Robust short-term scheduling based on information-gap decision theory for cascade reservoirs considering bilateral contract fulfillment and day-ahead market bidding in source systems

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Abstract
China is implementing a new power system reform, with one goal of renewable energy absorption such as hydropower. However, the forthcoming spot market challenges cascade hydropower generation in terms of the short-term hydro scheduling (STHS) problem. Specifically, STHS involves fulfilling bilateral market obligations and bidding for the day-ahead market with uncertainty. Coordination of these two tasks while managing market risks becomes a problem that must be urgently solved. Herein, we propose a method based on the information-gap decision theory (IGDT) to solve the cascade hydropower STHS problem, wherein the aforementioned tasks are coordinated simultaneously. The IGDT method was used to deal with the uncertainty of the day-ahead market price, and the robustness function was derived. A mixed-integer nonlinear programming model was used to describe the proposed problem, and a commercial solver was used to solve it. A four-reservoir cascade hydropower company was used as the research object. Through the robust dispatching results, the preset profit objectives of the power generation company were satisfied within the price information gap, and the day-ahead market bidding strategy and daily contract decomposition curve were obtained. The proposed model is found to be superior to the scenario-based probability method. Moreover, a comparative analysis of bilateral contract fulfillment showed that more profits can be obtained by coordinating contract fulfillment in the day-ahead market.

1. Introduction

1.1. Background and motivation
Hydropower is considered the most economical renewable resource and has been vigorously deployed and developed worldwide. China has been experiencing an unprecedented hydropower boom since 2000 \cite{1}. By 2019, the installed capacity of hydropower reached 256.4 GW \cite{2,3}. To promote clean energy consumption and the transformation of the energy structure, China started a new round of power system reform in 2015 and gradually established a medium-and long-term power market \cite{4}. To promote the construction of the power market system further, eight provinces or regions were selected as the first batch of pilot power spot markets in 2017. All these areas were included in simulated trial operations before the end of June 2019 \cite{5}, and a complete market system is gradually being formed.

The establishment of a market environment poses new challenges to a hydropower generating company (HGenCo), which must submit the best offer to the market; hydro scheduling is a necessary tool to realize optimal bidding decisions. Therefore research should be directed towards improving the hydro-power scheduling model, coping with the new tasks brought by the market environment, and improving the economic benefits of hydropower utilization \cite{6,7}.
For the forthcoming spot market \([4]\), studying STHS in the market environment is of great practical significance but faces the following difficulties:

(a) In the medium- and long-term periods, the reservoir inflow must be considered as random. However, short-term reservoir inflow can be regarded as deterministic, especially when the time range is only one day, and the reservoir inflow can be predicted reasonably accurately on a daily scale. Nonetheless, the accurate estimation of the day-ahead market price, i.e. the principal uncertainty of STHS, is difficult. Therefore, considering the fate of the predicted price is critical \([8]\).

(b) Bilateral contracts (BCs) signed by the HGenCo may affect its total revenue and participation in the day-ahead market. Long-term BCs that must be physically settled create the obligation for a certain amount of energy to be provided for several hours. This restriction affects the bidding space of the day-ahead market and significantly impacts the interests of the HGenCo. Therefore, signing of BCs in advance should be considered in the short-term planning and day-ahead bidding strategy of the HGenCo \([9]\).

1.2. Literature review

In the market environment, the scheduling and bidding of power generation companies have received considerable attention from researchers in the literature and involve many types of power plants, markets, and risks. For example, the authors in \([10]\) studied the optimal behavior of a hybrid power producer in day-ahead and intraday markets. The model proposed in \([11]\) considers price risk and provides bidding and offering strategies for pumped storage power stations to participate in the energy market. Two strategic bidding models for the participation of photovoltaic power producers in short-term electricity markets were proposed in \([12]\). A multi-stage model to coordinate wind-thermal-energy storage offering strategies in energy and spinning reserve markets was proposed in \([13]\). The variety of scheduling or bidding strategy studies in the literature is enormous. Thus, this study endeavored to review the most relevant works.

Many studies address STHS in the market environment. For instance \([14]\), addresses the self-scheduling of a hydro-generating company in a pool-based electricity market. In \([15]\), a novel mixed-integer nonlinear programming (MINLP) approach was proposed to solve the STHS problem in the day-ahead electricity market, considering the operational characteristics of hydropower. The authors in \([16]\) proposed a coordinated short-term scheduling method regarding water as a common pool resource shared by the operators, which can significantly improve profit and avoid spillages. In \([17]\), a method was proposed to ensure that the solution obtained based on the approximated mixed-integer linear programming (MILP) formulation for STHS remains feasible for the original nonlinear formulation. To maximize profit or technical efficiency, an MINLP model was proposed in \([18]\) for scheduling the short-term integrated operation of a series of price-taker hydroelectric plants. In \([19]\), an accurate optimization model for STHS with strong hydraulic coupling and head-dependent prohibited operating zones (FOZs) was presented. In \([20]\), a new method was proposed to introduce nonlinearity into the MILP formulation for STHS dynamically. Nevertheless \([14–20]\), assumed that accurate forecasts of the electricity market price are available, and the impact of the inaccurate price forecast on profit is ignored. However, according to the prediction method and market structure, the price prediction error may be between 5% and 36% \([21]\) and will significantly affect the economic benefits of the HGenCo; thus, the uncertainty of electricity prices should be considered.

Risk-based generation scheduling has attracted much attention in the energy market environment \([22]\). A risk-averse profit-based optimal scheduling of a hydro-chain in the day-ahead electricity market was conducted in \([23]\), implementing different risk-aversion constraints. In \([24]\), a stochastic mathematical model for maximizing profits was implemented by managing a potential price scenario tree. The authors in \([25]\) proposed an efficient method to solve the profit-based optimal self-scheduling of a hydroelectric company in the pool-based day-ahead electricity market by integrating a cultural algorithm with feasible sequential quadratic programming. In \([26]\), multi-stage mixed-integer linear stochastic programming was utilized to address uncertainties related to the hydropower participation in the day-ahead market. Furthermore, the authors in \([27]\) and \([28]\) proposed MINLP and a mixed-integer quadratic programming approach for STHS, respectively, considering complex hydraulic constraints, price scenarios, and risk aversion. A price-scenario-based method was adopted in \([25–28]\) to study hydropower bidding and scheduling. However, it is usually challenging to accurately obtain the probability distribution function in practical problems. Conversely, multiple sample scenes are needed to improve the reliability of the model, which increases the computational burden; the results do not provide intuitive guidance to decision-makers.

The information-gap decision theory (IGDT) is a non-probabilistic interval optimization-based method for enhancing decision-making under uncertainty that does not make any assumptions about the probability distribution, which is very useful in the case of high uncertainty or lack of sufficient
information [29]. The IGDT has been widely studied and applied in the field of power systems to address the uncertainty of wind power photovoltaic power generation [30, 31], market price [32], and system load [33]. This method, unlike those in the aforementioned studies [23–28], was used to address price uncertainty.

From another perspective, the study of STHS in the electricity market environment primarily considers single day-ahead market bidding. Furthermore, some studies consider multi-market bidding in day-ahead, intra-day, and real-time markets [34, 35]. The physical BC affects the bidding space of the day-ahead market and the bidding strategy. However, as far as we know, existing studies on STHS rarely consider the impact of bilateral physical contract performance on day-ahead market bidding; this study attempts to compensate for the aforementioned shortcoming.

1.3. Procedure
Against the background of the pilot spot market in China, this study aims to solve the problems faced by cascade hydropower stations (CHS) participating in the day-ahead market and compensate for existing research deficiencies. An IGDT-based robust short-term scheduling method is proposed for cascade hydropower, involving participation in the day-ahead energy markets with BC fulfillment, considering price uncertainty based on the IGDT. The IGDT method enables decision-makers to solve the hydropower self-scheduling problem with less computation without making any assumptions regarding the probability density of the uncertain parameters. The proposed robust model is not based on assumptions of uncertain price fluctuations to maximize the profit of the power station but to maximize the range of price uncertainty regarding the predicted value and find a scheduling solution that guarantees a certain predetermined revenue. Then, the proposed robust scheduling problem based on the IGDT is applied to construct the hourly bidding and bilateral physical contract fulfillment strategy, which can be submitted to the market every hour, whereby different risk levels of price forecasting are accounted for.

1.4. Contribution
In conclusion, the contributions of this study in comparison with other research works can be stated as follows:

(a) Considering the background of the newly reformed China electricity market, a novel short-term optimal operation model of cascade hydropower is proposed to obtain the daily contract decomposition curve and day-ahead market bidding strategy. The model incorporates the effects of the physical BC into the day-ahead market bidding, which realizes the coordination between BC fulfillment and the day-ahead market bidding in STHS.

(b) Uncertainties posed from the day-ahead market price are considered in the proposed model. Moreover, the non-probabilistic IGDT is used to deal with uncertainty. To the best of the authors’ knowledge, this study is one of the first to use IGDT to solve the short-term robust operation problem of CHS in the framework of the day-ahead market combined with the BC market.

(c) This method is constructed as an MINLP model via polynomial approximations of nonlinearities and model transformation. Case studies illustrate its effectiveness and applicability. The advantages of the IGDT method are verified via comparison with the scenario-based method, and the necessity of day-ahead market bidding incorporating BCs is verified via contract decomposition comparative analysis. The results provide a practical reference for risk-averse cascade hydropower decision-makers.

1.5. Page organization
This paper is organized as follows: section 2 briefly introduces the IGDT method. The STHS problem considering BCs is formulated in section 3. Section 4 extends the IGDT-based STHS method for constructing a BC fulfillment curve and day-ahead market bidding volume price pair. The primary inputs and parameters required in the model and the results are presented in section 5. Finally, the principal conclusions proved in the previous sections are collected in section 6.

2. IGDT
The IGDT, first proposed in [29], is a non-probabilistic interval optimization-based method for enhancing decision making with uncertainty. The IGDT does not involve any assumptions regarding the probability distribution, which proves very useful in the case of high uncertainty or insufficient information. In this method, the uncertainty is modeled by an interval around the forecasted value, and the range of uncertainty is maximized when the decision variables are set. The method also controls the risk of prediction error by ensuring the pre-set target level and by introducing the maximum confidence interval of the predicted value. More details and application cases can be found in [29, 30]. In this study, the forecasted day-ahead price is an uncertain parameter. Therefore, the maximum allowable deviation between the day-ahead price and the predicted value is obtained using the IGDT method. Each IGDT problem can be defined in three parts: the system model, uncertainty model, and performance requirements [33], which are explained hereafter.
2.1. System model
This component contains the input/output structure of the system. Given the current problems, the system model is represented by \( R(U, P) \) and evaluates the benefits of the HGenCo strategy based on the day-ahead price and plant schedules. In this model, \( U, P \) are the uncertain and decision variables, respectively.

2.2. Uncertainty model
The IGDT contains various types of uncertainty sets. The uncertainty model reflects information on day-ahead prices. In this study, the envelope boundary model with \( \tilde{\lambda}_t \) as the surrounding function is performed [36] and represented mathematically by equation (1). Based on this model, the related robustness and opportunity functions can be derived.

\[
U(\alpha, \tilde{\lambda}_t) = \left\{ \lambda_t : \left| \frac{\lambda_t - \tilde{\lambda}_t}{\lambda_t} \right| \leq \alpha \right\} \alpha \geq 0, \forall t \in T
\]  

(1)

where \( \alpha \) is the horizon of the uncertainty variable. \( \lambda_t, \tilde{\lambda}_t \) denote the market price and forecasted market price at time \( t \), respectively.

2.3. Performance requirements
This part of the IGDT represents the desired award from the system: the profit from the market in this problem. Fluctuations in the day-ahead market price may be profitable or unfavorable. The IGDT can be used to derive two types of performance functions: a robustness function and an opportunity function. The choice of function depends on the risk management strategy of the decision-maker. A risk-averse HGenCo will choose the robustness function to resist unexpected price violations. Specifically, the robustness function selects the occurrence of worst-case uncertainty and sets the decision variables to meet the pre-specified minimum requirements of the system. In this study, the immune function should examine the maximum allowable change in the price range obtained by the minimum profit specified by the decision-maker in advance. This can be expressed by equation (2).

\[
\hat{\alpha}(P, R_C) = \max \left\{ \alpha : \min_{\lambda_t \in U(\alpha, \tilde{\lambda}_t)} R(U, P) \geq R_C \right\}
\]  

(2)

where \( R_C \) is the predefined profit that the decision-maker wants to achieve and \( \hat{\alpha} \) is the maximum allowable range of price forecast error. If the observed price falls within the maximum confidence interval defined by \( \hat{\alpha} \), the minimum return \( R_C \) can be guaranteed.

3. STHS problem formulation
The formula of the HGenCo profit based on the STHS, which is the IGDT system model, is provided in this section.

In this context, STHS includes two tasks: fulfilling bilateral market obligations and bidding for the following day-ahead market under uncertainty.

3.1. Assumptions
The assumptions considered in this paper are as follows:

(a) The CHS participate in the day-ahead market with the bilateral physical contract.
(b) The CHS acts as a price-taker; its energy quotation cannot affect market prices.
(c) All hydropower stations belong to the same CHS and the same stakeholder.
(d) A single hydropower station is a market bidding unit [37].

3.2. Objective function
STHS can be described as determining the optimal water discharge, water storage, and water spillage of each reservoir under the condition of satisfying all hydraulic constraints to maximize benefits. Considering the coordination of BC fulfillment and day-ahead market bidding, the total profit of CHS in this study consists of BC revenue and day-ahead market revenue. The objective function expression is as follows:

\[
\max R = \sum_{i \in I} \sum_{t \in T} \left( p^i_{c,t} \lambda^i_{t} + (P_{i,t} - P^i_{c,t}) \tilde{\lambda}_t \right) \Delta t
\]  

(3)

where \( P^i_{c,t} \) is the planned power output for BCs of plant \( i \) in period \( t \) (MW); \( \lambda^i_{t} \) is the BC price of plant \( i \) (yuan MWh\(^{-1}\)); \( P_{i,t} \) is the total power output of plant \( i \) in period \( t \) (MW); \( \tilde{\lambda}_t \) denotes the forecasted market price in period \( t \) (yuan MWh\(^{-1}\)); \( T \) is the set of the time period; \( I \) is the set of power plants; \( \Delta t \) denotes the time period duration (1 h); and \( p^i_{c,t} \) and \( P_{i,t} \) are the decision variables of the model.

3.3. Operating constraints
(a) Water balance

\[
V_{i,t+1} = V_{i,t} + 3600(I_{i,t} - Q_{i,t} + \sum_{k \in K_i} Q^k_{i,\tau_{k,i}}) \Delta t
\]  

(4)

where \( V_{i,t} \) is the storage volume of the plant \( i \) in period \( t \) (m\(^3\)); \( I_{i,t} \) is the local water inflow of plant \( i \) in period \( t \) (m\(^3\) s\(^{-1}\)); \( Q_{i,t} \) is the water release of plant \( i \) in period \( t \) (m\(^3\) s\(^{-1}\)); \( Q^k_{i,\tau_{k,i}} \) is the water release of plant \( k \) in period \( t - \tau_{k,i} \) (m\(^3\) s\(^{-1}\)); \( K_i \) is the set of immediate upstream reservoirs of plant \( i \); and \( \tau_{k,i} \) is the water time delay between plant \( k \) and plant \( i \) (h). 3600 is introduced here, indicating 3600 s in 1 h.

(b) Reservoir storage constraint

\[
V_{i,\text{min}} \leq V_{i,t} \leq V_{i,\text{max}}
\]  

(5)

where \( V_{i,\text{min}} \) and \( V_{i,\text{max}} \) are the minimum and maximum storage limits of plant \( i \) (m), respectively.
(c) Water discharge
\[ Q_{i,min} \leq Q_{i,t} \leq Q_{i,max} \quad (6) \]
\[ Q_{i,t} = Q_{i,t}^f + s_{i,t} \quad (7) \]
where \( Q_{i,min} \) and \( Q_{i,max} \) are the minimum and maximum total water releases of plant \( i \) in period \( t \) (\( m^3 \cdot s^{-1} \)), respectively. \( Q_{i,t}, Q_{i,t}^f \), and \( s_{i,t} \) are the plant water release, plant generation discharge, and water surplus of plant \( i \) in period \( t \) (\( m^3 \cdot s^{-1} \)), respectively.

(d) Power output
\[ P_{i,min} \leq P_{i,t} \leq P_{i,max} \quad (8) \]
where \( P_{i,min} \) and \( P_{i,max} \) are the minimum and maximum power output of plant \( i \), respectively.

(e) Forbidden operation zones of hydropower plants
\[ (P_{i,t} - Z_{f,m}) (P_{i,t} - Z_{f,m}) > 0, \quad m = 1, 2, \cdots, M_i \quad (9) \]
where \( Z_{f,m} \) and \( Z_{a,m} \) are the lower and upper limits of the FOZ \( m \) of plant, respectively. \( M_i \) is the number of FOZs. The assembled mathematical techniques can be used to calculate the combined FOZs of each plant [38].

(f) Forebay level constraint and Forebay level function:
\[ Z_{f_i,\text{min}} \leq Z_{f_i,t} \leq Z_{f_i,\text{max}} \quad (10) \]
\[ Z_{f_i,0} = Z_{f_i,\text{begin}}, Z_{f_i,T} = Z_{f_i,\text{end}} \quad (11) \]
\[ Z_{f_i,t} = f_{i,2Z}(V_{i,t}) \quad (12) \]
where \( Z_{f_i,t} \) is the forebay level of plant \( i \) in period \( t \) (m); \( Z_{f_i,\text{max}} \) and \( Z_{f_i,\text{min}} \) are the minimum and maximum forebay level limits of plant \( i \) in period \( t \) (m), respectively; \( Z_{f_i,\text{begin}}, Z_{f_i,\text{end}} \) are the initial and final water levels of the plant \( i \) in period \( t \) (m) and are determined by the medium- and long-term scheduling; \( f_{i,2Z}(V_{i,t}) \) denotes the relationship between the forebay water level and the water storage of the reservoir \( i \). This univariate function is nonlinear and was formulated as fourth-order polynomials in this study.

(g) Net head
\[ H_{i,\text{min}} \leq H_{i,t} \leq H_{i,\text{max}} \quad (13) \]
\[ H_{i,t} = (Z_{f_i,t-1} + Z_{f_i,t})/2 - Z_{d_i,t} - \varepsilon_{i,t} \quad (14) \]
where \( H_{i,t} \) is the net head of plant \( i \) at period \( t \) (m); \( H_{i,\text{max}} \) and \( H_{i,\text{min}} \) are the maximum and minimum net head level of plant \( i \) (m), respectively; \( Z_{d_i,t} \) is the tailwater level of plant \( i \) in period \( t \) (m); and \( \varepsilon_{i,t} \) is the water head loss of plant \( i \) in period \( t \) (m).

(h) Tailwater level function
\[ Z_{d_i,t} = f_{i,2Q}(Q_{i,t}) \quad (15) \]
where \( f_{i,2Q}(Q_{i,t}) \) denotes the relationship between the tailrace level and the total water release of the reservoir \( i \). This univariate function is also nonlinear and formulated as fourth-order polynomials in this study, and it can be obtained by actual data fitting [39].

(i) Generation function
\[ P_{i,t} = f_{i,G}(Q_{i,t}^f, H_{i,t}) \quad (16) \]
where \( f_{i,G}(Q_{i,t}^f, H_{i,t}) \) is a bivariate function describing the relationship between power generation and the net water head, which can also be achieved by real data fitting.

3.4. Contract fulfillment constraints
\[ P_{i,t} = p_{i,t}^c + P_{i,t}^c \quad (17) \]
\[ C_i = c_i^p + c_i^f + c_i^e \quad (18) \]
where \( P_{i,t}^c \) is the planned power output for the day-ahead market of plant \( i \) in period \( t \) (MW), and \( C_i \) is the signed BCs of plant \( i \). The contract decomposition includes many typical decomposition curves. In this study, the peak-flat-valley curve mode is selected [4, 37]; \( c_i^p, c_i^f, \) and \( c_i^e \) represent the contract power outputs of the peak, flat, and valley, respectively.

4. IGDT-based robust scheduling method for the STHS problem

An IGDT-based robust scheduling method for the STHS problem is presented in this section to model price uncertainty and to manage risk. Equation (3) is the system model in the IGDT formulation. The envelope-bound model of equation (1) expounds the uncertainty model. Through selection of the immune function, the optimization based on the IGDT can be written as equation (19).

\[ \max \quad R \quad \alpha \quad (19) \]
subject to:
\[ R \geq R = (1 - \beta) R_0 \quad (20) \]
\[ R = \min \frac{\Delta_{\lambda_i}}{\Delta_{\lambda_i}} \sum_{i \in I} \sum_{t \in T} \left( (P_{i,t} - p_{i,t}^c) \left( \lambda_t + \Delta \lambda_t \right) \right) \right) \quad (21) \]
subject to:
\[ -\alpha \leq \frac{\left( \lambda_t + \Delta \lambda_t \right) - \lambda_t}{\lambda_t} \leq \alpha \quad (22) \]
The IGDT-based robust scheduling method for the STHS problem was bilevel optimization. The goal of the upper-level issue, which included the objective function equation (19) and constraint equations (20)–(18), was to maximize the allowable range of electricity price prediction error, provided that the pre-set profit is met. This level determines the plant schedules \( P_{i,t} \). The pre-set profit \( R_0 \) was calculated using the profit deviation factor and \( \beta \) risk-neutral profit \( R_0 \). \( R_0 \) was obtained by solving a short-term scheduling model based on the forecasted market price without considering the risk factors. The lower-level problem consists of equations (22) and (23), and the optimal solution was the utility revenue. The envelope-bound model is described in equation (23). This level is directed at the robust performance form to minimize the return of the utility concerning price changes. The bilevel model can be converted into a single level to solve the IGDT-based robust short-term scheduling method for cascade reservoirs based on commercial solutions.

Analysis of the low-level problems revealed that the profit fluctuation was primarily affected by the day-ahead market price because the model guaranteed the performance of bilateral physical contracts. Despite how the bidding output was arranged in the day-ahead market, the profit was the lowest when the price was at the minimum fluctuation boundary. Therefore, the above model can be simplified as follows:

\[
\begin{align*}
\text{max} & \quad \alpha \\
\text{s.t.} & \quad R \geq R_0 = (1 - \beta) R_0 \\
& \quad R = \sum_{i \in I} \sum_{t \in T} \left( (P_{i,t} - p^t_i) \left( \bar{\lambda}_t + \Delta \lambda_t \right) + p^t_i \Delta \lambda_t \right) \Delta_t, \\
& \quad \Delta \lambda_t = -\alpha \bar{\lambda}_t \\
& \quad (4) - (19)
\end{align*}
\]

5. Solution methodology

The optimal short-term scheduling problem for cascade hydropower was formulated as a mixed-integer nonlinear problem and solved using a commercial solver. To clarify the optimization model, a flowchart of the proposed IGDT-based STHS is shown in figure 1. The procedure of simulation and result derivation can be summarized as follows:

(a) The water inflow, signed BCs, characteristic CHS parameters, and day-ahead power price are all known input initialization data of the model.

(b) The STHS problem without price uncertainty is solved, that is, under the constraints of (4–19), the profit function in equation (3) was maximized by considering the predicted price data. Income \( R_0 \) was saved as the basis of the subsequent robustness model.

(c) The preset tolerance level (i.e. profit deviation factor \( \beta \)) was set by the decision-maker to construct the profit targets of the robustness models. Then, the robust model was solved to obtain the STHS results, which tally with the preset revenue and ensure the fulfillment of BCs and the arrangement of bidding power in the day-ahead market. The obtained horizon of the uncertainty of the day-ahead power price can be used to guide the declaration of the electricity price.

6. Case study

6.1. Data

The proposed IGDT-based model for STHS was examined on CHS with four reservoirs in series. The installed capacities of each power station were 180 MW, 1040 MW, 558 MW, and 880 MW. The topological graph of this CHS is illustrated in figure 2(a). Among these plants, the second one had a long-term regulation capacity, whereas the others only had daily regulation capacity. The other principal characteristic parameters of this CHS are listed in table 1. The STHS period considered in the optimization was one day, and the time scale was one hour. The actual water inflow of this CHS was taken as the known data of the model (figure 2(b)). Because China has not yet established a spot market for actual operation, this paper refers to the day-ahead market price of Nordpool as the forecast market price [40], which is depicted in figure 2(c). According to the actual characteristics of a provincial power grid in Southwest China, the peak period was set as [9, 12] \( \cup \) [18, 23], the flat period was [7, 9] \( \cup \) [12, 18], and the valley period was [1, 7] \( \cup \) [23, 24]. Figure 2(d) shows the peak, flat, and valley periods as well as the electricity prices of BCs on a corresponding day. The model was solved using LINGO 18.0, a commercial optimization software package [41]. All results were obtained on a personal computer containing an Intel Core i7 CPU with a 2.5 GHz processor and 16 GB RAM.
First Stage: Deterministic viewpoint

- Input initialization
- Solve STHS without price uncertainty
- Save results (Base case)

Set preset tolerance level (beta) by decision maker

Robust Optimization: Maximize alpha, regarding beta and base case

Save optimal solution

Second Stage: IGDT method

End

Figure 1. An overview of the proposed IGDT-based STHS.

Figure 2. Input data of the model. (a) Topological graph of cascade reservoirs. (b) Water inflow of cascade reservoirs. (c) Forecast clearing price of day-ahead market. (d) Medium- and long-term bilateral contracts for cascade reservoirs.
In section 6.2, the deterministic model is solved to obtain the basic revenue (i.e. \( R_0 \)) based on the above data. Then, the robust model is solved through the preset revenue target (i.e. \( R_s \)), and the rationality and effectiveness of the results are analyzed. In section 6.3, the effect of the IGDT method is verified by comparing the robust scheduling results with the scenario-based method. Moreover, to verify the necessity and advantages of optimizing BC decomposition in the proposed model, a comparative analysis was conducted with the comparative model, as shown in section 6.4.

### 6.2. Case study and discussion

First, the deterministic model for maximizing the generated revenue of CHS was solved.

The profit obtained was \( R_0 = 13.0359 \) million yuan (risk-neutral profit) and was composed of a medium- and long-term contract income of 8.97255 million yuan and a spot market revenue of 4.06335 million yuan, which was the basic income of the robust model. Then, without loss of generality, the profit deviation factor was 0.02 (i.e. \( \beta = 2\% \)). According to \( R_0 \), \( R_s \) was calculated as 12.775182 million yuan, which was the preset minimum acceptable profit target. The robust model considering the uncertainty of the electricity price was solved, and the maximum radius of uncertainty in day-ahead market prices (\( \alpha \)) was 0.065. Thus, when the actual price of the spot market fluctuates less than 6.5% from the predicted price, the profit of cascade hydropower enterprises will not be less than 12.775182 million yuan.

Next, the rationality and validity of the results are analyzed. The power output and water level change process of cascade hydropower stations are shown in figures 3(a)–(d). Plant B has the long-term regulation capacity; its water level changes stably with a small fluctuation range. The other three power stations are daily regulated, and the water level fluctuates wildly. The dispatching results are reasonable and satisfy various constraints, which are practical power generation plans.

Furthermore, the plan decomposition curve of BCs fulfillment and the bidding strategy (volume-price pair) of day-ahead market can be obtained. For each power station, the corresponding output of contract electricity during the entire optimization period can be submitted to the power exchange center as the result of contract decomposition; the time-sharing power curve of the daily contract is shown in figure 3(e). The output of each period allocated in the day-ahead market can be used as the bidding electricity quantity of the corresponding period in the spot market, and the lower boundary of the tolerable price fluctuation range in the corresponding period can be used as the corresponding declared price. The bidding information of each power station spot market is shown in figure 3(f).

The decision results are different owing to the different minimum acceptable incomes. To analyze its influence further, the deviation factor was discretized from 0.01 to 0.1 in 0.01 steps, and the robust model was solved. The robustness \( \alpha \) versus acceptable revenue targets \( R_s \) is depicted in figure 4(a), which reveals that, as expected, robustness decreases as \( R_s \) increases.

Thus, the lower the acceptable income of a cascade hydropower enterprise, the better the robustness of obtaining a short-term optimal scheduling scheme, and the greater its ability to resist greater fluctuations in the market price in the day-ahead market.

Cascade hydropower enterprises can track the market price signal in the spot market and pursue maximum benefits. However, because of the short-term complex operation constraints of hydropower stations and the influence of daily contracts, they can only transfer the spot output to the relatively high market price period as much as possible and maximize the profit through the coordination of multi-period day-ahead spot market bidding.

### 6.3. Verification of the IGDT performance

To verify the robustness of the proposed model further, 1000 electricity price scenarios were simulated by Latin hypercube sampling with a uniform distribution within the fluctuation range of the aforementioned robust model [42], as shown in figure 4(b). The short-term optimal operation scheme was obtained using a robust model. The scenarios were substituted into the test one by one, and the total revenue of the CHS under the corresponding scenarios was obtained. The distribution of profits is shown in figure 4(c). The income was not lower than the target income (12.775182 million yuan). Thus, when the spot market price fluctuated in the robust region, the short-term scheduling scheme of CHS based on the robust model considering the price uncertainty ensured that the generated revenue was not lower than the target value.

| Table 1. Main characteristic parameters of cascade hydropower stations. |
|-----------------|-----------|-----------|-----------|-----------|
| Plant parameters | A         | B         | C         | D         |
| Forebay level limits (m) | [865 885] | [690 745] | [580 585] | [483 490] |
| Power output limits (MW)  | [50 180]  | [200,1040] | [100 558] | [150 880] |
| Water release limits (m^3 s^{-1}) | [0, 6294] | [0, 9945] | [0, 10 866] | [0, 13 330] |
| Initial-final forebay level (m) | (881.85, 884.26) | (723.00, 722.59) | (582.10, 582.67) | (488.07, 488.79) |
| Water time delay (h) | 4         | 1         | 1         | —         |
After assessing the 1000 price samples, which were representative of a probabilistic approach, the expected value was 13.03969842 million yuan. However, the results were highly dependent on scenarios that described uncertain parameters. In reality, the expected value is difficult to infer. The advantage of this IGDT method is that it provides an optimal schedule that allows extreme uncertainty while ensuring revenue targets.

6.4. Contract fulfillment analysis

To further verify the effect of the model in contract decomposition and the necessity of optimizing contract decomposition, we performed comparative analysis. The comparison model decomposed the equal contract proportion every hour and was not coordinated with the day-ahead market bidding.

First, the revenue of unbiased forecast electricity prices was calculated. The model in this study (model 1) used a value of 12.775182 million yuan, and the revenue of the comparison model (model 2) was 12.553558 million yuan. Compared with that in the comparison model, the profit increment of the time-sharing power curve constructed by this model was 1.77%. We calculated the market price volatility ($\alpha$) in the same manner using different profit targets. The results of the comparison model and the present model are shown in figure 4(d).

According to the comparative analysis in figure 4(d), under the same profit target conditions, the model proposed in this paper resists spot market price fluctuations significantly more than does the comparative model. Taking the profit deviation factor of 0.05 as an example, the fluctuation range of spot market price obtained by this model was 0.18737,
whereas that of the comparative model was 0.13960, representing an increase of 0.04777.

7. Conclusion

In this paper, a robust scheduling model based on the IGDT is proposed for STHS from the standpoint of the newly reformed electricity market in China. Coordination between BC fulfillment and day-ahead market bidding in the context of the STHS problem was performed. The robustness function was obtained while considering the uncertainty of the day-ahead market price, and robust scheduling results satisfying the predetermined profit target of hydropower enterprises were obtained. The advantages of the model were verified via comparison with a scenario-based probabilistic approach. Additionally, the analysis of BC fulfillment validated the role of coordinating contract performance in day-ahead market bidding. The primary conclusions are the following:

(a) The proposed method obtained the short-term optimal operation scheme of cascade hydropower and provided an effective reference for decision-making regarding BC decomposition curves and day-ahead market bidding.

(b) Based on the IGDT to deal with the uncertainty of the day-ahead market price, a robust model was constructed to obtain a robust solution; that is, when the clearing price was within the estimated price information gap, the solution ensured that the expected goal was not worse than the preset target.

(c) This method incorporates the physical bilateral effects of the contract into day-ahead market bidding, which coordinates BC fulfillment and the day-ahead market bidding in STHS and provides greater benefits to power generation enterprises.

The model proposed in this paper provides a practical reference for cascade hydropower to participate in the newly reformed electricity market in China. However, with the deepening of the market reform and the demand for advanced dispatching, future research should consider a more comprehensive market structure and more uncertainty factors, such as auxiliary service market and uncertainty inflow to further improve the application value of the model. We will consider the above factors in follow-up research.

Figure 4. (a) Alpha vs profit under different beta. (b) Robust region of electricity price fluctuation. (c) Histogram of the profit. (d) Comparison of model effects under different contract decomposition modes.
Data availability

The data that support the findings of this study are available upon reasonable request from the authors.

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Credit authorship contribution statement

Xuguang Yu: methodology, software, visualization, Writing—original draft. Gang Li: conceptualization, validation, Writing—review and editing, funding acquisition. Yapeng Li: data curation, formal analysis, investigation. Chuntian Cheng: supervision, funding acquisition.

Conflict of interest

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

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