Dynamic simulation and assessment of the ecological benefits of hydropower as an alternative energy for thermal power under ecological civilization construction: A case study of Fujian, China

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Abstract
As ecological civilization construction receives growing attention in China, the eco-friendliness of the power supply structure is becoming increasingly important. Thermal power and hydropower are the two major power sources in China. Hydropower has both positive and negative effects on the ecosystem. However, there are few studies on the comprehensive impact of hydropower on the ecosystem. Therefore, the main innovation of this article is to integrally and comprehensively study the impact of hydropower to propose recommendations for hydropower development. The study of hydropower's effects on the overall ecosystem including resources, the environment, and economic society reflects the integrity, and the simultaneous study of hydropower's positive and negative effects reflects the comprehensiveness. First, this paper constructs a system dynamics (SD) model that can analyze the impact of replacing thermal power with hydropower on the ecosystem and proposes an improved coupling coordination degree (CCD) model. Then, this paper takes the province of Fujian as an example for SD scenario simulation and proposes recommendations for each indicator in the ecology subsystem. Finally, this paper performs CCD analysis on subsystems of the ecology subsystem in different policy scenarios and provides suggestions for future hydropower development in Fujian. Results show that hydropower technology improvement and efficiency increase (HTIEI) is more conducive to the development of the overall ecosystem. The scientificity of the current hydropower policy in Fujian is proven through theoretical analysis, and further hydropower development proposals are proposed. This paper provides a basis for the formulation of power generation policies and promotes ecological civilization construction for Fujian. The proposed methods in this paper can also provide tools for policy research on clean energy power generation.

KEYWORDS
coupling coordination degree model, ecological civilization construction, hydropower, system dynamics model

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1 | INTRODUCTION

The development mode of “grow first, clean up later” has placed enormous pressure on China during its industrial upgrading and the coordinated development of the social economy. The notion of ecological civilization has been receiving increasing attention from the government and its people. Ecological civilization construction has been accepted as a part of the Constitution of the People's Republic of China, indicating that it has risen to national-strategy height. Ecological civilization construction aims to strengthen economic and social progress premised on protecting or improving the ecological environment. Some indicators have been proposed to measure the level of China's ecological civilization construction, among which the economy, resources, the environment, and policy support have received extensive attention. This paper sets ecosystem indicators from three aspects, namely resources, the environment, and economic society.

Due to the strong dependence of China's economic development on energy, clean power generation is an important element for ecological civilization construction. Many scholars have studied the development and utilization of clean energy from different aspects. Among the total power generation in China in 2018, thermal power accounted for 73.32% and hydropower accounted for 16.24%. Hydropower and thermal power are the two most important sources of electricity supply in China. The power structure dominated by thermal power in China has serious negative impact. China is currently the country with most CO2 emissions in the world. The replacement of thermal power with hydropower can play a major role in energy conservation and emission reduction, but it could lead to submergence by reservoirs, causing damage to natural resources. Therefore, this paper aims to study the comprehensive benefits of hydropower on the ecosystem from the perspective of the replacement of thermal power with hydropower and to offer hydropower development proposals to promote ecological civilization construction.

There are many studies on the impact of hydropower on resources, the environment, economy, and society. Some scholars have studied hydropower development policies on the basis of its environmental benefits. De Faria et al researched the effect of large hydropower stations on the local social economy in developing countries. Some scholars studied the effects of hydropower projects on river basins, including animal and plant destruction, and river eutrophication. Arias et al and Liang et al analyzed the impact of hydropower projects on wetlands. Furthermore, some researchers studied environmental pollution, ecological structure changes, and ecological function degradation caused by hydropower development. Other scholars analyzed the comprehensive effects of hydropower development from various aspects, such as hydropower production efficiency and ecological cost, CO2 emissions and economic growth.

2 | IMPACT PATH ANALYSIS OF HYDROPOWER AND THERMAL POWER ON THE ECOSYSTEM

2.1 | Research boundary analysis

In the context of ecological civilization construction, this paper studies whether thermal power should be further replaced by hydropower, and what hydropower development policies should be adopted through analyzing the impact paths of hydropower and thermal power on the ecosystem.

Ecological civilization construction mainly includes three elements: resources, the environment, and economic society. For resources, the replacement of thermal power by hydropower can reduce coal consumption, the ratio of hydropower to thermal power can affect the energy structure, and reservoir construction floods forests and cultivated land. For the environment, reservoir construction causes river sedimentation, but the replacement of thermal power by hydropower can reduce pollutant emissions. For economic society, the difference between the cost of hydropower and thermal power affects economic cost, and hydropower and thermal power have different impact on human health. Accordingly, the system constructed in this paper includes five subsystems: hydropower subsystem, thermal power subsystem, ecological resource subsystem,
ecological environment subsystem, and ecological economy and society subsystem. It can be divided into two parts: a power subsystem and an ecology subsystem, as shown in Figure 1.

2.2 Subsystem analysis and effect framework construction

Based on the boundaries and main factors of the power subsystem and the ecology subsystem, this article analyzes their causality in depth, and studies the feedback and constraints between the factors. An effect framework among the subsystems is constructed through the SD software Vensim PLE. 6.2, as shown in Figure 2. For example, the paths of the hydropower subsystem affecting the ecological economy and society subsystem are as follows: hydropower installed capacity and hydropower engineering unit cost and average life of hydropower → annual hydropower cost; hydropower utilization hours and hydropower installed capacity → hydropower generation → reservoir sedimentation and greenhouse gas (GHG) emissions of hydropower → human health hazard.

3 MATERIALS AND METHODOLOGY

SD can incorporate the multiple factors of each subsystem within a general framework and effectively evaluate their dynamic
interactions. With visible display of the structure and consequences, SD models have been widely used in the simulation of socioeconomic and environmental processes. This paper tries to study the impact of hydropower on the ecosystem from a system and evolution perspective. In this paper, the power subsystem and ecology subsystem comprise multiple factors that present complex and dynamic interactions. Therefore, this study uses SD to deal with the dynamic interactions of these factors.

The coupling includes two aspects of coupling degree CD and CCD. The CD mainly reflects the degree of interaction among the systems. The CCD can measure the degree of harmony of the systems in the development process, focusing on the benign interaction among the systems, and reflecting the actual level and status of the system. The ecological civilization construction focuses on the comprehensive and coordinated development of resources, the environment, and economic society, rather than pulling the overall level by over-emphasizing the development in one aspect. Therefore, this study constructs a CCD model to analyze the CCD among the ecological resource subsystem, ecological environment subsystem, and ecological economy and society subsystem under different policy scenarios.

### 3.1 The SD model

This paper selects the province of Fujian as the research area and constructs an SD model. On the one hand, Fujian was one of the first provinces to propose the “ecological province” strategic concept. In 2014, Fujian was approved by the state as the nation’s first demonstration zone for ecological civilization. On the other hand, Fujian is rich in water resources, with a large number of hydropower stations. Therefore, it is significant to study the impact of hydropower on the ecosystem in Fujian.

This paper establishes a stock and flow diagram, as shown in Figure 3. The model’s simulation range is 2005-2025, and the simulation step is one year. The data for the model come from *Fujian Statistical Yearbook, Statistical Analysis Report on Land and Resources in Fujian Province, China Energy Statistical Yearbook, China Coal Industry Statistical Yearbook, National Electric Power Industry Statistics Express* and some industry standards and literature. The model converts the GDP calculated by the current year’s price into the actual value corrected at the constant price in 2005 to eliminate the influence of the price factor. The main equations are shown in Table A1 in the Appendix.

The model validity is judged by examining the difference between the model simulation values and historical statistics in 2005-2017. Several representative indicators were selected for testing. The maximum value of the absolute value of relative error is 5.56%, so the fitting degree between simulation values and the actual data is higher. Details are shown in Table A2 in the Appendix.

### 3.2 CCD evaluation

#### 3.2.1 Assessment indicator system

The indicator system is constructed according to the SD model and literature review, as shown in Table 1. This indicator system consists of seven indicators that reflect the impact of the power subsystem on the ecology subsystem.

The data of the first six indicators could be directly simulated by the SD model. Human health is mainly affected by air pollution, water quality, and GHG emissions. Several experts were invited to calculate the weights by using the order relation analysis method, and the following formula for C7 was obtained: $C7 = 0.4296 \times C3 + 0.2142 \times C5 + 0.3562 \times C4$.

#### 3.2.2 The CCD model

**Data preprocessing**

Most researchers use extreme standardization to standardize the original data when conducting CCD studies. However, in extreme standardization, the positioning of each datum within its data-evaluation range is calculated, but the processed data have no practical meaning. Benchmark progressive standardization keeps the practical meaning of each datum while satisfying dimensionless data processing, and the final evaluation result can reflect the actual situation. On the basis of single-benchmark progressive standardization in the literature, this paper first transforms the negative indicator into a positive indicator and then proposes an improved method that can better reflect the difference in indicator data.

$$A_{ij} = \begin{cases} 
X_{ij}/S(X_{ij}), & X_{ij} \text{ is the positive indicator} \\
S(X_{ij})/X_{ij}, & X_{ij} \text{ is the negative indicator}
\end{cases}$$  \hspace{1cm} (1)

where $i$ represents the year; $j$ represents the sequence of the indicator; $A_{ij}$ is the standardized value of the indicator; $X_{ij}$ is the original value of the indicator; and $S(X_{ij})$ is the target value of the indicator. When $X_{ij}$ is the positive indicator, $S(X_{ij})$ takes the maximum value of the simulation value over the years in all scenarios; when $X_{ij}$ is the negative indicator, $S(X_{ij})$ takes the minimum value of the simulation value over the years in all scenarios.

**Weight determination**

Most researchers use the entropy method for the weight determination of each indicator when applying the CCD model. However, it is difficult to reflect the subjective wills of decision-makers. This paper introduces the order relation analysis method, and the final weight obtained is a
Calculate the information entropy of the indicator $j$, $e_j$:

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} (P_{ij} \times \ln P_{ij}) (0 \leq e_j \leq 1)$$

where $m$ represents the number of years; and $A_{ij}$ is calculated by Equation (1).

Calculate the entropy redundancy of the indicator $j$, $g_j$:

$$g_j = 1 - e_j$$

Calculate the weight of the indicator $j$, $w'_j$:

$$w'_j = g_j / \sum_{j=1}^{n} g_j$$

where $n$ represents the number of indicators in a subsystem; $m$ represents the number of years; and $A_{ij}$ is calculated by Equation (1).
Subjective weight: order relation analysis method. For evaluation indicator set \( \{x_1, x_2, \ldots, x_n\} \), determine the order relation for the indicators:

\[
x_1 > x_2 > \ldots > x_n
\] (6)

Compare and judge the relative importance of indicators, determine the ratio of the importance of indicator \( x_{j-1} \) and indicator \( x_j \):

\[
w''_{j-1} / w''_j = r_j (j = n, n-1, \ldots, 2)
\] (7)

where the value of \( r_j \) can refer to Table 2.

Calculate indicator weight \( w''_j \):

\[
w''_j = \left(1 + \sum_{j=2}^{n} \prod_{i=j}^{n} r_i\right)^{-1}, w''_{j-1} = r_j w''_j (j = n, \ldots, 2)
\] (8)

**Comprehensive weight.**

\[
w_j = \alpha w'_j + \beta w''_j
\] (9)

where \( w'_j, w''_j \) represent the indicator weights calculated by the entropy method and the order relation analysis method, respectively; \( \alpha, \beta \) are undetermined coefficients, \( \alpha, \beta > 0, \alpha + \beta = 1 \).

In order to make the subjective information and objective information fully reflected in the alternative ranking, this paper establishes an optimization model for the coefficients \( \alpha \) and \( \beta \) in the comprehensive weight.

\[
\min Z = \sum_{i=1}^{m} \sum_{j} A_{ij} \alpha w'_j - A_{ij} \beta w''_j, \text{s.t.} \alpha + \beta = 1 (\alpha, \beta \geq 0)
\] (10)

**Evaluation of the comprehensive level of each subsystem**

The comprehensive level of subsystem \( x \) in year \( i \), \( P(X) \):

\[
P(X) = \sum_{j=1}^{n} w_j A_{ij}
\] (11)

where \( j \) represents the sequence of the indicator in subsystem \( x \).

| \( r_j \) | Description |
|---|---|
| 1.0 | Indicator 1 and indicator 2 are equally important |
| 1.2 | Indicator 1 is slightly more important than indicator 2 |
| 1.4 | Indicator 1 is significantly more important than indicator 2 |
| 1.6 | Indicator 1 is strongly important compared with indicator 2 |
| 1.8 | Indicator 1 is extremely important compared with indicator 2 |

Establishment of the CCD model.

\[
C = \frac{3 \sqrt{f(X) \times g(Y) \times h(Z)}}{f(X) + g(Y) + h(Z)}
\] (12)

where \( C \) represents the CD; \( f(X), g(Y), h(Z) \) represent the comprehensive level of each subsystem, calculated by Equation (11).

\[
D = \sqrt{C \times T}, T = \alpha f(X) + \beta g(Y) + \gamma h(Z)
\] (13)

where \( D \) represents the CCD; \( \alpha, \beta, \gamma \) represent the undetermined coefficients, \( \alpha + \beta + \gamma = 1 \); \( T \) is the comprehensive evaluation index of the three-dimensional system. This paper considers the three subsystems of the ecology subsystem to be equally important, so \( \alpha = \beta = \gamma = 1/3 \).

Divide CCD into four levels, as shown in Table 3.

4 | RESULTS ANALYSIS AND DISCUSSION

4.1 | Simulation results and analysis of SD model

4.1.1 | Parameter setting scheme

In this section, dynamic simulation is carried out by changing the parameters of the hydropower subsystem to study the influence of each hydropower parameter change on the main indicators of the ecology subsystem. The changed parameters include hydropower installed capacity, hydropower utilization hours, average life of hydropower, and hydropower engineering unit cost, as shown in Table 4.

4.1.2 | Current scenario

Part of the simulation results in the current scenario are shown in Figures 4-7.

1. As shown in Figure 4, total power generation, hydropower generation, and thermal power generation in Fujian all show an upward trend on the whole.
2. As shown in Figure 5, from 2005 to 2018, hydropower utilization hours and thermal power utilization hours both fluctuated greatly. During the simulation period, the hydropower utilization hours maintain a steady trend on the whole, and the thermal power utilization hours show a downward trend on the whole.
3. As shown in Figure 6, hydropower installed capacity and thermal power installed capacity both show an upward trend on the whole.
4. Figure 7 shows the comparison of annual hydropower cost, annual thermal power cost, and cost of unit power generation. The annual hydropower cost and the annual thermal power cost both show an upward trend on the whole, and since the annual power generations of hydropower and thermal power both show an upward trend, the cost of unit power generation tends to be modest on the whole.

4.1.3 Simulation results of increasing the hydropower installed capacity

Increasing the hydropower installed capacity means adding more hydropower generating units. The simulation results show that increasing the hydropower installed capacity has both positive and negative effects on the ecology subsystem. Specifically, it has both advantages and disadvantages for the ecological resource subsystem and the ecological environment subsystem, and has positive effects on the ecological economy and society subsystem.

1. For the ecological resource subsystem, increasing the hydropower installed capacity can reduce the coal consumption of unit power generation, but it will increase the reservoir inundation loss of unit power generation.

When the hydropower installed capacity is increased, the total power generation is increased while the power generation coal consumption stays the same, so the coal consumption of unit power generation is reduced, as shown in Figure 8. The increase in the hydropower installed capacity increases the total power generation and the water surface area of the reservoir, and the reservoir inundation loss of unit power generation is increased ultimately, as shown in Figure 9.

2. For the ecological environment subsystem, increasing the hydropower installed capacity can reduce the air pollution degree and GHG emissions of unit power generation, but it will increase the reservoir sedimentation of unit power generation.

Air pollutants mainly come from coal-fired emissions of thermal power. When the hydropower installed capacity is increased, the air pollution degree of unit power generation is decreased, as shown in Figure 10. The GHG emissions of hydropower mainly come from GHG emissions associated with dam construction, GHG generated by organisms in reservoirs, and GHG emissions associated with hydropower station operations. The GHG emissions of thermal power mainly come from coal-fired emissions. The GHG emission coefficient of hydropower is less than the GHG emission coefficient of thermal power.45 When the hydropower installed capacity is increased, the GHG emissions of unit power generation are decreased, as shown in Figure 11. The increase in the hydropower installed capacity increases the water surface area of the reservoir, and the reservoir sedimentation of unit power generation is increased ultimately, as shown in Figure 12.

3. For the ecological economy and society subsystem, increasing the hydropower installed capacity can simultaneously reduce the cost and human health hazard of unit power generation.

When the hydropower installed capacity is increased, the proportion of hydropower generation in the sum of hydropower and thermal power generation is increased. Since the annual thermal power cost is higher than the annual hydropower cost, the cost of unit power generation is reduced, as shown in Figure 13. The impact of the indicator change in the hydropower subsystem on human health is determined by its comprehensive impact on the ecological environment. Increasing the hydropower installed capacity has positive and negative impacts on the ecological environment, which ultimately has a positive impact on human health, as shown in Figure 14.

| TABLE 3 | Division of the development stages |
|------------------|------------------|
| Value of $D$     | $0 \leq D < 0.25$ | $0.25 \leq D < 0.5$ | $0.5 \leq D < 0.75$ | $0.75 \leq D < 1$ |
| Development stages | Seriously unbalanced | Slightly unbalanced | Barely balanced | With superior balance |

| TABLE 4 | Parameter setting scheme |
|------------------|------------------|
| Measures to strengthen the replacement of thermal power by hydropower | Parameter setting |
| Increase the hydropower installed capacity | Hydropower installed capacity +20% |
| Increase the hydropower utilization hours | Hydropower utilization hours +20% |
| Increase the average life of hydropower | Average life of hydropower +20% |
| Reduce the hydropower engineering unit cost | Hydropower engineering unit cost –20% |

Note: The water surface area of the reservoir remains unchanged when the hydropower utilization hours are increased.
The simulation results show that increasing the hydropower utilization hours in all aspects.

1. For the ecological resource subsystem, increasing the hydropower utilization hours can reduce the coal consumption of unit power generation and the reservoir inundation loss of unit power generation.

When the hydropower utilization hours are increased, the total power generation is increased while the power generation coal consumption stays the same, so the coal consumption of unit power generation is reduced, as shown in Figure 8. Since the water surface area of the reservoir is unchanged, the reservoir inundation loss of unit power generation is decreased, as shown in Figure 9.
2. For the ecological environment subsystem, increasing the hydropower utilization hours can reduce the air pollution degree, GHG emissions, and reservoir sedimentation of unit power generation, simultaneously.

When the hydropower utilization hours are increased, the total power generation is increased while the coal-fired emissions remain unchanged, so the air pollution degree of unit power generation is decreased, as shown in Figure 10. The GHG emission coefficient of hydropower is less than the GHG emission coefficient of thermal power. When the hydropower utilization hours are increased, the GHG emissions of unit power generation are decreased, as shown in Figure 11. The increase in the hydropower utilization hours increases the total power generation while the water surface area of the reservoir remains unchanged, so the reservoir sedimentation of unit power generation is decreased, as shown in Figure 12.

3. For the ecological economy and society subsystem, increasing the hydropower utilization hours can simultaneously reduce the cost and human health hazard of unit power generation.

When the hydropower utilization hours are increased, the construction cost is not increased while the total power generation is increased, so the cost of unit power generation is decreased, as shown in Figure 13. Increasing the hydropower utilization hours has positive effects on the ecological environment, so it has a positive impact on human health, as shown in Figure 14.

4.1.5 Simulation results of increasing the average life of hydropower

The simulation results show that increasing the average life of hydropower has positive effects on the ecology subsystem. Specifically, increasing the average life of hydropower has no effect on the ecological resource subsystem or the ecological environment subsystem, and has positive effects on the ecological economy and society subsystem.

The increase in the average life of hydropower only affects the cost of unit power generation. When the average life of hydropower is increased, the hydropower construction cost remains unchanged, so the annual depreciation expense of hydropower projects is reduced. As a result, the cost of unit power generation is reduced, as shown in Figure 13.

4.1.6 Simulation results of reducing the hydropower engineering unit cost

The simulation results show that reducing the hydropower engineering unit cost has positive effects on the ecology subsystem. Specifically, reducing the hydropower engineering unit cost has no effect on the ecological resource subsystem or the ecological environment subsystem, and has positive effects on the ecological economy and society subsystem.

The reduction of the hydropower engineering unit cost only affects the cost of unit power generation. When the hydropower engineering unit cost is reduced, the hydropower construction cost is reduced, so the annual depreciation expense of hydropower projects is reduced. As a result, the cost of unit power generation is reduced, as shown in Figure 13.

4.1.7 Scheme comparison

For the influence of each indicator change in the hydropower subsystem on each indicator in the ecology subsystem, the comparison results are shown in Figures 8-14.

1. For C1 (Figure 8), C3 (Figure 10), and C4 (Figure 11), increasing the hydropower installed capacity and increasing
the hydropower utilization hours reduce them by the same amount. But they remain unchanged when increasing the average life of hydropower and reducing the hydropower engineering unit cost.

2. For C2 (Figure 9) and C5 (Figure 12), increasing the hydropower installed capacity can lead to their increase, while increasing the hydropower utilization hours can reduce them. And increasing the average life of hydropower and reducing the hydropower engineering unit cost do not change them.

3. For C6 (Figure 13), changes in each indicator all reduce it. The effects of reducing the cost of unit power generation are ordered as follows: increasing the hydropower utilization hours > increasing the hydropower installed capacity > reducing the hydropower engineering unit cost > increasing the average life of hydropower.

4. For C7 (Figure 14), increasing the hydropower installed capacity and increasing the hydropower utilization hours can both reduce it, and the effect of increasing the hydropower utilization hours is better. Increasing the average life of hydropower and reducing the hydropower engineering unit cost have no effect on it.

The influences of each indicator change in the hydropower subsystem on each indicator in the ecology subsystem are summarized as shown in Table 5. “+” represents positive impact, “−” represents negative impact, and “/” represents no impact.

4.2 | CCD analysis

4.2.1 | Policy scenario setting

This paper sets three policy scenarios, namely current scenario, hydropower generating unit increase (HGUI), and hydropower technology improvement and efficiency increase (HTIEI), as shown in Table 6.

4.2.2 | CCD analysis in different policy scenarios

The comprehensive level and CCD among each subsystem in the ecology subsystem under different policy scenarios are shown in Figures 15-18.
In terms of subsystems, the ecological resource subsystem and the ecological economy and society subsystem tend to be steady on the whole, and the ecological environment subsystem is on a slow upward trend on the whole. This shows that, during the simulation and evaluation period, the replacement of thermal power by hydropower development in Fujian has gradually improved environmental benefits on the basis of maintaining certain economic and social benefits in general. The comparison of the comprehensive level of each subsystem in different scenarios is as follows: For ecological resource subsystem, there is HTIEI > current scenario > HGUI; for ecological environment subsystem, there is HTIEI > current scenario > HGUI in most years; and for ecological economy and society subsystem, there is HTIEI > HGUI > current scenario.

For ecology subsystem, the CCD remains steady on the whole. In the current scenario, the CCD over the simulation period is greater than 0.75, which belongs to “with superior balance,” indicating that the impact of hydropower and thermal power development in Fujian on resources, the environment, economy, and society is relatively balanced and could maintain this balance. The comparison result of the CCD in different scenarios shows that the performance of HTIEI is the best and that the order is HTIEI > current scenario > HGUI in most years.

### Table 5
| Indicator change in the hydropower subsystem | Ecological resource subsystem | Ecological environment subsystem | Ecological economy and society subsystem |
|--------------------------------------------|------------------------------|----------------------------------|------------------------------------------|
| Increase the hydropower installed capacity  | Reduction of C1              | Reduction of C3                  | Reduction of C6                          |
| Increase the hydropower utilization hours  | +                            | +                                | +                                        |
| Increase the average life of hydropower    | -                            | +                                | -                                        |
| Reduce the hydropower engineering unit cost| -                            | -                                | +                                        |

### Table 6
| Policy scenario | Parameter Setting |
|-----------------|-------------------|
| Current scenario| Current scenario  |
| Hydropower generating unit increase (HGUI) | Hydropower installed capacity +20% |
| Hydropower technology improvement and efficiency increase (HTIEI) | Hydropower utilization hours +20%; average life of hydropower +20%; hydropower engineering unit cost -20% |

In terms of subsystems, the ecological resource subsystem and the ecological economy and society subsystem tend to be steady on the whole, and the ecological environment subsystem is on a slow upward trend on the whole. This shows that, during the simulation and evaluation period, the replacement of thermal power by hydropower development in Fujian has gradually improved environmental benefits on the basis of maintaining certain economic and social benefits in general. The comparison of the comprehensive level of each subsystem in different scenarios is as follows: For ecological resource subsystem, there is HTIEI > current scenario > HGUI; for ecological environment subsystem, there is HTIEI > current scenario > HGUI in most years; and for ecological economy and society subsystem, there is HTIEI > HGUI > current scenario.

For ecology subsystem, the CCD remains steady on the whole. In the current scenario, the CCD over the simulation period is greater than 0.75, which belongs to “with superior balance,” indicating that the impact of hydropower and thermal power development in Fujian on resources, the environment, economy, and society is relatively balanced and could maintain this balance. The comparison result of the CCD in different scenarios shows that the performance of HTIEI is the best and that the order is HTIEI > current scenario > HGUI in most years.
4.3 Development proposals

1. According to the simulation results of the SD model, selective measures should be taken for each indicator of the ecology subsystem.

For C1, C3, C4, and C7, they could be decreased by increasing the hydropower installed capacity or hydropower utilization hours. For C2 and C5, they could be decreased by increasing the hydropower utilization hours. For C6, it could be decreased by increasing the hydropower installed capacity, hydropower utilization hours, and average life of hydropower or by reducing the hydropower engineering unit cost. In practice, the government can take measures in conjunction with different goals. The “13th Five-Year” Energy Development Special Plan of Fujian Province pointed out that it is necessary to promote energy conservation and emission reduction. Accordingly, it is possible to increase the hydropower installed capacity or increase the hydropower utilization hours to reduce coal consumption and air pollution.

2. Continue to implement the policy measures in the current hydropower development planning of Fujian—efficiency increase and capacity expansion (EICE).

The Fujian Provincial Government proposed the EICE of hydropower in the energy development plan. Specifically, EICE refers to expanding the hydropower installed capacity through technology improvement, without increasing the flooding of reservoirs or changing the main characteristics of reservoirs. In this paper, increasing hydropower installed capacity has two negative effects on the ecology subsystem, increasing the reservoir inundation loss of unit power generation and increasing the reservoir sedimentation of unit power generation. Therefore, EICE can avoid the negative effects on the ecological resource subsystem and ecological environment subsystem, realizing the simultaneous optimization of each indicator in the ecology subsystem.

3. According to CCD comparison and analysis in different scenarios, HTIEI is the priority policy to promote the replacement of thermal power by hydropower.

The same point of HTIEI and EICE is that they do not increase the flooding of reservoirs or change the main characteristics of reservoirs. The difference is that, by increasing the utilization hours, HTIEI does not increase the installed capacity, so there is no cost of adding installed capacity. The cost can be further reduced by increasing the average life and reducing the unit cost. Therefore, in addition to EICE, the following measures can be taken:

a. The Fujian Provincial Government pointed out that it is necessary to use rain and water information scientifically, arrange hydropower generation plans reasonably, and exert the effect of power station runoff control. This policy is conducive to improving the hydropower utilization hours.

b. Strengthen the supporting work of the power station. It is beneficial to improve the hydropower utilization hours by supporting the under-loaded power station, expanding users, and changing the practice of only pursuing installed capacity without being concerned with actual results.

c. Combined with local conditions, connect the hydropower to a large power grid as much as possible. Surveys have shown that connecting power stations to large power grids can increase the utilization hours and improve the power supply reliability.

d. Strengthen technical management and avoid blackouts. Strengthening technical training and implementing safety regulations and maintenance system strictly are beneficial to extending the average life of hydropower.
The Fujian Provincial Government proposed giving priority to the development of water resource projects that combine flood control, irrigation, power generation, etc. Considering the benefits such as irrigation and water supply, the responsible organization should apportion the project investment among beneficiary branches. This policy is helpful for reducing hydropower engineering unit cost.

4.4 Discussion

This study uses an integrated approach that enables the dynamic evaluation of CCD, which consists of an SD model and a CCD model. Currently, other methods for studying the impact of hydropower on the ecosystem can be divided into three categories. (a) statistical methods: statistics, comparison, and analysis based on sampled data or historical statistics such as yearbooks; (b) evaluation methods: evaluation of current situation or different scenarios; and (c) review methods: analysis and summary through literature review or hydropower case review. The above methods all have their own advantages, but they are not suitable for analyzing the complex interactions of multiple factors. Through the above methods, the impact of hydropower on the ecosystem cannot be studied from the system perspective and the evolution perspective simultaneously, and the coordinated development of each subsystem in the ecosystem cannot be evaluated. So the method used in this paper is the most suitable method for the research content and purpose of this paper.

The 2018 Hydropower Status Report issued by the International Hydropower Association (IHA) stated that, in 2017, global hydropower produced 4185 TWh of clean power, accounting for two-thirds of total renewable power generation. Therefore, the relationship between hydropower and the ecosystem is an international issue. For the countries where the power generation structure is dominated by hydropower like Brazil, and the countries with high levels of water resources development and few suitable new dam sites like Switzerland, the issues studied in this paper are significant for reference.

However, there are still some shortcomings in the obtained results. The indicators set for the ecology subsystem are few, and the setting of policy scenarios is not rich enough. Therefore, the guiding significance of the obtained results for practice is limited. How to enrich indicators of the ecology subsystem and set a corresponding policy scenario to simultaneously improve more indicators is a challenge.

5 Conclusions

This study analyzes the relationship between the five subsystems of hydropower, thermal power, resources, environment, and economic society, and takes the province of Fujian as an example to put forward proposals for the government for hydropower development. (a) This paper constructs an SD model to analyze the impact on the ecosystem of the replacement of thermal power with hydropower. (b) This paper carries out an SD scenario simulation for Fujian and puts forward corresponding suggestions. Taking Fujian as an example, this paper uses an SD model to simulate and analyze the influences of various indicator changes in the hydropower subsystem on each indicator in the ecology subsystem, and makes recommendations for each indicator in the ecology subsystem. (c) This paper proposes an improved CCD model combining single-benchmark progressive standardization and comprehensive weight methods, and provides policy recommendations based on CCD analysis results in different policy scenarios. The results show that, in the current scenario, the CCD over the simulation period belongs to “with superior balance”. According to the SD scenario simulation and CCD policy simulation, the comprehensive performance of “hydropower technology improvement and efficiency increase” is relatively superior, and hydropower development should be strengthened through this policy. In addition to hydropower, other types of clean energy are increasingly important. In the future, the impacts of other types of clean energy on the ecosystem will be studied synthetically to optimize the power supply structure roundly and promote the ecological civilization construction.

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CONFLICTS OF INTEREST
The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS
Lihui Zhang provided theoretical guidance. Jinrong Zhu and Zhenli Zhao organized the literature and collected the initial data. Jianxue Chai completed the paper.

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## APPENDIX

**Table A1** Calculation formulas of the main variables in system dynamics (SD) model

| Variable                                      | Calculation formula                                                                                                                                 |
|-----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------|
| Coal consumption of unit power generation    | Power generation coal consumption/(Hydropower generation + Thermal power generation)                                                                |
| Thermal power generation                      | Thermal power utilization hours*Thermal power installed capacity                                                                                   |
| Hydropower generation                         | Hydropower utilization hours*Hydropower installed capacity                                                                                         |
| Reservoir inundation loss of unit power generation | Reservoir inundation loss/(Hydropower generation + Thermal power generation)                                                                          |
| Reservoir inundation loss                     | Area of submerged forest + Area of submerged cultivated land                                                                                         |
| Area of submerged cultivated land             | Water surface area of the reservoir*0.5*Cultivated land coverage rate                                                                               |
| Area of submerged forest                       | Water surface area of the reservoir*0.5*Forest coverage rate                                                                                         |
| Reservoir sedimentation of unit power generation | Annual reservoir sedimentation/(Hydropower generation + Thermal power generation)                                                                  |
| Annual reservoir sedimentation                | Water surface area of the reservoir*Reservoir sedimentation coefficient                                                                             |
| Air pollution degree of unit power generation | Air pollution degree/(Hydropower generation + Thermal power generation)                                                                               |
| Air pollution degree                          | 0.352*SO2 emissions from thermal power + 0.333*Soot emissions from thermal power + 0.315*NOx emissions from thermal power |
| GHG emissions of unit power generation        | GHG emissions of hydropower and thermal power/(Hydropower generation + Thermal power generation)                                                  |
| GHG emissions of hydropower                   | Hydropower generation*GHG emission coefficient of hydropower                                                                                         |
| GHG emissions of thermal power                | Thermal power generation*GHG emission coefficient of thermal power                                                                                   |
| Cost of unit power generation                 | (Annual hydropower cost + Annual thermal power cost)/(Hydropower generation + Thermal power generation)                                             |
| Annual hydropower cost                        | Hydropower installed capacity*Hydropower engineering unit cost/Average life of hydropower                                                               |
| Annual thermal power cost                     | Total cost of thermal power construction/Average life of thermal power + Total cost of power generation coal                                           |
| Year | GDP (100 million) | Total energy consumption (10 000 tons of standard coal) | Total electricity consumption (100 million kW h) |
|------|-------------------|--------------------------------------------------------|-------------------------------------------------|
|      | Historical value  | Simulation value | Relative error | Historical value  | Simulation value | Relative error | Historical value  | Simulation value | Relative error |
| 2005 | 6554.69           | 6554.69         | 0.00%          | 5753.99          | 5753.99         | 0.00%          | 756.59            | 756.59          | 0.00%          |
| 2006 | 7524.78           | 7482.42         | -0.56%         | 6396.85          | 6364.79         | -0.50%         | 866.84            | 855.64          | -1.29%         |
| 2007 | 8668.55           | 8502.68         | -1.91%         | 7109.26          | 6998.33         | -1.56%         | 1000.33           | 984.72          | -1.56%         |
| 2008 | 9795.46           | 9618.19         | -1.81%         | 7734.20          | 7622.67         | -1.44%         | 1073.54           | 1058.06         | -1.44%         |
| 2009 | 11 000.30         | 10 830.60       | -1.54%         | 8353.67          | 8247.26         | -1.27%         | 1134.92           | 1120.46         | -1.27%         |
| 2010 | 12 529.35         | 12 140.60       | -3.10%         | 9189.42          | 8965.44         | -2.44%         | 1315.08           | 1283.03         | -2.44%         |
| 2011 | 14 070.46         | 13 547.10       | -3.72%         | 9980.23          | 9692.53         | -2.88%         | 1515.86           | 1472.16         | -2.88%         |
| 2012 | 15 674.49         | 15 048.00       | -4.00%         | 10 479.44        | 10 165.00       | -3.00%         | 1579.51           | 1532.12         | -3.00%         |
| 2013 | 17 398.68         | 16 639.30       | -4.36%         | 11 189.91        | 10 831.50       | -3.20%         | 1700.73           | 1646.25         | -3.20%         |
| 2014 | 19 121.15         | 18 315.30       | -4.21%         | 12 109.72        | 11 737.00       | -3.08%         | 1855.78           | 1798.66         | -3.08%         |
| 2015 | 20 842.06         | 20 068.60       | -3.71%         | 12 179.97        | 11 804.40       | -3.08%         | 1851.86           | 1794.76         | -3.08%         |
| 2016 | 22 592.79         | 21 889.90       | -3.11%         | 12 357.75        | 11 965.60       | -3.00%         | 1968.58           | 1909.44         | -3.00%         |
| 2017 | 24 422.80         | 23 768.10       | -2.68%         | 12 889.97        | 12 531.60       | -2.78%         | 2112.73           | 2054.00         | -2.78%         |

| Year | Total power generation (100 million kW h) | Total power generation (100 million kW h) | Total power generation (100 million kW h) |
|------|-----------------------------------------|-----------------------------------------|-----------------------------------------|
|      | Historical value  | Simulation value | Relative error | Historical value  | Simulation value | Relative error | Historical value  | Simulation value | Relative error |
| 2005 | 778.25         | 779.29          | 0.13%          | 0.6256          | 0.6248          | -0.13%         | 0.3739           | 0.3734          | -0.13%         |
| 2006 | 904.25         | 881.31          | -2.54%         | 0.6147          | 0.6307          | 2.60%          | 0.3835           | 0.3935          | 2.60%          |
| 2007 | 1039.28        | 1014.26         | -2.41%         | 0.6963          | 0.7135          | 2.47%          | 0.2998           | 0.3072          | 2.47%          |
| 2008 | 1085.84        | 1089.80         | 0.36%          | 0.6872          | 0.6847          | -0.36%         | 0.3680           | 0.3667          | -0.36%         |
| 2009 | 1170.71        | 1154.08         | -1.42%         | 0.7536          | 0.7645          | 1.44%          | 0.2357           | 0.2391          | 1.44%          |
| 2010 | 1356.32        | 1321.52         | -2.57%         | 0.6566          | 0.6739          | 2.63%          | 0.3345           | 0.3433          | 2.63%          |
| 2011 | 1578.99        | 1516.32         | -3.97%         | 0.8055          | 0.8388          | 4.13%          | 0.1806           | 0.1881          | 4.13%          |
| 2012 | 1622.62        | 1578.09         | -2.74%         | 0.6892          | 0.7086          | 2.82%          | 0.2935           | 0.3018          | 2.82%          |
| 2013 | 1789.94        | 1695.64         | -5.27%         | 0.7153          | 0.7551          | 5.56%          | 0.2250           | 0.2375          | 5.56%          |
| 2014 | 1869.96        | 1852.62         | -0.93%         | 0.6830          | 0.6894          | 0.94%          | 0.2430           | 0.2453          | 0.94%          |
| 2015 | 1882.80        | 1848.60         | -1.82%         | 0.5890          | 0.5999          | 1.85%          | 0.2475           | 0.2521          | 1.85%          |
| 2016 | 2004.61        | 1966.73         | -1.89%         | 0.4566          | 0.4654          | 1.93%          | 0.3079           | 0.3139          | 1.93%          |
| 2017 | 2185.58        | 2115.62         | -3.20%         | 0.5212          | 0.5385          | 3.31%          | 0.1906           | 0.1969          | 3.31%          |