China's Booming Hydropower: Systems Modeling Challenges and Opportunities

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China has been experiencing an unprecedented hydropower boom since 2000. By the end of 2015, the nation's cumulative installed hydropower capacity was four times larger than that of the United States (Uria-Martinez et al. 2015), reaching 320 gigawatts (GW), accounting for 26% of the global hydropower capacity (IHA 2016). As a pace-setter for producing electricity from renewable energies (Observ'ER 2013), China has entered a new era of hydropower generation made possible by a series of massive projects with unique features, including the world's largest hydropower station (Three Gorges, 22.5 GW), the largest hydro-turbine unit (800 MW), and the largest number of giant cascaded hydropower systems (10 basins having cascaded systems with capacities more than 10 GW, the largest one holding 32 GW in 2015). To add to this list, the country boasts the largest hydropower aggregation in one regional power grid (China Southern Power Grid, 100 GW in 2015), as well as the largest interprovincial hydropower transmission capacity (73.8 GW in 2015, 100 GW by 2020).

Managing such a complex hydropower network is a mammoth task on the edge of engineering and sciences. This paper outlines the challenges associated with China's large-scale hydropower system development, providing critical insights in three topical areas of hydrypower generation, transmission, and absorption. The paper also highlights areas where the long and rich history of water resources systems research and state-of-the-art modeling approaches can help address these challenges.

Hydropower Generation

China's geographically disconnected hydropower systems distributed on different rivers are connected through system-wide energy demands and various operational constraints. China's operational hydropower challenges can be divided into three main categories: (1) operation of cascaded hydropower system on the supply side of power generation network; (2) operation of multiple cascaded hydropower reservoir systems that cross provincial and river basin boundaries; and (3) cooperative operation of transmitted hydropower and other types of energy at the recipient side of the network for reliable and economically efficient absorption of the delivered hydroelectricity. The first category is a classical, well-known problem while the real challenges that currently hinder China's hydropower development arise from the latter two categories.

Operational Complexity

China's installed hydropower capacity is growing rapidly, with numerous plants connected to the hydropower network, and many more in the planning phase or under construction. As of 2016, Yunnan Province alone has 190 hydroelectric plants (521 units), with plans to increase the plants to more than 200 before 2020. Significant complexity arises due to the fact that large-scale hydropower systems within this enormous network need to utilize the various reservoirs' storage capacities and asynchronous precipitation to reduce spillage. The operations need to comply with detailed, stringent regulations such as power reduction depth (reservoir-specific range of unit output adjustment to flatten the net load curve) for peak load shifting, and to balance a multitude of stakeholder objectives (e.g., electricity generation, flood control, urban water delivery, irrigation, navigation, environmental protection, and socioeconomic resilience) that create upstream-downstream conflicts. Furthermore, delivering hydroelectricity to eastern provinces introduces transmission constraints. Engineering expertise, experience, and thorough understanding of operation procedures, security standards, regulations, past system behavior (i.e., historical data), and specifications of hydropower plants can help reduce dimensions of the constraints and decision variables for optimal management of large-scale hydropower systems.

Configurational Complexity

The Chinese hydroelectricity generation network is characterized by cascaded reservoirs with large units (e.g., 300, 400, or 500 MW). Giant units with a capacity of 700 MW or more are being used extensively in the southwestern hydropower projects. Distinct features of the cascaded reservoirs, besides size of unit capacity, include high head and multiple irregular-shaped vibration zones that are particularly sensitive to head (Cheng et al. 2012). Head-sensitive hydropower plants are typically used as peaking resources to meet high-frequency demands for flattening the net load curve in multiple power grids. However, repeated running through vibration zones can cause severe abrasion and fatigue, or even explosion of turbines. Hydraulic connection and electrical limitations exacerbate these issues in cascaded systems. Therefore, uninterrupted functionality of units in the cascaded head-sensitive plants is a stubborn problem that is different from the common plant operations with small capacity and relatively regular-shaped vibration zones.

Optimal operation of cascaded reservoirs (Heidari et al. 1971; Chow et al. 1975; Turgeon 1981; Karamouz et al. 1992; Yi et al. 2003) is of substantial importance, and continues to be an active area in Chinese hydropower systems research (Cheng et al. 2011, 2013, 2015; Shen 2014). The efficiency of systems with giant head-sensitive turbines can be increased using the hydro unit commitment (HUC) approach, which aims to optimize the scheduling of units within a hydropower plant for typical operations planning horizons (e.g., 1 day or 1 week), a task that is complicated by dynamic interrelation between energy output and irregular-shaped vibration zones. Combinatorial mathematics, dynamic programming, and mixed-integer linear programming (MILP) have been successfully applied for short-term scheduling of hydropower systems of Wujiang River and Lancang River (Cheng et al. 2012, 2016).

Risk Management

Risk management is salient for hydropower generation, which is inherently intertwined with and affected by hydrologic stochasticity (e.g., intra-annual and interannual streamflow variability, particularly in extreme hydrologic and climatic events). Understanding the potential effects of hydrologic uncertainty is critically important for optimizing the current operations and developing contingency plans. Likewise, it is indispensable for feasibility assessment of future development plans. For example, glacier melt is estimated to contribute about 12% of annual runoff in Yarlung Tsangpo River and Nujiang River (Zhang et al. 2013), two untapped basins where hydropower development is planned for after 2020. Climate change increases streamflow uncertainty by influencing the magnitude and timing of snowmelt in the basins. Hydrologic modeling can provide valuable insights about rainfall-runoff and snowmelt processes (e.g., Gyawali and Watkins 2013) to guide hydropower system development. However, the scarcity of hydrometric stations, meteorological stations, and environmental monitoring stations creates a major hurdle for accomplishing this task. The data challenge can be partially overcome through the use of remotely sensed data (Han et al. 2016), although combining satellite remote sensing data snapshots with relatively long hydrologic time series is an additional source of uncertainty.

The hydropower penetration in China's southwestern provinces, whose eastward-transmitted electricity will serve over 25% of recipient regions' load demand, may exceed 80% by 2020. Prolonged droughts can cause power shortages both in supply regions and recipient regions, encouraging an increase in hydropower storage by building large reservoirs in the upstream, which has triggered great debates about the environment, ecological integrity, socioeconomic stability, and power generation. Assessing the potential risks associated with current and future conditions of storage, streamflow forecasts, and compensation regulations with other energy sources remains an important multidimensional problem.

Hydropower Transmission

A disproportionate share (70%) of the Chinese hydropower is concentrated in the southwest, while over 40% of electrical consumption occurs in eastern China where local energy resources are insufficient. Long-term projects like West-East Electricity Transfer (WEET) are underway to transmit electricity eastward via high/ultrahigh voltage (UHV) transmission lines. However, hindered by multiple stakeholders and cumbersome procedures, the planned construction of UHV transmission systems lags far behind the development of hydropower stations, especially in the southwest. On the other hand, the increasing hydropower capacity in the southwest exceeds local demand. In 2015, hydroelectric power generation in the southwest was curtailed by more than 25,000 GWh, almost equaling the total electricity generated by Ireland in 2014 (BP 2015), in part, due to the limited transmission capacity. A national network of regional transmission systems is the cornerstone to energy distribution, essential for successful market penetration of renewables. The key question is how to use spatial and temporal characteristics of energy generation from hydropower, wind, and solar photovoltaic (PV) in the planning, design, and siting of transmission lines and large-scale generation bases. This is particularly important in a vast country like China where nationwide energy distribution, production, and consumption are all conspicuously uneven.

Hydropower Absorption

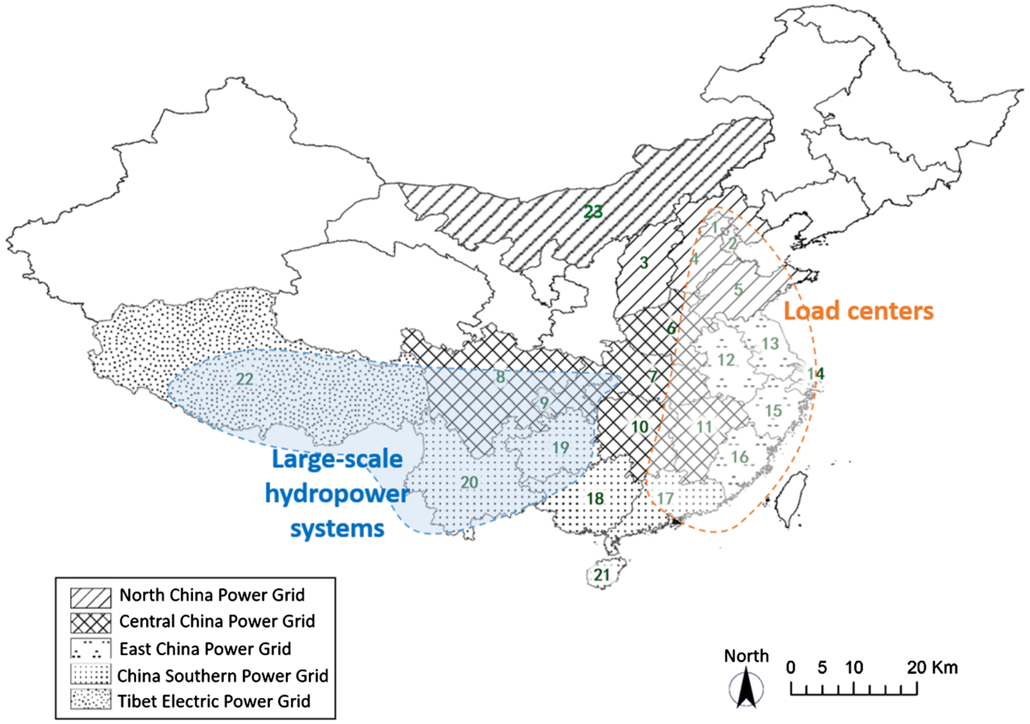
Significant peak-to-valley differences of demand load in China cause a heavy electricity balancing burden. In the absence of a free electricity market, the electricity balancing depends primarily on supply-side output adjustment. However, the current energy structure in most regions lacks the required flexibility for flattening the net load curve. Presently, coal-fired thermal power dominates China's energy system, and intermittent renewables are not considered reliable peaking resources. Pumped storage, which accounts for 97% of global energy storage capacity, comprises a small share (i.e., 7%) of total installed hydropower in China compared to 22% in the United States (IHA 2016). The southwest hydropower generation often peaks in the summer, when demand for power in recipient regions is at a low point, putting a strain on peak regulation. Thus, absorption of abundant hydroelectricity in the recipient regional power grids, especially during off-peak periods, is a bottleneck for further hydropower development.

For instance, the maximum load difference between peak and off-peak in the East China Power Grid (ECG), which serves 20% of the national electrical consumption, increased from 28.6 GW in 2005 to 66.32 GW in 2014. As the largest recipient of southwestern hydropower, ECG uses hydroelectricity to satisfy its summer peak load, but struggles to absorb it during off-peak periods. In fact, ECG has to compel local coal-fired plants (71% of local capacity in 2015) to greatly curtail output during off-peak periods due to lack of fast-ramping gas turbines and storage capacity.

Portfolio-Based Multigrid Renewable Energy Network Optimization

The growing Chinese energy network is a system of systems with multiple recipient regions that are connected, including the East China Power Grid, North China Power Grid, and Central China Power Grid, each consisting of many subgrids (Fig. 1). The recipient grids absorb southwestern hydroelectricity and wind-generated power from northern China. The west–east power connection with multiple provinces, power grids, and energy sources on both sides is particularly important. The power absorption in eastern China needs to optimize local pump stations and thermal units, while allocating eastbound hydroelectricity and local power generation among its five provinces to flatten each net load curve. Previous modeling efforts have not addressed inefficiencies arising from institutional and legal coordination barriers, as well as difficulty of portfolio-based energy network optimization.

Power grids in the recipient regions grapple with absorbing surplus energy during light load periods. Nonetheless, the eastward



No.	Administrative area
1	Beijing
2	Tianjin
3	Shanxi
4	Hebei
5	Shandong
6	Henan
7	Hubei
8	Sichuan
9	Chongqing
10	Hunan
11	Jiangxi
12	Anhui
13	Jiangsu
14	Shanghai
15	Zhejiang
16	Fujian
17	Guangdong
18	Guangxi
19	Guizhou
20	Yunnan
21	Hainan
22	Tibet
23	Western Inner Mongolia

Fig. 1. Regional power grids

hydroelectricity delivery is planned to increase. Until sufficient storage capacity is commercially available, peak regulation and storage optimization of the existing network can provide practical solutions to ease the current situation. Furthermore, the competitiveness of renewables, especially hydropower, in a free energy market should be investigated. In this regard, contributions from the systems community in terms of systems modeling and operations optimization can provide in-depth understanding of available opportunities to increase efficiency. In particular, data mining and super-computing capabilities hold promise for dimension reduction and efficient power distribution.

Peak Regulation and Storage Optimization

In order to absorb delivered hydroelectricity at the recipient end, the supply side (e.g., the cascaded hydropower plants in southwest China) should coordinate with the recipient-side plants in east China including hydropower, thermal power, nuclear power, and renewables. Hence, besides the well-known multipurpose reservoir operation problems (flood risk reduction, urban water supply, agricultural water supply, environmental flows, navigation, recreation, human displacement, etc.), management of large-scale hydropower systems should balance supply-side and recipient-side tradeoffs. The complex resource-management problems that are currently common in China can become ubiquitous in other countries planning large-scale energy network coverage. Large-scale hydropower stations should offer regulation service for multiple grids. For example, China Southern Power Grid covers five provincial power grids where three hydropower-rich provinces (Guangxi, Guizhou, Yunnan) serve Guangdong Province. Most hydropower stations in Guangxi, which receives large amounts of annual precipitation, are poor in regulation capacity (i.e., they are run-of-river stations). By contrast, hydropower stations in Guizhou and Yunnan are large reservoirs with high regulation capacity and lower annual precipitation than Guangxi. To efficiently use the system-side storage capacity, an agreement should be developed among the aforementioned three provinces to allow plants in Guangxi to generate more hydroelectricity during wet seasons while water is stored in large reservoirs in the other two provinces for use in dry seasons, which certainly involves tradeoffs between multiple stakeholders.

Each regional power grid at the receiving end of the southwestern hydropower consists of multiple subgrids with different load curves, providing opportunities for efficient peak regulation without additional storage capacity. Meticulous planning based on time lags and different amplitudes of load curves of the subgrids can allow some subgrids to absorb surplus external hydroelectricity during peak load periods while others are still in their relative off-peak periods. However, it is a formidable challenge to optimize the electricity generation and transmission based on cascaded reservoir operation and hydropower transmission coordination among the five grids in order to efficiently satisfy local demand and then meet the demand from Guangdong (Shen et al. 2015; Wu et al. 2015). Multiscale scheduling of a network of hydropower plants to offer regulation services to power grids (e.g., peak shaving) becomes significantly more complex when dynamic load and electricity exchange among each grid are considered.

While available pumped storage capacity is limited, new pumped storage plants take years to complete. Hence, optimal management of local pumped storage is necessary. Targeted regulation services is a promising strategy to address this constraint by prioritizing those subgrids whose flexibility is the lowest. Besides the complexity of modeling interactions among multiple grids, transmission capacity constraints and temporal coupling of dynamic load demand make optimization of pumped storage in multigrid hydropower systems a challenging undertaking (Shen et al. 2014; Cheng et al. 2015).

Economic Incentives and Externalities

Absence from the electricity market coupled with sanctions from revenue-generating policies disincentivize power enterprises and grid companies to take full advantage of hydropower. Without an electricity market, the competitiveness of power generation depends primarily on prices and policies set by the government. For example, the price of hydroelectric energy, in general, and pumped storage, in particular, is artificially low as compared with the price of coal-fired plants in China. Unlike coal, water is free, which puts hydropower at an inherent advantage in terms of energy generation cost. Furthermore, the cost of storage service that is required for eastward hydropower transmission is currently not internalized in the hydropower price. On the other hand, hydropower plants, especially pumped storage plants, offer important ancillary services (e.g., flattening the net load curves, and energy storage) that under current policies cannot be used to generate revenue, although they are essential for the integration of renewables in the power grid. However, an open electricity market (e.g., ancillary service market) is inevitable if China wants to make significant progress toward accomplishing its renewable energies target before 2030. Thus, it is vital to develop economic-based systems models of China's hydropower in an energy market setting in order to offer insights for improving institutions and market structure.

Furthermore, there is a need to better understand and account for the environmental externalities of hydropower development (Hadian and Madani 2013; Madani and Khatami 2015). The ecosystems in southwest China are fragile. Significant, regular fluctuation of discharge and water level can cause loss of habitat, degrading aquatic ecosystems (e.g., Renöfält et al. 2010). The cascaded hydropower plants in the southwest are mostly large reservoirs with considerable water storage (Liu et al. 2015). Providing adequate environmental flows can help mitigate ecological degradation (Olivares et al. 2015). The conflicts associated with water allocation among multiple competing sectors and stakeholders, including power enterprises and power grid companies, are becoming more tangible. Interactions and feedbacks among energy production, water stress, food security, land use, climate change, and socioeconomic stability make it more difficult to balance diverse stakeholder objectives within multicriteria decision-making frameworks (Hadian and Madani 2015).

Model Dimension Reduction

Mathematical modeling of a system of systems comprising hundreds of hydropower plants can be prohibitively laborious, and computationally intractable. Dimension reduction is a promising modeling strategy to handle the difficulty of solving such complex models. Redefining the problem based on technical attributes of the system components can significantly reduce the workload for optimal operation of large-scale hydropower systems (Cheng et al. 2013). For instance, plants with low regulation capability can be represented as run-of-river plants in long-term hydropower operations. Similarly, in short-term operations, low-flexibility plants can be assumed to follow the previous scheduling if their forecasted load demands and inflows do not vary significantly as compared to previous days. This helps simplify the optimization modeling to focus only on optimal scheduling of large high-flexibility plants, which play a major role in providing electric service. During dry seasons, hydropower plants with small reservoir storage capacity could offer regulation service only during peak-load periods. These dimension reduction techniques, common in hydropower systems modeling studies (e.g., Archibald et al. 1997; Turgeon and Charbonneau 1998; Madani et al. 2008; Madani and Lund 2009; Guégan et al. 2012; Cheng et al. 2013), are derived from engineering experience to reframe intractable hydropower systems modeling problems into computationally efficient models while ensuring practicability and acceptable precision.

Research and Development

China is making large investments in research and development to support its booming hydropower sector. Currently, balancing power generation, flood control, navigation, and water supply with ecosystems and the environment is considered a national priority area. Several projects have been launched to improve hydropower management. In 2015, the National Natural Science Foundation of China (NNSFC) initiated a major research enterprise, with a budget of over 200 million RMB, to support adaptive utilization of headwaters in the southwest. Additionally, since early 2016, the Ministry of Science and Technology of China (MOST) has allocated significant funding resources (2.5 billion RMB) to a key 5-year national technology research and development program to investigate highly efficient utilization of water resources. Furthermore, the Chinese Academy of Engineering (CAE) has developed a master research plan that, among other things, aims to improve understanding of the role of hydropower in the optimization of energy systems under the constraint of carbon emission reduction.

Conclusions

China's grand vision to develop a sustainable energy system relies heavily on hydropower, with the plan to increase the cumulative installed capacity to 380 GW before 2020. While optimal operation of a complex network of large-scale hydropower plants poses a great challenge, it also provides unique opportunities for new theories and modeling techniques from the systems community. The hydropower sector can significantly benefit from frameworks to evaluate the impacts of hydrologic uncertainty on power generation in order to develop effective adaptation strategies. Peak regulation and absorption of abundant hydroelectricity are two key issues. Furthermore, the country's ongoing electricity market reform will create new operational challenges for the hydropower sector. There is a critical need to model complex hydraulic and electrical relations in large-scale cascaded hydropower systems, accounting for temporally linked power generation constraints in multigrid systems with dynamic load demand from multiple recipients and multilevel nonstationary transmission capacity. The multitude of stakeholders and ecological and socioeconomic concerns further complicate hydropower development and management in China, as in any other part of the world.

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