, thereby reducing by 50 % the required compression power. Their approach involves compressing CO_2 to an intermediate liquefaction pressure, liquefying it, and then pumping the liquid CO_2 to the target pressure for transportation. The main disadvantage of this approach is the sub-zero condensing temperatures required for CO_2 liquefaction, which can be challenging to maintain. Alabdulakarem et al. (2012) also targeted CO_2 liquefaction, finding that an ammonia-based vapor compression cycle (VCC) could reduce power consumption by 5.1 % compared to conventional multi-stage compression.
While the aforementioned studies focus on process improvements and alternatives, other researchers have investigated energy recuperation methods. Kurtulus et al. (2018) examined the implementation of an organic Rankine cycle (ORC) for heat recuperation from CO_2 compression stages. Their study demonstrated that utilising the heat generated during compression could reduce the compression energy needs by approximately 8 %, depending on the selected organic fluid. Further advancements were made by Farajollahi et al. (2017), who designed a post-combustion CO_2 capture process for a thermal power plant. They incorporated an ORC for heat recovery during CO_2 compression, which resulted in a 2 % improvement in plant efficiency. Muhammad et al. (2020) suggested the implementation of a supercritical CO_2 (sCO_2) cycle for heat integration with a heat pump (HP) system. Their methodology aims to replace one or more compression stages with HP systems, thereby reducing compression energy requirements by 15.8 %. The advantage of their approach lies in the use of process sCO_2, which minimizes coolant usage and the primary drawback is the additional electric power consumption introduced by the HP systems. All these studies aim on improving the energy requirements of the CO_2 compressions but the prospect of using the capture process for heat integration is neglected.
Building on these insights, the novelty of this work lies in investigating the heat integration between the capture process and an integrated compression process-supercritical Rankine cycle (sRC). This is implemented by using sCO_2 from the final compression stage of the process as the working fluid in an sRC to integrate heat from the compression stages. Two scenarios are tested and compared to a conventional four-stage CO_2 pressurization process without heat integration. The first proposed scenario utilizes only an sRC with sCO_2, while the second combines the aforementioned sRC with the heating of the CO_2-rich stream from the capture process at the final compression stage. This holistic approach promises to enhance the overall energy efficiency of the CCS system, making it a more viable and sustainable solution for industrial CO_2 emissions reduction.

2. Methods and models

CO_2 compression is performed in multiple stages due to material limitations and efficiency considerations. Typically, the target pressure for CO_2 compression is set at 150 bar. Achieving this pressure necessitates four compression stages because the temperature increases significantly after each stage, which must be managed effectively. According to Biyikli (2024), integrally geared compressors (IGCs) are ideal for CO_2 compression processes. Each stage's compressor can be designed individually, allowing the impeller diameter to be reduced to counteract the shrinking flow coefficient resulting from decreased volume flow after each stage. Such design flexibility ensures optimal performance at each stage of compression.

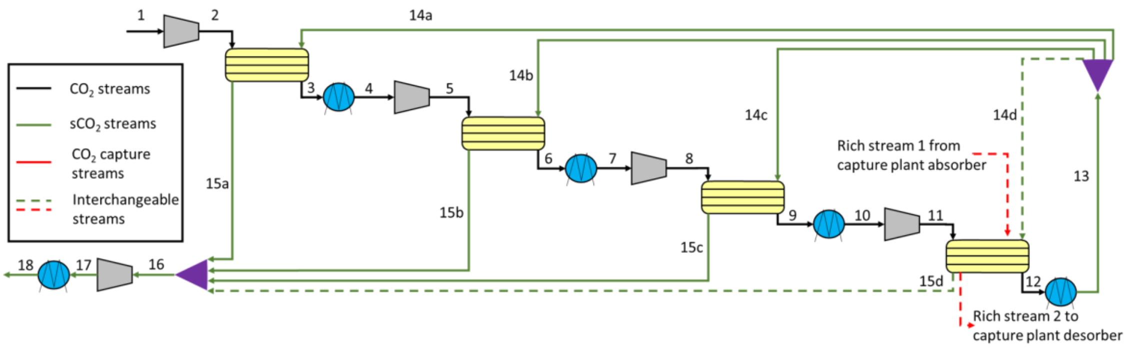

Figure 1: Process flowsheet diagram of the proposed processes

To maintain the integrity and efficiency of the compressors, it is crucial to operate them at temperatures below 190 °C. Consequently, the temperature limit for each compression stage in this study is set 10 °C below this threshold. In conventional CO_2 compression processes, the temperature increase after each compression stage is addressed with a cooling stage. This cooling allows for further pressure increase and improves the overall compression efficiency.

Alternatively, this study proposes utilising the pressurised CO_2 from the final (fourth) compressor in a supercritical Rankine cycle (sRC), as depicted by stream 13 in Figure 1. In this scenario, the stream's pressure is set at 200 bar, and the temperature at 35 °C, allowing the CO_2 to be in a supercritical state, conducive for heat integration. The pressure is set higher than needed for transportation so that a turbine can be implemented after the compression process for electricity generation. This allows the generation of electricity and still meeting the 150 bar necessary for compression after that. This high-pressure sCO_2 stream is divided into four separate streams and fed to the integrated heat exchangers. These heat exchangers cool the heated CO_2 after each compression cycle, thereby reducing the cooling energy requirements. The total flow of sCO_2 is split to ensure that the temperature of the streams after the heat exchangers (streams 15a-d in Figure 1) is consistently at 100 °C. Despite the efficient cooling capacity of sCO_2, an additional cooling stage is required after each heat exchanger to further cool the CO_2 to 30 °C before it enters the next compression stage. After passing through the sRC, the sCO_2 streams are recombined and directed to a turbine (stream 16 in Figure 1) for electrical power generation, harnessing the energy from the high-pressure CO_2.

Another viable and often neglected alternative proposed in this work involves utilising the hot stream from the final compression stage to heat the CO_2-rich stream from the capture process before it enters the regeneration unit. This alternative is depicted by the red-colored streams in Figure 1. The CO_2-rich stream is typically preheated by an economizer, a heat exchanger that harnesses heat from the lean liquid stream leaving the reboiler of the capture plant's desorption unit. Any additional heat applied to this CO_2-rich stream benefits the process by lowering the energy requirements of the reboiler, which is the most energy-intensive part of the capture system. Utilising the liquid CO_2-rich stream offers two additional advantages. First, heat transfer is enhanced due to the presence of denser liquid than the sCO_2. Second, the sCO_2 stream is distributed to three heat exchangers (instead of four in the previous case), increasing the flow of sCO_2 through them. In this configuration, the temperature after the heat exchangers (streams 15a-c in Figure 1) is maintained at 100 °C, similar to the previous case. It is also important to note that using the CO_2 of the first three compression stages for heating the CO_2-rich stream has a negligible effect on the liquid stream. Therefore, the CO_2-rich stream can only be heated using the hot stream from the fourth and final compression stage, where the CO_2 is in a supercritical state.

In this study, all tested processes are simulated using Aspen HYSYS® (AspenTech, 2024), as it can reliably simulate the CO_2 compression. The Peng-Robinson property package is selected for the simulation of the CO_2 and sCO_2 streams due to its comprehensive set of properties suitable for the fluid. For the CO_2-rich stream from the capture process, the Acid Gas – Chemical Solvents property package is utilized, as it includes the necessary reaction and property estimation parameters for the Monoethanolamine (MEA) – CO_2 – H_2O system. The simulations consider realistic operating conditions and potential inefficiencies. The adiabatic efficiency of the compressors was set at 75 % to reflect typical industrial performance and account for heat losses. Heat exchangers were configured in a counterflow arrangement to maximize heat transfer efficiency, with sCO_2 and CO_2-rich streams passing through the shell side to enhance heat recovery. This detailed approach ensures a comprehensive understanding of the CO_2 compression process, highlighting the potential for energy savings and efficiency improvements through innovative heat integration methods.

3. Results and discussion

3.1 Stream properties

The implementation of the process is performed for a typical gas-fired power plant with a CO_2 mass flow rate of 2,779 t/d. The data for the CO_2-rich stream are sourced from the work of Kazepidis et al. (2021), where the CO_2 capture process was designed and optimised for the same power plant. As mentioned in section 2, the temperature of the sCO_2 after the heat exchangers is set at 100 °C for both tested cases. The mass split ratio of the sCO_2 stream is adjusted to maintain this temperature, with the values presented for both cases in Table 1.

Table 1: Mass flow split ratio of sCO_2 stream for the tested cases

Stream	sRC cycle (%)	sRC + CO_2 rich stream (%)
14a	25	41
14b	7	33
14c	18	26
14d	50	-

Table 2 presents the pressure and temperature conditions of the streams shown in Figure 1. The temperature limit after each compression stage is set at 180 °C. From these results, it is evident that four compression stages are necessary, as the temperature would exceed 190 °C with fewer compression stages, exceeding the temperature limit of mainstream industrial compressors. The sCO_2 streams exiting the heat exchangers have lower temperatures in the sRC and CO_2-rich stream cases, indicating better potential for heat integration. The first compression stage is from atmospheric pressure to 4 bar increasing the temperature to 176 °C. Subsequently, the pressure is raised to 15 bar and at the third compression stage to 45 bar. At the final stage the pressure is set to 200 bar, at this stage the CO_2 is at supercritical conditions. Such an increase (155 bar) is possible with one stage because of the supercritical behaviour. The sCO_2 can be used for heat integration as its density is close to that of a liquid. Although the CO_2-rich stream is heated by only two degrees, it is important to note that this liquid stream has a very large flow rate of 1,477 kg/s. Hence, the heat duty of the corresponding heat exchanger is 5.11 MW. This small temperature increase is significant not only for the compression process but also for the capture process.

Table 2: Stream properties comparison in the two sRC cases

	sRC cycle		sRC + CO_2-rich stream	
Stream of Figure 1	Temperature (°C)	Pressure (bar)	Temperature (°C)	Pressure (bar)
1	40	1	40	1
2	176	4	176	4
3	133	4	106	4
4	30	4	30	4
5	158	15	158	15
6	147	15	103	15
7	30	15	30	15
8	137	45	137	45
9	110	45	98	45
10	30	45	30	45
11	178	200	178	200
12	127	200	90	200
13	35	200	35	200
14a,b,c,d	35	200	35	200
15a,b,c,d	100	200	100	200
Rich stream 1	–	–	88	1.2
Rich stream 2	–	–	90	1.2
16	100	200	100	200
17	82	150	82	150
18	50	150	50	150

3.2 Energy analysis

In order to evaluate the performance of the proposed CO_2 compression process, a third scenario was simulated. In this scenario, CO_2 compression is performed in four stages without any heat integration, representing the conventional process used as a baseline for comparison. This scenario assumes that the pressure after the final compression stage is set to 150 bar, as there is no requirement to exceed the transportation pressure in this conventional method.

Figure 2 presents the energy requirements for all scenarios under investigation. Notably, the conventional case demonstrates the lowest compression energy requirements due to its highest pressure being limited to 150 bar, compared to the other scenarios where the highest pressure reaches 200 bar. This higher maximum pressure results in increased energy consumption for compression, but it is essential to consider the potential benefits of integrating heat recovery.

In the proposed scenarios, the integrated heat from the sRC plays a significant role in reducing the overall energy consumption. Both heat integration scenarios show significant heat recuperation, with the scenario utilising both sRC and the CO_2-rich stream exhibiting the best performance. This outcome is anticipated, as the dual-fluid approach leverages both the sCO_2 and the CO_2-rich stream. Specifically, the sCO_2 flow is divided into three streams for heat integration during the first three compression stages, while the CO_2-rich stream absorbs the heat from the last compression stage. The use of two fluids for heat recovery enhances the overall efficiency. The energy generation from the turbine, although modest at 0.28 MW in both heat integration scenarios, becomes significant over a yearly operational period. To further investigate energy analysis, Table 3 presents the integrated heat and cooling duties for each compression stage across the tested scenarios. The proposed cases include an additional turbine stage, which generates electricity by reducing the pressure from 200 bar to 150 bar, but also need a cooling stage before CO_2 transportation. This cooling stage at the turbine increases the total energy requirements in the sRC-only scenario, making them 2 % higher than in the conventional scenario. The data indicate that using a sRC in conjunction with the CO_2-rich stream significantly reduces the cooling duty required at each compression stage. This results in a substantial reduction of 4.72 MW compared to the conventional case without heat integration, despite operating at a higher pressure. The heat recuperated from the sRC in the first three compression stages equals to 2.63 MW for the sRC-only case and 5.25 MW for the sRC with the CO_2-rich stream case. The larger sCO_2 flows in the sRC with the CO_2-rich stream scenario enable nearly double the energy recuperation compared to the sRC-only scenario. In the sRC-only case, the first three compression stages utilize 50 % of the sCO_2. In contrast, the combined sRC and CO_2-rich stream scenario utilizes all the sCO_2, maximizing the heat recovery potential. This comprehensive approach underscores the benefits of integrating multiple heat recovery streams within the CO_2 compression process, demonstrating significant energy savings and efficiency improvements over conventional methods.

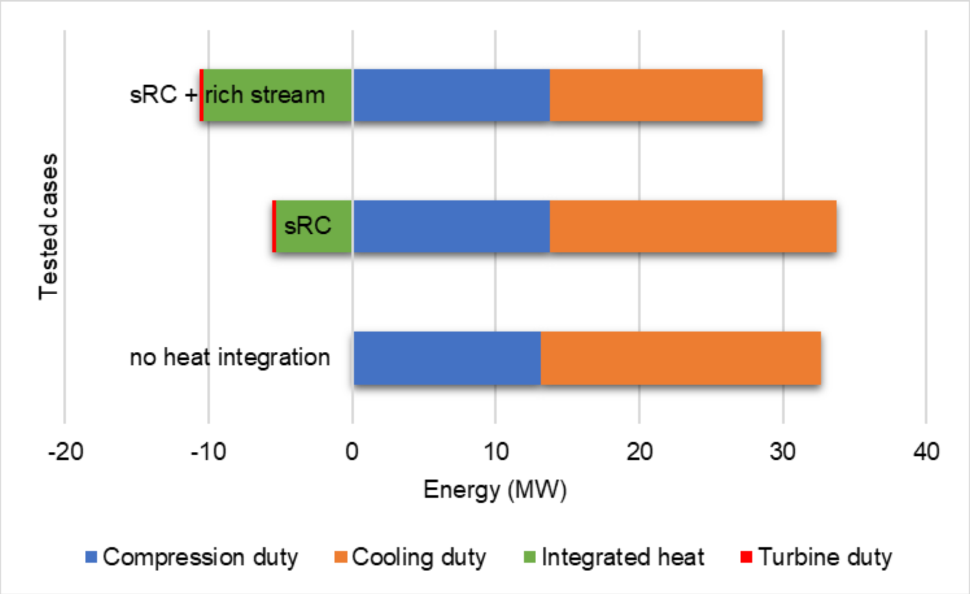

Figure 2: Energy requirements comparison among the two proposed cases and the no heat integration case, negative energy values indicate energy savings from heat integration

Table 3: Integrated heat and cooling duty of every compression stage for the tested cases

	sRC cycle		sRC + CO_2-rich stream		no heat integration
Stages	Integrated heat exchanger duty (MW)	Cooler duty (MW)	Integrated heat exchanger duty (MW)	Cooler duty (MW)	Cooler duty (MW)
1	1.31	3.07	2.15	2.23	4.39
2	0.37	3.64	1.73	2.28	2.93
3	0.95	3.04	1.37	2.62	4.52
4	2.63	7.00	5.11	4.51	7.70
Electric power generated	0.28	3.18	0.28	3.18	–
Total	5.54	19.93	10.64	14.82	19.54

In the fourth compression stage, CO_2 is heated up to 178 °C, necessitating substantial cooling. In the sRC with the CO_2-rich stream case, the liquid CO_2-rich stream is used in the integrated heat exchanger. In the sRC-only case, the remaining 50 % of the sCO_2 from the previous compression stages is used. The significant heat integration in the sRC case is offset by increased compression duty and cooling requirements. The conventional case operates at a lower pressure, resulting in lower total energy requirements than the sRC case. In the combined sRC and CO_2-rich stream case the presence of two fluids (sCO_2 and CO_2-rich stream) helps to overcome the higher-pressure energy penalty. Heat integration in this combined case significantly reduces the total cooling needs of the process. This highlights the advantage of employing two fluids, as validated by the results.

4. Conclusions

Using sCO_2 as a fluid for heat integration in a CO_2 compression process implies an energy penalty for the needed increased pressure from the 150 bar needed for transportation, to at least 200 bar. This increases the compression duty but allows heat integration with the same fluid that is pressurised. From the investigation of this work, the case that uses only the sRC integrates a significant amount of energy (5.3 MW), but due to the higher pressure than the conventional case it ends up needing 2 % more energy than the conventional case. These results indicate that the sCO_2 from the process cannot be used alone for efficient heat integration. On the other hand, the implementation of the sRC with the combination of the CO_2-rich stream provides the potential for significant heat integration from the CO_2 compression process. Despite the higher pressure from the conventional case there are significant energy benefits. This is only possible by addressing the CCS system as a whole, which allows heat integration from different processes. Overall, this approach provides energy savings equal to 13 % compared to the conventional case, so it appears to be a viable solution for reducing energy requirements in the CO_2 compression process.

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