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Reform and renewables in China: The architecture of Yunnan's hydropower dominated electricity market

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ABSTRACT

Reforms currently under way in China's electricity markets bear important implications for its decarbonization objectives. The southwestern province of Yunnan is among the provinces piloting the current iteration of power market reforms. As such, lessons from Yunnan will inform future market reform and renewable energy policies in China and potentially elsewhere. The dominance of hydropower in Yunnan's energy portfolio and the particular transmission constraints it faces, offer an interesting case study of the challenges of decarbonization. We report on market architecture reforms and aggregate market data collected from the Yunnan Power Exchange. We review four elements in the reformed market architecture. Market pricing rules, transitional quantity controls, the generation rights market, and inter-provincial trade. The specifics of market reform reflect a compromise between decarbonization, inter-provincial competition, grid security and development objectives and contribute to understanding of how the dual transitions of hydropower decarbonization and market liberalization interact. We conclude on six insights regarding the role of the grid operator, security checks on trade, integration of cascade hydropower, the inclusion of renewables in the generation rights market, price controls, and market participant price uncertainty.

1. Introduction

Energy conservation and emissions reduction in China is both a domestic need as well as part of the country's commitment to the international community [1]. This is particularly important in the Chinese power industry. Since the economic reforms of the 1980's, China has enjoyed rapid economic growth, urbanization, and poverty alleviation. These transformations have been supported by rapid growth in electricity generation and consumption [2]. The cumulative installed power generation capacity of China reached 1.519 Terawatts by the end of 2015, ranking it number one globally and accounting for about 23% of the world's total installed capacity [3]. Coal-based thermal power accounts for nearly 65.9% of China's installed power generation capacity. The power industry is responsible for 57.9% of total carbon emissions and 34.6% of total sulfur emissions [4]. As a result, seven of the 10 most polluted cities in the world are in China [5].

In order to move to a low carbon economy, development of clean and renewable energy has become part of national policy. The country boasts the largest installed renewables capacity and has taken a leading role in international climate negotiations [6–8]. In the last two decades, China saw rapid development of its hydropower capacity, rising from 20 GW in 1980 to 330 GW in 2016. An increase of more than 16 fold. Hydropower is the largest source of renewable energy in China, accounting for 20.9% of China's installed capacity [9].

Deploying renewable energy has a set of generic issues; intermittency, interconnection, energy storage, peaking capacity, and

Abbreviations: OECD, Organization for Economic Cooperation and Development; TWh, Terawatt Hours; GWh, Gigawatt Hours; SPCC, State Power Corporation of China; SGCC, State Grid Corporation of China; CSG, China Southern Power Grid; NDRC, National Development and Reform Commission; SERC, State Electricity Regulatory Commission; YNPX, Yunnan Power Exchange; YNPG, Yunnan Power Grid; RMB, *Renminbi* (Yuan) Official Currency of the PRC; PRC, People's Republic of China; EOEC, Ex-ante Obligatory-use Electricity Contract; MTQ, Minimum Trade Quantity; UHV, Ultra-High Voltage; DOP, Difference of Prices

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stranded assets amongst others [10–12]. Although renewables deployment is happening rapidly, a key issue highlighted by the State Council in its 2015 *Opinions on Further Deepening the Reform of the Electric Power Systems: Document No. 9* is that the usage of that renewable capacity is not keeping up [13]. In northern China, rapid wind capacity deployment meant that at one point, as much as one third of wind capacity was not connected to the grid and that the capacity factor for China's wind power in 2006 and 2007 was 0.16 (compared to OECD members achieving 0.2–0.3) [14,15]. Inefficiencies also occurred in the rapid deployment of hydropower. Due to poor energy planning, lagging power grid construction, falling demand, and gaming between different interests, hydropower generation in southwest China was curtailed by more than 25 TWh in 2015 [16]. In 2016, 28.7 TWh of hydropower was wasted in Sichuan alone [17]. Officially published values for abandoned water and energy spillage exceed 60 TWh [18]. In Yunnan, it has been reported that wasted hydropower grew from 5 TWh in 2013 to 31 TWh in 2016 [19]. Wasted clean and renewable energy is a serious problem for China's hydropower, one which partly motivates electricity market reform, namely promoting hydropower consumption via the establishment of intra- and inter-provincial markets.

In the complex framework of China's power system and the specifics of Yunnan's oversupplied hydro-dominated electricity portfolio, the building of electricity market faces many challenges. The literature on China's policies promoting renewable energy is rich and lively. One area of interest is that of dispatch reform and its role in better utilization of renewable resources [20–23]. Other contributions have evaluated the effectiveness of feed-in-tariffs and renewable portfolio standards among other mechanisms implementing renewable energy legislation [24]. These are largely considered successful but not always well integrated with economic reforms in electricity [25,26]. Among very recent contributions, one investigated the effect market reform has on the utilization of distributed renewables and found institutional barriers exit to employing market flexibility potentially required for decarbonization and the adoption of intermittent generation [27].

This paper examines the effectiveness of power market reforms in China's Yunnan Province for efficient use of hydropower to facilitate the attainment of the country's decarbonization objectives. We begin with brief reviews of the theory of market reform and the history of China's electricity markets to highlight salient factors in market reform and then turn to examine Yunnan's electricity market architecture in detail. We report aggregate data from the first year of trading on the Yunnan Power Exchange (YNPX) trading platform [28] highlighting four salient reforms to market architecture: 1) Pricing mechanisms and controls; 2) Transitional quantity controls; 3). Tradable generation rights; and 4) Interprovincial trade. This paper illustrates how market reform interacts with decarbonization and other objectives in the case of the architecture employed in Yunnan's market reform trial. How quickly and efficiently renewables are adopted will depend on the specifics of market reforms and the mechanisms these employ to that end [27]. We show how Yunnan's market rules are locally adapted to suit Yunnan's particularities (hydro-dominated supply, oversupply, and stagnant consumption growth). Finally, we show how the choice of market rules involves a balancing of interests which does not always create the circumstances most suited to renewables deployment and conclude on six potential areas for further reform.

2. Theories of market reform and its architecture

To reflect on market reform in China generally, and in Yunnan specifically, it is worth reviewing theoretical and practical issues in electricity market reform. Free market advocates argue central planners lack information needed for efficient resource allocation [29]. Instead, the argument goes, market prices send appropriate signals about profitable investment which ultimately fulfil social needs efficiently. Proponents of central planning might respond that the market does not reflect all necessary information either. Commensuration of all values under a monetary unit of account results in strategic, social, or environmental needs remaining unaccounted for. Under central planning competing needs are considered in their own valuation (be it physical quantities or otherwise) and planners allocate resources to meet these needs as far as possible [30]. When markets fail, vertical integration, regulation or government control can be more appropriate [31,32].

The choice between markets and planning is one of deciding which transactions happen under which institutions [33]. Questioning the sources of transaction costs can inform this decision for any given transaction. The first question is whether investment is required in assets specific to the participants in the transaction. Given asset specificity, parties to the transaction become mutually dependent for the efficient use of this asset. This issue is related to market-failure under monopoly which emerges when consumers of a product or service do not have a substitute or alternative producer to switch to [34–36]. The monopolist can then use this power to push prices over costs and generate monopolistic profits. The incentive for abusing this dependence to extract additional rents from the counter-party generates a transaction cost and makes a spot market an inappropriate structure for the transaction. A second question is that of the social cost of a market approach. If substantial safeguards are deemed imperative for protecting against costly market adjustments, then regulation and control is required and neither a spot market nor long-term contracting are efficient [33].

A monopoly occurs in electric utilities where a single power distribution infrastructure is required (e.g., in a city or urban district) which makes competition impossible [37,38]. In the case of network-level electricity markets, trade in electricity does not require a specific investment as there are typically multiple buyers and sellers in the market. However, investment in a transmission network does. The grid cannot supply anyone other than the connected buyers and sellers. Likewise, generators and consumers are dependent on the grid operator for market access. Instead of spot markets, procurement of network infrastructure is done through long-term contracts, strict regulation, or direct ownership and control [39].

Transitions from planning to electricity markets suffer from issues of market power, particularly in regulating the transmission network [38,40–42]. A "textbook architecture" for competitive electricity markets recognizes competition will not be possible in transmission [38]. Firms owning transmission networks must therefore be separated (or "unbundled") from generation and retail. If not, they could give preferential treatment to their generators or otherwise exploit their control over transmission. The architecture therefore envisages independent regulators mandated to set charges grid users pay to trade on the network which the grid operator receives. Regulators must pressure operators to offer an efficient service while being sufficiently capitalized for investments needed in grid expansion, improvement and maintenance [36,37,43]. The regulator must be independent so as to not be influenced by either consumers, producers, or the grid operator as each may seek to influence pricing and regulation in their favor.

3. History of electricity reform in China

Different eras have been identified in the history of China's power sector reforms. A recent study considers 6 periods since the founding of the People's Republic of China, identifying decarbonization as a contemporary strategic objective which does not sit comfortably alongside existing development and reform objectives [1]. Older reviews focused on the reforms after the initial market opening in the mid 1980's, and found another distinct period after the 2002 reforms [44–47]. The most recent reforms are marked by the 2015 issuance of Document 9 by the State Council [48]. Although the history of power market reform in China has already been covered in detail in these historical accounts, it is worth highlighting recurring themes relevant to Yunnan's efforts at market reform.

One issue is that of decentralization. During the 1980's central government responded to power shortages by reducing its control over electricity planning, allowing provincial governments to make investment decisions [44,49–51]. These reforms raised capital and relieved power shortages but newly empowered provinces sought to protect local investments through barriers to inter-provincial trade while independent generators were still disadvantaged relative to state companies [49]. This decentralized approach to capacity expansion was contentious because of ensuing incoherent planning but has remained in place under Document 9 [13]. This relates also to renewables deployment which Document 9 states should be promoted, noting however that further utilization of renewable electricity through inter-provincial trade is encouraged but will happen under the guidance of local governments [13,48]. While other rules have been established to promote renewable energy, institutional barriers remain in practice.

Another recurring issue is that of market power. Sector governance was revamped between 1997 and 1998 as part of a broader reorientation towards a socialist market economy. The Ministry of Electric Power, was dissolved and its functions and personnel were transferred to the newly established State Power Corporation of China (SPCC). Corporatization did not however promote competition [41,49]. Between 1998 and 2000, the SPCC in fact replaced or incorporated all regional power companies and all provincial power companies [44,52]. This failure of the 1997 reforms constituted one of the core objectives of reforms in 2002 [44,53]. The SPCC was then broken into 2 grid companies (the State Grid Corporation of China (SGCC) and the China Southern Power Grid (CSG)) as well as 5 generating groups. Today, distributors are largely still subsidiaries of the grid and Document 9 states that further unbundling will happen gradually [54]. Document 9 quite explicitly recognizes the competing issues of grid stability and market opening and makes no illusion about the relatively limited degree of free competition to be pursued under the 13th Five-Year Plan (2016–2020), pushing instead for a gradual and orderly transition from plan to market [13].

Previous reform trials suffered from problems in both decentralization and market power. In 1999, the SPCC and its regulator selected 6 provinces for transmission unbundling and market liberalization trials but local generators were still sheltered from competition by the SPCC and the following year the State Council suspended these trials [44]. Between 2003 and 2006, markets trials in the Northeast China power pool and by the CSG were all ultimately called off due to difficulties in integrating pre-existing regulated contracts with the new market contracts and a lack of clarity over market rules and the bidding process [50]. Plans for further trials on the North China and Central China grids were also aborted. On the Central China grid this was due to large quantities of hydropower, differences in government set prices and tariffs across provinces, and other institutional difficulties [50]. The SGCC established an exchange center in 2006 as part of these reform trials [44]. The regulators were however uninformed about this and there was subsequent criticism that the establishment of market exchanges directly under grid control allowed it to set market rules and retain de facto control over generators. In 2013, a new set of provinces (including Yunnan) were selected for market reform trials which began in 2015 [44,50].

A third issue recurring in China's electricity reform is regulatory independence. As part of the 1997 reforms, the National Development and Reform Commission (NDRC) took over central economic planning, including setting prices for projects and furthering the reform agenda [44]. The State Electricity Regulatory Commission (SERC) was also established as the sector regulator, although it was initially under-resourced and too closely related to the SGCC to regulate independently [44,49,52]. Earlier reviews and Document 9 all highlight that regulatory independence remains an important issue [13,22,49,50]. Prices for transmission and distribution continue to be determined by the NDRC after negotiation with the grid operator. The NDRC is also tasked with setting wholesale and retail electricity prices as well as transmission charges and so faces a balancing act between competing interests along the value chain.

Document 9 sees electricity prices increasingly being set by markets between generators and large consumers, although public services and other targeted sectors will remain under NDRC prices. Document 9 highlights that NDRC prices often lag behind changes in costs and that planned prices do not reflect all relevant factors adequately [13]. Market price mechanisms are then to be explored but not single-mindedly pushed through. Safety and stability, as well as the ongoing need to expand electricity access in rural regions remain paramount. As we turn to the provincial level in Yunnan we will see these issues reappear but with important local challenges to the process of reform and the pursuit of decarbonization.

4. Yunnan's hydropower dominated electricity

4.1. Yunnan's electricity fundamentals

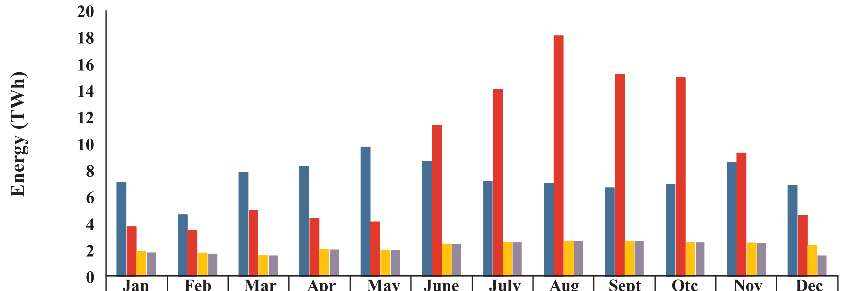
Yunnan's electricity market is dominated by large hydropower capacity and falling provincial consumption leading to falling hydropower utilization rates. Market reforms seek to promote hydropower consumption through the introduction of a pricing mechanism, quantity controls and tradable generation rights, as well as market-based inter-provincial trade.

Yunnan has a population of 47.4 million and is located in southwestern China sharing international borders with Vietnam, Laos, and Myanmar [55]. The altitude difference between the highest point in Yunnan and the lowest is more than 6000 m and average annual precipitation is more than 1100 mm. The Jinsha River (upper Yangtze River), Lancang River (upper Mekong River), Nu River (upper Salween River) are the main rivers flowing through Yunnan, providing massive hydropower resources which are typically developed in a mix of large and small hydropower facilities cascaded along these and other rivers [16].

Yunnan's annual power consumption in 2015 was 143.8 TWh and generation was 255.3 TWh, with an average annual generation capacity growth rate of 25.5% reaching 61 GW by the end of 2016. Hydropower accounted for 73% of Yunnan's total capacity and 81% of annual generation (another 15% of generation comes from thermal) [56]. The remainder comes from wind and other renewables. If all 61 GW were running throughout the year, only 42% of hydropower capacity would be required to meet Yunnan's annual consumption. Overcapacity can also be seen in the fact that cumulative installed generation capacity in Yunnan accounts for 5.3% of the national total, while the gross power consumption accounts for just 2.8% of the national total [9]. The rapid development of hydropower has meant that oversupply is increasingly a problem. In rainy years and even in some years with average rainfall, provincial demand can be met by hydropower alone.

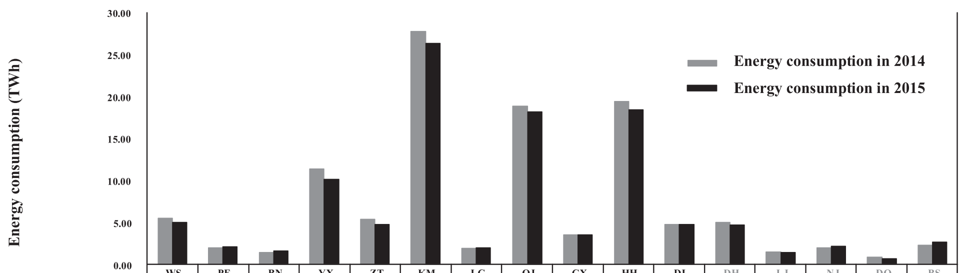
Fig. 1 shows aggregated data from the YNPX in its first year of trading (2015) where 'market supply' refers to the quantity suppliers offered on the market, 'market demand' refers to buyer bids, and 'market cleared' refers the quantity actually traded on the market. We show market data as compared to the quantities mandated under planned generation ('non-market'). Clearly, supply is substantially larger than market demand throughout the year. During the summer months, market supply substantially outstrips even the quantities of planned generation.

Oversupply is further exacerbated due to low economic growth in Yunnan. Compared with the fast development of power supply, electricity demand growth in the province has been slower than expected. Annual growth in power consumption peaked at 19.92% in 2011, but in 2015 was at − 9%. Low growth in electricity consumption is largely due to lower than expected GDP growth which at 8%, was substantially lower than the projected 11% [9]. Large consumers in Yunnan are mainly energy-intensive companies, such as electrolytic aluminum, yellow phosphorus and ferroalloy producers. The NDRC set retail prices relatively high for some of these producers and consequently some have



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Otc	Nov	Dec
non-market	7.079	4.645	7.808	8.23	9.698	8.604	7.155	6.981	6.668	6.934	8.531	6.864
market supply	3.714	3.482	4.945	4.383	4.1	11.325	14.028	18.114	15.155	14.956	9.227	4.607
market demand	1.864	1.73	1.578	1.995	1.974	2.425	2.545	2.63	2.62	2.542	2.518	2.33
market cleared	1.757	1.667	1.528	1.984	1.969	2.419	2.541	2.627	2.617	2.539	2.501	1.545

Fig. 1. Quantity of supplier and consumer bids and electricity cleared in Yunnan's market in 2015 (data from YNPX trading platform) as compared with planned supply quantities ('non-market') [57].



	WS	PE	BN	YX	ZT	KM	LC	QJ	CX	HH	DL	DH	LJ	NJ	DQ	BS
Energy consumption in 2014	5.51	2.01	1.45	11.40	5.40	27.75	1.94	18.83	3.52	19.41	4.80	5.04	1.50	1.97	0.85	2.31
Energy consumption in 2015	5.03	2.12	1.61	10.15	4.81	26.31	2.00	18.18	3.53	18.44	4.79	4.73	1.41	2.19	0.69	2.68
Annual growth rate	-8.77	5.62	10.81	-11.01	-11.00	-5.20	3.23	-3.42	0.29	-5.02	-0.21	-6.21	-6.21	11.48	-19.20	15.87

Fig. 2. Energy consumption comparison of each prefecture in Yunnan (data from YNPG [59]). Values in grey belong to prefectures not participating in the market.

reduced production. The fact that market prices can be lower and would thereby spur industrial growth is among the motivating factors for the Yunnan government and grid to pursue market reform.

Power consumption in Yunnan's 16 prefectures is depicted in Fig. 2 with the 5 prefectures that did not participate in the market having their values shown in grey. It should be noted that Yunnan itself has a fragmented power grid where some prefectures have semi-autonomous grids, relying on small scale hydropower for electrification [20,58]. Baoshan (BS) is isolated from the YNPG and did not participate in the market. Since we use aggregated data from the Yunnan Power Exchange (YNPX), we cannot distinguish between producers by size, however voltage criteria (Section 4.2), mean it is unlikely any small scale hydropower participated in the market. Other non-participating prefectures were Dehong (DH), Nujiang (NJ), Diqing (DQ), which are all autonomous prefectures, and Lijiang (LJ).

Levels and type of industrialization are different in each prefecture, so the market has different effects on consumption in each. Puer (PE) and Banna (BN) showed an annual electricity consumption growth rate of over 5%, mainly because they are not highly industrialized and further development is driving consumption growth. In Lincang (LC) and Chuxiong (CX), the annual growth rate was also positive. Negative annual electricity consumption growth rates were observed in Wenshan (WS), Qujing (QJ), Honghe (HH), Dali (DL) and the provincial capital Kunming (KM). Yuxi (YX) and Zhaotong (ZT) had annual growth rates lower than − 10%. Overall, larger prefectures all saw a contraction and only the smaller prefectures saw rising electricity consumption. Concern about a slowing Chinese economy and a contraction in demand for industrial outputs meant lower market prices did not offset the reduction in Yunnan's producers' electricity consumption.

Thermal power is nearer provincial load centers than hydropower and plays an important role in stable operation of the power grid. In the dry season, thermal power is still important as a guaranteed supplier and its continued operation remains an objective like elsewhere [60]. However, with hydropower oversupply, utilization of thermal capacity has dropped and thermal generators are losing the revenue needed to finance their role in peaking and the dry season.

Due to the over-supply of hydropower and the lack of demand, many hydropower stations are having to release water without generating electricity, which is known as "spilling" [13,55]. Two way to mitigate this problem are: 1) the further development of market mechanisms to encourage more efficient use of these resources, 2) the further development of the inter-provincial transmission network in order for some of this over-supply to be sold to eastern load centers such as Guangdong, Zhejiang or others, as part of the West to East Electricity Transfer Project.

4.2. Market architecture

Yunnan's electricity market opened for trading on the 1st of January 2015. The Yunnan government stated that the market promotes mutual development, energy security, market-pricing and social stability [57,61]. Yunnan's electricity market is a monthly market with no real-time balancing market, no ancillary services or reserves market but a market in generation rights (comparable to a capacity market) has been established.

The market architecture was designated the 3–1-3–4 System (see Fig. 3). This designation stands for the fact there are 3 types of participants, 1 power exchange, 3 markets, and 4 trading mechanisms. In addition to buyers and sellers, the YNPG participates by operating the grid and performing security checks on market transactions. The three markets are provincial, inter-provincial, and generation rights markets. The 4 mechanisms are: bilateral trading, pool-based trading, listing, and finally, government determination.

Market participation does not extend to all producers and consumers. Only industrial consumers who meet national industrial, energy efficiency, and emission reduction requirements can buy electricity in the market from generators. Sellers are limited to only thermal plants with a voltage of 220 kV or above and hydropower plants of 220 kV or above who opened after 2004. This means that typically only large generators are allowed to participate in the market. This also

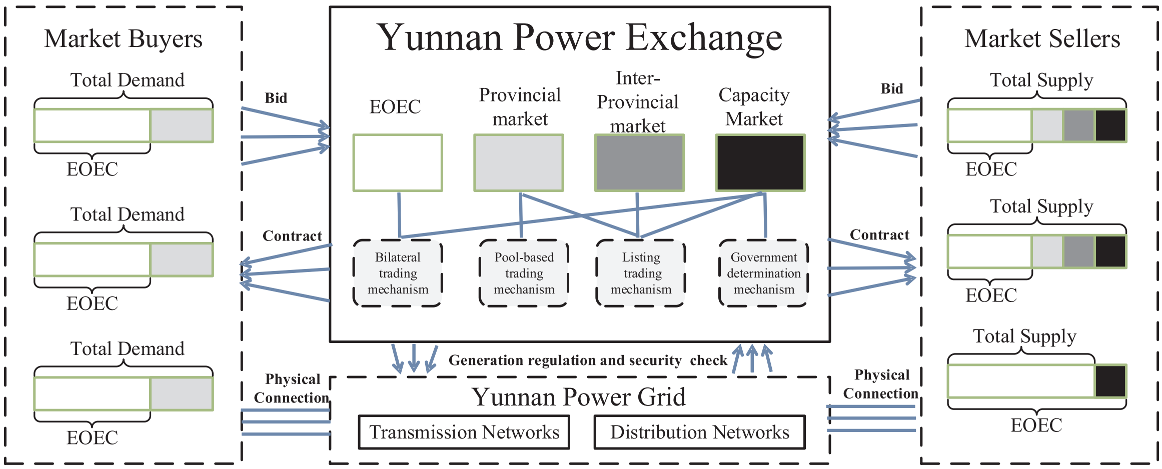


Fig. 3. Yunnan's 3-1-3–4 market system as adapted from [57]. Three participant types are in the left, bottom and right boxes, with the mechanisms of trading in the middle for the different markets. Ex-ante Obligatory-use Electricity Contracts (EOECs) are transitional quantity controls (see Section 4.4).

means that, not all of the cascaded hydropower along a river will be eligible to participate in the market. All other generators and consumers must still sell to and buy from the Yunnan Power Grid (YNPG) at NDRC prices. These participation conditions mean that our data do not distinguish between generators or consumers by location, state or private ownership, or any criteria other than the eligibility criteria.

Fig. 4 depicts the stages of trading, showing how each is subject to a security check. The YNPG performs this to account for line congestion on both buyer and seller side, interconnections among cascade hydropower, and the risk of spillage. The results of the security check are returned to YNPX in the form of generation quantity caps which YNPX applies as constraints to another round of bid clearing. The security check is based on technical requirements, not market factors such as cost or price. For example, if a transmission line is congested, generation is curtailed according to capacity. This means the grid retains substantial control over generation.

One of the reasons that cascade coupling remains part of the security check, is an issue of market power under supply dominated by cascade hydropower. Most of Yunnan's electricity is generated in such systems where multiple dams are built along one river [16]. The hydraulic couplings between plants mean that the output of upstream generation affects the feasible generation downstream. Release strategies upstream are commercial secrets but downstream schedules cannot be made without this information. Efficient performance of the entire cascade is likely only possible if generation is integrated under one operator [62]. Problems of competition along a cascade create incentives for anti-competitive behavior and alongside security of supply issues meant the grid and authorities preferred to remain under a relatively stringent security check [38,42].

4.3. Prices in the trading pool and listing

Electricity trading happens in at least two sequential stages which are conducted in order to ensure that all demand is cleared. The effect of this policy on the bidding strategies of buyers and sellers is unclear, particularly given the various trading systems used in successive stages and uncertainties induced by the pricing mechanism. Before trading on the structured markets, participants are free to submit contracts agreed in direct negotiations between the buyer and seller. While direct contracting provides the opportunity to reduce uncertainty, participants may be discouraged from doing so by the fact that better prices may be available in the subsequent structured stages of trading.

The first structured trading mechanism is a trading pool where buyers bid a quantity and a price-cut to their NDRC prices (the bid price equals the NDRC price minus the price-cut). Meanwhile, sellers bid a quantity and a price-cut from their NDRC price. Bid prices are then adjusted by line loss and transmission charges to give effective bid prices. Buyers and sellers are then sorted by the difference of prices (DOP) and paired if their price difference is not negative. Buyers are awarded contracts with a unit price of their bid price minus half their DOP. This means buyers get a cheaper effective price than they bid for and sellers get a higher effective price (see Appendix A for a more detail on the pricing mechanism).

The second structured stage is the listing of demand remaining from the trading pool where differences between the remaining buyers and seller bids were negative. Now, sellers offer another bid with a new quantity but the same price-cut as before. Buyers select from these bids which although above the buyer bid, are below NDRC prices. If multiple buyers select the same listing, their demanded quantity is divided between the suppliers pro-rata. Another round of security checks and constrained bid clearing follows in the same manner as in the trading pool.

Fig. 5 shows the difference between average NDRC prices and average market prices for Yunnan consumers in 2015. The difference was highest in April and May. From June to October, reservoirs must lower their water levels for flood prevention in the wet season by releasing water for generation or spilling, meaning large price-cuts in the pre-flood season.

In June 2015, YNPX implemented the *Bidding Price Floor Program* which set a price floor at 0.15RMB/kWh making any supply bids below this price void. It was lowered to 0.1 RMB/kWh in 2016, then raised again to 0.13 RMB/kWh in 2017 [57,63,64]. Usually, there are at least minor differences in price between generator bids. However, in the wet season, the price floor becomes binding and many seller bids fall to the same price so rules governing how equally priced bids are allocated between buyers become more important. In Yunnan, rationing is done by dividing the quantity demanded among generators proportionally to the quantities in the generators' bids [57]. In combination, the price floor and pro-rata rationing guarantee that producers will receive at least some contracts and that none is left without revenue. Note that the average price in Fig. 5 will still be above the price floor as some contracts will still be made above the price floor.

4.4. Transitional quantity controls

As with earlier trials, not all electricity generated or demanded was opened for market trade. In 2015, only 30% of a baseline quantity could be exchanged on the market. This restriction was called the “Ex-ante Obligatory-use Electricity Contract” (EOEC). It was reduced from 70% of the market participant's quantity to 50% in 2016 and was entirely

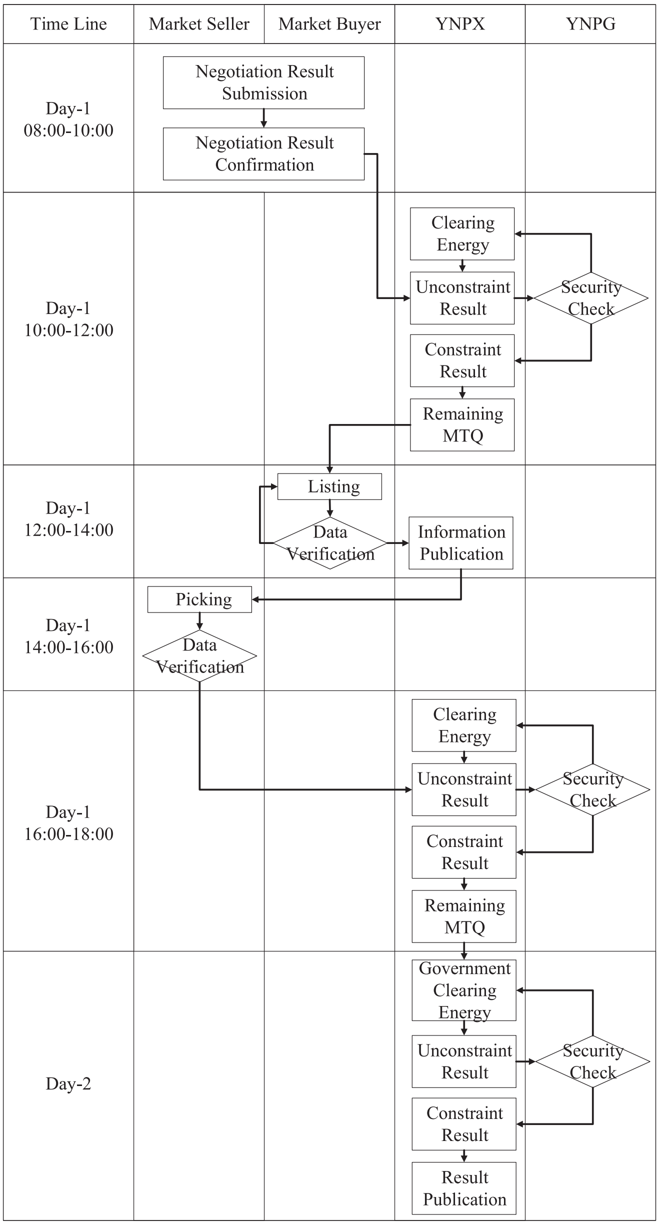


Fig. 4. Integrated framework of three-phase trading mechanism as adapted from [57].

removed in 2017. The EOEC allows a gradual relaxation of controls, smooth transition away from pre-existing contracts and ameliorates concerns over market power where participants with large market shares use this to skew market outcomes in their favor.

Buyers' EOECs were set equal to their consumption in April 2014. This was considered a reasonable minimum market share since NDRC prices are high during the dry season and consumption is generally lower. For sellers, annual EOECs were determined using the following equation:

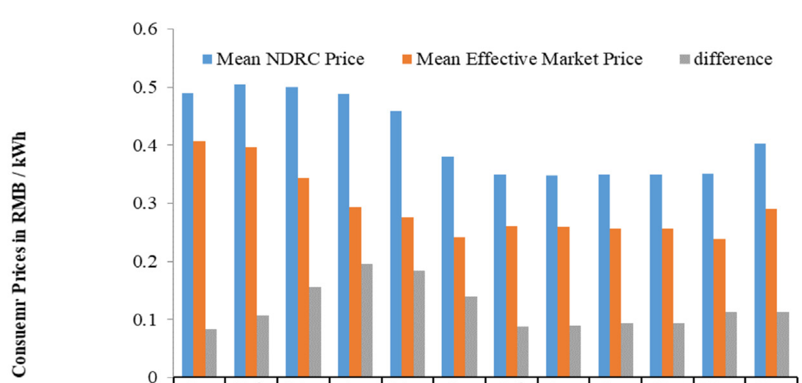
$$Q_{Obli,i} = \frac{(Q_{tsd} - Q_{rpg} - Q_{pmd})Capa_i}{\sum_{i=1}^{I} Capa_i}$$

Where $Q_{Obli,i}$ represents the annual EOEC for plant i, Q_{tsd} represents total predicted regulated demand as determined by YNPX (these are mostly public services such as hospitals, water supply, etc.). Q_{rpg} represents total generation by plants still regulated and not in the market, Q_{pmd} represents market demand as predicted by YNPX and $Capa_i$ represents nameplate capacity of plant i.

These annual EOECs were then allocated by month. Hydropower plants' annual EOECs were allocated according to the monthly generation capacity according to YNPG power system schedule optimization. The allocation of thermal plants' annual EOECs across months was based on two criteria: (1) In the flood season, absorb hydropower as much as possible and use thermal capacity for power grid stability. (2) The remaining EOEC was then allocated across other seasons according to thermal plants' installed capacity.

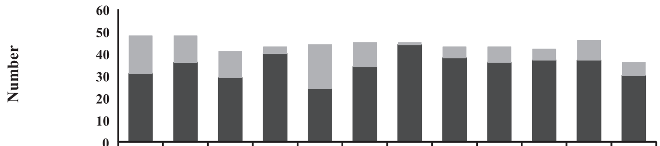
Buyer EOECs guarantee minimum market share for buyers. This can be important for small and medium sized companies which could not deter efforts by larger competitors to push up prices. For sellers, EOECs have a symmetric effect. The preponderance of hydropower creates a particular problem of market power. Hydropower has extremely low marginal costs, particularly in the summer and is able to drive out thermal capacity which is required to meet demand in the dry season [65,66]. EOECs therefore helped guarantee thermal generators' revenue for the first few years of reform.

57 generators and 7042 consumers were eligible to participate in the market but not all did. The number of sellers and buyers trading in 2015 are shown in Figs. 6 and 7 with 'cleared' indicating the number of buyers and sellers who have had their bids successfully converted to contracts and were not left without a transaction. As for market buyers, only about 12% of qualified buyers bid in the market. This is potentially due to the fact that many buyers have experienced a downturn in activity and so their demand is below their EOEC. As shown in Fig. 7, almost all demand was cleared. One reason for the outstanding demand is that as buyers do not know their counterparty in advance, and hence the costs associated with the trade, they may submit price-cuts that



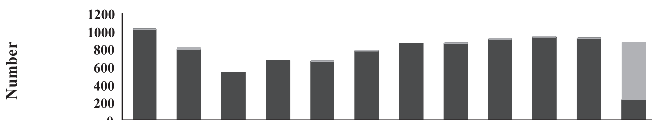
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean NDRC Price	0.49	0.504	0.5	0.489	0.459	0.381	0.349	0.348	0.349	0.349	0.351	0.403
Mean Effective Market Price	0.407	0.397	0.344	0.293	0.275	0.242	0.261	0.259	0.256	0.256	0.238	0.29
difference	0.083	0.107	0.156	0.196	0.184	0.139	0.088	0.089	0.093	0.093	0.113	0.113

Fig. 5. Consumer Electricity Prices in Yunnan in 2015 (data from YNPX trading platform).



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Otc	Nov	Dec
uncleared sellers	17	12	12	3	20	11	1	5	7	5	9	6
cleared sellers	31	36	29	40	24	34	44	38	36	37	37	30

Fig. 6. Number of market sellers by month (YNPX trading platform data).



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Otc	Nov	Dec
uncleared buyers	11	18	0	0	4	2	0	2	1	1	7	635
cleared buyers	1016	795	535	670	660	779	860	865	909	931	917	233

Fig. 7. Number of market buyers by month (YNPX trading platform data).

push them below price-floors or competitive rates. This is particularly a problem for some fertilizer producers who already have extremely low NDRC regulated prices. A small share of demand is also unmet due to transmission congestion. Based on solely participant numbers, concerns about market power are much greater on the seller side than on the buyer side as expected.

There are about 45 sellers each month, accounting for nearly 80% of qualified sellers. Sellers not participating in the market are mainly thermal generators who were unable to compete with low marginal costs of hydropower. Based on market data, we calculated the Hirschman-Herfindahl Index of power suppliers at 2125.87, indicating moderate market concentration. The greater problem of market power is the issue of cascade hydropower.

4.5. The market in generation rights

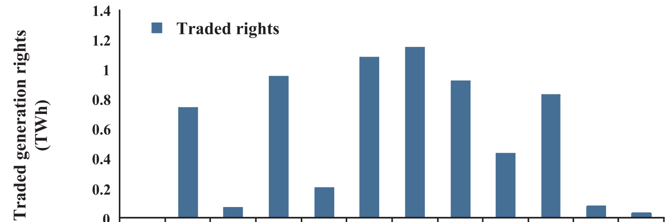
In China, generation rights markets have been trialed before where plants which used up their planned generation could purchase additional generation rights from less efficient plants [21,67]. In Yunnan, the capacity market was set up to reduce emissions cost effectively and provide thermal capacity remuneration. Thermal generators can sell their generation rights to hydropower generators and accrue revenue without emitting pollution. Thermal generators could only sell to hydropower and hydropower can only trade amongst itself.

A measure called the Minimum Trade Quantity (MTQ) was also used. MTQ's were set for each thermal plant by YNPX and these generators were then obliged to trade this quantity in the capacity market. Given all generators have EOEC's, MTQ's were taken out of these. A three-phase trade mechanism was used to guarantee fulfilment of each plant's MTQ, as shown in Fig. 4.

First, thermal plants and hydro plants are free to negotiate the trading quantity and price and submit results to the YNPX. After the security check, generation rights are exchanged. The second-phase is listing of remaining MTQs or other generation rights supplied. Hydropower plants which have idle capacity can choose to buy these and contracts are allocated by buyer's quantity bids pro rata.

The final stage comes through a determination by the Yunnan government if a thermal plant's traded rights remain below its MTQ. Its generation is divided into different blocks with different selling prices derived from the markets based on its prices across different buyers and its NDRC determined prices. Thermal capacity blocks are sorted in ascending price order and rights are sold to hydropower generators until its MTQ is fulfilled. Although the MTQ was only in place for 2015, other mechanisms still exist by which generators are obliged to trade.

Traded generation rights for each month in 2015 are shown in Fig. 8. In total, about 6.483 TWh of capacity was traded between hydropower and thermal power. With an average selling price of



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Otc	Nov	Dec
Traded rights	0	0.741	0.064	0.952	0.202	1.084	1.15	0.924	0.428	0.83	0.078	0.03

Fig. 8. Traded generation rights by month (YNPX trading platform data).

0.17RMB/kWh for generation rights, this market brought in 1.1 billion RMBs (about 117 million US dollars) in revenue for thermal power without any coal being fired and contributed to a reducing Yunnan's carbon intensity and local air-pollution. It also reduced the amount of spilled hydropower and gave thermal capacity a source of revenue.

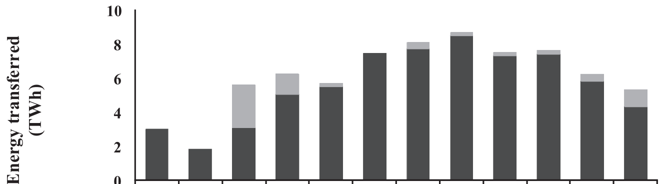
4.6. Inter-provincial trade along the southern route

The West to East Electricity Transfer Project is part of a development initiative to boost growth of the inland provinces [68]. Given that the Southern Grid is only weakly connected to other regional grids and transmission expansion plans are not in place to change this, Guangdong will likely remain Yunnan's main customer. In 2008, Yunnan's electricity ranked second cheapest with an average price of 0.24 RMB / kWh while Guangdong ranked most expensive (0.47 RMB / kWh) [51]. Inter-provincial trade then makes both economic and environmental sense as Yunnan's cheap hydropower surplus is exported to Guangdong to both reduce Guangdong's electricity costs and coal consumption. However, as inter-provincial transmission capacity has grown, the quantity traded has not necessarily kept up.

In 2015, Yunnan's interconnection with Guangdong and Guangxi consisted of 20.3 GW high voltage transmission capacity and 10 GW of ultra-high voltage (UHV) transmission capacity. Another 5 GW UHV line was completed in November 2017 [69–71], and the total transmission capacity will rise to 46 GW by the end of 13th 5-year plan (2020). In 2014, 87.7 TWh were transferred to Guangdong, accounting for nearly 40% of total generation in Yunnan and approximately 16% of Guangdong's consumption. From these values a transmission line utilization ratio of approximately 25% can be deduced. This, in addition to the further transmission capacity currently being developed, indicates that transmission capacity may not be the key constraint on inter-provincial trade.

Transmission lines are owned and operated by CSG while inter-provincial trade agreements over quantity and price involve the NDRC, CSG, and the relevant provincial governments [68]. This process seeks to balance the interests of generators, consumers, and transmission. Decision-making authority rests with the NDRC for the final say over prices but it consults with the provincial governments, respective grids and CSG. The NDRC sets CSG transmission charges, the sales price, and the buyers (primarily Guangdong) purchasing price.

Three problems face this trade. 1) While Guangdong's consumers may benefit from lower prices, producers will suffer under increased competition. It is unclear whether growth in GDP due to lower electricity prices and higher subsequent tax revenues would offset losses incurred due to local producers being outcompeted by imports from Yunnan. Additionally, the question of the displaced workforce would also be pertinent. 2) Purchasing prices resulting from the West-East agreements are not always below average Guangdong prices. Given a fixed quantity exported under the agreement, Yunnan's exported electricity does not compete in the market and faces no incentive to drive prices down. Yunnan's sale price has been increasing (at times markedly) and could thereby undermine its attractiveness to Guangdong [68]. As Guangdong becomes increasingly dependent on Yunnan's hydropower, concerns may arise about Yunnan extracting monopolistic



	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Otc	Nov	Dec
in the market	0	0	2.5	1.2	0.15	0	0.4	0.2	0.2	0.2	0.4	0.973
in the agreement	2.965	1.791	3.090	5.025	5.508	7.463	7.706	8.486	7.308	7.414	5.814	4.318

Fig. 9. Electricity transferred to Guangdong in 2015 (YNPX trading platform data).

rents from this dependence. 3) Yunnan's agreement fulfilment rate in the dry season was never above 76% during the 11th 5-year plan (2006–2011) [68]. This was driven by insufficient hydropower resources in the dry season. This uncertainty imposes an added cost on Guangdong's grid and generators who must compensate idle capacity needed as a backup for the dry season.

While the transmission agreement constitutes the largest share of inter-provincial trade, an additional quantity is traded in an inter-provincial market. Trade in the inter-provincial market uses listing. Demand in the inter-provincial market comes from Guangdong's electricity import demand beyond the transmission agreement. The only difference between inter-provincial trade and Yunnan's internal market is the determination of prices. The price-cut from NDRC prices used here is determined by negotiation between provincial governments, not by market participants.

Fig. 9 shows that about 6.223 TWh were sold to Guangdong in 2015 on the YNPX as opposed to as part of the inter-provincial agreement. This amounts to 8.51% of total transfer. This electricity would not have been transferred without the inter-provincial market and would likely have been spilled. At an average selling price of 0.25RMB/kWh, the inter-provincial market generated 1.52 billion RMBs (about 245 million USD) of revenue for generators in Yunnan. While market-based inter-provincial trade may offer environmental and economic benefits, the question of mutual trust and competition between the provinces make attaining the more difficult.

5. Areas for further reform

As Yunnan reforms its electricity sector, the central issue is the balance that must be struck between the conflicting interests of grid stability, continued thermal generation, the promotion of competition, and the reduction in renewable energy spillage. Earlier trials stalled under similar strains and it remains to be seen how further liberalization unfolds from this still strictly controlled market. The previous section reviewed how different aspects of market design were being adjusted to meet multiple objectives of reform and decarbonization. Pricing and trading stages drive demand, price floors guarantee revenue, quantity controls deal with stranded thermal assets and market power, and interregional trade improves hydropower utilization rates.

Even as Yunnan's market and others in China may not be aiming to achieve the same liberal market design, the ‘textbook architecture’ discussed initially provides a useful benchmark against which to compare Yunnan's reforms. Document 9 clearly stated that the government will retain asset ownership and that inter-regional trade will develop at the guidance of provincial governments. These aspects of market architecture, although diverging from the ‘textbook architecture’, will not be developed further here. Important remaining issues and potential reforms identified for which Document 9 left a space are the following:

- Review the role of the grid operator
- Review conditions of security checks
- Integrate cascade hydropower and use long-term contracting
- Give distributed renewables tradeable generation rights
- Promote inter-provincial trade in generation rights
- Price controls and stranded assets
- Reduce transaction costs by reducing price uncertainty due to DOP and other charges

5.1. Grid operator controls

From literature and as well as the history of China's reforms, it is clear that the ability of the grid operator to exercise market power through control over transmission is a potential barrier to reform. Under current reforms, grid operators retain key responsibilities including: owning the exchange, introducing price floors, administering security checks, determining the EOECs and MTQ's, as well as provincial and inter-provincial transmission. Demand response measures are also a grid responsibility which creates a conflict of interest and should be unbundled but Document 9 does not envisage this happening [48,72].

The EOEC and capacity market have allowed for some of these issues to be dealt with gradually and supporting an orderly transition for both liberalization and renewables deployment. Strict controls during reform came through the EOEC, MTQs and the security check. The EOECs were reduced over the course of the two years and have now been abolished. The security check however remains in place and will do so for the foreseeable future. Grid operators remain indispensable partners in transitions to renewables and market reform. Policy formulation must maintain a close relationship with the grid but move to give generators independence where feasible. Cascade hydropower dominance creates a potentially serious barrier to competition.

5.2. Review security checks

One way to further liberalize Yunnan's electricity market is by reviewing the grid's security checks. In particular, the role of security checks in managing cascade hydropower and transmission congestion. Congestion management is based on generator capacity rather than price. This problem is acute for small hydropower with low capacity often connected to smaller branches of the network with lower voltage and transmission capacity. Algorithms for curtailing production under conditions of line congestion could cut more expensive generators first. These algorithms could be reviewed by the NDRC and the SERC but remain under control of the grid in order to find a feasible transition pathway towards more efficient market solutions while still pursuing grid expansion, stability and renewables dispatch. A market in transmission rights is an alternative although this has been shown to potentially offer greater incentive for market participants with market power to manipulate markets in order to capture the scarcity rents created by a congested transmission line [64].

5.3. Cascade hydropower

In Yunnan, the preponderance of cascade hydropower systems adds a layer of complexity for power planning and grid operation hydraulic coupling is part of the security check. This can result in inefficient curtailment or allocation of water between hydropower plants. Market-oriented approaches should leave release decisions to generators and use capacity or generation rights markets to guarantee supply to the grid. Integrating along cascades and leaving operation of these to a single operator would encourage optimal release policies. It is likely that such integrated cascades would dominate the market and the issue of their market power then becomes pertinent. Such market power can be mitigated through the procurement of their services through regulated forward contracts as these reduce their incentive to manipulate the associated electricity markets [42,66]. These contracts would be concluded outside a month-by-month market, but could be implemented through the direct negotiation stage in the current trading system. Longer term contracting also has potential benefits in coordinating thermal and renewable generation [60]. The clearest way to discourage market manipulating activities by cascade operators would be to interconnect their electric grid more closely with the wider southern grid where even a large cascade cannot affect prices. This again raises the issue of inter-provincial trade.

5.4. Tradeable generation right for renewables

Yunnan reduced emissions by approximately 5.58 million tons of CO2 through the establishment of the generation rights market with hydropower buying thermal generation rights. Tradable generation rights for distributed renewables could mitigate the problem of intermittency while further reducing emissions. Intermittent generators could buy generation rights when unable to meet contracts. This however requires a day-ahead market where distributed renewables already have a high degree of certainty over generation.

Priority purchase rules for renewables have been introduced under the Renewables legislation which means grid operators look to dispatch distributed renewables as much as possible. While protected by priority rules, renewables generators bear none of the risk associated with intermittency and enjoy relatively high NDRC prices. Without that risk, renewables generators have no reason to bid in the generation rights market.

5.5. Inter-provincial trade in generation rights

In 2015 and 2016, Guangdong demand for Yunnan electricity was traded in the listing market but not in 2017. Potential benefits of interprovincial trade are hindered by mutual dependence and issues around stranded assets. Some of these issues could potentially be dealt with if a common capacity market or generation rights market existed. If Yunnan hydropower generators could purchase generation rights from Guangdong generators it would open the possibility for mutual benefit as well as further reductions in CO2 intensity while ameliorating concerns about security of supply and stranded assets. Such a market could help to raise the agreement fulfilment rates for Yunnan generators during the dry season and provide Guangdong generators with an additional source of revenue. Thermal generators in Guangdong would have the incentive of winning expensive Guangdong contracts and purchasing cheap Yunnan capacity to meet these. This would however also require allowing hydropower to buy thermal generation rights, which was not allowed previously.

Issues around potential abuse of market power in these markets would have to be explored. These could likely be dealt with by a system of supervision and monitoring shared between the governments involved in the Southern Grid. Each would have an interest in checking the other's participants and could refer cases to the NDRC or SERC for arbitration.

5.6. Price controls and stranded assets

In the wet season, as hydropower generators spill more, prices are cut further and the floor becomes binding. In combination with pro-rata rationing the price floor guarantees each producer receives at least some contracts and none is without revenue. A ‘textbook architecture’ would not support price floors arguing that while it supports existing capacity it incentivizes further development and contributes to oversupply [38]. Removing price floors on bidding would continue to sink prices to marginal costs and producers with higher marginal costs would likely be pushed out of the market. This would signal the need to stop further capacity expansion and would reward energy storage technologies. Hydropower generators have extremely low marginal costs in the wet season and would potentially even accept negative prices to reduce spillage. Some existing capacity would then no longer be profitable and may end up stranded. Most likely the price floor will remain as maintaining spills and overcapacity is less disruptive than incurring the social cost of displaced workforce and liquidation of stranded assets.

5.7. Reduce price uncertainty

It is unclear what effect the pricing mechanism has on the bidding strategies employed. Part of the reason for this is that the associated costs of a transaction are not clear to the participants in advance. Some effective bids fell below the price floor because of uncertainty as to the costs driving effective bidding price. The determination of bids must take into account several uncertainties: who will be the counter-party; what are their NDRC prices, transmission and other charges; what will be their price-cut; in which stage of trading is the best deal available. Further research is required to determine the optimal bidding strategy in this context and what the aggregate outcomes of these strategies will be. Likely these uncertainties create transaction costs making trade less attractive and outcomes less efficient. The pricing system should be simplified to reduce these uncertainties to for example, a simple unit charge adjusted periodically and tailored to the participants specific charges.

6. Conclusion

Yunnan's oversupply of hydropower and weak local demand motivate market reforms while the need for coordination of cascade hydropower and grid stability constrains market operation under the security check. Market prices are beneficial for Yunnan consumers as they can fall below NDRC prices and the pricing and market architecture are designed to boost demand. Quantity controls and the generation rights market allowed for a smoother transition from plan and existing contracts to a market trade. Generation rights and interprovincial market trade also contributed substantially to reducing emissions and reducing renewable energy wastage. Each of these areas could be further reformed to harness market efficiencies but is often challenged by institutional barriers and other risks.

The grid is best placed to understand the requirements of reliable electricity supply and is again at the forefront of both liberalization and decarbonization. Future reforms should explore how to further relax the control the grid exerts over generators. In particular, the content of the security check should be reviewed. The issue of hydropower dominance plagued earlier trials and remains an issue in Yunnan as it means the security check must be more intrusive. The use of long-term contracts with integrated cascades may be more appropriate if sufficient interprovincial market integration cannot be achieved to enable effective competition.

In Yunnan, as elsewhere, technological transition is mediated by technical and social conditions. Local interests shape both technology choices and choices over institutional arrangements. In turn, these institutions affect technology deployment and utilization. Market-oriented policy instruments exist for managing the risks to grid stability and security of supply, but liberalization requires relinquishing control and accepting the volatility of market dynamics. The potential costs are not negligible and strong commitment is required to bear these. Document 9 stated neither rapid liberalization nor re-centralization are on the menu. The preferred route entails a gradual transition to market-based resource allocation and a redoubled commitment to renewables deployment.

Acknowledgements

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Data statement

We report on aggregated data from the Yunnan Power Exchange electricity trading platform. This data is reported under the figure where it is show but original datasets are subject to commercial confidentiality requirements and are hence not publishable.

Appendix A. Technical note on the pricing mechanism

All sellers ($j \in J$) and buyers ($i \in I$) are paired into $I \times J$ pairs and differences of price (DOP) of $I \times J$ pairs are calculated by the following formulae:

$$\begin{cases} DOP_{i,j} = P_{bb,i} - P_{sb,j} - P_{trans,i} - P_{loss,j} - P_{fund,i} \\ P_{bb,i} = P_{br,i} - P_{bc,i} \\ P_{sb,j} = P_{sr,j} - P_{sc,j} \\ P_{loss,j} = P_{sr,j}\frac{\delta}{1-\delta} \end{cases}$$

Where $DOP_{i,j}$ is the price difference between market buyer i and market seller j, $P_{bb,i}$ and $P_{sb,j}$ are the bid prices for buyer i and seller j.$P_{trans,i}$ is the transmission tariff for buyer i which is set by the NDRC. Table 1 shows how these vary according to the output voltage of the seller and the month for which trading happens. $P_{loss,j}$ is the line loss for seller j, with δ being the generic line loss rate set by the NDRC at 5.24% for the YNPG. $P_{fund,i}$ is the power fund contribution fee applied to buyer i by the NDRC. $P_{br,i}$ and $P_{sr,j}$ are the prices of electricity for buyer i and seller j as determined by the NDRC.$P_{bc,i}$ and $P_{sc,j}$ are the price-cut bid by buyer i and seller j. $I \times J$ pairs are then sorted according to DOP values in descending order. Obviously, pairs with negative DOP values will enter into a contract. Pricing is shown in Fig. 10.

The selling and buying prices for financial settlement of each pair are determined based on a modified *pay-as-bid* principle which adjusts the effective prices by their DOP. The formulae below show how this is done:

$$\begin{cases} P_{buying,i,j} = P_{bb,i} - \frac{1}{2}DOP_{i,j} \\ P_{selling,i,j} = P_{sb,i} + \frac{1}{2}DOP_{i,j} \end{cases}$$

Table 1
Transmission tariffs [57].

Voltage	Transmission Tariff (January & February in 2015)	Transmission Tariff (since March 2015)
220 kV	0.086RMB/kWh	0.055RMB/kWh
110 kV	0.105RMB/kWh	0.071 RMB/kWh
35 kV and below	0.125RMB/kWh	0.086 RMB/kWh

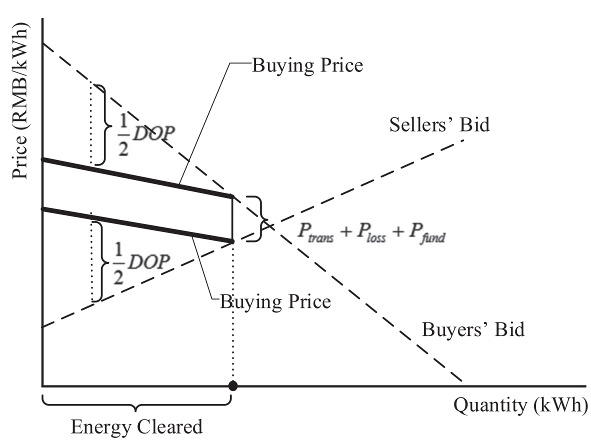

Fig. 10. Electricity clearing in Yunnan's trading pool as adapted from [57].

Table 2
Hypothetical Bids by 2 Buyers and 2 Sellers.

Market Participant	On-grid Price/price of electricity (RMB/kWh)	Bidding Price-cut (RMB/kWh)	Bidding Demand (10^4kWh)	Transmission Tariff (RMB/kWh)	Government Funds Tariff (RMB/kWh)
SA	0.282	0.03	880	–	–
SB	0.324	0.09	6000	–	–
BA	0.541	0.12	7133	0.055	0.0495
BB	0.555	0.11	4200	0.071	0.0495

Table 3
DOP Calculation for Hypothetical Bids.

Pair	Seller Bid Price (RMB/kWh)	Buy Bid Price (RMB/kWh)	Line Loss (RMB/kWh)	DOP (RMB/kWh)
SA-BA	0.252	0.421	0.01559	0.04891
SA-BB	0.252	0.445	0.01559	0.05691
SB-BA	0.234	0.421	0.01792	0.06458
SB-BB	0.234	0.445	0.01792	0.07258

Table 4
Effective Price Determination for Hypothetical Bids.

Pair	Energy Cleared (10^4kWh)	DOP (RMB/kWh)	Selling Price (RMB/kWh)	Buying Price (RMB/kWh)
SB-BB	4200	0.07258	0.40871	0.27029
SB-BA	1800	0.06458	0.38871	0.26629
SA-BB	0	0.05691	–	–
SA-BA	880	0.04891	0.39655	0.27645

Where $P_{buying,i,j}$ represents the effective price paid by buyer i for seller j's contract. $P_{selling,i,j}$ represents the effective price seller j receives for a contract with buyer i. To illustrate, we assume that there are two sellers (SA, SB) and two buyers (BA, BB) in the market. Their hypothetical bids are shown in Table 2.

During clearing, each seller is paired with each buyer, and DOPs are calculated for these pairs. They are then sorted by DOP values in descending order. As shown in Table 3, the SB-BB pair has the biggest DOP (0.07258 RMB/kWh) and the SA-BA pair has the smallest DOP (0.04891 RMB/kWh), so electricity is cleared in the SB-BB pair and the SA-BA pair and their prices are given by the formula mentioned above. The process data are shown in Tables 3 and 4.

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