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A study on investment decision of BECCS power plant based on real options

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ABSTRACT

In order to explore the investment strategy issues of biomass carbon capture and storage (BECCS) power plants and the influence of cost control and policy incentives on the investment strategy of BECCS power plants so as to realize the wide application of BECCS technology in China, based on real options theory, this paper establishes a triple tree model for investment decisions in BECCS power plants by fully considering uncertainties such as crude oil price, coal price, biomass fuel price, investment cost, and operation cost. The net present value (NPV) and total investment value (TIV) of the BECCS power plants are determined by the algorithm analysis to explore the investment decision problem of the BECCS power plants. In addition, this paper uses sensitivity analysis to explore the impact of carbon trading market, cost control and policy incentives on the investment strategy of BECCS power plants. The results show that (1) the TIV of BECCS power plants in 2021 is CNY 9468.95, so the investment project is feasible, but since the NPV of BECCS power plants in 2021 is less than zero, it is not suitable for immediate investment, and investors should postpone the investment to make a profit; (2) The decrease in coal price has the largest effect on the increase in NPV of BECCS power plants, and the decrease in biomass fuel price and the increase in the investment subsidy factor have a significant contribution to the increase in NPV of BECCS power plants, but even if the coal price and biomass fuel price change by -100% or the government takes the full amount of subsidy for the initial investment cost, immediate investment still cannot be achieved. Therefore, in addition to cost control and policy incentives under the current carbon trading market, the government has to seek other more effective ways to promote the deployment of BECCS power plants.

Keywords: biomass-carbon capture and storage technology, real options, triple tree model, sensitivity analysis

1. INTRODUCTION

Global warming has made climate issues a serious challenge shared by countries across the globe. The International Energy Agency (IEA)[1] suggests that energy-related carbon dioxide emissions will rise to a record high of 3,663 million ton in 2021. CO2 emissions are increasing year on year, and in response to global warming, 178 parties from around the world signed the Paris Agreement, which aims to maintain the global mean temperature rise below 2°C above pre-industrial levels and work to limit the temperature rise to 1.5°C above pre-industrial levels. The Intergovernmental Panel on Climate Change (IPCC) identified biomass with carbon capture and storage (BECCS) as a means of achieving the removal of carbon dioxide (CDR) from the environment, which may be applied to achieve zero net carbon emission.[2][3] If BECCS triples or nearly quadruples the share of zero-carbon and low-carbon energy supply by 2050, it could potentially keep global warming below 2°C.[3] If BECCS power plants were built and used, they could help the country reach its "carbon-neutral peak" goal.

With the aim of exploring the BECCS power plant investment strategy problem and thereby realizing the widespread deployment of BECCS technology in China, this paper establishes a triple tree model for investment decisions in BECCS power plants by fully considering uncertainties such as carbon quota price, coal price, biomass fuel price, investment cost, and operation cost. The net present value and total investment value of the BECCS power plants are determined by the algorithm analysis to explore the investment decision problem of the BECCS power plants. In addition, this paper uses sensitivity analysis to explore the impact of carbon trading market, cost control, and incentive policies on the investment strategy of BECCS power plants.

The following are the innovations of this paper: first, the existing literature on BECCS investment and incentive strategies has set biomass or coal as the only

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fuel for the plant, while this paper sets biomass and coal to be blended in a ratio of 1:9; second, most of the existing literature explores only incentive policies, arguing that incentives are needed for BECCS deployment, while this paper considers incentives alongside cost control; finally, this paper concludes by introducing three novel elements: biomass fuel, biomass charcoal, and CCER, which are not included in the model proposed by the previous studies.

2. INTRODUCTION TO THE MODEL

2.1 Real options

In order to effectively reduce the risk of investment failure, the delayed option is chosen in this paper. The total investment value can then be expressed as:

$$\mathrm{TIV} = \mathrm{NPV} + \mathrm{VDO} \tag{1}$$

Where TIV is the total investment value, NPV is the net present value, and VDO is the deferral option value.

Table 1 BECCS power plant investment decision rules

NPV	TIV	Decision
$\mathrm{NPV} > 0$	$\mathrm{TIV} > \mathrm{NPV}$	Delayed investment
$\mathrm{NPV} > 0$	$\mathrm{TIV} = \mathrm{NPV}$	Invest Now
$\mathrm{NPV} \le 0$	$\mathrm{TIV} > 0$	Delayed investment
$\mathrm{NPV} < 0$	$\mathrm{TIV} = 0$	Give up investment

2.2 Model construction

The investment income includes income from electricity price subsidies, carbon quota trading, CCER trading, crude oil, and biomass carbon emissions. The capital costs include fuel cost, investment cost, operating cost, transportation cost, sequestration cost, and utilization cost.[4] Based on the above revenues and costs to obtain BECCS power plant revenue V:

$$V = P_eQ_e + P_cQ_c + \gamma P_nQ_e + P_oQ_u + P_bQ_b - P_{rb}Q_{rb} - P_{rc}Q_{rc} - I_0e^{-\alpha t}(1-\theta) - M_0e^{-\beta t} - C_t - C_s - C_0 \tag{2}$$

Where P_e is the electricity tariff subsidy, Q_e is on-grid electricity, P_c is the carbon quota price, Q_c is carbon emission volume, γ is the grid baseline emission factor, P_n is the CCER price, P_o is the crude oil price per barrel, Q_u is the quantity of crude oil obtained using BECCS-EOR technology, P_b is the biomass carbon price, Q_b is the quantity of biomass carbon, P_{rb} is the biomass fuel price, Q_{rb} is the quantity of biomass fuel, P_{rc} is the coal price, Q_{rc} is the quantity of coal, I_0 is the initial investment cost, θ is the investment subsidy factor, M_0 is the initial operating cost, α and β are the impacts of technological advances on investment cost and operating cost, C_t is transportation cost; $C_t = u_tQ_c$ where u_t is transport cost per unit of CO_2, C_s is sequestration cost; $C_s = u_sQ_s$ where u_s is Sequestration cost per unit of CO_2, and C_0 is utilization costs, $C_0 = u_0（Q_c - Q_s）$ where u_0 is utilization costs per unit of CO_2.

Assuming that the BECCS power plant is put into service at time t_0 and has a life of t_2, the BECCS technical transformation happens at time t_1, the investment construction period is one year, the capture equipment is put into service at time t_1+1 until the end of the plant's life, r_0 is used as the benchmark discount rate, and the residual value of the capture equipment is 0.The following formula may be used to calculate the NPV of the BECCS power plant, assuming continuous compounding interest:

$$\mathrm{NPV} = \left(P_eQ_e + P_cQ_c + \gamma P_nQ_e + P_oQ_u + P_bQ_b - P_{rb}Q_{rb} - P_{rc}Q_{rc} - M_0e^{-\beta t1} - C_t - C_s - C_0\right)\frac{e^{-r0} - e^{r0(t1-t2)}}{e^{r0}-1} - I_0(1-\theta)e^{(r0-\alpha)t1} \tag{3}$$

The carbon quota price is put into the triple tree model of the delayed options, and the expanded crude oil price is put into the NPV formula to figure out the NPV of each node of the delayed investment period $\mathrm{NPV}_{(i,j)}$:

$$\mathrm{NPV}_{(i,j)} = \left(P_eQ_e + P_cQ_c + \gamma P_nQ_e + P_oQ_u + P_bQ_b - P_{rb}Q_{rb} - P_{rc}Q_{rc} - M_0e^{-\beta t1} - C_t - C_s - C_0\right)\frac{e^{-r0} - e^{r0(t1-t2)}}{e^{r0}-1} - I_0(1-\theta)e^{(r0-\alpha)t1}(0 \le i \le n, i \le j \le 2i+1) \tag{4}$$

The NPV of each node is compared to zero, and the greater of these is the investment value of that node $\mathrm{IV}_{(i,j)}$ as follows:

$$\mathrm{IV}_{(i,j)} = \mathrm{MAX}\{\mathrm{NPV}_{(i,j)}, 0\} \tag{5}$$

In the real delayed option, you can figure out the total investment value $\mathrm{TIV}_{(I,J)}$ for each node by working backwards from the end of the delayed investment period to the beginning, using the investment value of each node as a starting point:

$$\mathrm{TIV}_{(I,J)} = \mathrm{MAX}\{\mathrm{IV}_{(i,j)},\ \left(P_u\mathrm{TIV}_{(i+1,j)} + P_m\mathrm{TIV}_{(i+1,j+1)} + P_d\mathrm{TIV}_{(i+1,j+2)}\right)e^{-r\Delta t}\} \tag{6}$$

2.3 Uncertainties

3.3.1 Crude oil price P_o

Crude oil price per barrel P_o exhibits volatility and uncertainty as a scarce resource, both economic and non-economic factors can have a significant impact on its price. Hence, P_o can show a trend of volatility and uncertainty.[5] It is assumed that P_o fluctuates over the life of the real option $[0, T]$ and follows a geometric Brownian motion.

$$\frac{dP_o}{P_o} = \mu^o d_t + \sigma^o d_z^o \tag{7}$$

Where μ^o represents the expected growth rate of the crude oil price at time t, σ^o represents the volatility of the crude oil price, and d_z^o represents the standard Wiener process increment. The values of μ^o and σ^o can be solved from historical data using the following equations:

$$U_t = \frac{P_o^{t+1}}{P_o^t}, \quad (t = 0,1,2,\dots,n) \tag{8}$$

$$\begin{cases} \bar{U} = \frac{1}{n}\sum_{t=0}^{n}(U_t - 1) \\ S^2 = \frac{1}{n-1}\left[\sum_{t=0}^{n}(U_t - 1)^2 - n\bar{U}\right] \end{cases} \Rightarrow \begin{cases} \bar{U} = \mu_{daily}\Delta t \\ S^2 = \sigma_{daily}^2\Delta t \end{cases} \Rightarrow$$

$$\begin{cases} \mu^o = 252\mu_{daily} \\ \sigma^o = \sqrt{252}\sigma_{daily} \end{cases} \tag{9}$$

This paper uses a triple tree model to analyze the crude oil price P_o in order to improve the accuracy of the analysis. Since the crude oil price P_o is volatile, it will have three states of change in the time period from moment t to moment $t + \Delta t$, i.e., rising as uP_o, falling as dP_o, and remaining as P_o unchanged. Where u and d are the up and down coefficients of the crude oil price P_o, the following equation can be found:

$$u = M + \sqrt{M^2 - 1} \tag{10}$$

$$d = M - \sqrt{M^2 - 1} \tag{11}$$

$$P_u = \frac{e^{r\Delta t}(1+d) - e^{(2r+\sigma^2)\Delta t} - d}{(d-u)(u-1)} \tag{12}$$

$$P_m = \frac{e^{r\Delta t}(u+d) - e^{(2r+\sigma^2)\Delta t} - 1}{(1-d)(u-1)} \tag{13}$$

$$P_d = \frac{e^{r\Delta t}(1+u) - e^{(2r+\sigma^2)\Delta t} - u}{(1-d)(d-u)} \tag{14}$$

Where $M = \frac{e^{r\Delta t} + e^{(3r+3\sigma^2)\Delta t} - e^{(2r+\sigma^2)\Delta t} - 1}{2[e^{(2r+\sigma^2)} - e^{r\Delta t}]}$; r is the risk-free rate.

3.3.2 Coal price P_{rc}

As a result of the reform of the coal pricing system, coal price P_{rc} is now set by the market and is unpredictable. It has been shown[6] that Geometric Brownian motion fits well with how the coal price changes, so that the coal price can satisfy the following equation:

$$\frac{dP_{rc}}{P_{rc}} = \mu^{rc}d_t + \sigma^{rc}d_z^{rc} \tag{15}$$

Where μ^{rc} represents the expected growth rate of the coal price at moment t, σ^{rc} represents the volatility of the coal price at moment t, and d_z^{rc} represents the standard Wiener process increment.

3.3.3 Biomass fuel price P_{rb}

Alterations in the demand for power may result in alterations in the demand for biomass fuel from BECCS power plants; as a result, there is uncertainty around the biomass fuel price P_{rb}. Studies have demonstrated[7] that changes in the biomass fuel price are consistent with Geometric Brownian motion. As a result, the following equation may be satisfied for the biomass fuel price:

$$\frac{dP_{rb}}{P_{rb}} = \mu^{rb}d_t + \sigma^{rb}d_z^{rb} \tag{16}$$

Where μ^r represents the expected growth rate of the biomass fuel price at moment t, σ^r represents the volatility of the biomass fuel price, and d_z^r represents the standard Wiener process increment.

3.3.4 Investment cost I_t and operating cost M_t

As a result of the decrease in BECCS technology investment costs as well as operation costs brought on by gradual technological advancement, investment cost as well as operation cost are uncertain. If we make the assumption that the development of BECCS can be described by a learning curve, with I_0 and M_0 representing the initial investment cost and the initial operating cost, I_t and M_t representing the investment cost in period t and the operating cost during period t, then the formulas for I_t and M_t can be expressed as follows:

$$I_t = I_0 e^{-\alpha t} \tag{17}$$

$$M_t = M_0 e^{-\beta t} \tag{18}$$

We then consider a government investment subsidy for investing in BECCS technology.

$$I_t = I_0 e^{-\alpha t}(1 - \theta) \tag{19}$$

$$M_t = M_0 e^{-\beta t} \tag{20}$$

3. *ANALYSIS OF CALCULATION EXAMPLES*

3.1 General parameter setting

This paper analyzes the performance of a 10.8 MW biomass gasification coupled with coal-fired power plant and applies its data to a case study of a 30-year lifespan BECCS project with a delayed real option of 10 years. A biomass and coal blend ratio of 1:9 [8] is used, as ratios below 10% the biomass co-burning may lead to ash accumulation, slagging, corrosion and other problems under control, and the cost of these effects can be ignored.[9] In order to save space, reference data for BECCS plant parameters are not listed. If necessary, please contact the author to provide them.

3.2 Crude oil price P_O estimation

This paper selects the January 2, 2009–December 31, 2019 international WTI crude oil price, with the average price of 71.49 USD/barrel as the initial crude oil price $P_{o(0,0)}$. When we use the historical data to calculate the volatility of crude oil prices changes, we get the following results: $\sigma^o = 0.2354$, the rising $u = 1.5417$, the falling $d = 0.6486$, the probability of a rising price $p_u = 0.2130$, the probability of an unchanged price $p_m = 0.6956$, and the probability of a falling price $p_d = 0.0914$. Calculating a triple tree unfolding table of crude oil prices throughout the lifetime of the BECCS technical delayed real option for power plant is possible when the data presented above is used as the foundation for the calculation.

3.3 Empirical analysis

4.3.1 NPV of BECCS power plant investment

Based on the above, the NPV of the BECCS power plant investment, taking into consideration the government investment subsidy at each node over the term of the delayed real option, is calculated according to Equation (4), which means that the NPV at each node for $\theta = 1$ is shown in Table 3.

Table 3 NPV for each node of the BECCS power plant over the deferred investment period (CNY0.1 million)

2021	2022	2023-2029	2030	2031
-17843.62	-17061.98	……	32566.71	58020.70
	-17669.42	……	15250.63	31886.96
	-18063.47	……	4018.81	14935.71
		……	-3266.53	3940.54
		……	……	……
				-16344.06

Currently, the NPV of investing in the BECCS power plant is -1784361900.68 CNY, making it unsuitable for investment. Even in 2022, after considering three scenarios of rising, unchanged, and falling carbon quota prices, the maximum and minimum NPV values are still negative, indicating that investing in BECCS power plants is not a wise decision. This trend continues from 2023 to 2027, where the maximum NPV value of the investment in BECCS power plants remains negative. Only from 2028 onwards, the maximum NPV value becomes positive, which could make BECCS power plant investments worth considering. However, from 2021 to 2031, the proportion of saved paths is relatively low, with only 6.67%, 11.76%, 15.79%, and 19.05% saved paths from 2028 to 2031. Therefore, while investing in BECCS power plants might be an option from 2028 onwards, the probability of incurring losses is higher than the probability of gaining profits.

4.3.2 TIV of BECCS power plant investment

Based on the above, the NPV of each node in the delayed investment period of the BECCS power plant is compared to zero according to equation (5), and the greater of these is the value of the investment at that node. Based on this, the TIV of each node under the delayed real option can be obtained by taking the investment value of each node and working backwards from the final term of the delayed investment to the initial moment, as shown in the Table 2.

Table 2 TIV per node over the deferred investment period for the BECCS power plant (CNY)

2021	2022	2023-2029	2030	2031
9468.95	54876.37	……	3256670912.53	5802069905.65
	3786.74	……	1525062515.03	3188695900.84
	158.49	……	453503256.47	1493571035.55
		……	49436804.19	394054355.72
		……	……	……
				0.00

The total value of the BECCS power plant investment in 2021, calculated using the real options method, is 9468.95 CNY. However, the NPV of the BECCS power plant investment in 2021 is negative, indicating that while the investment project is feasible, it is not suitable for immediate investment. Therefore, investors should delay the investment to make a profit. The preservation path ratios from 2021–2031 are 100.00%, 100.00%, 80.00%, 57.14%, 44.44%, 36.36%, 30.77%, 26.67%, 23.53%, 21.05%, and 19.05%. Overall, the TIV and preservation path ratios for each node over the delayed investment period are higher then the NPV approach. This is because the NPV approach does not consider the operational management flexibility and strategic value associated with the uncertainty of the BECCS project. As a result, investors may underestimate the true value of the project and forego investment.

4. SENSITIVITY ANALYSIS

Combining several important factors, this paper will conduct sensitivity analyses on the crude oil prices, carbon quota price, CCER price, coal price, biomass fuel price, initial investment cost, electricity tariff subsidy, and investment subsidy factor.

4.1 Impact analysis of crude oil prices

It can be seen from the Figure 1 that NPV and TIV are gradually becoming larger as the international WTI crude oil price increases. But NPV is always negative and TIV is significantly higher than NPV, even if the price of crude oil increases to 100 USD/barrel. According to the BECCS power plant investment decision rules, the investment does not immediately trigger. The optimal execution time of the standard American call option with no dividend payment in discrete time is the moment of expiration[10], and the optimal investment time of the BECCS power plant is always 2031 as the crude oil price changes from 50 USD/barrel to 100 USD/barrel.

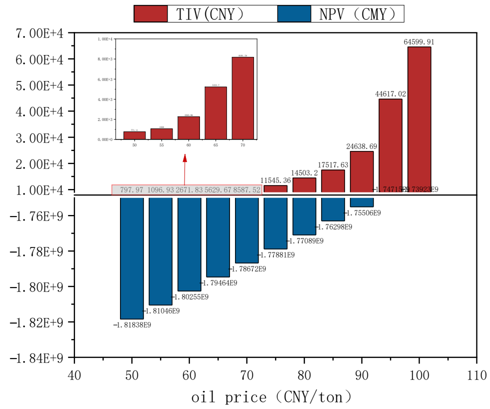

Figure 1 NPV and TIV of BECCS power plants at different crude oil price

4.2 Impact analysis of carbon trading market

China's carbon trading market offers two types of trading: carbon quota trading based on total emission control and voluntary emission reduction trading based on projects. **错误!未找到引用源。**While the current carbon quota price and CCER price make investment possible, the returns are not immediate.

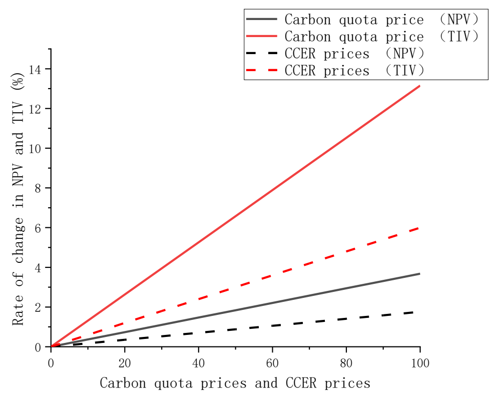

Figure 2 Sensitivity analysis of carbon quota price and CCER price

Figure 1 demonstrate that as carbon quota and CCER prices increase, NPV and TIV increase, but NPV remains negative and TIV is significantly higher than NPV. With the gradual increase in CCER price from 0CNY/ton to 1CNY00/ton, NPV only increases by 1.76% and TIV increases by 6.00%. Compared to the 3.68% increase in NPV and 13.15% increase in TIV caused by the change in carbon quota price, the contribution of CCER to the NPV and TIV of BECCS plants is smaller. The VDO decreases as the carbon quota price and CCER price increase. Even with carbon quota or CCER price increase to 100CNY/ton, investment is not immediately triggered due to the larger value of delayed options. Cost control and incentive policies are necessary to ensure the deployment of BECCS power plants, in addition to considering the impact of carbon quota and CCER prices.

4.3 Impact analysis of cost control

BECCS power plants have not been widely adopted in China due to their high costs. A sensitivity analysis was conducted on the coal price, biomass fuel price, and initial investment cost to explore their impact on investment decisions. As each of these factors is set separately in a 10% gradient, decreasing to 100% from the existing price.

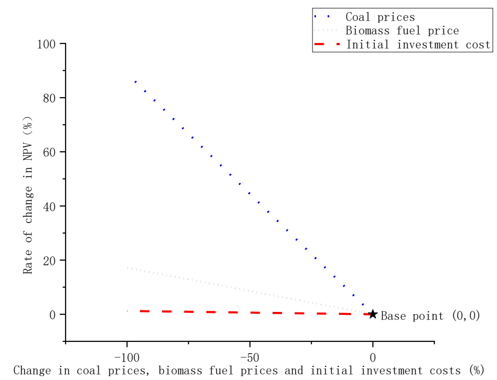

Figure 3 Sensitivity analysis of coal prices, biomass fuel prices and initial investment costs

As the prices of the three factors fell, the NPV and TIV increased, but the NPV remained negative even at 0 CNY/ton. It can be seen from the Figure 3 that a reduction in coal prices had the greatest impact on NPV, increasing it by about 89% but still not enough to trigger investment. The decline in biomass fuel prices increased NPV by about 17%, with initial investment costs having the least impact on net present value, increasing by about 1.2%. This indicates that high costs are a disincentive to invest in BECCS power plants, and cost control measures alone may not be enough to trigger investment. Government subsidies are essential.

4.4 Impact analysis of policy incentives

Dividing the investment subsidy factor in a gradient of 0.1 from 0 to 1 and dividing the electricity tariff subsidy in a gradient of 0.005 from 0 to 0.050. As the investment subsidy factor and electricity tariff subsidy increase, NPV and TIV are gradually becoming larger and VDO is gradually decreasing, but the NPV of BECCS power plants is always negative due to the presence of a high delayed option value. Even if the government fully subsidizes the initial investment cost or electricity tariff, the investment cannot be made immediately.

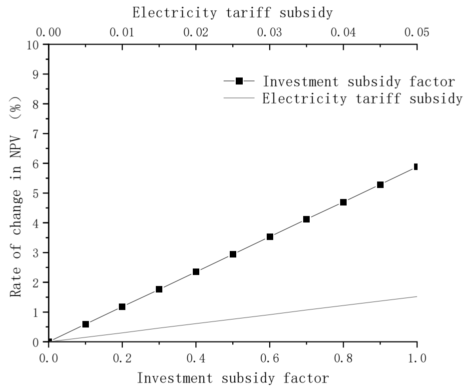

Figure 4 Sensitivity analysis of electricity tariff subsidies and investment subsidy factors

Figure 4 shows that increasing the investment subsidy factor resulted in a 5.88% NPV increase, while increasing the electricity tariff subsidy resulted in only a 1.52% increase. Therefore, relying solely on subsidies may not effectively promote BECCS power plant deployment at current carbon trading market due to cost pressures. Other effective promotion strategies beyond cost control and policy incentives are needed.

5. CONCLUSION

The TIV of the BECCS power plant investment in 2021 is 9468.95 CNY, making the investment feasible, but not suitable for immediate investment due to a negative NPV. Investors should wait until 2031 to profit. The TIV of BECCS power plant investment increases with rising carbon quota price and CCER price, but high investment costs and lack of policy incentives make immediate investment difficult in China's current carbon trading market. Decreases in coal price have a significant impact on the NPV of BECCS power plants, but even a -100% change does not warrant immediate investment. Biomass fuel price and initial investment cost have minor incentive effects. Investment subsidy factor and electricity tariff subsidy have limited effects on the NPV of BECCS power plants. When the investment subsidy factor is 1, the NPV increase is only about 5.88%. The electricity tariff subsidy has an even smaller incentive effect on the NPV.

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DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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