Feasible Paths for Small Hydropower Participation in Electricity Market Trading in Sichuan Province Under Seasonal Inflow Constraints

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Abstract—*Sichuan Province boasts abundant small hydropower (SHP) resources, but its operational revenue has continued to decline in recent years, facing dual pressures from seasonal inflow constraints and the acceleration of electricity market reform. This paper takes Sichuan's SHP as the research object and systematically analyzes its feasible paths for participating in electricity market trading under seasonal inflow constraints. First, it sorts out the resource distribution and output characteristics of Sichuan's SHP, as well as the main trading varieties and rule systems for SHP. Second, it dissects the main problems under the current model from three dimensions: deviation settlement mechanism, wet-dry price structure, and policy environment changes. Third, it designs three types of trading paths—medium- and long-term (MLT) contracts as the mainstay, incremental participation in spot/grid agency power purchase during the wet season, and contract energy transfer during the dry season—and provides differentiated selection suggestions from three dimensions: installed capacity, regulation capacity, and inflow forecasting. The research shows that the three paths can be used in combination to form a strategic framework of "basic contracts + marginal increments + risk transfer". Run-of-river (ROR) power plants without regulation capacity should focus on using contract transfer to hedge under-generation risks; daily regulation power plants have intraday price spread arbitrage capabilities; annual regulation power plants can achieve strategic arbitrage. A dynamic switching mechanism based on inflow forecasting (increasing contract proportion in wet years and initiating transfer in advance in dry years) helps improve annual revenue stability. This paper provides operable market trading strategy references for Sichuan SHP owners and theoretical basis for policymakers to improve market rules adapted to SHP characteristics.*

Index Terms—*Sichuan Small Hydropower, Seasonal Inflow, Electricity Market Trading, Feasible Paths, Medium- and Long-Term Contracts, Spot Market, Contract Transfer.*

I. CURRENT SITUATION OF SICHUAN SMALL HYDROPOWER AND ELECTRICITY MARKET

A. SHP Resources and Inflow Characteristics

The distribution of SHP resources in Sichuan Province shows significant regional concentration characteristics. From the administrative region perspective, the prefecture-level cities (autonomous prefectures) with the top installed capacity are mainly concentrated in the upper reaches of rivers in western and southwestern Sichuan. As shown in Table 1, the total installed SHP capacity in Ya'an City, Liangshan Yi Autonomous Prefecture, Aba Tibetan and Qiang Autonomous Prefecture, and Ganzi Tibetan Autonomous Prefecture accounts for 65.9% of the province's total, forming the core distribution belt of Sichuan's SHP. Among them, Ya'an City ranks first in the province with an installed capacity of 1.544 million kilowatts, accounting for 22.5%; Liangshan Prefecture follows closely with an installed capacity of 1.386 million kilowatts, accounting for 20.2%. The two cities (prefectures together account for more than 40% of the province's total. In terms of the number of power stations, Ya'an City and Liangshan Prefecture have 516 and 487 SHP stations respectively, with an average single-station capacity of about 0.30 million kilowatts, showing the typical characteristics of "large number and small single station". In addition to the above core areas, Mianyang, Leshan, Yibin, Luzhou and other cities also have a considerable scale of SHP resources. From the overall provincial perspective, the total installed SHP capacity in Sichuan is about 6.86 million kilowatts, with a total of 2, 355 power stations and an average single-station capacity of only 0.29 million kilowatts. In terms of regulation capacity, the vast majority are ROR power plants, and those with daily regulation or above capacity account for less than 15%, which determines that SHP output is highly dependent on natural inflow.

Table 1 Statistics of SHP Installed Capacity by Prefecture-level City in Sichuan Province

Prefecture-level City (Autonomous Prefecture)	SHP Installed Capacity (10, 000 kW)	Proportion of Provincial SHP (%)	Number of Power Stations
Ya'an City	154.4	22.5	516
Liangshan Yi Autonomous Prefecture	138.6	20.2	487
Aba Tibetan and Qiang Autonomous Prefecture	89.3	13.0	312
Ganzi Tibetan Autonomous Prefecture	71.5	10.4	198
Leshan City	58.2	8.5	203
Mianyang City	42.7	6.2	167
Yibin City	31.4	4.6	98
Luzhou City	28.9	4.2	87
Other Prefecture-level Cities	71.0	10.4	287
Provincial Total	686.0	100	2355

The output fluctuation of Sichuan's SHP has a highly positive correlation with seasonal inflow. The hydrological characteristics of major rivers in the province show a typical pattern of "distinct wet and dry seasons", and the output coefficient of SHP changes periodically with the inflow rhythm. As shown in Table 2, the wet season is from June to October every year, with an inflow coefficient as high as 0.70-0.75, that is, the inflow in these 5 months accounts for more than 70% of the whole year. During this period, SHP can maintain full or near-full generation, with an output coefficient of 0.85-0.95, but also faces prominent water abandonment pressure. The flat water season is May and November, with the inflow coefficient dropping to 0.12-0.15 and the output coefficient correspondingly falling to 0.60-0.75, and the unit utilization rate decreases significantly. The dry season is from December to April of the following year, with an inflow coefficient of only 0.10-0.15, that is, the total inflow in 5 months is less than 15% of the whole year. During this period, the output coefficient of ROR SHP is only 0.30-0.50, and a large number of units are in idle or inefficient operation. This output fluctuation caused by seasonal inflow—from near-full generation in the wet season to less than half in the dry season—is the core constraint that SHP must face when participating in electricity market trading. The output coefficients in Table 2 are typical operation data for ROR power plants, and power plants with regulation capacity can smooth fluctuations to a certain extent.

Table 2 Inflow Coefficient and Output Coefficient in Wet/Flat/Dry Seasons

Period	Months	Inflow Coefficient (Annual = 1)	Output Coefficient (Rated Output = 1)	Typical Characteristic Description
Wet Season	June-October	0.70-0.75	0.85-0.95	Abundant inflow but water abandonment pressure
Flat Season	May, November	0.12-0.15	0.60-0.75	Inflow declines, unit utilization rate decreases
Dry Season	December-April (next year)	0.10-0.15	0.30-0.50	Severe inflow shortage, large number of units idle or inefficient operation

B. Electricity Trading Varieties for SHP

After multiple rounds of reform and institutional iteration, Sichuan's electricity market is currently in a critical stage of transformation from "medium- and long-term dominated" to "medium- and long-term and spot market integration". In September 2025, Sichuan officially launched the spot trial operation medium- and long-term connection trading, marking that the provincial electricity medium- and long-term market has officially entered a new model of "time-segmented organization and D-2 continuous trading" connected to the spot market. In the same year, the Sichuan Provincial Development and Reform Commission, Energy Bureau, and Energy Regulatory Office jointly issued the Sichuan Electricity Spot Market Construction Plan (Draft for Comments), proposing to establish an electricity spot market system under the new model of "multi-power source participation, full electricity optimization, and full water season operation". Against this background, the trading varieties for SHP have expanded from traditional medium- and long-term contracts to a diversified framework covering medium- and long-term, spot, contract transfer, and ancillary services. The following subdivides various trading varieties and their time-series characteristics in combination with the latest rules (as of the end of 2025).

1) Medium- and Long-Term Electric Energy Trading

Medium- and long-term trading is the basic channel for SHP to participate in the market. According to the Overall Plan for Sichuan Provincial Electricity Market Trading in 2025, electricity wholesale trading varieties include: conventional direct purchase, abandoned hydropower consumption, green electricity trading, new energy storage trading, virtual power plant trading, grid agency power purchase market-based trading, contract energy transfer trading, etc. Among them, the varieties directly related to SHP are as follows:

Conventional Direct Purchase Trading: The most important source of contract energy for SHP. Trading is conducted on an annual, monthly, and intra-monthly basis, and the electricity quantity and price are determined through bilateral negotiation, centralized bidding, or listing. Under the 2025 rules, water season price limits are set for electric energy trading except green electricity trading: the upper limit in the wet season is 211.43 yuan/MWh, the upper limit in the flat season is 333.84 yuan/MWh, and the upper limit in the dry season is 415.63 yuan/MWh. This "low in wet season and high in dry season" price limit structure matches the seasonal output characteristics of hydropower.

Abandoned Hydropower Consumption Trading: A special variety specially designed for surplus hydropower in the wet season. This trading aims to promote the market-based consumption of abandoned hydropower in the wet season, and the upper limit of the trading price is determined by floating the original hydropower benchmark electricity price in the wet season, that is, 211.43 yuan/MWh. For ROR SHP with higher-than-expected inflow, this variety provides a channel for electricity consumption beyond medium- and long-term contracts, but the price level is significantly lower than the contract price in the dry season.

Guaranteed SHP Electricity: Inherits part of the planned attributes. According to Sichuan Electricity Spot Market Rules V2.0, guaranteed SHP electricity is decomposed by grid enterprises according to the typical load curve of industrial and commercial users by month. This part of electricity enjoys a relatively priority settlement order and has the function of a "ballast stone" for stable revenue during the transition period of SHP marketization.

2) Spot Market Trading

The Sichuan Electricity Spot Market (V2.0) is the core content of the 2025 rule iteration. According to the Sichuan Electricity Spot Market Trading Implementation Rules (V2.0 Draft for Comments), the spot market organization structure is determined as "day-ahead pre-clearing without settlement, intraday full-time rolling optimization, and real-time clearing and settlement".

Day-ahead Market Stage: Based on market boundaries such as declaration information, forecast information, and constraint information of operating entities, centralized optimization calculation is carried out using Security-Constrained Unit Commitment (SCUC) and Security-Constrained Economic Dispatch (SCED) algorithms, and the unit combination, power generation output curve, and time-of-use electricity price for the operation day are obtained through clearing. However, the day-ahead market clearing result is only used as a reference for the next day's power generation operation arrangement and is not used for settlement.

Intraday Rolling Optimization Stage: According to changes in market boundaries, rolling optimization is carried out on reservoir operation and unit combination for the remaining periods of the operation day to provide a reference for real-time market clearing.

Real-time Market Stage: Based on the real-time latest boundary conditions and the sealed declaration information of operating entities before the day-ahead market, the real-time market power generation output curve and time-of-use electricity price are obtained through rolling clearing using the SCED algorithm, which is used for real-time production scheduling and market settlement.

For SHP, the participation method in the spot market is "quantity and price declaration"—directly dispatched hydropower by the provincial dispatch center participates in the spot market by declaring quantity and price. This means that SHP needs to declare the next day's power generation output curve and quotation in advance, and the market forms a time-of-use nodal electricity price through system-wide optimization clearing. Due to the limited output forecasting accuracy of ROR SHP, this mechanism puts forward high requirements for its bidding strategy.

3) Spot Market Connected Medium- and Long-Term Trading

This is a brand-new trading model launched in September 2025 and a key institutional innovation for the connection between medium- and long-term and spot markets. Under the new model, power generation enterprises, electricity sales companies, and wholesale users can carry out medium- and long-term trading for 24 periods per day from Day D to Day D+2 on Day D-2 (2 days before trading). The trading target is the medium- and long-term contract energy for 24 periods per day from 2 to 4 days in the future, which realizes seamless connection with the D-1 day-ahead spot and D-day real-time spot trading.

The trading types under this model include:

Electric Energy Increment Trading: Increase the medium- and long-term contract energy for future periods;

Electric Energy Decrement Trading: Reduce the held medium- and long-term contract energy for future periods;

Contract Energy Transfer Trading: Transfer the rights and obligations of contracts to other market entities.

The core value of this model is that SHP can flexibly adjust the medium- and long-term contract positions according to short-term inflow forecasts (2-4 day window), making the contract curve closer to the actual output, thereby reducing deviation assessment losses. For ROR power plants with limited forecasting accuracy, this "short-cycle, multi-period" trading design significantly improves strategic flexibility.

4) Ancillary Service Market

At present, Sichuan Province has clearly stated that after the continuous settlement trial operation of the spot market, the provincial peak shaving ancillary service market will no longer operate, and ancillary services such as frequency regulation and reserve will be jointly optimized and cleared with the spot market. As a flexible resource, SHP can obtain additional revenue by providing frequency regulation, reserve and other services in the ancillary service market. However, due to the limited output regulation capacity of ROR SHP, the feasibility of its participation in ancillary services needs to be evaluated in combination with the regulation performance of specific power plants.

5) Settlement Mechanism

All electricity in the Sichuan electricity wholesale market is settled at the spot market price, and medium- and long-term contracts are settled on a price difference basis. The spot market adopts a "daily clearing and monthly settlement" settlement model: daily clearing calculation is carried out according to market clearing and execution results, and settlement basis is issued on a natural month basis for electricity fee settlement. The power generation side takes 1 hour as the settlement period.

For SHP, the core settlement formula is:

$$\text{Final Revenue} = \text{MLT Contract Energy} \times \text{Contract Price} + \text{Deviation Energy} \times \text{Spot Price}$$

Among them, the "take-or-pay, deviation settlement" principle means that the positive deviation (over-generation) between actual power generation and contract energy is settled at a lower price, and the negative deviation (under-generation) needs to be purchased at a higher price to make up. This asymmetric mechanism is the fundamental institutional constraint driving SHP to optimize trading strategies.

Table 3 Tradable Electricity Market Varieties and Time-series Characteristics for SHP

Trading Variety	Sub-type	Trading Time Scale	Pricing Mechanism	Core Function	SHP Applicability
Medium- and Long-Term Electric Energy Trading	Conventional Direct Purchase	Annual/Monthly/Intra-monthly	Bilateral negotiation/centralized bidding/listing	Lock basic revenue	Main channel, dependent on inflow forecasting
	Abandoned Hydropower Consumption	Wet season monthly/intra-monthly	Centralized bidding, wet season price limit	Consume surplus electricity in wet season	Suitable for over-generated electricity
	Guaranteed SHP Electricity	Annual decomposition	Decomposition according to typical curve	Ballast stone for stable revenue	Transitional guarantee variety
Spot Market	Day-ahead Market	Day-ahead pre-clearing	Quantity and price declaration, SCUC/SCED clearing	Form next day operation plan	No settlement, only reference
	Intraday Rolling	Intraday full-time	Rolling optimization	Revise day-ahead plan	Provide reference for real-

Trading Variety	Sub-type	Trading Time Scale	Pricing Mechanism	Core Function	SHP Applicability
	Optimization				time market
	Real-time Market	Real-time	Quantity and price declaration, SCED clearing	Actual production scheduling and settlement	Core settlement basis
Spot Connected Medium- and Long-Term	Increment/Decrement/ Contract Transfer	D-2 day (2 days before trading)	Bilateral/centralized, 24-period continuous trading	Flexibly adjust contract positions	Core innovative variety, suitable for short-cycle forecasting
Ancillary Service Market	Frequency Regulation/Reserve	Joint clearing with spot	Quantity and price declaration	Obtain additional service revenue	Requires regulation capacity support

C. Main Problems Under the Current Model

SHP faces three structural dilemmas under the current electricity market rules. First, the deviation settlement mechanism imposes asymmetric penalties on ROR power plants—over-generated electricity is settled at a decreasing coefficient discount, while under-generated electricity needs to be made up at a higher price, and low inflow forecasting accuracy makes it difficult to avoid contract execution deviations. Second, the water season price limit shows the characteristic of "low in wet season and high in dry season". About 70% of the annual electricity is released in the wet season with the lowest electricity price, while the output is limited in the dry season despite high electricity prices. The asymmetric distribution of "quantity increase with price decrease" and "quantity decrease with price increase" further compresses the overall revenue space. Third, policies such as self-supply zone reform and environmental protection clearance are accelerating, and SHP faces dual institutional pressures of "full market entry" and "partial exit". Coupled with the frequent iteration of spot market rules, the uncertainty of the operating environment has increased significantly. The superposition of these three constraints puts SHP owners in a passive position in the marketization transformation, and it is urgent to design differentiated trading paths adapted to seasonal inflow characteristics.

II. FEASIBLE TRADING PATHS FOR SHP UNDER SEASONAL CONSTRAINTS

A. Path 1: Medium- and Long-Term Contracts as the Mainstay

Medium- and long-term contracts are the basic trading tool for SHP to participate in the market and the most mature and widely applicable path at this stage. The core logic of this path is: according to inflow forecasting, pre-lock the contract electricity price of most expected electricity in the annual, monthly, and intra-monthly markets, so as to hedge spot price fluctuation risks and ensure the stability of basic revenue. For SHP with relatively stable inflow laws and basic forecasting capabilities, medium- and long-term contracts are a "ballast stone" trading strategy.

At the operational level, this path needs to be dynamically adjusted in combination with wet and dry season characteristics. In the wet season (June-October), inflow is abundant but the electricity price is at the annual low level. SHP should first ensure that the contract energy can cover 85%-95% of the expected power generation to avoid triggering low-rate penalties in deviation settlement due to over-generation; at the same time, an appropriate 5%-15% electricity space can be reserved for participating in abandoned hydropower consumption trading or the spot market to capture marginal revenue. In the flat season (May, November), inflow declines and the electricity price is moderate. The contract signing proportion can be appropriately reduced to 70%-85%, retaining more electricity to game in the spot market in the hope of obtaining time-of-use revenue higher than the contract price. In the dry season (December-April next year), the output is seriously insufficient, and the core risk is "under-generation" rather than "over-generation". Therefore, the contract signing proportion should be controlled at 60%-75% of the expected output, leaving a buffer space for the actual power generation lower than expected due to dry inflow, and avoiding being forced to purchase electricity at a high price to make up the contract during the high price period. The differentiated signing strategies for different seasons can be summarized as shown in Table 4.

The applicable conditions of this path are relatively clear: the power plant has relatively reliable historical inflow data and short-term forecasting capabilities; the owner has certain judgment ability on the price trend of the medium- and long-term market; the power plant has a moderate scale and can independently complete annual and monthly trading declarations. Its main advantages are relatively simple operation, controllable transaction costs, and guaranteed basic revenue; the disadvantage is that it may miss part of the spot high-price revenue due to conservative signing in the wet season, and still need to bear the deviation risk caused by inflow uncertainty in the dry season.

Table 4 Suggestions on Monthly Medium- and Long-Term Contract Signing Proportions

Period	Months	Contract Signing Proportion (of Expected Power Generation)	Strategy Points
Wet Season	June-October	85%-95%	High proportion signing
Flat Season	May, November	70%-85%	Moderately reduce signing proportion
Dry Season	December-April (next year)	60%-75%	Low proportion signing, buffer for insufficient inflow, prevent high-price electricity purchase to make up

B. Path 2: Incremental Participation in Spot/Grid Agency Power Purchase in the Wet Season

The core logic of Path 2 is: in the wet season, taking advantage of the characteristic that the marginal cost of SHP approaches zero, the "incremental" electricity beyond the coverage of medium- and long-term contracts (that is, the over-generated electricity beyond the contract part) is actively invested in the spot market or grid agency power purchase channels to obtain marginal revenue. This path is not a substitute for medium- and long-term contracts but a supplement to them—that is, on the premise of maintaining the basic contract position, the surplus electricity that is difficult to accurately predict in the wet season is consumed at a premium through market-based methods to reduce water abandonment losses.

In practice, the key to this path lies in the identification and pricing of "increments". SHP owners first need to determine a relatively conservative basic contract energy based on inflow forecasting (such as the 85%-90% contract proportion in the wet season in Table 4), which is used to lock stable revenue. For the over-generated electricity that may occur beyond the forecast, do not rush to sign high-proportion contracts in advance, but flexibly declare in the D-2 day 24-period continuous trading window or the day-ahead market. According to Sichuan electricity market rules, power generation enterprises can participate in spot clearing in the day-ahead market by "declaring quantity and price", and the real-time market clearing price will reflect the system supply and demand marginal conditions. During the peak load period in the wet season (such as evening), the spot price may be significantly higher than the wet season price limit of medium- and long-term contracts (211.43 yuan/MWh), and the incremental electricity can obtain excess revenue at this time; while in the valley period, even if the spot price is low, since the variable cost of SHP is extremely low, it can still cover the short-term marginal cost. In addition, grid agency power purchase is also one of the outlets for incremental electricity—when the spot market price is not ideal, SHP can choose to consume incremental electricity through the grid agency power purchase channel, with a relatively stable price, but the revenue ceiling is lower than the peak period of the spot market.

The implementation of this path requires the following conditions: first, having short-term (2-4 days) inflow forecasting capability to judge the possible scale of incremental electricity; second, having the operational capability to participate in D-2 day or day-ahead market declarations, and being able to flexibly adjust the quantity and price declaration strategy according to the forecast results; third, being able to bear certain spot price fluctuation risks, because the spot price in some periods of the wet season may be lower than the contract price. The main advantage of this path is that it can fully tap the marginal revenue potential in the wet season, reduce water abandonment losses, and improve the overall annual revenue level; the disadvantage is that it has high requirements for the owner's market prediction ability and declaration operation ability, and the uncertainty of spot prices will bring additional revenue fluctuations. Table 5 gives suggestions on incremental electricity strategies under different spot price scenarios in the wet season.

Table 5 Strategy Selection for Incremental Electricity Participation in Spot/Grid Agency Power Purchase in the Wet Season

Spot Price Scenario	Price Level (yuan/MWh)	Recommended Strategy	Expected Effect
High Price	> Wet season price limit (211.43)	Incremental electricity fully participates in the spot market	Obtain excess marginal revenue
Medium Price	180-211.43	Partially participate in spot, partially go through grid agency power purchase	Balance revenue and risk
Low Price	< 180	Prioritize grid agency power purchase or abandon declaration	Avoid low-price settlement losses

C. Path 3: Contract Energy Transfer in the Dry Season

The core logic of Path 3 is: in the case of severe inflow shortage in the dry season and the actual output is likely to be lower than the contract energy, part or all of the medium- and long-term contract rights and obligations are transferred to other market entities in advance through the contract energy transfer market, so as to avoid the high-price electricity purchase to make up risk caused by "under-generation". The essence of this path is a risk pre-management tool—actively reduce contract exposure before the deviation actually occurs, rather than passively accept punitive settlement afterwards.

In specific operation, this path is usually dynamically implemented before the dry season (i.e., October-November) and during the dry season operation. At the annual or monthly contract signing stage, SHP owners should actively control the dry season contract signing proportion, as described in Table 4, to 60%-75% of the expected output, which itself is a primary risk mitigation measure. However, due to the interannual variability of dry season inflow, the actual output may be further lower than expected. At this time, the owner can transfer part or all of the unexecuted dry season contract energy to other market entities in the D-2 day 24-period continuous trading window or the intra-monthly contract transfer market—usually thermal power, large hydropower, or new energy power plants with surplus electricity, which can better perform the contract due to relatively stable output or regulation capacity. The transfer price is determined through bilateral negotiation, usually at a discount based on the original contract price, and the discount rate reflects the performance cost borne by the transferee. Although the transfer will bring a certain price difference loss (for example, transferring at 90%-95% of the original contract price), this cost is significantly lower than the loss of being forced to purchase electricity to make up at 1.1 times or even 1.5 times the average price due to under-generation.

The implementation of this path requires the following conditions: first, the power plant owner needs to have medium-term (monthly) inflow trend judgment ability to predict whether it is necessary to start contract transfer before the dry season begins; second, being familiar with the operation process and time window of the contract energy transfer market; third, establishing a stable information docking channel with potential transferees to quickly complete the transfer transaction when needed. The main advantage of this path is that it can effectively lock the lower limit of revenue in the dry season and avoid the dilemma of "less power generation, more money loss" caused by dry inflow; the disadvantage is that contract transfer will produce a certain price difference loss, and if the inflow situation is better than expected (actual power generation is close to or reaches the contract quantity), early transfer will lead to opportunity loss.

Therefore, this path needs to be combined with dynamic monitoring and phased operation. It is not advisable to transfer all at once, but to make decisions in batches according to rolling inflow forecasts. Table 6 gives the decision framework for dry season contract transfer.

Table 6 Decision Framework for Dry Season Contract Energy Transfer

Inflow Forecast Scenario	Contract Holding Proportion (Relative to Forecast Output)	Transfer Strategy	Expected Effect
Severe dry inflow (high probability)	60%-75% → 30%-40%	Transfer 40%-50% of contract energy in advance	Significantly reduce under-generation risk exposure
Normal inflow (baseline scenario)	60%-75%	Maintain original position, dynamic monitoring	Balance bottom line and game
Better-than-expected inflow (low probability)	60%-75% → 75%-85%	Reverse increase contracts or reduce transfer	Capture additional revenue opportunities

D. Comprehensive Comparison of Paths

The above three trading paths are aimed at different seasonal characteristics and risk exposures, and each has differentiated applicable scenarios, operation logic, and revenue-risk characteristics. Path 1 (medium- and long-term contracts as the mainstay) is a full-time basic strategy, applicable to all types of SHP. Its core function is to lock basic revenue and hedge spot fluctuation risks. Its advantages are simple operation and low transaction costs, while its disadvantage is insufficient flexibility and possible missed high-price opportunities in the spot market. Path 2 (incremental participation in spot/grid agency power purchase in the wet season) is a supplementary strategy for over-generated electricity in the wet season, applicable to power plants with short-term forecasting capabilities and market declaration capabilities. Its core logic is to use the advantage of near-zero marginal cost to obtain excess revenue from the spot market and reduce water abandonment losses, but it requires the owner to bear certain spot price fluctuations. Path 3 (contract energy transfer in the dry season) is a hedging strategy for under-generation risk in the dry season, applicable to ROR power plants with high output forecasting uncertainty. It is essentially a risk pre-management tool, exchanging a small loss of discount transfer for avoiding large losses of high-price electricity purchase to make up, but may produce opportunity losses due to better-than-expected inflow.

From a practical operation perspective, the three paths are not mutually exclusive but a strategy toolbox that can be used in combination. A complete annual trading strategy should be: taking Path 1 as the annual basic framework, dynamically adjusting the monthly contract signing proportion; on this basis, enabling Path 2 in the wet season to flexibly put over-generated electricity into spot or grid agency power purchase channels; enabling Path 3 in the dry season to dynamically reduce contract exposure according to inflow forecasts. This combined strategy of "basic contracts + marginal increments + risk transfer" can achieve a systematic balance between revenue and risk under seasonal inflow constraints. Table 7 comprehensively compares the core characteristics of the three paths.

Table 7 Comprehensive Comparison of the Three Trading Paths

Comparison Dimension	Path 1: Medium- and Long-Term Contracts	Path 2: Wet Season Incremental Spot/Grid Agency Power Purchase	Path 3: Dry Season Contract Transfer
Applicable Season	Whole year	Wet season (June-October)	Dry season (December-April next year)
Core Function	Lock basic revenue, hedge spot fluctuations	Tap marginal revenue, reduce water abandonment	Avoid under-generation risk, prevent high-price make-up
Operation Logic	High proportion signing, reserve a small amount of elasticity	Flexible declaration of increments after short-term forecasting	Transfer contracts in advance after inflow prediction
Forecasting Capability Requirement	Medium- and long-term trend judgment	Short-term (2-4 days) accurate forecasting	Medium-term (monthly) trend judgment

III. CASE ANALYSIS

After completing the description of the extreme high temperature scenario, it is necessary to further characterize the operation of the combined cooling, heating and power microgrid from the perspective of optimal scheduling.

A. Path Selection Based on Installed Capacity

The installed capacity of SHP directly affects its market participation ability and transaction cost structure, and thus forms significant differences in path selection. From the actual situation of Sichuan's SHP, power plants can be divided into three categories: micro and small power plants (below 10, 000 kW), medium-sized power plants (10, 000-50, 000 kW), and power plant clusters with basin scheduling capabilities. Different scale levels correspond to different strategic logics.

Micro and small power plants (installed capacity < 10, 000 kW) account for more than 70% of Sichuan's SHP in number. Their core characteristics are small single-station capacity, scattered distribution, and limited human and technical resources. For such power plants, the transaction cost of independently participating in medium- and long-term and spot markets is too high—including declaration operation, data management, deviation accounting and other links require full-time personnel, and the annual revenue scale of the power plant is difficult to cover the corresponding costs. Therefore, the optimal path is not to pursue refined trading strategies but to take reducing participation costs as the primary goal. Specifically: first, rely on the guaranteed SHP electricity share as much as possible, and use the settlement mechanism decomposed by grid enterprises according to typical curves to reduce the frequency of independent trading; second, adopt a "follow strategy" in medium- and long-term contract signing, refer to the average signing level of power plants in the same basin or adjacent areas, and avoid deviation penalties caused by independent forecasting errors; third, take grid agency power purchase as the main outlet for incremental electricity in the wet season, rather than directly participating in spot declaration. Contract energy transfer has a high operation threshold for such power plants and can be temporarily not taken as a key strategy. In general, the strategic core of micro and small power plants is "simplified operation, passive following, and cost reduction".

Medium-sized power plants (installed capacity 10, 000-50, 000 kW) have relatively sufficient personnel and technical conditions and can independently complete market declaration, data tracking, and strategy adjustment. Such power plants are the main applicable objects of the three trading paths. In the annual strategy, Path 1 (medium- and long-term contracts as the mainstay) should be taken as the annual basic framework, and the contract proportion should be dynamically adjusted according to wet and dry seasons; enable Path 2 in the wet season, use short-term inflow forecasting to declare incremental electricity to participate in the spot market and tap excess revenue; pay attention to Path 3 in the dry season, predict the contract completion rate according to the medium-term inflow trend, and start contract transfer in a timely manner. Medium-sized power plants should establish basic inflow forecasting capabilities—at least being able to obtain meteorological and hydrological forecast data for the next 2-4 days in the basin where they are located, and make declaration decisions accordingly. In terms of organizational structure, it is recommended to equip at least 1-2 full-time traders responsible for market tracking, report filling, and strategy implementation.

Power plant clusters with basin scheduling capabilities are a special type of Sichuan's SHP, usually controlled by the same entity with multi-stage cascade power plants on the same river, with a total installed capacity of 50, 000-100, 000 kW or even higher. The core advantage of such entities is that they can use the output complementarity between different power plants in the basin to smooth the overall output fluctuation through cascade optimal scheduling and improve contract execution accuracy. Studies have shown that under cascade hydropower scheduling, the deviation rate of each station can be controlled at a low level. For such entities, all three paths can be fully utilized, and there is room for further optimization: first, adopt the method of "total quantity control and sub-station decomposition" in medium- and long-term contract signing, and use the overall contract to buffer single-station deviations; second, in the wet season, combine basin inflow forecasting to declare spot electricity in cascade; third, in the dry season, conduct internal contract adjustment between different power plants to reduce the demand for external transfer. In addition, such entities have the potential to participate in the ancillary service market and can obtain additional revenue by providing frequency regulation, reserve and other services using cascade regulation capabilities. Table 8 summarizes the path selection suggestions under different installed capacities for reference by various SHP owners.

Table 8 Path Selection Suggestions for Different Installed Capacities

Installed Capacity	Typical Characteristics	Recommended Path Combination	Core Strategy Points
Micro and small power plants (< 10, 000 kW)	Large number, small single station, limited resources	Mainly guaranteed electricity + grid agency power purchase outlet	Simplified operation, passive following, reduce transaction costs
Medium-sized power plants (10, 000-50, 000 kW)	Have basic operation capabilities	Path 1 as the basis + Path 2/3 enabled opportunistically	Establish forecasting capabilities, dynamically adjust contract proportion
Basin clusters (total of multiple stations > 50, 000 kW)	Cascade scheduling available, smooth fluctuations	Full use of three paths + internal adjustment	Total quantity control, sub-station decomposition, explore ancillary services

B. Path Selection Based on Regulation Capacity

The regulation capacity of SHP is the core technical parameter that determines its output flexibility and market adaptability. According to the difference in reservoir regulation performance, SHP can be divided into three categories: no regulation (ROR), daily regulation, and annual regulation (or seasonal regulation). Power plants with different regulation capacities have essential differences in feasible paths and operation space when coping with seasonal inflow fluctuations and implementing market-based trading strategies.

No regulation (ROR) power plants are the main body of Sichuan's SHP, accounting for more than 85%. Such power plants have no water storage capacity and "generate electricity according to the available water", with output completely subject to the natural runoff process. In market-based trading, the core dilemma faced by ROR power plants is: contract energy needs to be signed in advance, but the actual output can only passively follow the inflow. This mismatch between "rigid contracts" and "flexible output" is the fundamental source of deviation penalty risks. For ROR power plants, the core of the trading strategy is not "optimizing output" (because it cannot be actively regulated) but "optimizing the contract curve to fit the forecast output as much as possible". Specifically: in Path 1 (medium- and long-term contracts as the mainstay), the conservative signing proportion suggested in Table 4 of this paper should be adopted, especially controlling the contract proportion in the dry season at 60%-75% to leave buffer space for dry inflow; in Path 2 (wet season incremental spot), flexibly declare incremental electricity in the D-2 day window based on short-term inflow forecasts, and it is not advisable to lock wet season contracts too much in advance; in Path 3 (dry season contract transfer), it should be focused on using, because ROR power plants have the highest under-generation risk in the dry season, and transferring contracts in advance is the most effective hedging method. ROR power plants should not participate in the ancillary service market because they lack active regulation capacity and cannot meet technical requirements such as frequency regulation and reserve.

Daily regulation power plants have a certain scale of daily regulation reservoir capacity, which can store part of the water in the wet period of the day and release it for power generation during the peak load period. Although this capacity is not enough to change the overall output pattern between wet and dry seasons, it provides limited regulation elasticity on the intraday time scale. For daily regulation power plants, their market participation ability is significantly improved compared with ROR power plants: first, a relatively active contract signing proportion can be adopted in Path 1 (can float near the upper limit suggested in Table 4), because daily regulation capacity helps reduce intraday output deviations; second, they have stronger spot game capabilities in Path 2—daily regulation power plants can arrange more power generation during peak load and high electricity price periods, thereby obtaining intraday price spread revenue; third, they have preliminary participation conditions in the ancillary service market and can provide part of frequency regulation services. It should be pointed out that daily regulation capacity can only smooth intraday fluctuations and cannot solve the problem of uneven output between wet and dry seasons, so there is no essential difference from ROR power plants in the dry season contract transfer strategy.

Annual regulation (or seasonal regulation) power plants account for an extremely low proportion in Sichuan's SHP, usually large-scale power plants or basin leading reservoirs. Such power plants have cross-seasonal water storage capacity, which can store part of the water in the wet season for use in the dry season, thereby actively adjusting the output timing on an annual scale. This capacity fundamentally changes the logic of SHP participation in the market: no longer "passively adapting" to seasonal inflow, but "actively allocating" annual power generation. In terms of path selection, the strategic space of annual regulation power plants is significantly expanded: first, in Path 1, the constraint of conservative signing can be broken, and the dry season contract proportion can be increased to more than 85% to lock high-price revenue; second, in Path 2, they can strategically participate in the spot market, use water storage capacity to reduce power generation when the spot price is low and increase power generation when the price is high, realizing arbitrage operation of "generate more when price is high, generate less when price is low"; third, the demand for contract transfer in Path 3 is greatly reduced, because they have their own regulation capacity to perform contracts; in addition, such power plants are ideal providers of ancillary services and can obtain considerable additional revenue through frequency regulation, reserve, etc. It should be emphasized that annual regulation capacity is extremely scarce in Sichuan's SHP, and the suggestions in Table 9 are mainly for the few power plants with this condition.

Table 9 Path Combination Suggestions for Different Regulation Capacities

Regulation Capacity	Path 1	Path 2	Path 3	Ancillary Services
No regulation (ROR)	Conservative signing (lower limit of Table 4), passively follow inflow	Flexible declaration of increments after short-term forecasting	Focus on using, transfer in advance to avoid under-generation risk	Not available
Daily regulation	Relatively active (upper limit of Table 4), smooth intraday deviations	Capture intraday peak-valley price spreads, optimize power generation periods	Similar to ROR, still need to pay attention to dry season risks	Preliminary available, can try frequency regulation
Annual/seasonal regulation	Break conservative constraints, high proportion signing in dry season	Strategic arbitrage, generate more when price is high, generate less when price is low	Demand greatly reduced, mainly internal adjustment	Both frequency regulation and reserve available

C. Dynamic Switching Strategy Based on Inflow Forecasting

The above path selection based on installed capacity and regulation capacity provides a strategic positioning from a static perspective, but in actual operation, SHP also needs to face interannual inflow uncertainty—the hydrological conditions of wet years, flat years, and dry years are significantly different, and the same power plant should adopt differentiated trading strategies under different hydrological year types. Therefore, establishing a dynamic switching mechanism based on inflow forecasting is the key to improving annual revenue stability.

The core logic of dynamic switching is: before the start of the wet season every year (usually April-May), according to the seasonal precipitation forecast issued by meteorological and hydrological departments, upstream inflow trend analysis, and historical hydrological statistical data, make a prediction of the hydrological year type of the current year (wet year/flat year/dry year), and adjust the trading strategy parameters of each stage of the whole year accordingly. As the operation progresses, the prediction can be revised according to the actual inflow situation in the middle of the wet season (July-August), and short-term inflow changes can be continuously tracked in the D-2 day window to form a three-level dynamic decision-making system of "annual tone setting, monthly revision, and short-term fine-tuning".

In the wet year scenario, the annual inflow is generally abundant, the water abandonment pressure in the wet season increases, but the output situation in the dry season is expected to improve. Strategically, the contract signing proportion in the wet season should be appropriately increased (from 85%-95% to the upper limit of 90%-95%), because over-generated electricity faces a lower settlement rate, and locking contracts in advance is more beneficial; at the same time, the contract proportion in the dry season can be appropriately increased (from 60%-75% to 70%-80%), using the expectation of improved dry season inflow in wet years to strive for a higher proportion of high-price revenue. The incremental spot participation strategy of Path 2 can be more active, but it should be noted that the spot price in wet years may be suppressed due to abundant supply. The demand for contract transfer in Path 3 is relatively reduced in wet years.

In the flat year scenario, the inflow conditions are close to the multi-year average level, and the baseline strategy given in Table 4 can be implemented with moderate elasticity.

In the dry year scenario, the annual inflow is generally dry, the output in the wet season is limited, and the output in the dry season is seriously insufficient. Strategically, the contract signing proportion in the wet season should be appropriately reduced (from 85%-95% to 80%-90%) to avoid high-price electricity purchase to make up due to insufficient inflow; more importantly, the dry season contract proportion should be significantly reduced (from 60%-75% to 50%-65%), and the contract transfer operation of Path 3 should be started in advance, transferring part of the contracts before the dry season (October-November). The incremental participation space of Path 2 is limited because there is less over-generated electricity itself; while Path 3 should be upgraded to the core strategy and run through the entire dry season.

Table 10 Path Switching Rules Under Wet/Flat/Dry Year Scenarios

Hydrological Year Type	Wet Season Contract Proportion Adjustment	Dry Season Contract Proportion Adjustment	Path 2 Strategy	Path 3 Strategy
Wet Year	Increase to 90%-95% (upper limit)	Increase to 70%-80%	Active incremental participation, but pay attention to price suppression	Reduced demand, less transfer
Flat Year	Implement according to baseline 85%-95%	Implement according to baseline 60%-75%	Regular implementation	Regular implementation
Dry Year	Decrease to 80%-90% (lower limit)	Decrease to 50%-65%	Limited incremental space	Core strategy, start transfer in advance

IV. CONCLUSION

This paper takes Sichuan's SHP as the research object, focuses on the core technical characteristic of seasonal inflow constraints, and systematically analyzes the feasible paths for SHP participation in electricity market trading. Sichuan's SHP has the overall characteristics of large installed capacity, concentrated distribution, high proportion of ROR power plants, and weak regulation capacity. Its output fluctuation has a highly positive correlation with seasonal inflow—concentrated inflow in the wet season leads to water abandonment pressure, while insufficient inflow in the dry season causes unit idleness. At the same time, Sichuan's electricity market is in an accelerated transformation stage from "medium- and long-term dominated" to "medium- and long-term and spot market integration". The deviation settlement mechanism, wet-dry price limit structure, and the gradual advancement of the spot market together constitute the external institutional environment for SHP participation in the market. Under the dual squeezes of "hydrological constraints" and "institutional transformation", the traditional "guaranteed quantity and price" operation model of SHP is no longer sustainable.

In response to the above dilemmas, this paper designs three types of trading paths: Path 1 (medium- and long-term contracts as the mainstay) serves as the annual basic strategy, locking basic revenue through differentiated seasonal signing proportions; Path 2 (incremental participation in spot/grid agency power purchase in the wet season) uses the advantage of near-zero marginal cost of SHP to tap excess revenue and reduce water abandonment losses; Path 3 (contract energy transfer in the dry season) avoids the high-price electricity purchase to make up risk caused by under-generation by transferring contracts in advance. The three paths can be used in combination to form a complete strategic framework of "basic contracts + marginal increments + risk transfer".

In terms of path selection, this paper provides differentiated suggestions from three dimensions: installed capacity, regulation capacity, and inflow forecasting. Micro and small power plants should take simplifying operations and reducing costs as the primary goal; medium-sized power plants are the main applicable objects of the three paths; basin clusters can further explore internal adjustment and ancillary services. No regulation (ROR) power plants should focus on using Path 3 to hedge under-generation risks; daily regulation power plants have intraday price spread arbitrage capabilities; annual regulation power plants can achieve strategic arbitrage. In addition, establishing a dynamic switching mechanism based on inflow forecasting—increasing contract proportion in wet years and initiating contract transfer in advance in dry years—helps further improve the stability of annual revenue.

From the policy and practical perspective, the research conclusions of this paper have the following implications for Sichuan SHP owners and policymakers. For SHP owners, they should select an appropriate combination of trading paths according to their own installed capacity, regulation capacity, and technical conditions, and especially attach importance to establishing basic inflow forecasting capabilities and market tracking mechanisms to avoid unnecessary deviation losses due to information lag or improper operation. For policymakers, it is advisable to set appropriate exemption thresholds or buffer clauses in the deviation assessment mechanism in view of the particularity of ROR SHP to reduce the institutional threshold for their participation in the market; at the same time, continue to improve spot connection mechanisms such as D-2 day 24-period continuous trading to provide SHP with more flexible contract adjustment tools and help them achieve a smoother marketization transformation under seasonal inflow constraints.

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