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RESEARCH ARTICLE

Hydropower Pricing Options for Cross-Border Electricity Trading in China Based on Bi-Level Optimization

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ABSTRACT Regional cross-border electricity trading is popular in price and cooperation. It is a reliable path to alleviate the shortage of power supply during rapid economic growth. As an important export commodity, the pricing options for hydropower directly relate to the cooperation intention of business parties. This study demonstrates the price formation methods and internal relationships of cascade hydropower stations in CBET. To simulate the decision-making of a bilateral forward contract, a bi-level optimization model was constructed, and the objectives of each layer represent the interests of both parties. The BOM was linearized with Karush-Kuhn-Tucker conditions and strong duality, and finally solved using mixed-integer linear programming. The prices of CHSs in southwestern China were calculated under different pricing options and the results were absorbed in an actual transaction case. Consequently, the complementarity between different exporting countries was verified. The most suitable pricing option for CBET was determined, that is the unified electricity price based on the marginal cost, to be 481 CNY/MW · h, which is 20% to 60% higher than the thermal and photovoltaic from other countries. Furthermore, national policy support and economic subsidies are key guarantees for the sustainable development of CBET, which can reduce the discount electricity price to below that of thermal generation by 30%.

INDEX TERMS Hydropower, pricing options, cross-border electricity trade, bi-level optimization, MILP.

NOMENCLATURE

The notations are stated below for quick reference: other symbols have been defined as required throughout the text.

A. INDICES

t	Index for time periods running from 1 to T.
k	Index for CHSs owned by China from 1 to K.
r	Index for nonstrategic countries from 1 to R.
w	Index for downstream stations of CHSs from 2 to Ω_K.

B. CONSTANTS AND FUNCTIONS

λ_k	Price of station k in China.
λ_r	Price of nonstrategic country r.
$D(t)$	Generation cost of station k.
b_C^*	Transmission unit-price in China.
$\underline{O}_k(t), \overline{O}_k(t)$	Minimum/maximum water release from station k in period t.
$\underline{V}_k, \overline{V}_k$	Minimum/maximum volume of reservoir k.
$\underline{N}_k, \overline{N}_k$	Minimum/maximum power output of station k.
$R_k(t)$	Inflow to station k in period t.
D_U	Monthly total import electricity demand.
F_C	Transmission capacity of interconnection line in China.
F_r	Transmission capacity of interconnection line in nonstrategic country r.
Ps_C	Surplus power supply capacity in China.
Ps_r	Surplus power supply capacity in non-strategic country r.

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$f_{1k}(\cdot)$	Relationship between fore-bay elevation and volume of reservoir k.
$f_{2k}(\cdot)$	Relationship between tail-race elevation and water discharge from reservoir k.
L_k	Loss constant of station k.
l_C	Transmission comprehensive loss coefficient in China.
l_r	Transmission comprehensive loss coefficient in nonstrategic country r.
M_1	Constant equal to 8.64×10^5.
M_2	Constant equal to 0.0036.
M_3	Constant equal to 9.81×10^{-3}.

C. VARIABLES

$N_k(t)$	Power output of station k in period t.
$N_r(t)$	Power output from nonstrategic country r in period t.
$O_k(t)$	Water release from station k in period t.
$Q_k(t)$	Water discharge from station k in period t.
$S_k(t)$	Water spillage from station k in period t.
$V_k(t)$	Volume of reservoir k in period t.
$Hu_k(t)$	Fore-bay elevation of reservoir k in period t.
$Hd_k(t)$	Tail-race elevation of reservoir k in period t.
$H_k(t)$	Net head of station k in period t.
$\eta_k(t)$	Generation efficiency of station k in t.
$\omega_k^{x,y}(t)$	Weight of data point (x, y) of plant k in period t.
$z_k(t)$	Binary variable which is equal to 1 if the hydropower station k is on-line in period t.
$zp_k(t)$	Binary variable for plant k in period t which is equal to 1 if the interpolation cell is in the upper quadrangle.

D. DUAL VARIABLES

The dual variables below are associated with the following constraints:

θ_{kt}	Supply and demand balance between importer and exporter.
μ_{kt}^C	Transmission capacity of China.
μ_{rt}	Transmission capacity of nonstrategic country r.
ν_{kt}^C	Surplus power generation of China.
ν_{rt}	Surplus power generation of nonstrategic country r.
ξ_{kt}	Minimum power output of station k in period t.
ξ_{rt}	Minimum power output from nonstrategic country r in period t.

E. SETS

T	Periods.
K	Hydroelectric stations/reservoirs.
R	nonstrategic countries.
Ω_K	Downstream stations of CHSs.
X, Y	Sets of data points (x, y) used in the interpolation of the performance curve.

F. ACRONYMS

CBET	Cross-border electricity trading.
CHS	Cascade hydropower station.
BOM	Bi-level optimization model.
MILP	Mixed-integer linear programming.
KKT	Karush-Kuhn-Tucker.
UN	United Nations.
SLOT	Single-level optimization task.
EA	Evolutionary algorithms.
DP	Dynamic programming.
POA	Progressive optimality algorithm.
PSO	Particle swarm optimization.
MCP	Market clearing price.
BEP	Break-even price.
UEP	Unified electricity price.
GEP	Green electricity price.
NTP	Thermal price in a non-strategic country.
NPP	Photovoltaic price in a non-strategic country.
DEP	Discount electricity price.
CNY	Chinese yuan.

I. INTRODUCTION

With the appeal for carbon neutrality by the UN, several countries have taken measures to reduce carbon emissions [1]. China has also promised to achieve peak carbon emissions and neutrality by 2030 and 2060, respectively [2]. As the most extensive source of clean and renewable energy, hydropower bears the brunt of a growing load demand and low-carbon energy-saving production [3]. In China, hydropower installed capacity and annual power rank first in the world, and by the end of 2020, at least 30% of national hydropower resources remain available for development [4], however, these resources are concentrated in international rivers [5], such as Yarlung Zangbo - Brahmaputra River, Lancang - Mekong River, etc. The unique geographical location and sensitive political influence will lead to huge impediment. Therefore, it is necessary to explore the potential of cooperative development, grid interconnection and electricity transactions in the basin and surrounding countries in advance to ensure the implementation of the project [6], [7].

While in some surrounding countries, the shortage of power supply has gradually become a key constraint to economic and social development. For instance, there are about 280 million people, about 20% of the total population, who are unable to receive a normal power supply in India; furthermore, with increasing populations, the situation will be more severe [8]. Bangladesh, Cambodia, Vietnam, and other South Asian countries have faced the same difficulties. The complementarity of supply and demand between countries is obvious, making it possible to promote CBET. Considering these, hydropower was set as a medium for CBET between China and South Asian countries [9], focusing on its pricing options and effects on cooperation, which will provide support for the expansion of energy and electricity cooperation in the future.

A. LITERATURE REVIEW

There are many successful CBET practices in the world [10], [11], [12]. Although differences in the depth and mode of cooperation are physical presence, its role in improving the national or regional power structure, reducing the cost of power generation, and reducing CO_2 emissions has been confirmed by many energy policy-makers and researchers. With perfect market mechanisms as a guarantee, Europe is making great efforts to develop a unified regional power market [13]. Owing to the late start and relatively backward process of power reform, cooperation between India and Nepal [14], or within the Greater Mekong Subregion [15], all choose bilateral contracts for a reasonable effect. The research on CBET focuses on several aspects: 1) evaluation of benefits, risks, and barriers of CBET [16], [17]; 2) the path choice of cooperation, pool-based [18] or bilateral contracts, forward [19], or spot [20]; and 3) model and solution for transaction scale optimization [21] (as discussed herein). We attempt to maximize the consumption of renewable energy and fill the power gap of the importer; that is, the exported power operates as the base load of the system. Therefore, a long-term optimization model was established.

The decision-making process of competition in the electricity market, including forward contracts and spot transactions, is described by a BOM [20], [22], [23]. Participants can be divided into generators and purchasers, and their different interest demands correspond to their different objectives [24]. Of course, the constraints on both sides are different, especially in that hydropower may introduce many nonconvex and nonlinear constraints [25], [26]. As defined in [27], both parties act as leaders and followers, respectively, that is, the upper and lower levels of bi-level optimization; it is clear that each level has its own objectives and constraints. Bi-level programming is known to be NP-hard in mathematics [28]; however, with the improvement in solution procedures, it is easier to get a more accurate global optimal solution after transforming into a single-level optimization task with KKT conditions [29] or a penalty function [30], or directly nested and computed with evolutionary algorithms [31].

When hydropower is indispensable in the system, the original BOM or SLOTs derived from it are all nonlinear, with many non-convex constraints and discrete integer or binary variables. Sufficient research has been conducted to address this issue. Others choose DP and POA to solve hydropower scheduling problems with single plants and CHSs, respectively [32], [33]. They have two drawbacks: it is difficult to reach a global optimal solution, and the multiplicity of variables will cause dimensional problems [34]. As mentioned above, EAs, such as the PSO [35], [36] and Mayfly algorithms [37] also achieve good results; the stability of these algorithms is questioned due to the numerous random numbers applied in population coding and optimal sampling. Mixed integer linear programming exhibits good performance with respect to adding constraints and solution efficiency and has been widely used to solve large-scale hydro scheduling problems [38]. MILP is a consummate in mathematics, and many mature solvers such as CPLEX by IBM and Gurobi are available. Linear constraints are strictly applied in the calculation; as a result, linearization techniques of hydraulic constraints are also a focus of researchers [39], [40].

The operation modes of hydropower differ greatly from those of thermal power [41]. Electricity price and natural inflow are non-negligible uncertain information for hydropower operation [42]; as for competition in the electricity market, the influence of the former is more significant. The appropriate hydropower price reflects the construction costs and interests of investors. Different generation structures, market modes, and reform processes correspond to various pricing options [43], [44], [45], [46]. In the UK's power pool, the unified market clearing price comes from the bidding of supply and demand sides, while long-term contracts are settled with "contracts for difference" [43]. With a nod to PJM, MCP is correlative to power flow, that is, location margin prices [44]; however, in Brazil [45] and China before 2002, the generation target for renewable hydropower was given by the system operator, and there was no corresponding electricity price. The concept of electricity price rose to prominence among the Chinese people after 2002, and gradually changed from a modality involving government approval to competitive bidding (after a spot-transaction pilot project in 2017) [46].

B. APPROACH AND CONTRIBUTION

As the pace of hydropower development gradually turns to international rivers in China, the CHSs participating in CBET seem inevitable. The present work has a focus on the price mechanism of CHSs in CBET, which is complex but crucial for the renewable energy consumption and cooperation. Five pricing options are proposed based on the basic principles of economics, hydropower characteristics and transaction practice. Their influences on the export scale, revenue and import cost of electricity are evaluated by solving a multi-dimensional, nonlinear BOM. Finally, the appropriate pricing options are obtained in a simplified interconnection network comprising hydropower, thermal and photovoltaic, and the trend in the development of hydropower participating in CBET in the future is discussed.

The main contributions are listed as follows.

- Hydropower is involved in CBET besides traditional thermal and increasing photovoltaic power, whose production scheduling and optimal operation are very different from the others. It has proven suitable for the future trend of hydropower development in China;
- The price mechanism of the CHSs participating in CBET is revealed, that is, government provides proper subsidies based on the cascade unified electricity price. This will satisfy the interests of both importer and exporter and ensure the smooth progress of projects.
- The competitiveness of the CHSs and other export power is assessed. At the initial stage of operation, the

hydropower price is about 20% to 60% higher than the others. However, with the deepening of cooperation, it has more room for reduction, which can be lower than that incurred during thermal generation by 30%.

C. OUTLINE OF THE PAPER

The remainder of this paper is organized as follows. In **Section II,** the principles, methods, and internal connections of different pricing options are proposed. **Section III** presents the BOM, the corresponding linearization technique, and the solution algorithm. **Section IV** introduces an actual transaction case with different types of power sources. **Section V** provides the results, which are discussed in detail. The conclusions and drawbacks are summarized in **Section VI**.

II. HYDROPOWER PRICING OPTIONS

Electricity prices are regarded as the bridge between energy harvesting and monetary income, which directly affects the profits of electric power enterprises and their ability to expand reproduction, ultimately affecting the sustainable development of the power industry. Unlike thermal plants, whose capital is concentrated on coal, the investment in CHSs is mainly for the construction and maintenance of reservoirs and dams [47]. Large reservoirs and dams are indispensable to CHSs, but require larger investments, longer construction periods, and more difficult capital recovery than runoff stations [48], making it necessary to guide investment through rational pricing mechanisms [49].

Hydropower is a special commodity that contains the exchange property of a general commodity but cannot be stored. The following principles and rules are followed in price setting. 1) Cost compensation, that is, material and manpower consumed in plant construction and power generation, shall be fully recovered through sale of energy; 2) Limited profit, that is, sufficient profit to attract capital, but not impose too onerous a burden on the purchaser [50], [51]; 3) Highlighting contributions, that is, the seasonal compensation and comprehensive contribution of reservoirs should be emphasized; and 4) Simple calculation. The total cost composition of a hydropower station during its operational period is shown in FIGURE 1.

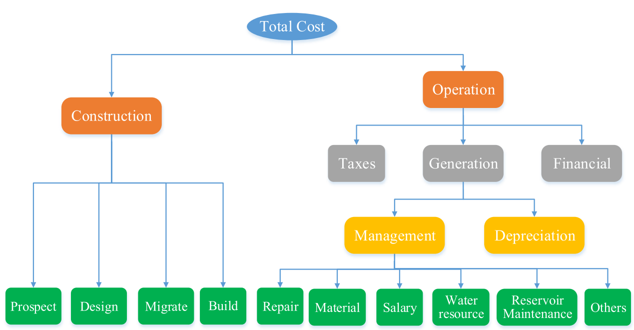

FIGURE 1. The full life cycle cost for a hydropower station.

According the principles above and the reality of CBET, five options are proposed:

First, the BEP is defined as the price that balances income and costs. It is assumed that the operating period is 30 years, which is calculated using the annual average generating capacity, and the price that makes the total revenue equal to the cost during this period is the BEP (the BET of each station in the CHSs is different).

Then, the price of reservoirs is reduced using a UEP in CHSs to overcome the disadvantages of the pool-based market. The unified operation period is defined as 30 years after the completion of the first reservoir, and the price of each power station in the CHSs is the same. When the total revenue of the system balances the cost during this period, the UEP is obtained.

Compared with conventional non-renewable energy, such as coal or gas, hydropower will emit less greenhouse gas in the same operation cycle [52], [53], [54], which is the embodiment of its environmental benefits under the current carbon-neutral and green industry requirements. The Chinese Government has decided to provide certain benefits and subsidies for exporting hydropower due to its significant contribution to energy conservation and emissions reduction. The GEP is derived by including these subsidies in the green electricity price.

In the context of global energy interconnection, it is impossible for countries to import electricity from a single source. In contrast, they meet the load demand through CBET with different countries and different types of power sources. We take other exporting countries as nonstrategic countries, whose prices naturally become importance references for price decision. In this situation, two strategies can be adopted: one is that we equalize our price with that of nonstrategic country, the other is that a discount is given relying on subsidies from government. Therefore, the last three options (NTP, NPP and DEP) are proposed to satisfy the requirements of market competition.

The sources and relationships of the five hydropower pricing options are shown in Figure 2. The calculation results of the different options are introduced into the model described in Section III, and the influences of these opinions on the scale and income of CBET are discussed in Section V.

III. MODEL AND ALGORITHM

The real decision-making process of a CBET forward contract is simulated, in which the exporter makes effort to maximize income, but the importer pursues the minimization of expenditure to fill the power gap. Cascade hydropower generation faces numerous constraints, and importers have multiple options to acquire electricity, which are all described in this section. For forward contracts, we consider a period of one month.

A. HYDROELECTRICGENERATOR'SOFFEROPTI-MIZATION

1) OBJECTIVE FUNCTION

$$\text{Maximize} \sum_{k=1}^{K} \sum_{t=1}^{T} M_1 D(t) \left[\lambda_k N_k(t) - b_C^* N(t) \right] \quad (1)$$

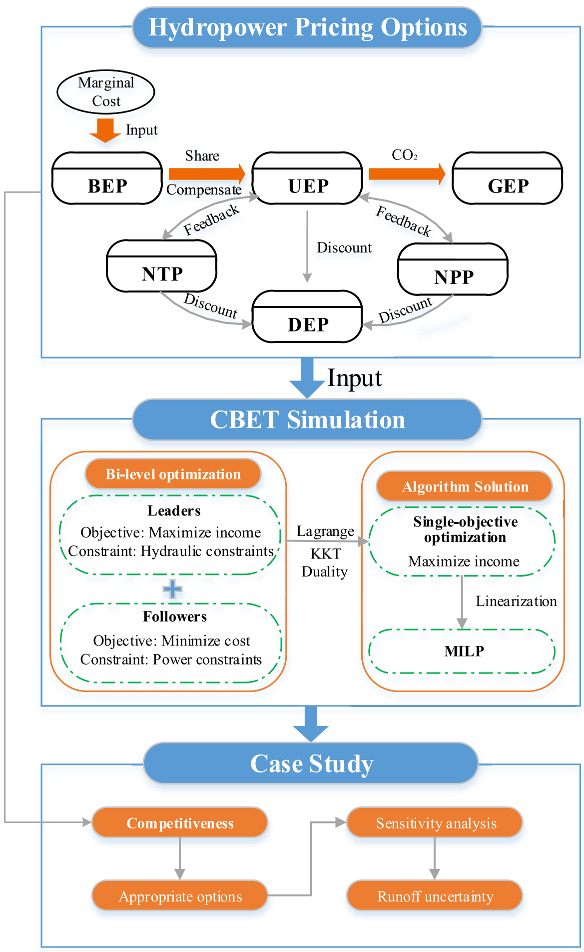

FIGURE 2. **The sources and relationship of hydropower pricing options and technology roadmap.**

In (1), the first term is related to the real income of the generator and the other terms are related to the cost of delivering electricity. The transmission unit price is an independent constant determined by a local grid manager in China. Eq. (1) denotes the maximization of the total generation income.

2) WATER DISCHARGE, SPILLAGE, AND RELEASE

$$O_k(t) = Q_k(t) + S_k(t), \forall k \in K, \quad \forall t \in T \tag{2}$$

$$\underline{Q}_k(t) \le Q_k(t) \le \overline{Q}_k(t), \quad \forall k \in K, \forall t \in T \tag{3}$$

$$\underline{O}_k \le O_k(t) \le \overline{O}_k, \quad \forall k \in K, \forall t \in T \tag{4}$$

Constraint (2) defines the total water release from a hydro station as the sum of water discharge and spillage. Constraints (3) and (4) establish the lower and upper limits for the water discharge and release, respectively. For hydropower plants, determining the minimum and maximum water release is necessary for the ecological protection of the basin.

3) RESERVOIR VOLUME

$$\underline{V}_k \le V_k(t) \le \overline{V}_k, \forall k \in K, \forall t \in T \tag{5}$$

Constraint (5) sets the minimum and maximum limits for reservoir volume, which can represent the regulation and storage capacity of the reservoir for natural runoff.

4) WATER BALANCE

This constraint is expressed in Eqs. (6) and (7),

$$V_k(t) = V_k(t-1) + M_2[R_k(t) + I_k(t) - O_k(t)], \quad \forall k \in K, \forall t \in \{2, \ldots, T\} \tag{6}$$

where:

$$I_k(t) = \begin{cases} \sum_{w \in \Omega_k} O_w(t), & \text{if } t \ge 1 \\ 0, & \text{otherwise} \end{cases}$$

$$V_k(1) = V_k(0) + M_2[R_k(1) - O_k(1)], \quad \forall k \in K \tag{7}$$

For a one-month period, the delay between CHSs is ignored.

5) RESERVOIR FORE-BAY AND TAIL-RACE ELEVATIONS

$$Hu_k(t) = f_{1k}[V_k(t)], \forall k \in K, \forall t \in T \tag{8}$$

$$Hd_k(t) = f_{2k}[O_k(t)], \forall k \in K, \forall t \in T \tag{9}$$

Constraints (8) and (9) introduce nonlinearity into the model, increasing the difficulty of the solution.

6) RESERVOIR NET HEAD

The reservoir net head is set as in [22], with the fore-bay and tail-race elevations and head loss:

$$H_k(t) = (1 - L_k)[Hu_k(t) - Hd_k(t)], \quad \forall k \in K, \forall t \in T \tag{10}$$

7) HYDROELECTRIC POWER GENERATION FUNCTION

The generation from a hydropower station is calculated by (11),

$$N_k(t) = M_3 \eta_k(t) Q_k(t) H_k(t), \forall k \in K, \quad \forall t \in T \tag{11}$$

where the generation efficiency and net head are non-linear and non-convex functions, as described in [34], and the former is affected by the latter. The expected output curve is a common tool used to show the relationship between power generation, water discharge, and net head; therefore, Eq. (11) is linearized.

8) HYDROELECTRIC POWER GENERATION LIMIT

$$\underline{N}_k \le N_k(t) \le \overline{N}_k, \forall k \in K, \quad \forall t \in T \tag{12}$$

Under this constraint, the generation can be maintained below the rated power to supply stable and high-quality electricity.

9) TYPES OF VARIABLES

$$
\begin{aligned}
&O_k(t) \geq 0, Q_k(t) \geq 0, S_k(t) \geq 0, \forall k \in K, \quad \forall t \in T, \\
&V_k(t) \geq 0, Hu_k(t) \geq 0, Hd_k(t) \geq 0, \forall k \in K, \quad \forall t \in T, \\
&H_k(t) \geq 0, \forall k \in K, \quad \forall t \in T \qquad (13)
\end{aligned}
$$

B. ELECTRICITY PURCHASING COST OPTIMIZATION

1) OBJECTIVE FUNCTION

$$
\text{minimize } M_1 \sum_{t=1}^{T} D(t) \left[\sum_{k=1}^{K} \lambda_k N_k(t) + \sum_{r=1}^{R} \lambda_r N_r(t) \right] \quad \forall k \in K, \forall r \in R, \forall t \in T \qquad (14)
$$

In (14), the first term is related to the cost of renewable hydropower from China, and the second represents the cost of importing electricity from non-strategic countries.

2) SUPPLY AND DEMAND BALANCE

$$
\sum_{k=1}^{K} N_k(t) + \sum_{r=1}^{R} N_r(t) = D_U : \theta_{tn}, \forall k \in K, \forall r \in R, \forall t \in T \qquad (15)
$$

In Eq. (15), power transmission amounts from China are all hydropower-based; however, all types of export power from nonstrategic nations can be accumulated and then calculated.

3) NETWORK CONSTRAINTS

$$
\sum_{k=1}^{K} N_k(t) \leq F_C(1 - l_C) : \mu_{kt}^C, \forall k \in K, \forall t \in T \qquad (16)
$$

$$
N_r(t) \leq F_r(1 - l_r) : \mu_{rt}, \forall r \in R, \forall t \in T \qquad (17)
$$

The transmission network can be simplified as follows: hydropower plants share one tie-line for power exporting. Transmission lines between importer and nonstrategic countries are considered. Based on this, the capacity loss from different voltage levels, congestion, *etc*. is measured by the transmission comprehensive loss coefficient.

4) POWER LIMITS

$$
\sum_{k=1}^{K} N_k(t) \leq Ps_C : \nu_{kt}^C, \forall k \in K, \forall t \in T \qquad (18)
$$

$$
N_r(t) \leq Ps_r : \nu_{rt}, \forall r \in R, \forall t \in T \qquad (19)
$$

We assume each country prioritizes their own electricity demand and then participates in CEBT.

5) TYPES OF VARIABLES

$$
N_k(t) \geq 0 : \xi_{kt}, N_r(t) \geq 0 : \xi_{rt}, \quad \forall k \in K, \forall r \in R, \forall t \in T \qquad (20)
$$

C. BI-LEVEL OPTIMIZATION MODEL

The variable in (1) must follow,

$$
N_k(t) \in \left\{ \underset{N_k(t), N_r(t)}{\arg \text{Minimize}} \sum_{t=1}^{T} D(t) \left[\sum_{k=1}^{K} \lambda_k(t) N_k(t) + \sum_{r=1}^{R} \lambda_r(t) N_r(t) \right] \right. \qquad (21)
$$

and is subject to

$$
\left. (14) - (20) \right\}. \qquad (22)
$$

As a result, a BOM is established, of which the upper bound maximizes the hydroelectric generator's offer, and the lower bound minimizes electricity purchasing costs.

D. LINEARIZATION TECHNIQUES

The electricity purchasing cost optimizations (14) to (20) are convex and linear, and thus can be replaced by its KKT conditions. For any convex problem, these conditions are sufficient for achieving a global maximum. Finally, using standard techniques, the bi-level problem is converted into a single-level MILP and solved using CPLEX.

1) KKT CONDITIONS

$$
\lambda_k D(t) - \theta_{tn} + \mu_{kt}^C + \nu_{kt}^C - \xi_{kt} = 0, \forall k \in K, t \in T \qquad (23)
$$

$$
\lambda_r D(t) - \theta_{tn} + \mu_{rt} + \nu_{rt} - \xi_{rt} = 0, \forall r \in R, t \in T \qquad (24)
$$

$$
\sum_{k=1}^{K} N_k(t) + \sum_{r=1}^{R} N_r(t) = D_U, \forall k \in K, \forall r \in R, \forall t \in T \qquad (25)
$$

$$
0 \leq F_C(1 - l_C) - N_k(t) \perp \mu_{kt}^C \geq 0, \forall k \in K, \forall t \in T \qquad (26)
$$

$$
0 \leq F_r(1 - l_r) - N_r(t) \perp \mu_{rt} \geq 0, \forall r \in R, \forall t \in T \qquad (27)
$$

$$
0 \leq Ps_C - N_k(t) \perp \nu_{kt}^C \geq 0, \forall k \in K, \forall t \in T \qquad (28)
$$

$$
0 \leq Ps_r - N_r(t) \perp \nu_{rt} \geq 0, \forall r \in R, \forall t \in T \qquad (29)
$$

$$
0 \leq N_k(t) \perp \xi_{kt} \geq 0, \forall k \in K, \forall t \in T \qquad (30)
$$

$$
0 \leq N_r(t) \perp \xi_{rt} \geq 0, \forall r \in R, \forall t \in T \qquad (31)
$$

The $\perp$ in conditions (26) $\sim$ (31) denotes the complementary slackness between each constraint and its associated Lagrange multiplier.

2) KKT COMPLEMENTARY SLACKNESS CONDITIONS

The form of a complementary slackness condition:

$$
f(x) \leq 0 \perp \phi \geq 0 \qquad (32)
$$

is equivalent to

$$
f(x) \leq 0 \qquad (33)
$$

$$
\phi \geq 0 \qquad (34)
$$

$$
f(x)\phi = 0 \qquad (35)
$$

which introduces nonlinearity; therefore, we linearize it with a binary auxiliary variable, ψ, which is equal to 1 if $f(x) < 0$ and 0 otherwise; that is,

$$-M \cdot \psi \leq f(x) \leq 0 \tag{36}$$

$$0 \leq \phi \leq M \cdot (1 - \psi) \tag{37}$$

$$\psi \in \{0, 1\} \tag{38}$$

where M denotes a sufficiently large constant. Finally, Eqs. (26) ~ (31) can be replaced by Eqs. (36) to (38).

3) STRONG DUALITY

To optimize the electricity purchasing cost, the strong duality condition and some of the KKT equalities are used.

The strong duality theorem states that if a problem is convex, the objective functions of the primal and dual problems have the same optimum value. Thus,

$$\begin{aligned}\sum_{t=1}^{T} D(t)\left[\sum_{k=1}^{K}\lambda_k N_k(t) + \sum_{r=1}^{R}\lambda_r N_r(t)\right] &= \theta_{tn} D_U \\ &- \sum_{t=1}^{T}\left[\sum_{k=1}^{K}\mu_{kt}^{C} F_C (1 - l_C)\right. \\ &\left. + \sum_{r=1}^{R}\mu_{kt}^{r} F_r (1 - l_r) + \sum_{k=1}^{K}\nu_{kt}^{C} Ps_C + \sum_{r=1}^{R}\nu_{rt} Ps_r\right]\end{aligned} \tag{39}$$

4) RESERVOIR FORE-BAY AND TAIL-RACE ELEVATIONS

The relationship between $f_{1k}(\cdot)$ and $f_{2k}(\cdot)$ is generally formulated as a fourth-order polynomial function, which is nonlinear during the calculation. Therefore, the curves are linearized as follows:

$$Hu_k(t) = \begin{cases}\underline{Hu}_k, & V_k(t) = \underline{V}_k \\ HU_{k,0} V_k(t) + HU_{k,1}, & Hu_{k,n-1} \leq Hu_k(t) \leq Hu_{k,n} \\ \overline{Hu}_k, & V_k(t) = \overline{V}_k\end{cases}$$
$$\forall k \in K, , \forall t \in T, n = 1, 2, \ldots, N \tag{40}$$

where $(V_{k,n-1}, Hu_{k,n-1})$ and $(V_{k,n}, Hu_{k,n})$ represent the feature points of $f_{1k}(\cdot)$, the fore-bay elevation and water volume that have been given, $Hu_{k,0} = \underline{Hu}_k$, $V_{k,0} = \underline{V}_k$, $Hu_{k,N} = \overline{Hu}_k$, and $V_{k,N} = \overline{V}_k$. The coefficients in Eq. (40) are as follows:

$$HU_{k,0} = \frac{V_{k,n} - V_{k,n-1}}{Hu_{k,n} - Hu_{k,n-1}} \tag{41}$$

$$HU_{k,1} = \frac{V_{k,n-1} Hu_{k,n} - V_{k,n-1} Hu_{k,n}}{Hu_{k,n} - Hu_{k,n-1}}. \tag{42}$$

Similarly,

$$Hd_k(t) = \begin{cases}\underline{Hd}_k, & O_k(t) = \underline{O}_k \\ HD_{k,0} O_k(t) + HD_{k,1}, & Hd_{k,n-1} \leq Hd_k(t) \leq Hd_{k,n} \\ \overline{Hd}_k, & O_k(t) = \overline{O}_k\end{cases}$$
$$\forall k \in K, , \forall t \in T, n = 1, 2, \ldots, N \tag{43}$$

where $(O_{k,n-1}, Hd_{k,n-1})$ and $(O_{k,n}, Hd_{k,n})$ represent the feature points of $f_{2k}(\cdot)$, the tail-race elevation and water discharge of which have been provided, $Hd_{k,0} = \underline{Hd}_k$, $O_{k,0} = \underline{O}_k$, $Hd_{k,N} = \overline{Hd}_k$, and $O_{k,N} = \overline{O}_k$. The coefficients in (43) are as follows:

$$HD_{k,0} = \frac{O_{k,n} - O_{k,n-1}}{Hd_{k,n} - Hd_{k,n-1}} \tag{44}$$

$$HD_{k,1} = \frac{O_{k,n-1} Hd_{k,n} - O_{k,n-1} Hd_{k,n}}{Hd_{k,n} - Hd_{k,n-1}} \tag{45}$$

5) HYDROELECTRIC POWER GENERATION FUNCTION

As mentioned, Eq. (11) cannot be involved in calculations with CPLEX; therefore, we linearize it with binary variables [26, 39] as follows:

After long-term operation monitoring, it is convenient to obtain the water discharges corresponding to different power outputs from the hydropower plant, as represented by several points in the plane. Connecting the points with the same net head, we form a family of nonlinear curves, and then extract the corresponding curves of the maximum, the minimum and designed net head, which are recorded as H3, H2, and H1 respectively (Figure 3).

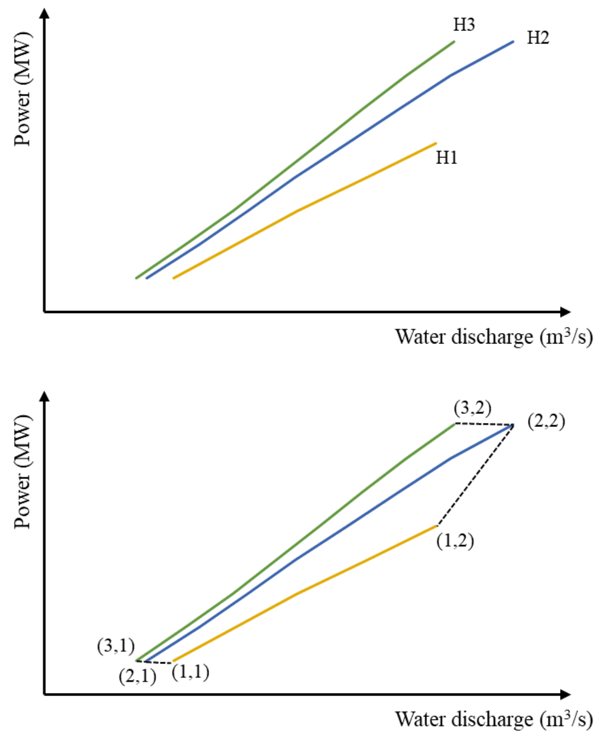

FIGURE 3. Typical performance curves of hydropower plant.

In Figure 3, six vertices are denoted by their position (x, y) in the subspace defined by power output and water discharge. The region formed by the union of these vertices is divided into two quadrangles. For interpolation purposes, we associate weights $\omega_k^{x,y}(t)$ for each vertex, which are used to compose an interpolation function based on the three reference curves. This technique uses only a single binary variable $zp_k(t)$, that defines the quadrangle being used. If the plant operates in the upper quadrangle, then $zp_k(t) = 1$, and the four upper vertices are used in the interpolation, otherwise $zp_k(t) = 0$ and the four lower vertices are used. This technique allows to calculate operating points (power output, net head and water discharge) which are located in intermediate regions of the three reference curves.

Constraints (46) to (54) represent the hydropower generation function using the interpolation technique:

$$\sum_{x\in X}\sum_{y\in Y}\omega_k^{x,y}(t) = z_k(t), \forall k \in K, \forall t \in T \tag{46}$$

$$h_k(t) \le \sum_{x\in X}\sum_{y\in Y}\omega_k^{x,y}(t)\,H_k^{x,y} + H_k^{3,1}\left[1 - z_k(t)\right], \forall k \in K, \forall t \in T \tag{47}$$

$$h_k(t) \ge \sum_{x\in X}\sum_{y\in Y}\omega_k^{x,y}(t)\,H_k^{x,y}, \quad \forall k \in K, \forall t \in T \tag{48}$$

$$Q_k(t) \ge \sum_{x\in X}\sum_{y\in Y}\omega_k^{x,y}(t)\,Q_k^{x,y}, \quad \forall k \in K, \forall t \in T \tag{49}$$

$$N_k(t) \ge \sum_{x\in X}\sum_{y\in Y}\omega_k^{x,y}(t)\,N_k^{x,y}, \quad \forall k \in K, \forall t \in T \tag{50}$$

$$\omega_k^{2,1}(t) + \omega_k^{2,2}(t) \le 1, \forall k \in K, \forall t \in T \tag{51}$$

$$\omega_k^{1,1}(t) + \omega_k^{1,2}(t) \le 1 - zp_k(t), \forall k \in K, \forall t \in T \tag{52}$$

$$\omega_k^{3,1}(t) + \omega_k^{3,2}(t) \le zp_k(t), \forall k \in K, \forall t \in T, \tag{53}$$

$$\omega_k^{x,y}(t) \ge 0, z_k(t) \in \{0,1\}, zp_k(t) \in \{0,1\} \tag{54}$$

Constraint (46) relates the vertex weights and on/off states of a plant. Constraints (47) and (48) calculate the interpolated net head values: Constraints (49) and (50) interpolate the water-discharge and power-output values, respectively. Constraints (51) to (53) select the vertices used in interpolation. Constraint (54) relates to the type of variable.

E. MIXED-INTEGER LINEAR MATHEMATICAL FORMULATION

The problem of a CEBT forward contract has been summarized as a single-level MILP, described as follows:

$$\mathit{Maximize}\ (1) \tag{55}$$

Subject to:

$$(2) \sim (7) \tag{56}$$

$$(10), (12), (13) \tag{57}$$

$$(40), (43) \tag{58}$$

$$(46) \sim (54) \tag{59}$$

$$(23) \sim (25) \tag{60}$$

$$(36) \sim (38), (39) \tag{61}$$

Constraints (56) and (57) are inherently linear hydro constraints, whereas (58) represents the linearization of the reservoir characteristic curve, and (59) indicates the linearization of the hydro production function. The KKT conditions and their linearization are described in (60) and (61), where (60) denotes the equality conditions, and (61) denotes the complementary slackness and strong duality conditions, respectively. Constraints associated with the types of variables are enforced in Eqs. (57) and (59).

IV. CASE STUDY

A. NETWORK STRUCTURE

To discuss the topics proposed herein, a simple interconnection system, including hydro, photovoltaic, and thermal from three countries, was simulated, as shown in Figure 4. The cascade hydropower system comprises five stations in China, the first two have reservoirs, and the rest are runoff plants, however, the photovoltaic and thermal power from non-strategic countries is simplified into one power station, respectively, whose installed capacity is the surplus power supply capacity of each country. Heterogeneous energy is connected and transmitted through tie lines of different voltages and to meet the demand of the same power importer. Among them, all hydropower plants share one tie-line for exporting power.

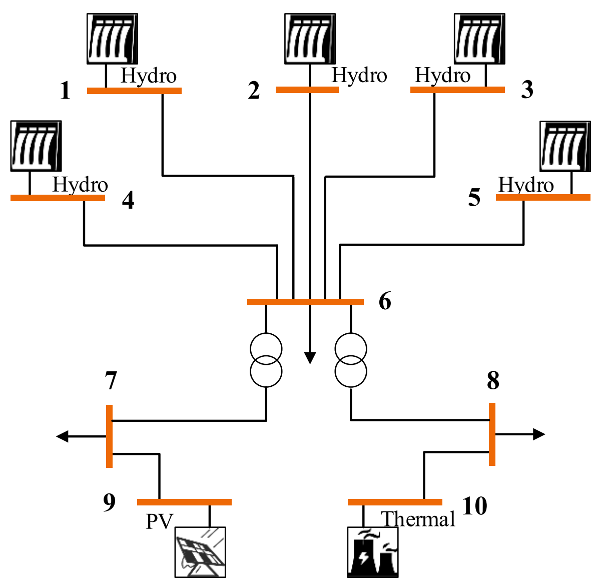

FIGURE 4. A simulated interconnection system.

B. DATA

CHSs are being developed and constructed in the watershed of southwestern China, whose power generation will be consumed by CBET within a neighboring country. The dynamic parameters are listed in Table 1, where SA and DA denote the seasonal and daily adjustment performances of the reservoir, respectively. The cost parameters of each hydropower station are strictly confidential in any country, so only calculated results from five options in Section II are listed in Table 2, where the prices of nonstrategic countries come from historical transaction information, and the NTP, NPP, and DEP denote the exported thermal, exported photovoltaic, and discount electricity price, respectively.

TABLE 1. Dynamic parameters of the CHSs.

Hydropower station	A	B	C	D	E
Installed capacity (MW)	1700	2600	800	920	2600
Maximum water level (m)	1842	1690	/	/	1130
Minimum water level (m)	1802	1650	/	/	1120
Maximum water discharge (m^3/s)	1473	967	1414	1616	1834
Minimum water release (m^3/s)	160	166	168	184	165
Adjustment performance	SA	SA	/		DA

TABLE 2. Price of each hydropower station with different options.

Price Options	BEP	UEP	GEP	NTP	NPP	DEP
	CNY/MW·h					
A	2658					
B	268					
C	238	481	561	400	300	285
D	259					
E	529					

Natural inflow is crucial for hydropower operation. The dependability of the monthly inflow process of the wet, moderate, and dry years in hydrological terms is 25%, 50%, and 75%, respectively, and can be selected as inputs for comparison. Figure 5 shows a typical monthly inflow process for hydropower station A.

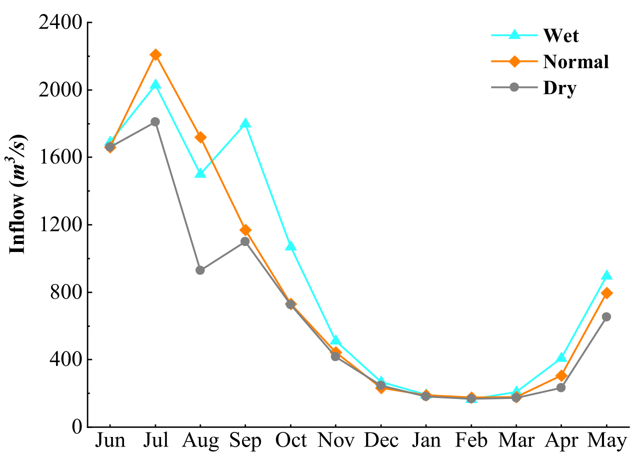

FIGURE 5. Monthly inflow of hydropower station a in typical years.

Other parameters such as electricity demand, surplus power supply capacity, and transmission capacity can be found elsewhere [24]. The transmission comprehensive loss coefficients for each country were 0.1, 0.3, and 0.2, respectively. The period is set to one month, and the model is run on an Intel Core i5 processor (2.70 GHz) with 8 GB of RAM. The CPLEX solver in MATLAB™ is used to solve this problem.

V. RESULT AND DISCUSSION

A. ANALYSIS OF PRICING OPTIONS

The different pricing options in Section II exhibit obvious characteristics. The prices for each hydropower station with different options are displayed in Table 2 and FIGURE 6. When applying BEP, each station in the CHSs has a different price; in particular, Station A has the highest price because of its huge investment in reservoir and dam construction. The next is E, and the lowest is C; however, there is no such difference in other options, which is the inevitable result of different price-formation principles. It is noted that the UEP for our CHSs is relatively high in response to their poor construction conditions and costly salary bill, which exceeds that of the NTP and NPP. The environmental and social value of hydropower is reflected in the GEP, which makes it higher than the UEP. The Chinese Government supports and encourages CBET, which is an important guarantee of the potential for a significant price reduction of exported hydropower.

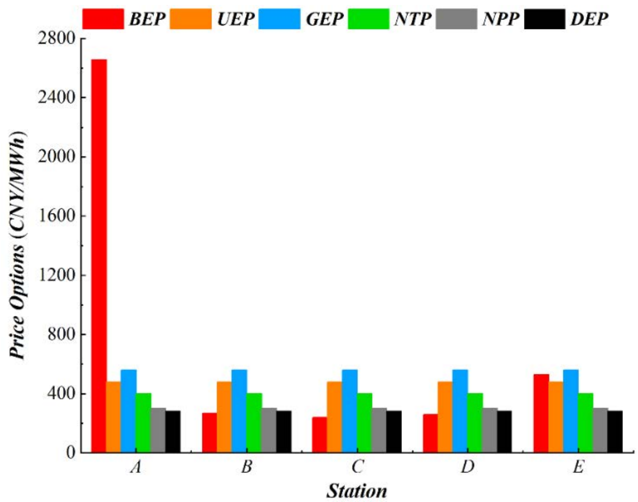

FIGURE 6. Price of each hydropower station with different options.

Generation income is a crucial factor for decision-making, but we also show solicitude for the accommodation of renewable energy, which is equally important in countries with serious hydropower surpluses. First, we solve the upper hydroelectric generator's offer optimization, which is a nonlinear program used to assess the effects of different pricing options. In this case, the total income with the BEP is 26.03 billion CNY, and the UEP is nearly 49.1% (12.79 billion CNY). When selling at a discount, revenue will be reduced to 20% (5.21 billion CNY).

It is interesting to note that hydropower generation under the UEP exceeds that under the BEP (nearly 464 MW) and is concentrated in the dry season (April), as shown in Figure 7. Furthermore, the volume and progress of generation are the

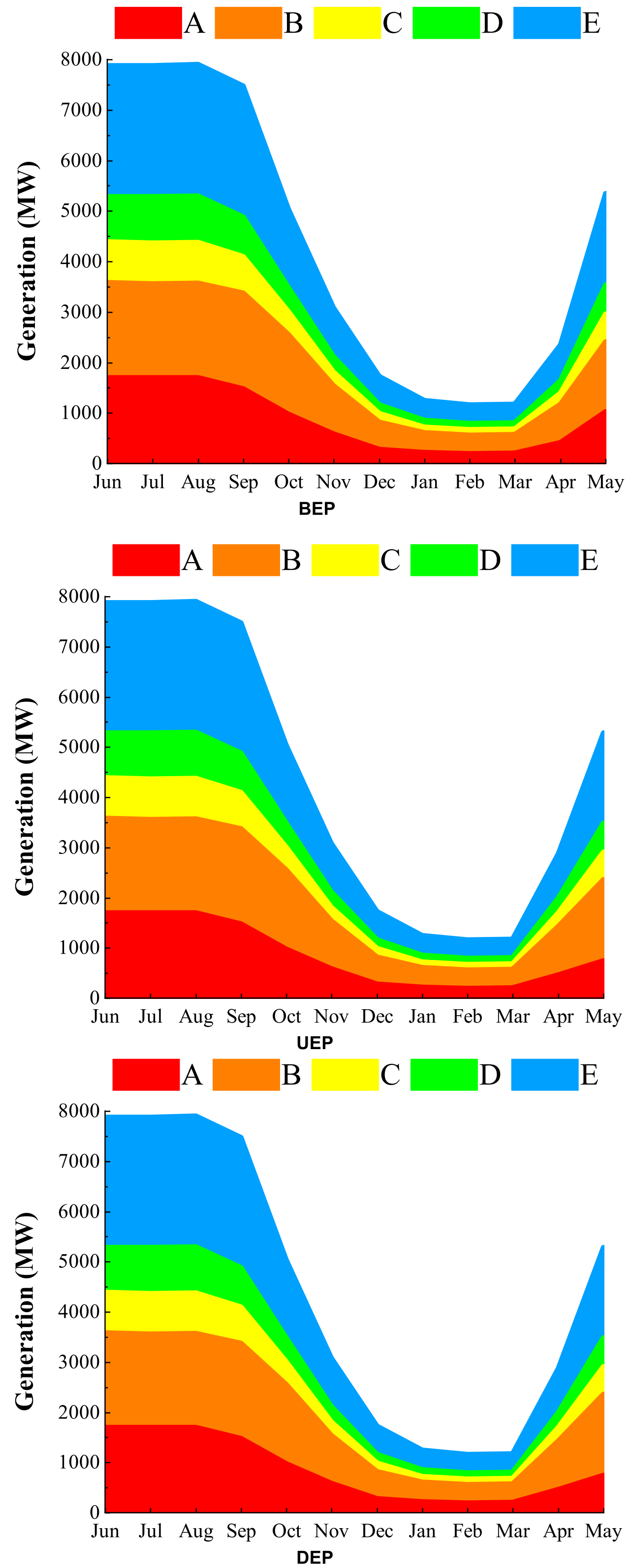

FIGURE 7. Hydropower generation capacity under BEP, UEP, and DEP.

same as those under UEP when each station has the same price (limited by the length of the article, we only show this in terms of DEP).

More clean renewable hydropower energy can be absorbed, which reflects joint regulation with cascade reservoirs; however, this problem adds many new constraints to the operation of CHSs, which are closely related to electricity import expenditure. With the coordination of income and expenditure, these issues must be discussed.

B. EFFECTS OF BI-LEVEL OPTIMIZATION

Electricity cannot be stored, which requires the supply of, and demand for, electricity to be balanced in each period, as described by Eq. (15). As previously mentioned, exporting power provides the base load, and the load demand is stable in any period. The box in Figure 8(a) shows the annual load demand of the importing country; therefore, the CHSs are constrained to adjust the generation process to match the demand and minimize the cost of importing electricity. The results are shown in FIGURE 8 (b), where BEP is taken as an example.

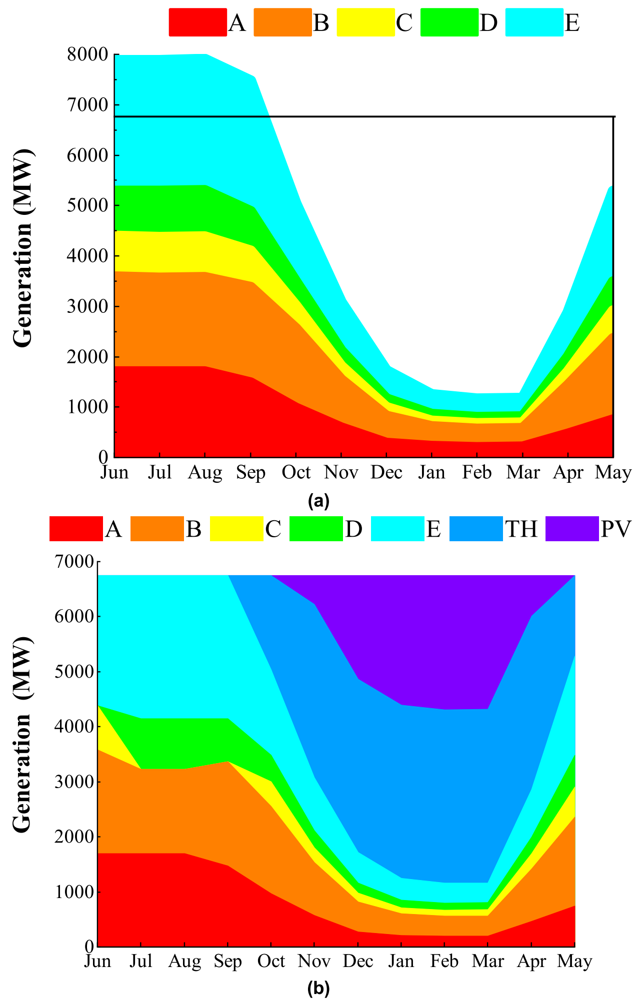

FIGURE 8. The generation process under BEP in bi-level optimization, (a) and (b).

The surplus hydropower generation in wet periods, beyond the box in FIGURE 8 (a), must be abandoned; this applies to the other five pricing options and will inevitably cause a loss of revenue. CHSs are strongly coupled; therefore, a change in the annual generation process is inevitable. The numerical calculation shows that the power generation and revenue of bi-level optimization are reduced by 7.92% and 1.1%, respectively, which is equivalent to 283 million CNY under BEP. As for the UEP, they are all reduced by 7.85%, equivalent to 1.0 billion CNY, and other options are discussed in more detail in the next section.

As shown in FIGURE 8 (b), there is significant complementarity among hydro, thermal, and photovoltaic power, which is an advantage of CBET. The other two can perfectly fill the demand gap for hydropower during the dry season, thus ensuring the stability of power importation. The BOM is thus deemed rational and reasonable for forward contract decision-making, and the effects of different options on export income, scale, import cost, and which option is the most suitable for CBET in this case, are the main topics in the next section.

C. ALGORITHM PERFORMANCE ANALYSIS

POA, PSO, and MILP were used in turn to solve the single-objective optimization problem transformed from the bi-level optimization model. It is noticed that the last requires to linearize the objective and constraints, while the others do not. The calculations were all based on UEP and run on an Intel® Core i5 processor (2.70 GHz) with 8 GB of RAM. The number of iterations in PSO and POA was set to 500, and performance comparation mainly focused on maximum profit of generators and time cost.

TABLE 3. Performance of different algorithms.

Algorithm	Maximum profit Billion CNY	Time s	Iterations
PSO	11.82	5.8	500
POA	10.56	15.5	500
MILP	11.78	2.52	138

As shown in Table 3, the maximum profits under PSO and MILP are similar, while the time cost of PSO is over twice than that of MILP. Furthermore, the objective value fluctuates around 11.82 and remains unstable in subsequent calculations. Turning to POA, the objective is reduced by nearly 10% compared with MILP, but the time cost is greater. The PSO can be trapped by local optimization. In summary, the MILP can easily reach a global optimal solution with minimum time cost. In addition, the linearization does not result in a significant reduction in accuracy (this is consistent with the literature [38], [39], [40]).

D. APPROPRIATE PRICING OPTIONS

Here, we no longer only focus on the scale and income of the CHSs, but pay more attention to the influences of different hydropower pricing options on income for exporting countries along with different types of power, and the cost of importing countries.

First, pricing options have a direct influence on power import costs and export income. Figure 9(a) shows the total cost under different options and Figure 9(b) illustrates the monthly distribution of the three sources under the UEP. The income and cost of hydropower are proportional; an importer will pay the most when in BEP, as well as giving the most revenue to the exporter. The cost of 39.01 billion CNY is nearly 1.6 times that under UEP and 3.6 times that under DEP. Instead, hydropower generator will receive 25.74 billion CNY, nearly 2.2 times that under UEP and over 5 times that under DEP.

The significance of forward contracts is to protect the benefits of both parties, allowing the hydropower generator to become the largest winner. As shown in FIGURE 9 (b), all costs flow to hydropower during wet seasons, and thermal and PV power are used as supplements at other times. This explains why the costs of the other two power sources are almost constant, as shown in Figure 9(a). PV, which has a lower price, is preferred to reduce import costs. The specific influences of thermal and photovoltaic power are explained in the next section. The monthly distribution of the three sources under other options is akin to that in Figure 9(b) (not shown due to word count limitations).

With respect to the scale of hydropower, except for the BEP, the total annual generation of hydropower under the other options is the same, but there is a slight deviation between the PV and thermal power (Table 4). The annual electricity import process is shown in Figure 10, and there is little overall difference, except for some small details pertaining to the BEP and UEP. The difference in the total annual hydropower generation between the BEP and other options based on the UEP can be explained by joint regulation with cascade reservoirs, as mentioned above.

Benefit-sharing is the most important factor driving contract success. High prices may reduce the willingness to import electricity; however, excessive discounting imposes a huge financial burden on exporting countries. The annual income and costs for the different pricing options are listed in Table 5. The cost and income between the UEP and NTP are close, which is an important basis of our pricing scheme.

As mentioned above, hydropower prices are higher than those of PV and thermal power, such as at Station A. The BEP seems to be unbalanced; therefore, it is not considered. Finally, our pricing scheme is as follows. The import unit price of hydropower is set as the UEP or NTP, that is, 481 and 400 CNY/MWh, respectively. The Chinese Government will compensate for generators according to the GEP, which cost 2.85 and 5.73 billion CNY respectively each year, to support and encourage CBET with renewable hydropower.

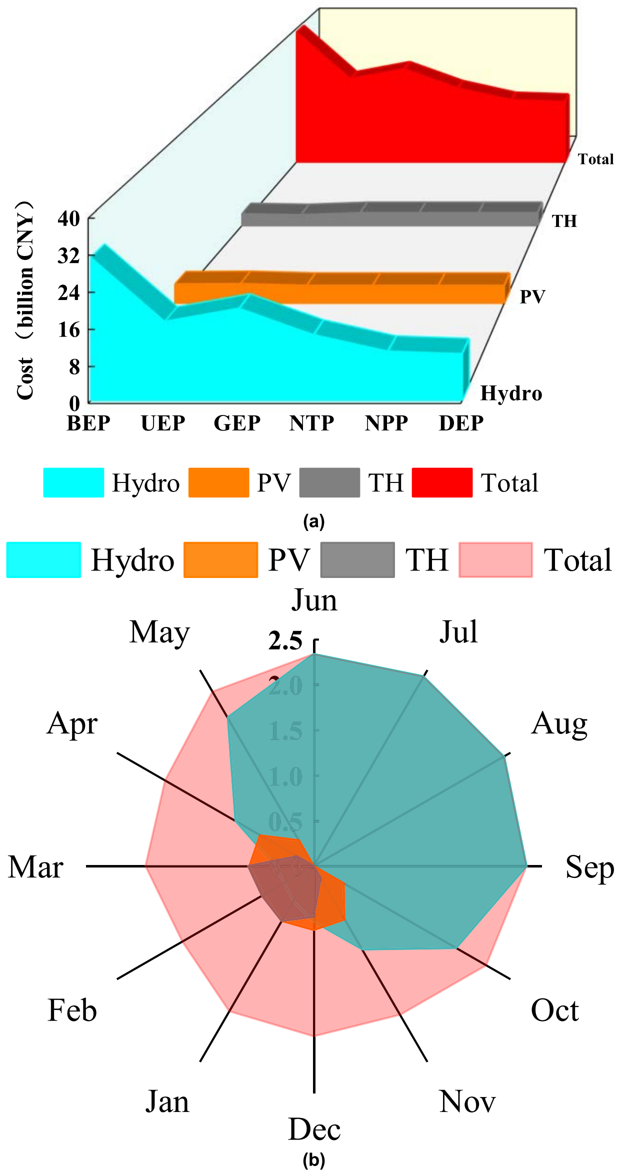

FIGURE 9. Total and monthly cost under different pricing options, (a) and (b).

TABLE 4. Total annual power generation under different pricing options.

Price Options	BEP	UEP	GEP	NTP	NPP	DEP
	TW·h					
Hydro	35.27	35.60	35.60	35.60	35.60	35.60
PV	15.72	16.04	14.61	14.61	14.61	14.61
Thermal	8.14	7.49	8.93	8.93	8.93	8.93

Over time, the marginal cost of hydropower must fall, which makes its price lower than that of PV and thermal power, such as in NPP and DEP. In this situation, the importer obtains more clean energy at a low cost. The pressure on the importing government has gradually decreased.

TABLE 5. Annual incomes and costs under different pricing options.

Price Options	BEP	UEP	GEP	NTP	NPP	DEP
	Billion CNY					
Income	25.74	11.78	14.63	8.9	5.34	4.8
Cost	39.01	24.93	27.92	22.19	18.63	10.81

E. SENSITIVITY ANALYSIS

Compared to import demand, surplus power supply capacity is sufficient in each country, so we focus on the limits of transmission capacities and prices of PV and thermal power. Therefore, four scenarios are established to assess the influences of nonstrategic countries with different power sources, that is, 1) transmission capacity of PV expands five-fold and the price remains unchanged; 2) the price of thermal power is discounted until it is lower than that of PV, and the transmission capacity remains unchanged; 3) the transmission capacity of thermal power expands five-fold and the price remains unchanged; 4) the price of thermal power is discounted until it is lower than that of PV, and transmission capacity expands five-fold. In these scenarios, the hydropower prices are set as the UEP, and the parameters of each scenario are listed in Table 6.

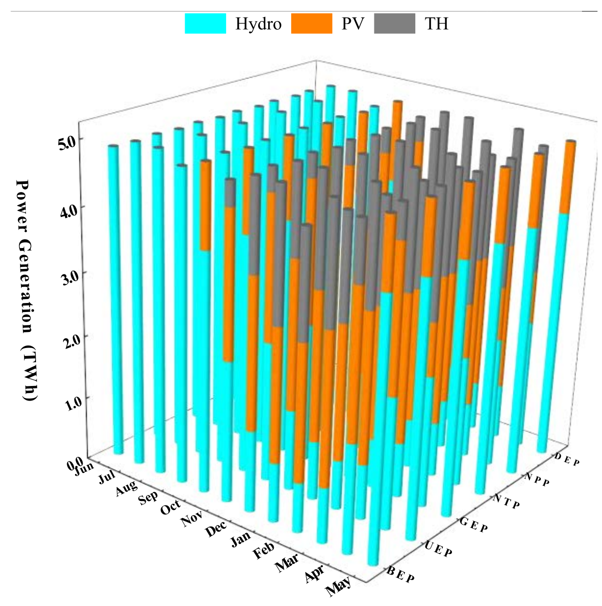

FIGURE 10. The annual electricity import process under different pricing options.

TABLE 6. Parameters of different scenarios for sensitivity analysis.

Scenario	1	2	3	4	5
Price of PV (CNY/MW·h)	300	300	300	300	300
Price of TH (CNY/MW·h)	400	240	400	240	400
Transmission capacity of PV (GW)	22.5	4.5	4.5	4.5	4.5
Transmission capacity of TH (GW)	3.4	3.4	17	17	3.4

Scenario 5 is set as a control group with origin parameters, and the cost for electricity import in different scenarios is shown in Figure 11 and compared with FIGURE 9 (b). The calculations show that the reduction in cost mainly depends on an increase in cheap PV and discounted TP in Scenarios 1 and 4, respectively. The conclusions (with sensitivity analysis) are as follows.

1) In cross-border bilateral negotiations, hydropower revenue is only related to price options and generation capacity, but is independent of actions of nonstrategic countries;

2) With the development of transmission capacity between countries, popular, cheaper, clean, and renewable energy will gradually replace more expensive, traditional thermal power. As a result, CBET plays an important role in global energy transformation.

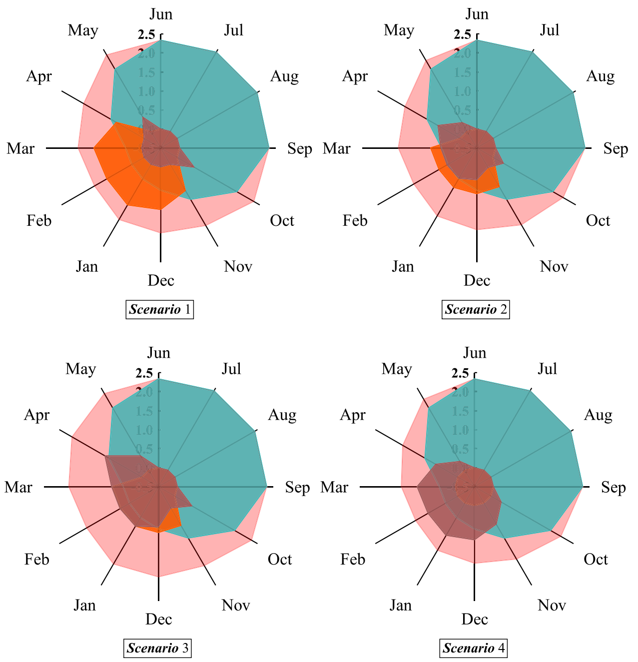

FIGURE 11. The cost of electricity imports in different scenarios.

F. RUNOFF UNCERTAINTY

In hydropower optimization, runoff uncertainty is referred to as the uneven distribution of natural inflow within a year and the differences in precipitation over different years [55], as shown in FIGURE 5. The former has been overcome with the regulation of huge reservoirs and attempts have been made to meet the objective function as far as possible, as mentioned.

The complementarity between the power sources in CBET can eliminate the influence of the latter to the maximum extent. As for the CHSs in this case, the deviations of maximum annual generation capacity among typical years are 3.83 and 2.74 GW, respectively. However, all import demands are satisfied (FIGURE 12). With the deepening of cooperation and the expansion of transmission capacity, this advantage of CBET will become more prominent.

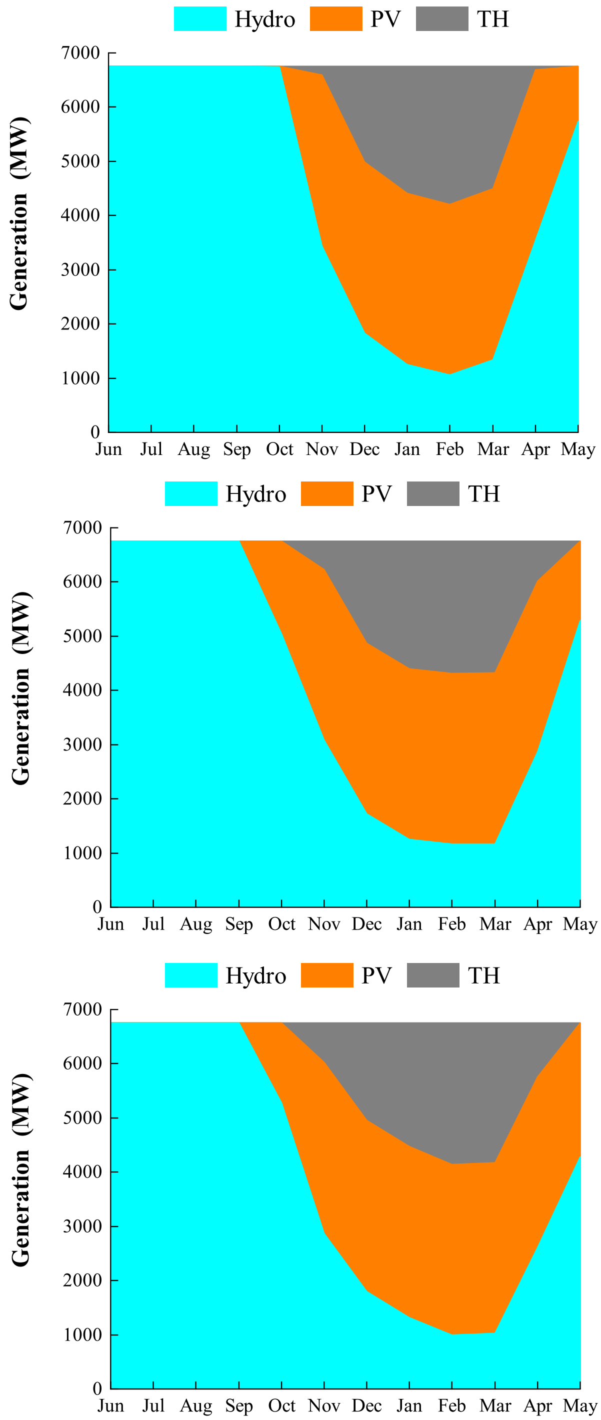

FIGURE 12. The generation process in different typical years.

VI. CONCLUSION

Participation in regional CBET with surplus hydroelectric potential is proposed in China, with the help of rationalized transaction strategies, importing countries obtain stable and clean power supplies, while surplus resources accrue practical benefit. Forward contracts are key to continuous cooperation, and appropriate electricity pricing is at the core of any such negotiation. For this purpose, five different pricing options were proposed, the results of which were used in a BOM to simulate the scenario of exporting electricity from a hybrid power source. The BOM with many nonlinear and non-convex constraints was transformed into a MILP using a series of linearization techniques, and then solved.

A typical CBET case involving four neighboring countries and three types of power sources was constructed for model testing and discussion. The MCP corresponding to different options for each station in the cascade is involved in the BOM, and then their influences on the scale of renewable energy, generation income and import costs were estimated. The main conclusions are as follows: hydropower, thermal, and renewable PV showed complementarity in filling the load gap of an importer. Countries have deep potential for cooperation. With the reduction in the marginal cost of hydropower, this potential will gradually increase. Then, hydropower participating in CBET is shown to form the trend in the future, the UEP based on the marginal cost seems the optimal pricing options. Last but not the least, the price competitiveness of the CHSs is limited at the initial stage of operation, which is about 20% to 60% higher than the others. Government may consider providing subsidies to maintain cross-border cooperation. However, with the deepening of cooperation, it has more scope for reduction, even to some 30% below that associated with thermal generation.

Different hydropower prices in the wet and dry seasons are popular in China and have proven to be a better way to reflect water values; therefore, we shall attempt to apply this strategy to CBET in the future. With the deepening of cooperation, more market modes, except for forward contracts such as cross-border spot electricity trading, will become the focus of future research. In addition, we will select some topics of risk analyzing to measure the risk of hydropower participation in CBET in future work.

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