Thermal integration of different compression-train configurations for coal-fired power plant with carbon capture

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Received: 29 May 2020 / Accepted: 15 January 2021 / Published online: 6 March 2021

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Abstract

Different compression-train configurations in a coal-fired power plant with CO₂ capture were thermally integrated to reduce the energetic impact of the capture process and global warming potential for the life cycle of the power plant and the production of the absorbent. The thermal integration was performed using formal optimization techniques, with consideration given to all the available streams for the different compression-train configurations. The different compression-train configurations produced different temperature levels in the process streams and different heat exchanger networks, which included the power plant, compression train, and waste energy recovery technologies, such as organic Rankine cycles. The initial observation was that for the different configurations of the compression trains, the best result in terms of the net power output was 374.26 MW_e, with a reduction of 84.3% in the global warming potential compared with a power plant without carbon capture. This result was obtained for an eight-stage train with integrally geared centrifugal compressors. Subsequently, with thermal integration, the configuration that included advanced supersonic shockwave compressors exhibited the best conditions for the heat transfer between hot and cold streams, achieving a reduction of 84.65% in the global warming potential and a net power output of 382.9 MW_e.

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Graphic abstract

Keywords Coal-fired power plant · Compression train · Thermal integration · Global warming potential

Abbreviations

COE	Cost of electricity
CFPP	Coal-fired power plant
CTC	Compression-train configuration
DOE/NETL	Department of Energy and National Energy Technology Laboratory
GWP	Global warming potential
HEN	Heat exchanger network
HRSG	Heat recovery steam generator
MEA	Monoethanolamine
ORC	Organic Rankine cycle
PCC	Post-combustion carbon capture

Introduction

Electric power is primarily produced through processes that use fossil fuels. Coal-fired power plants (CFPPs) account for 70% of the total energy produced by these processes (Hanak

et al. 2015), but such power plants have lower heating value efficiencies of approximately 45% (Li et al. 2019). These processes generate the largest proportion of electrical power and emissions among all the power generation technologies used and even when the CFPP power generation had a diminution of 3% in 2019 mainly due to the COVID-19 pandemic, coal is still the leader fuel in electricity generation (IEA 2020b). In contrast to that diminution, it was seen an increment in the use of coal in Asia, specifically in China, where the use of coal in power plants has exceeded 50% of the domestic coal consumption (Wang et al. 2021); also there are more CFPPs under construction or approved to be built (Ouyang et al. 2021), maintaining the 36% of the total power generation for the CFPPs (IEA 2020a). Around the world, it is expected a 2.6% rise in global coal demand in 2021 because of an expected recovery in the world economy, driven by higher electricity demand and industrial output. Because of this, countries like the USA and countries in Europe may have their first increases in coal consumption

in nearly a decade (IEA 2021). Governments and companies around the world have goals to achieve net-zero emissions in the coming decades, more specifically on 2050 (GCCSI 2020); achieving this target could prevent the estimates of 1.5 °C of global warming between 2030 and 2052 if the growth continues at the current rate (IPCC 2019). It became fundamental to solve the dilemma of how to reconcile the rising demand for energy with the needs of reducing the greenhouse gas emissions and fight the global climate change (Gallagher et al. 2021). That is why, all possible alternatives must be considered to reduce the greenhouse emissions but maintaining an adequate level of power generation to ensure that society's requirements continue to be satisfied. Analyzing carbon capture processes has been an important strategy for achieving these goals (Pacala and Socolow 2004; Desideri and Antonelli 2014; Zhai et al. 2017). However, further research is needed to make the coupling of power plants and carbon capture processes sustainable via methods such as thermal integration, environmental analysis, safety analysis, and optimization (Gingerich and Mauter 2018). In addition, practical alternatives for achieving environmental and power goals have been proposed. Various methods or processes for CO₂ capture have been studied to determine the best configuration (Araujo and Medeiros 2017). These include the oxy-combustion process, where the power plant suffers an energy penalty depending on the conventional combustion (Xiong et al. 2011); CaO-based capture, where a large amount of CO₂ is captured in a fluidized-bed process (Wang et al. 2011a, 2011b); and processes that use membranes (Gong et al. 2017), ionic liquids (Farahipour and Karunanithi 2014), and microalgae (Sarat-Chandra et al. 2018). Within these methods, the most advanced technology used for CO₂ sequestration is a process involving post-combustion capture using chemical absorption. This technology has been investigated with different absorbents, including ammonia (Linnenberg et al. 2012), glycerol as a green absorbent (Flowers et al. 2017), aqueous potassium carbonate (Ghosh et al. 2009), and alcohol amines such as monoethanolamine (MEA), diethanolamine, and triethanolamine (Suleiman et al. 2016; Boucif et al. 2008; Nuchitprasitichai and Cremaschi 2013; Cormos et al. 2018; Wang et al. 2011a, 2011b). Many investigations have been conducted on these types of amines in water solutions and using mixtures of two or more amines. The kinetics and thermodynamics of the amines were studied via simulations and pilot plants (Choi et al. 2009; Zhang et al. 2002; El-Hadri et al. 2017). The main equipment used in the post-combustion process is an absorption tower, in which the CO₂ in the combustion gases reacts with an absorbent that is regenerated using a stripping column. The solvent is recovered and recirculated, and the CO₂ is separated and subsequently sent to the compression train as a stream with a CO₂ concentration of $\geq 90\%$. Because of the large amount of CO₂ generated in

a CFPP, the main obstacle to its sustainable capture is the energy expenditure due to the regeneration of the solvent and the power expended in the compression of the CO₂ stream (Goto et al. 2013). As previously mentioned, many alternative solvents have been considered, among which MEA is currently the most widely used (Zhang et al. 2017). Despite the potential for reducing CO₂ emissions with a carbon capture process, a reduction in the net power output is inevitable with the use of these systems. Several studies have focused on this important limitation.

Parvareh et al. (2014) comprehensively reviewed the integration of solar energy in CFPPs with carbon capture. The main aim of using solar energy is to reduce the energy penalty for the use of carbon capture technologies, which indicates the importance of developing alternative methods to reduce the net power output loss. Luo et al. (2015) examined the heat transfer between the streams of the compression train using the heat recovery steam generator (HRSG) and stripper reboiler of the capture process. Farajollahi and Hossainpour (2017) proposed the use of organic Rankine cycles (ORCs) to exploit the low-grade heat and increase the thermal efficiency of the plant; however, the process streams were matched heuristically. Sanchez del Rio et al. (2017) proposed the integration of a CFPP with post-combustion carbon capture (PCC) using a gas turbine windbox. In this configuration, only a single match between streams was proposed. Oh et al. (2018) proposed a system integration approach for reducing the energy penalty of capture processes in a CFPP and compared their results with those for a pilot-scale plant.

Although previous studies have addressed process integration in CFPPs with carbon capture and compression, none of them involved the use of formal optimization techniques to identify the most suitable matches between process streams. In the best cases, previously reported works used heuristic approaches to determine the optimal matches, and a maximum of three streams were considered in the heat integration.

Methods have been proposed for the formal optimization of a heat exchanger network (HEN). For example, Khalilpour and Abbas (2011) performed a pinch analysis for a 227 MW CFPP. However, it is important to note that pinch analysis is a sequential approach in which the number of heat exchangers and the area are not optimized. Hanak et al. (2014) performed a heat integration and exergy analysis for a CFPP with PCC and a compression train with nine compression stages.

This study analyzed a CFPP with CO₂ capture and different compression-train configurations (CTCs). Each of these configurations offered an alternative for thermal integration, which was performed using formal mathematical programming techniques because of the different levels of energy that could be transferred as a result of the changes in the

and condenser with an outlet temperature of 39 °C (Fig. 2), where the steam extracted to regenerate the absorbent was extracted from the IP/LP crossover point of the steam cycle. A simulation was also performed to obtain the parameters for calculating the net power and GWP, such as the heat of the reboiler, required power in the compression train, extracted steam, output power of the steam turbines, power

of the output ORC, contribution of GWP in the production of MEA, contribution of GWP in the stage of the CFP, and flow of captured CO₂. Table 2 presents the main parameters for the simulation of the CFPP, PCC process, and ORC.

Figure 3 shows a simulation of the capture process and CTCs in which a stream duplicator was used to maintain the same stream from the stripper to the compressors. The

Fig. 2 Simulation of steam turbines

Table 2 Main parameters of CFPP, PCC, and ORC process simulation

Parameter	Value	References
Coal flow rate (kg/h)	185,759	Oh et al. (2018)
Coal conditions (°C/bar)	15/ 1.01325	DOE/NETL (2013)
Air flow rate (kg/h)	1,748,073	DOE/NETL (2013)
Lean amine inlet conditions (bar/°C)	5.0033/34.95	Zhang et al. (2009)
Absorber pressure (bar/stages)	1.5/20	Zhang et al. (2009)
Rich amine inlet conditions (bar/°C)	9.8133/ 105	Zhang et al. (2009)
Stripper pressure (bar/stages)	2.4/20	Zhang et al. (2009)
Stripper reboiler duty (MW)	431.94	Zhang et al. (2009)
R245FA flow (kg/s)	13.4	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
Pump discharge pressure (bar)	8	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
Hot stream outlet temperature (°C)	48	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
Evaporator outlet temperature (°C)	90	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
ORC turbine discharge pressure (bar)	2.805	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
ORC condenser outlet temperature (°C)	30	Filiz-Ozdil-Tumen and Ridvan-Segmen (2016)
SSWC CTC stage pressures (bar)	15.57/153	Witkowski and Majkut (2012)
CC-4 CTC stage pressures (bar)	4.9/16.5/50/153	Witkowski and Majkut (2012)
CC-6 CTC stage pressures (bar)	4.3/9.6/21.5/44.9/82.7/153	Witkowski and Majkut (2012)
CC-8 CTC stage pressures (bar)	2.775/4.924/8.734/15.55/27.45/48.64/86.27/153	Witkowski and Majkut (2012)
Intercoolers gas outlet temperature (°C)	30	Witkowski and Majkut (2012)

Fig. 4 Thermal integration scheme

different cases. These power values were then added to the results of the thermal integration conducted in SYNHEAT.

Table 3 presents details of the hot and cold streams considered for all the thermal integrations for each CTC. The cold streams were the same for each scenario studied. C1 was the stream at the inlet of the stripper reboiler, and its temperature conditions were obtained from the Aspen Plus simulations. C2 was the stream that was fed into the ORC evaporator, and the hot streams were the compression-train hot streams of each configuration scenario.

The heat capacity flow rate of each hot and cold stream was calculated from the simulation results and for the scenario of ORC evaporator stream C2, whose heat capacity flow rate was initially calculated for a 0.2602 MW ORC. For each scenario studied, the value of the heat capacity flow rate was incremented in the thermal integration in SYNHEAT until the stream began to consume hot utility instead of using the compression-train hot streams. Thus, the maximum duty transferred to stream C1 in the scenario analyzed without an ORC was maintained.

Calculating GWP and net power output by varying capture level percentages

The scheme for analyzing the GWP and net power output is shown in Fig. 5. The main objective was to observe the variation in the aforementioned parameters according to the decrease in the capture level, which directly affected the amount of greenhouse gases emitted, amount of absorbent fed, amount of LP steam extracted for the desorption, amount of heat in the reboiler of the stripper, GWP values in the stages considered, global GWP, and production of energy. The simulation results were used to calculate the net energy generated from the process and the GWP for each point in the sensitivity analysis for each CTC. When calculating the GWP, the emissions due to the production of the absorbent and the emissions in the CFPP were considered. The net power was calculated using Eq. (1), which shows the gross power generated in the steam turbines and ORC

Table 3 Hot and cold streams for each scenario studied

Study scenario	Hot and cold stream temperatures (°C in/out)					
CFPP + PCC + SSWC	H1 (254/38)	H2 (273/38)	C1 (108/118.7)	C2 (48/90)		
CFPP + PCC + CC-4	H1 (136/38)	H2 (155/38)	H3 (151/38)	H4 (154/38)	C1 (108/118.7)	C2 (48/90)
CFPP + PCC + CC-6	H1 (121/38)	H2 (110/38)	H3 (113/38)	H4 (110/38)	H5 (98/38)	H6 (80/38)
	C1 (108/118.7)	C2 (48/90)				
CFPP + PCC + CC-8	H1 (83/38)	H2 (89/38)	H3 (91/38)	H4 (92/38)	H5 (93/38)	H6 (95/38)
	H7 (95/38)	H8 (71/38)	C1 (108/118.7)	C2 (48/90)

Fig. 5 Scheme of GWP and net power output estimation

minus the power values for the auxiliary energy consumption (P_{aux}), which is taken from the DOE/NETL and equal to 30.41 MWe; the energy consumption in the compression train (P_{comp}), which depends on each study case; and the energy used in the capture process (P_{cap}), which depends on the LP steam extracted from the HRSG to the PCC. The CFPP efficiency was calculated using Eq. (2), where HHV was taken from the report by Oh et al. and is equal to 27,113 kJ/Kg and F_{coal} is the flow rate of coal to the CFPP. The values in equivalent grams of CO_2 from the IPCC were used as the parameters, and data from the ECOINVENT database (2019) were used for the absorber emissions. The points considered in the analysis were for capture levels of 90%, 70%, 50%, and 25%, and thermal integration was conducted for the SSWC configuration to obtain the GWP and net power output for each point.

$$nP = \text{Gross power} - (P_{aux} + P_{cap} + P_{compr}) \quad (1)$$

$$n = \frac{nP}{HHV * F_{coal}}. \quad (2)$$

To obtain another decision criterion for the CTCs, an economic analysis was performed in Aspen Plus, in which the equipment cost, capital cost, and annual operation and maintenance cost were calculated in separate simulations for each CTC. Using these data, the cost of electricity (COE) was calculated for each CTC considered. The COEs of the standalone CFPP were identical for all the cases and were calculated using Eq. (3) in the DOE/NETL report.

$$COE = \frac{CCF * TOC + OCFIX + OCVAR}{CF * MWH}. \quad (3)$$

Here, COE represents the revenue produced by the generator (\$/MWh); $CCF=0.124$ represents the capital charge factor; TOC represents the total overnight capital (in base-year dollars); OCFIX represents the sum of all the fixed annual operating costs (in base-year dollars); OCVAR represents the sum of all the variable annual operating costs, including the fuel at a capacity factor of 100% (in base-year dollars); CF represents the plant capacity factor, which was

assumed to be constant (85%) over the operational period; and MWH represents the annual net megawatt-hours of power generated at a 100% capacity factor.

Results and discussion

Table 4 and Fig. 6 present the results of the simulations for a CFPP with carbon capture for all the CTCs, for a capture level of 90% CO_2 recovery. The net power output of each scenario differed from that of the CFPP without capture. The first scenario corresponded to the advanced SSWCs, and the subsequent scenarios corresponded to centrifugal compressors (CC-4, 6, and 8).

The net power output decreased by 31–34% for each scenario compared with the CFPP without carbon capture and thermal integration, and the GWP decreased by 83–84% for each scenario. The best results for the net power (374.26 MW_e) and GWP (a decrease of 84.3%) were obtained for the eight-stage integrally geared centrifugal compressors (CC-8) compared with the power plant without carbon capture. This is because the CC-8 configuration had a lower energy consumption. The SSWC configuration had a lower net power output because of the energy consumed to compress the CO_2 to make its GWP greater than that of the CC configurations. Figures 7, 8, and 9 show the heat transfer networks obtained for each configuration. Different matches and results were obtained.

Case 1: SSWC configuration

Figure 6 shows the HEN of case 1, in which there were four matches between the hot and cold streams. The main conclusions were as follows:

- Steams H1 and H2 were coupled with C1, and 41.578 MW of power was transferred; this reduced the LP steam to be extracted to satisfy the remaining 390.4 MW of heat required for the stripper reboiler operation.
- Streams H1 and H2 were used to evaporate the working fluid in the ORC, which produced 1.526 MW.

Table 4 Results of simulations

Result	CFPP	CFPP + PCC + SSWC	CFPP + PCC + CC-4	CFPP + PCC + CC-6	CFPP + PCC + CC-8
Stripper reboiler duty (MW)	—	431.94	431.94	431.94	431.94
Power consumed by compressors (MW)	—	46.12	42.18	38.45	37.12
Net power output (MW _e)	550	365.26	369.2	372.93	374.26
CO_2 captured (kg/s)	110.3	110.3	110.3	110.3	110.3
GWP (e- CO_2 g/kWh)	802.15	129.07	127.7	126.42	125.97
CFPP efficiency (HHV)	39.3%	26.1%	26.38%	26.64%	26.74%

Fig. 6 GWP and net power output results

Fig. 7 HEN for SSWC configuration

Fig. 8 HEN for CC-4 configuration

- The required consumption of the cold utility to cool the streams of the compression train without thermal integration was 64.249 MW; with the obtained HEN, it decreased to 21.184 MW.

Case 2: CC-4 configuration

Figure 7 shows the HEN obtained for case 2. There were eight matches between the hot and cold streams. The main results were as follows:

Fig. 9 HEN for CC-6 configuration

- H1, H2, H3, and H4 were coupled with C1, and the heat transfer between them was 19.409 MW; this reduced the amount of LP steam that needed to be extracted to provide the remaining 412.53 MW of heat required for the stripper reboiler operation.
- The heat in streams H1, H2, H3, and H4 was transferred to C2 to evaporate the working fluid in the ORC, which produced 3.43 MW.
- The required consumption of the cold utility to cool the streams of the compression train without thermal integration was 69.635 MW; with the HEN, it decreased to 46.852 MW.

Case 3: CC-6 configuration

Figure 9 shows the HEN obtained for case 3; there were six matches between the hot and cold streams, and the observations were as follows:

- Stream H6 was not used in the HEN because of its low temperature.
- H1 was coupled with C1, and 0.357 MW of power was transferred; this reduced the amount of LP steam that needed to be extracted for the stripper reboiler, whose heat requirement became 431.58 MW.
- Streams H1, H2, H3, H4, and H5 were used to evaporate the working fluid in the ORC, which produced 3.243 MW.
- The consumption of the cold utility decreased from 64.791 to 61.269 MW with thermal integration.

Case 4: CC-8 configuration

None of the hot streams were used to transfer heat to the C1 or C2 streams in case 4. This was because all the streams had a temperature below 100 °C; thus, the stripper reboiler duty and consumption of cold utility to cool the streams of the

compression train maintained the same value. A match with stream H6 was observed only when the heat capacity flow rate of the C2 stream in the thermal integration decreased. However, it required an additional consumption of hot utility in the ORC, which contributed to the cold utility utilized to condense the working fluid and had an energy production of only 0.1 MW (in the ORC). This had a negligible impact on the global process. The only match in this scenario was between the hot water streams at the output of the stripper reboiler and the ORC that could generate 4.67 MW_e, which contributed to the global energy production of the CFPP.

The results for the net power output and GWP are presented in Table 5 for the scenario with thermal integration, in which the GWP initially decreased because the net power output of each scenario increased as a result of the matches between the hot and cold streams calculated for each scenario. In contrast to the case without thermal integration, in which the CC-8 configuration exhibited the best energetic and environmental results, the SSWC configuration with thermal integration produced a higher net power output of 382.9 MW_e and a lower GWP (by 84.65%) than the scenario without carbon capture; it also had a lower consumption of cold utility in the compression-train intercooler. This was because the hot streams attained temperatures higher than 200 °C, which allowed for thermal integration with the stripper reboiler and ORC, yielding better results compared with those of the other configurations, whose streams had temperatures below 150 °C. Figure 10 shows a flowchart of a CFPP with carbon capture and an SSWC configuration with initial thermal integration between compression-train hot streams H1 and H2, and the stripper reboiler and streams of the working fluid used in the ORC.

Based on the analysis of the variation in the capture level, the GWP and net power were obtained for capture levels ranging from 0 to 90% for each CTC. The variation in the GWP against the net power output is shown in Fig. 11 for the SSWC configuration, because it was the CTC with thermal

Result	CFPP	CFPP + PCC + SSWC	CFPP + PCC + CC-4	CFPP + PCC + CC-6	CFPP + PCC + CC-8
Stripper reboiler duty (MW)	–	390.4	412.53	431.58	431.94
LP steam extracted (kg/s)	–	162.1	171.3	179.21	179.36
Power consumed by the compressors (MW)	–	46.12	42.18	38.45	37.12
ORC power output (MW _e)	–	5.8	7.9	7.91	4.67
Net power output (MW _e)	550	382.9	382.64	380.9	379.61
CO ₂ captured (kg/s)	110.3	110.3	110.3	110.3	110.3
GWP (e-CO ₂ g/kWh)	802.15	123.12	123.21	123.35	124.42
CFPP efficiency (HHV)	39.3%	27.4%	27.34%	27.22%	27.12%

integration that exhibited the best energetic result. The net power output increased as the amount of carbon captured decreased; decision makers can use this to observe the tradeoffs between the environmental impact and the power generation. The minimum GWP value obtained for the four CTCs was 123.12 eCO₂/kWh, which corresponded to the

With regard to the economic aspect, Table 6 presents the COE calculation results for each case studied. The CTC with the smallest COE in this study was C-4 (114.84 \$/MWh), and the COE exhibited an increase of

Fig. 11 Net power versus GWP for CTCs with various capture levels

95.05%–97.09% for each case, compared with that of the standalone plant. The economic, energetic, and environmental results differed among the cases. The results can help decision makers identify the best option based on the scenario that best suits their needs, which depends on different factors such as a country's regulations or environmental goals pertaining to the reduction of greenhouse gas emissions and the available economic resources, and then invest in the technologies required to meet those needs.

Conclusions

This study analyzed the coupling of a coal-fired power plant with monoethanolamine-based post-combustion carbon capture and organic Rankine cycles through thermal integration. The main results obtained were the global warming potential and net power output values for different compression-train

configurations. The centrifugal compressor 8 configuration initially exhibited the best energetic results, with the smallest reduction in energy production (31.95%) compared with the supersonic shockwave compressor configuration (33.58%); this corresponded to a difference of 9 MW_e between the two configurations. The base case scenario had no thermal integration, and as the number of compression stages increased, the required amount of energy for the operation of the compression-train configuration decreased. Hence, there were differences in the net power output values of the coal-fired power plants with different compression-train configurations. Subsequently, with thermal integration, because the compression-train configurations with fewer compression stages attained higher temperature levels, they achieved better results in terms of the net power. The supersonic shockwave compressor configuration had the highest energy production because it had the lowest energy penalties as a result of the match between the hot streams of the compressors and the stripper reboiler stream. The difference in the net power results for the compression-train configurations with the highest power (supersonic shockwave compressors) and the compression-train configurations with the lowest power (centrifugal compressors 8) for scenarios with thermal integration was 4.6 MW_e. The supersonic shockwave compressors exhibited a decrease of 29.83% in the global coal-fired power plant energy production. The analysis performed in this study indicated that thermal integration or a decrease in the capture level of each compression-train configuration could significantly reduce the energetic penalty as a result of the reduction in the amount of steam extracted using the energy generated by the organic Rankine cycle. Additionally, reducing the capture level affected the economic and design aspects of the compressors, absorption and stripping towers, and all the equipment required for the organic Rankine cycle, as well as for the capture process.

Table 6 Economic results

Result	CFPP	CFPP + PCC + SSWC	CFPP + PCC + CC-4	CFPP + PCC + CC-6	CFPP + PCC + CC-8
TOC (\$) × 1000	1,113,445	1,522,778	1,515,271	1,519,078	1,529,272
Total operating cost (\$/year)	53,267,785	81,295,885	81,453,485	81,121,885	80,535,485
Fuel cost (\$/year)	58,217,892	58,217,892	58,217,892	58,217,892	58,217,892
COE (\$/MWh)	58.9	115.08	114.89	115.46	116.09

Acknowledgements The authors acknowledge the financial support provided by CONACYT and the Scientific Research Council (CIC_UMSNH) for the development of this project, as well as the support from the faculty of Chemical Engineering at the Universidad Michoacana de San Nicolás de Hidalgo.

Authors' contributions Gerardo Esquivel-Patiño was involved in methodology, writing—original draft, and software. Fabricio Nápoles-Rivera was involved in conceptualization, resources, funding acquisition, and writing—review and editing.

Funding The authors acknowledge the financial support of CONACYT and CIC_UMSNH.

Declarations

Conflict of interest The authors declare they have no conflicts of interest that might influence the work reported in this paper.

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