Market Solutions to China's Wind Integration Problem: Are Current Reforms Sufficient?*

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Abstract

China has deployed wind and solar energy at an unprecedented scale, supporting 42% annual growth in wind capacity over the last decade and establishing the world's largest solar fleet almost entirely in the last five years. However, rapid growth and changes in the generation mix have led to substantial waste (curtailment) of these renewable resources, increasing costs and environmental impacts from its predominantly coal-fired power fleet. Multiple technical and political causes have been identified—ranging from inadequate transmission infrastructure to policies favoring conventional coal energy—but there has been little quantification of their respective impacts on curtailment that would help prioritize policy solutions. Concurrently, China has recently accelerated electricity market restructuring, aiming to diminish the role of government in the sector. International experiences indicate that appropriately designed markets can positively impact renewable energy integration, but that benefits depend significantly on the details of new institutions, not simply that markets are engaged. In this study, interviews were conducted (2015-2016) with key grid, government and other stakeholders in three regions of northern China on the specific processes of dispatch and scheduling, market design and implementation processes, and how these markets alter dynamics on timescales relevant for curtailment. These findings help tailor a highly-detailed power systems model, unit commitment optimization, that examines quantitatively the underlying causes of curtailment and potential impacts of reforms. Results show the strong roles of local

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government and grid actors in all stages of market creation and implementation as well as the importance of key technical constraints that limit the abilities of political actors to pursue their own interests. Furthermore, the model quantitatively demonstrates why the preferred market design—monthly and annual contracts—will fall short of addressing curtailment.

1 Introduction

Over the last decade, China has undergone the largest electricity infrastructure expansion program in history, with annual increases in electricity demand by 6.2% and total generation capacity by 8.6%, building on average 92 gigawatts, roughly the capacity of the entire UK grid, each year (CEC, 2017; DUKES, 2017). Of this, wind energy has been deployed at a massive scale with 43% annual capacity growth, and solar energy capacity is now double Japan, the next largest country, virtually all of which was built in the last five years (IEA, 2017). These rapid changes, in growth and in composition, have led to significant waste (curtailment) of these renewable resources, adding costs and increasing environmental impacts associated with its coal-fired power fleet. Due to the physical constraints and economic complexities of electricity systems operation, this is an inherently difficult problem to attribute. Multiple causes have been identified —ranging from inadequate transmission infrastructure to legacy government planning of generation—but there has been little quantification of the respective impacts of a range of technical and political factors.

Electricity systems traditionally began as vertically-integrated utilities (VIUs), wherein the entire supply chain from generation to customer retail was within a single organization that may be owned by a government ministry or by a firm operating under an exclusive government franchise. Since the 1980s and accelerated most recently in 2015, China has joined many other countries and regions in broad reforms designed to restructure these utilities (also known as “deregulation”), introducing competition in some of the segments of the supply chain through diversification of actors and market-based pricing.[1] China’s stated goals are to enhance efficiency and address renewable energy integration challenges, which potentially entails large changes to institutional setting as well as technology choices.

Theoretical work and international experiences indicate that appropriately designed markets can have a positive impact on renewable energy integration. However, lessons from the wide range of countries that have created competition in electricity also indicate that the benefits—typically measured in electricity

[1]Throughout, “market” or “exchange” are used in a very general sense to refer to any process by which buyers or sellers of electricity nominally compete with each other outside of the traditional planning process. This encompasses many processes that would not satisfy a regulator’s conception of a market, but it is a shorthand to ease reading and bypass having to make a threshold argument about which (if any) qualifies as a “market”. This definition also aligns with how Chinese official documents themselves refer to these experiments.

prices—depend significantly on the details and interactions of the new institutions, not simply that markets are engaged.[2] For example, using three rather aggregated metrics of restructuring in a panel regression—privatization, independent regulation, and competition—Zhang et al. (2008) estimated that some benefits derive from the interaction of both privatization and independent regulation.

Owing to its bureaucratic structure, China's market creation process will possibly be quite distinct from industrialized countries where these market designs were developed. Local governments, which are not separated from central powers in a formal federalist structure, nevertheless retain substantial autonomy in market opening policies, continuing the legacy of decentralization under the entirely planned economy. The grids, which evolved from the state ministry to state-owned enterprises, have retained enormous influence in policy-making and implementation, compounded by the critical lack of independent regulatory powers within the Chinese government.

Using a methodological approach that iterates between engineering models and case studies, this paper examines the political and economic institutions of China's electricity sector, the underlying causes of wind curtailment, and the probable impacts of current reform policy on renewable energy outcomes. Three northern regions with substantial wind development are chosen for qualitative case study. These are augmented by detailed modeling of a single region of China—the Northeast—that captures technical constraints as well as important institutions influencing generator scheduling. Finally, these results inform and are appropriately scoped by further qualitative data collection and analysis.

The findings demonstrate that provincial governments have significant autonomy in market design and that policies adopted by many local governments in China—i.e., medium-term bilateral contract markets replacing government planned quotas—will likely fall short of addressing curtailment. These suggest that larger power markets encompassing multiple provincial jurisdictions and with short-term (e.g., hourly) varying prices will be necessary to achieve substantial efficiency and renewable energy gains. These markets are also implemented with only incremental changes to grid institutions, which retain substantial autonomy and their own sets of interests. While the exact impact of increasing medium term contracts will depend on market rules as well as agents' bidding behavior, increasing contracted amounts will likely make the job of the dispatch operator more difficult.

[2] For reviews of the effects of electricity sector reforms in developing countries see Zhang et al. (2008) and Jamasb et al. (2017); for a review of the current status in U.S. states see Brooks (2015); and for a review of EU member countries see Teixeira et al. (2014).

2 Literatures

2.1 Engineering and Political Economy Challenges of Renewable Energy Integration

Delivering electricity is fundamentally different than supplying any other commodity: electricity supply and demand must be balanced instantaneously within a small margin to maintain quality; it cannot cost-effectively be stored on a large-scale (i.e., inventory-less); it travels instantaneously on a path that cannot be completely directed; and it involves complex network interactions among suppliers and consumers (Hunt, 2002). As a result, there exists a significant coordination challenge of matching generation and consumption down to the level of minutes and shorter intervals. Electricity generation technologies also introduce various constraints and non-linearities: conventional fossil-fuel and nuclear generators have minimum stable outputs and lengthy startup (shutdown) sequences and renewable energies are both variable (i.e., less controllable) and uncertain (i.e., difficult to forecast hours to days in advance) (Bozzuto, 2009). As systems move toward hybrids of renewable and conventional energies, the engineering challenges of delivering reliable electricity will increase.

Engineering interventions to improve renewable energy integration typically target flexibility of system operation, such as the frequency of scheduling decisions for conventional units, the structure of short-term balancing operations, and what types and how much “reserve” (backup) generation are necessary (Xie et al., 2011; Holttinen et al., 2011). The cost and ability to provide flexibility also depends on infrastructure investments that have expected lifetimes of 20-80 years.

The integration of renewable energy also alters the political economy of a large and important sector that is frequently the target of government intervention, leading to transfers from politically-connected incumbents to new entrants; increased coordination demands on complicated and entrenched bureaucracies; and allocation issues of renewable energy subsidies, additional grid investments, and system balancing costs (Davidson et al., 2016). Successful examples of high wind integration may exhibit simplified bureaucratic coordination and cost allocation rules: for example, the Texas grid is disconnected from other states and not subject to federal jurisdiction, and has a tradition of socializing grid investment costs (Fischlein et al., 2013). In other cases, where the issue has more political salience such as Europe, mandatory dispatch rules with stiff penalties are seen by the renewable energy industry as essential supporting policies (EWEA, 2014).

Electricity sector institutions are also changing as a result of market liberalization reforms (sometimes referred to as “deregulation”). Historically, electric utilities were government-run or regulated private monopolies due to the unique economics of infrastructures that discourage direct competition as well as the public—or at minimum, politically salient—goods they provide (Newberry, 2002). However, the generation segment, which consists of interconnected electric power plants that supply electricity to the grid, is a key activity that lacks a natural monopoly and hence can be open to competition (Joskow and Schmalensee, 1983). A “textbook model” of electricity restructuring exists in regulatory economics literature, which includes how and which markets to create as well as relevant institutions to oversee their functioning (Hunt, 2002; Joskow, 2008). Based on three decades of international experiences, it is also clear that many motivations exist for introducing markets: countries with well-developed electricity systems may wish to promote competition to enhance consumer choice and reduce government intervention as an end in itself. Countries with systems still under development may seek to attract more private finance to supplement the overburdened public sector. Exogenous macroeconomic events such as financial crises and “structural adjustments” encouraged by international development organizations may also precipitate electricity sector reforms (Williams and Ghanadan, 2006; Jamasb et al., 2017).

There is significant debate, focused predominantly on U.S. and European systems, about the ability of current electricity markets to accommodate large quantities of intermittent renewable energy (Ahlstrom et al., 2015; Pollitt and Anaya, 2016; Neuhoff et al., 2016). Because of the fundamental need to instantaneously balance supply and demand, designs generally include some form of “spot market” at its core, with a market-clearing marginal price for power that varies by location and on hourly or shorter time scales (Schweppe et al., 1988). These were designed with fuel-burning generators in mind (Conejo and Sioshansi, 2018). Renewable energy sources, by contrast, lack fuel costs and hence have close to zero marginal costs. Nevertheless, a spot market can address many of the above system flexibility issues with accommodating renewable energy, if it is well-designed: e.g., no restrictive price caps and floors, higher time (e.g., intra-hourly) and locational granularity, and co-optimization with transmission capacity allocation and reserves (Ahlstrom et al., 2015; Neuhoff et al., 2016). Renewable energy will generally be infra-marginal generators, dispatched in most cases—in particular, preferentially to conventional sources—unless there are issues such as network stability. Variability in prices such as caused by sudden changes in renewable energy create monetary incentives for flexible resources to balance the system.

On the other hand, some argue that markets are not well-adapted to renewable energy; hence, many systems are adjusting designs in response to renewable energy (Pollitt and Anaya, 2016). First, as low marginal cost generators take up a larger part of the system, overall revenues from energy markets tends to decline. Reserve markets and/or capacity markets (i.e., paying generators for available capacity, typically on yearly or longer horizons) would need to fill in for the conventional generators' lost revenues (Ahlstrom et al., 2015). Issues of allocating scarce transmission capacity across market borders might be enhanced with more variable flows from renewable energy (Neuhoff et al., 2016). Distributed renewable energy generation presents new challenges, because they are connected on low-voltage networks and do not face the same set of price incentives (Pollitt and Anaya, 2016; MITEI, 2016).

There is little indication that all systems will converge on the same design. The complex nature and ordering of creating new market-supporting institutions ensure that there is still substantial diversity across countries. In addition, even once a reform path is agreed upon, there may still be significant divergences: vested interests capture weak economic and regulatory institutions, poor financial systems limit the ability to invest, and the sizes and resource mixes vary substantially (Jamasb, 2006).

Once neighboring markets are established, increasing trade has well-recognized benefits in terms of reducing costs and integrating renewable energy by accessing cheaper generators, sharing back-up generators (reserves), and reducing market power (GE, 2010; Borenstein et al., 2002). However, creating markets that cross traditional political boundaries for electricity system regulation has been particularly fraught. For example, the EU has created a common internal energy market that clears cross-country transactions prior to within-country system operation: these two stages incorporate different representations of the network (hence, of the underlying physics), which can affect market outcomes and renewable energy integration (Neuhoff et al., 2016). Protectionism, institutional and market design differences, and insufficient regulatory oversight may all lead to restrictions on trade.

An important area of research, given these complexities, is attributing the effect of electricity market interventions and related political economies on system outcomes. By far, the most widely studied metrics are total production cost or average consumer prices. Many studies are single country-level cases, possibly supported by quantitative indicators (e.g., Sioshansi and Pfaffenberger, 2006). Cross-country studies are reviewed in Zhang et al. (2008) and Sen et al. (2018), which are dominated by panel regressions with institution dummies. These analyses point to significant interaction effects among different institutions: for example, using three metrics of restructuring in a panel regression study—privatization, independent regulation, and competition—significant effects of privatization were only found when coupled with establishing independent regulators (Zhang et al., 2008).

However, these statistical approaches do not directly consider the physics or system operation constraints elaborated above, creating problems of measurement validity and attribution. For example, a single country-wide number derived from market concentration of top firms is frequently used to represent the competitiveness of a country's electricity system (Zhang et al., 2008; Sen et al., 2018). Market power, wherein some actors are able to unilaterally alter the price through strategic bidding, is a key concern, but its effect is highly dependent on locational (i.e., network) configurations and constraints over short time periods (Borenstein et al., 2002), difficult to capture with units of analysis of country-year. Furthermore, market design and subnational trading arrangements potentially have much bigger impacts on efficiency, such as the expansion of the centralized PJM market into a portion of the mid-western U.S. previously using bilateral contracting mechanisms, which led to an estimated greater than $160 million annual savings (Mansur and White, 2012).

Literature on the politics of the provision, as opposed to production, of electricity and other infrastructure-related public goods has included some attention to the physical and regulatory contexts. For example, providing electricity access cannot be easily targeted to electoral districts, which differ from electricity service network boundaries (Golden and Min, 2013). Different providers associated with liberalization, such as non-regulated and regulated private companies, also have implications for the ability of politicians to reward constituencies (Post et al., 2017). Examining levels of intermittency captures in even greater detail distribution networks (Post et al., 2018). This literature on infrastructure provision has effectively exploited geographic variation in statistical estimations.

In order to attribute causes for costs and renewable energy generation outcomes, however, quantitative simulations incorporating greater technical detail are needed. Models used in practice by power system operators are typically large optimizations that minimize costs subject to various technical constraints (Stoft, 2002). Sufficiently simplified to aid analysis, these models have been applied in Europe to understanding the renewable energy impacts of a handful of relatively well-established market designs (Aravena and Papavasiliou, 2017; Weijde and Hobbs, 2011). However, the impacts on system performance of a greater variety of institutions arising in contexts without satisfactorily competitive conditions have been under-explored. These relationships—and their interactions—go to the heart of which institutions and market design choices matter most when restructuring electricity sectors and why.

2.2 Three Decades of Electricity Market Creation in China

China began to restructure its electricity sector in the 1980s, allowing private investment in the sector, and subsequently over 1998-2002, converting its former state-run electricity ministry into a state-owned grid company, creating new regulatory and policy bodies, and establishing five new large state-owned generation companies accounting for roughly of half of the market (State Council, 1998, 2002). However, governments (both local and central) never gave up their significant roles in the sector, including both setting prices and allocating quantities. Pilots to create spot markets all failed, due to opposition and co-option by protectionist local governments, firms seeking to maintain high rents, and grid companies whose revenues became threatened, whilst regulatory bodies exercised insufficient oversight (Andrews-Speed, 2013; Zhang and Heller, 2007).

To examine the interrupted processes of reforms, foremost is the relationship between central and local governments, which is at the center of much scholarship on decision-making in authoritarian China. While all part of the same basic hierarchy and formally subject to the ultimate authority of the central government, local governments (provincial and sub-provincial) are given significant autonomy over many aspects of governance. The purpose of granting this discretion was initially to encourage self-sufficiency in the planned economy, and later to experiment with different forms of markets in the economic reform period beginning in the 1980s (Schurmann, 1968; Naughton, 1995).

Localization leads to a proliferation of bureaucracies, which can be understood as bureaucratic games driven by various lines of authority and the bargaining power of key actors (Allison, 1969). In the literature on China, this form of "fragmented authoritarianism" has been shown to lead to overly complex formal structures that are bypassed only through informal consensus-building measures at various levels (Lieberthal and Oksenberg, 1988). This literature on Chinese bureaucracy was informed early on by cases of electricity sector investments, and the electric power annual plans for generation and consumption also share many of these features (Ma and He, 2008). With the abolishment of the government-run utility in 1998, the provinces retained their prerogative to determine plans. Provincial governments have been noted in the past to use this power to give preference to their own generators at the expense of centrally-managed plants (Bai and Qian, 2010), and to promote forms of contracting that reduce electricity prices for local industries (SCEO, 2015). With respect to wind energy challenges, provincial governments have incentives to give preference to coal generation whose tax revenues are larger and distributed at various government levels (Zhao et al., 2013).

In contrast to the dominant central-local theory, which views inter-governmental exchanges as the primary driver of industrial policy in China, new theories with a plurality of actors are also emerging. In the electricity sector, grid companies play crucial roles in both designing and implementing policy due to their authority on technical matters and distinct information asymmetries over government agencies (Xu, 2016). Chinese grid officials were effective in preventing a much larger break-up favored by many government stakeholders during the 2002 reforms, resulting in only two large multi-provincial grid companies (Chen, 2010). During the current round, they also lobbied effectively to maintain ties to the newly created electricity exchanges, specifying their "relative independence" (*xiangdui duli* | 相对独立) from the grid company (State Council, 2015). In wind energy deployment, others have noted a three-party game between the center, the province and the grid for control over electricity system operations, whose outcome is seen as the result of bargaining and interest alignment (Dai, 2015; Lema and Ruby, 2007).

Similar to cross-national studies on the benefits of restructuring, missing in much of the analyses on the politics of Chinese electricity reforms is a detailed consideration of the technical constraints on grid operations, which limit the ability of actors to control the bureaucratic game and pursue their interests. Including these operational realities may provide insights into why and how certain reforms are chosen, and explain why desired outcomes are not achieved.

In 2015, China embarked on a new round of electricity sector reforms, nominally designed to achieve objectives of efficiency as well as encourage the integration of renewable energy (State Council, 2015). The current reform path emphasizes reducing the amount of planned electricity sales sold to the grid by generators at the government-set price, with prices determined directly with electricity generators (NEA, 2016c). Small consumers are being targeted through separate retail electricity reforms, where newly formed retail companies contract on their behalf similar to the large contracts. The reforms also call for prioritizing hydropower, solar and wind in annual planning processes, and increasing inter-provincial trade (NDRC and NEA, 2015).

Converting portions of government production quotas into market-based contracts follows the principle of "growing out of the plan" observed in other sectors and products, particularly during the waves of corporatization and privatization in the 1990s (Naughton, 1995). The flexibility of how to "grow" was frequently left to local governments, which combined with streamlined bureaucratic promotion incentives and profit sharing among local government-owned enterprises and local governments, is attributed for China's economic success (Ang, 2016). During this process, new styles of property rights relying on formal as well as informal institutions were developed (Oi and Walder, 1999), and numerous attempts at independent regulation were made (Pearson, 2007).

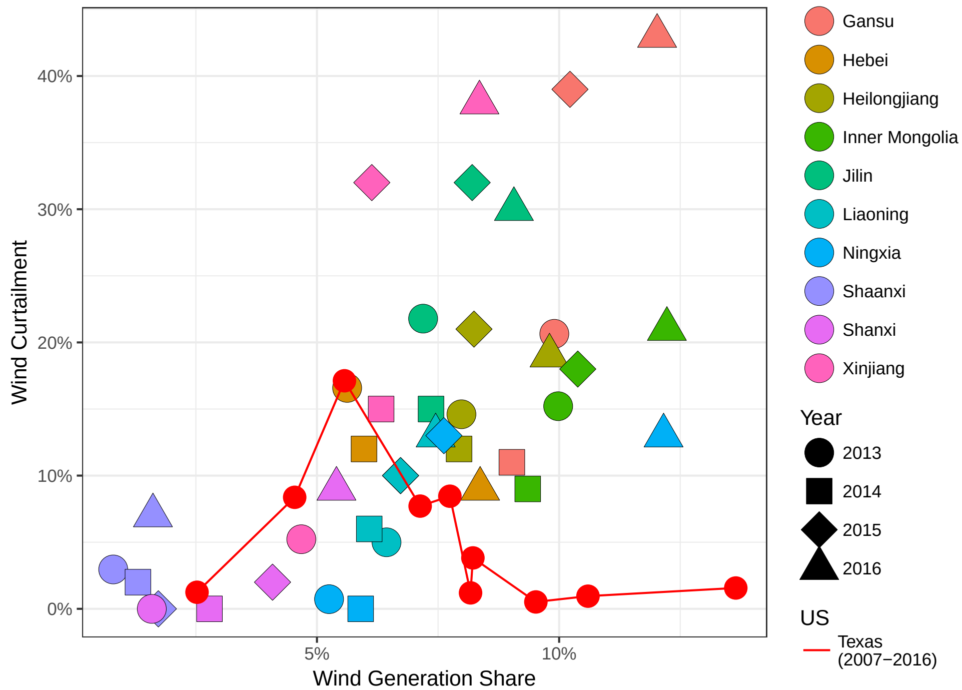
Amidst institutional changes, technologies in the sector have been rapidly evolving: wind and solar energy capacity has increased over 100 times in the last decade (2007-2016) (CEC, 2017). This rapid growth, concentrated in a handful of northern provinces, has created serious integration challenges, with curtailment[3] (or forced spillage) of wind electricity rising above 40% in some areas, and solar curtailment

[3]Curtailment typically refers to when the full amount of available renewable energy is not used. As it has zero fuel cost and is not storable, this energy can be seen as being "wasted". By contrast, reducing generation at a coal plant also reduces fuel consumption (hence, costs).

above 30% (NEA, 2017,b). These rates are much higher than similar size international systems: for example, Texas has roughly the same percentage of wind penetration and only 1% of curtailment, which has come down from record highs of 17% in 2009 primarily due to relieving bottlenecks in transmission lines from wind regions to demand centers (Fischlein et al., 2013). In Figure 1, major wind provinces are shown geographically, and wind curtailment as a function of the wind generation share for 2013-2016 is plotted together with the evolution of Texas over the last decade.

There is substantial debate on the causes of China's wind integration problem, with a range of engineering and political economy-related factors identified: transmission bottlenecks, an inflexible fossil generation mix, poor siting of wind generators, low equipment quality, and protectionist policies supporting coal generation (Zhao et al., 2012; Kahrl et al., 2013; Huenteler et al., 2018). Establishing causality is increasingly important as grid integration has risen to the number one issue in the 13th Five-Year Plan (2016-2020) on Wind Energy Development (NEA, 2016a), and a battery of central policies have attempted to address it, including: strengthening mandatory renewable energy dispatch policies in place since 2005; establishing minimum capacity factor requirements by province (NDRC and NEA, 2016); and freezing new permitting in high-curtailment provinces (NEA, 2017a). In addition to command and control approaches, a growing number of policies—including high-level reform documents—call for market mechanisms. Similar to the debate over the effectiveness of market approaches to address renewable energy integration in developed markets, the details of approaches in the context of each system need to be closely examined.

For example, the Chinese government's preferred approach to market reforms deviates from lessons from other restructured electricity markets, which place large emphasis on physically accurate and short-term spot markets to accommodate renewable energy. In China, reforms encourage medium-term bilateral contracts, while deeming spot markets (e.g., daily or hourly) to trade these and to incentivize flexibility to address imbalances as merely "supplementary" (NEA, 2016c), and have not been implemented in any pilot to date. The Chinese approach appears to be most similar to that the of the UK, where bilateral contracting also predominates. However, the UK's short-term imbalance mechanism is important for firms to manage their contracts efficiently, and was predated by a functioning short-term market (the "pool") (National Grid, 2011; Newbery, 2005). In particular, the UK faced challenges with integrating intermittent renewable energy, which led to the creation of specific financial contracts known as contracts for differences (DECC, 2015), not currently entertained in any Chinese government documents. Given these apparently incomplete markets and other questions about China's institutional ability to regulate this type of market, market approaches may be insufficient.



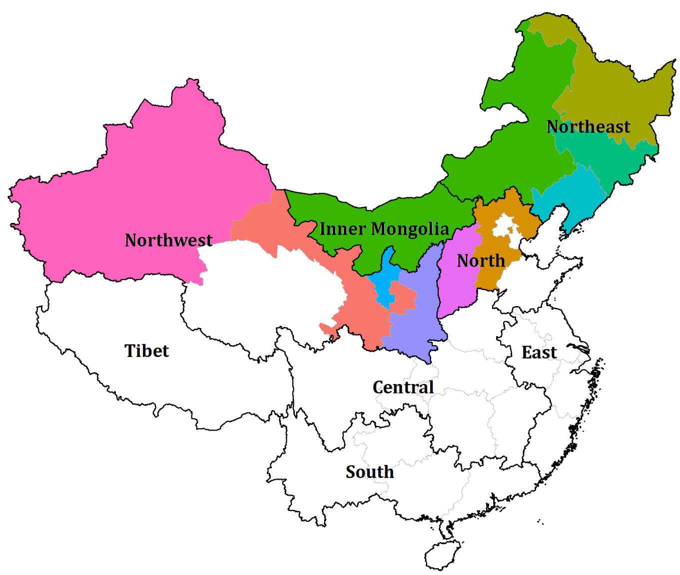


Figure 1: Wind curtailment in major wind provinces of China, 2013-2016, and Texas (*top*). Source: NEA, Wiser and Bolinger, 2017. Note: actual data is from the ERCOT grid region whose borders differ slightly from the state of Texas.
Grid regions of China (*bottom*). Inner Mongolia is split between the west in Inner Mongolia Grid Company (here, 'Inner Mongolia') and the east in Northeast Grid. Light grey lines are provincial borders. Source: author's illustration.

Hence, details of both institutional make-up and grid operations are important when evaluating current practice and prospective benefits of various reforms. The weight of international evidence indicates that these factors increase in importance for renewable energy integration analyses relative to more traditional cost-focused studies. Through quantitative modeling and an iterative multi-method approach outlined in the next section, this study provides greater clarity on the potential effectiveness of market and non-market approaches by precisely identifying causes of curtailment and analyzing a wide range of liberalization pathways.

3 Methodology

3.1 Iterative Multi-Method Approach

Accurately representing complex technical and institutional interactions motivates an iterative multi-methods approach that combines a commonly-used engineering-economic model with case studies of electricity system operations and markets in several regions of China. Here, I adopt a "pragmatic" approach that builds on both qualitative and quantitative methodologies to examine these questions from multiple vantage points (Tashakkori and Teddlie, 1998, p. 12). Whereas case studies have strong internal validity by focusing in detail on the processes that occurred between independent variables and dependent outcomes (George and Bennett, 2005), quantitative models allow for generalizable insights assuming underlying physical and economic drivers remain constant across systems.

The method proceeds as follows: case studies generate narratives of grid operations institutions—"humanly-devised constraints" that shape how different actors interact (North, 1990)—which also highlight the relevant universe of political factors. Based on these processes, a subset of political factors with potentially important impact on outcomes are chosen to be modeled in the engineering-economic model, which captures the interaction of these with relevant technical constraints. Results from the model are analyzed based on the cross-case comparison of underlying processes. Finally, quantitative exploration informs and focuses data collection in subsequent interviews. The key quantitative outcomes of interest are cost-efficiency of electricity production and integration of wind energy. Wind integration is measured by curtailment rates,[4] the percentage of available wind energy that is wasted, i.e. not successfully utilized by the grid.

Beyond simply the concept of triangulation, where biases in multiple methods are reduced through complementary use of different methods, this iterative approach combines different methods "simultaneously",

[4]Curtailment is the most visible metric of integration challenges, since it is generally economical to utilize as much as possible of the free wind resource from already built wind installations. Other approaches may look at balancing costs incurred by other generators (Holttinen et al., 2011) as well as grid connection delays, particularly prevalent in China (Lu et al., 2016).

though distinct from a "nested analysis" in at least two dimensions (Lieberman, 2005). It does not start with a large-N analysis to test preliminary models and drive case selection; and the statistical analysis is replaced by a detailed engineering model at the same unit of small-N analysis and at a level of granularity sufficient to capture major impacts on short-term scheduling decisions. Because of the smaller number of potential cases (China has only 31 provinces, of which less than ten have significant wind development) and the inherent complexity of explanatory regulatory and technical factors on outcomes, a cross-case statistical analysis would be difficult to appropriately specify and maintain statistical power. Instead, a model that captures realistic operational decision-making situations is proposed as the quantitative tool for theory-testing.

3.2 Semi-Structured Interviews

Cases of provincial- and regional-level electricity systems operation were chosen to identify relevant political processes between central and local governments, and between grid company and government. Selection criteria were limited to regions that have significant wind penetration and to cases representative of different institutional and physical characteristics. Three cases were chosen—the Northeast Grid (NE), the Western Inner Mongolia Grid (WIM), and the Northwest Grid (NW)—which vary across export/import relationships with neighbors, grid company management, and coal capacity (see Table 1). This is near complete coverage of high wind regions, except for the North Grid region excluded because of time constraints.

Regional Grid	Abbrev.	Characteristics
Northeast Grid	NE	Relatively isolated grid, pronounced coal overcapacity
Western Inner Mongolia Grid	WIM	Independent grid company (adjacent to NE)
Northwest Grid	NW	Centrally-designated energy exporting region

Table 1: Regional grid cases

Semi-structured interviews (52, in total) were conducted in Chinese over multiple visits in 2015-2016 with respondents from grid companies, local and central governments, generation plants, and research organizations (see Table 2). Within grid companies, respondents were from the dispatch control centers (the department primary responsible for systems operations), planning offices, and affiliated research institutes. Local government respondents were from provincial planning agencies (e.g., Development and Reform Commissions (DRC) and Economic and Informatization Commissions (EIC)) and energy regulators (National Energy Administration (NEA) local branches). Central government respondents were from the NEA. Generation plant respondents were managers and engineers from wind farms and coal-fired power plants. Research respondents include academics as well as grid company-affiliated research organizations.

Region	# Respondents
Beijing (Center)	13
Northeast	13
Northwest	19
W. Inner Mongolia	7

Organization	# Respondents
Government	8
Grid Company	11
Industry	27
Research	6

Table 2: Respondents

For each case, qualitative data collected via interviews as well as government work reports and news accounts are analyzed with a process tracing lens, examining causal processes along the chain (e.g., annual planning, market experiments and system operation) from independent to dependent variables (Bennett and Checkel, 2015). For ease of reading and to maintain confidentiality of respondents, data from interviews are not attributed in the case descriptions. Public sources are attributed where available. Specifically, question guides and the process tracing framework were designed to accomplish the following:

1. Disaggregate the rule-making and implementation process of system operation;
2. Explore intermediate variables such as market trading and grid company roles with respect to stated goals and economic theory; and
3. Test assumptions necessary for causal inference using quant models.

3.3 Quantitative Grid Model

Electric power systems operation, due to instantaneous balancing, physical laws of electricity flows, and a range of constraints on electricity generation, results in a large coordinated production problem across a system of diverse assets and on time horizons ranging from sub-second to multi-year. The focus of this research is on operations (*yunxing* | 运行), which I define as decisions made annually or on shorter timescales within which the existing physical assets cannot be modified, to distinguish from long-term planning (*guihua* | 规划) such as investment decisions. Annual production planning timeframes (*jihua* | 计划) are common in the Chinese government hierarchy. The focus on operations is justified by the result that a well-functioning operational scheme (whether via markets or regulated electric utilities) will match short-run efficiency with long-run efficiency goals; or, in other words, an appropriate operational scheme is essential to achieve long-term efficiency goals (Pérez-Arriaga and Meseguer, 1997). Investment decisions, arguably the greater focus of China's reform efforts prior to 2015, do carry important implications for system outcomes, but given the challenge of existing plant curtailment and the current reform emphases on generation markets, the set of assets is treated as exogenous in this study.

Among models on operational time scales, the unit commitment and economic dispatch optimization (UC) is essential for determining system performance on metrics of cost and wind integration (Xie et al., 2011). In most systems, this is conducted on a daily basis to determine the schedule of generator start-up and shut-down decisions (known as "commitments") and predicted outputs for the next day based on forecasts of demand and supply availability (Padhy, 2004).

Due to its central role in power system operations, UC models are the focus of continued research efforts to improve solution times and accuracy. I start here with a standard formulation with binary variables for commitments (Ostrowski et al., 2012) (which I will refer to as the "full model") and modify by clustering commitments of similar generators into integer variables (Palmintier and Webster, 2014) (the "clustered model"), balancing accuracy and the ability to solve a large system (> 500 generators) over a long enough time horizon (1 week) to consider relevant Chinese institutions. The full problem formulation and solution method are in the Appendix and in Davidson and Pérez-Arriaga (2018). Schematically, the model minimizes production costs by choosing appropriate values of production variables subject to (s.t.) various constraints:

$$Z = \min_{\boldsymbol{x},\boldsymbol{y},\boldsymbol{z}} \sum_{p,g,t} \left(\mathbf{c}^\top \boldsymbol{x}_{\boldsymbol{p},\boldsymbol{g},\boldsymbol{t}} + \mathbf{d}^\top \boldsymbol{y}_{\boldsymbol{p},\boldsymbol{g},\boldsymbol{t}} \right) \tag{1}$$

$$\begin{aligned} \text{s.t.}\quad & \text{Supply/demand balance} \\ & \text{Network losses} \\ & \text{Minimum/maximum outputs} \\ & \text{Ramp limits} \\ & \text{Minimum up/down times} \\ & \text{District heating requirements} \\ & \text{Hydropower storage} \\ & \text{Reserve requirements} \\ & \text{Relevant Chinese institutions} \end{aligned} \tag{2}$$

$\boldsymbol{x}$: commitments $\boldsymbol{y}$: outputs $\boldsymbol{z}$: other variables $\mathbf{c}$: start up costs $\mathbf{d}$: variable operation costs
$\boldsymbol{p}$: provinces $\boldsymbol{g}$: generators $\boldsymbol{t}$: time steps (1 hour)

The optimization simulates the decision-making situation faced by a central planner such as a vertically-

Assumption	Description	Application to China
Welfare maximization subject to constraints	Objective is to minimize cost of supplying a fixed demand, exclusive of investment decisions, subject to various constraints.	Holds if objective function consists only of costs or prices, and all other considerations (e.g., legacy planning institutions) are constraints that cut off part of decision-space.
Single optimizing agent	Under perfectly competitive conditions (no strategic exercise of market power) in a bid-based central auction, individual bidding behavior can be ignored.	While no bidding is done in China through, e.g., short-term centralized energy auctions, this assumption holds if dispatch decisions incorporate marginal costs in the objective function.
Perfect information	Projected demand and supply availabilities (i.e., wind resource) are known perfectly at beginning of time period.	Strictly not true. Holds to the extent that knowledge of demand and supply forecast errors would not change scheduling decisions (i.e., commitments).
Zonal demand and supply	Demand and supply zones are aggregated to the provincial level.	Holds if intra-provincial network constraints are never binding (resulting in congestion), and intra-provincial network losses are negligible.

Table 3: Quantitative reference model assumptions

integrated utility, but it equivalently represents the optimal set of market transactions from the perspective of an independent market operator under perfectly competitive conditions, i.e., no strategic use of market power (Pérez-Arriaga and Meseguer, 1997). In this case, the bidding behavior of individual firms may be ignored, simplifying greatly the modeling burden. There are four key assumptions of this model: constrained welfare maximization, a single optimizing agent, perfect information, and provincial zonal demand and supply, described in Table 3.

Using this modeling framework, the effects of different institutional combinations can be measured with respect to the reference scenario of a central optimization. Because of the complexities in actual system operation, including operator discretion, opaque bargaining processes, and insufficient quantifiable data on various smaller decisions, it is difficult to calibrate and validate the model against actual historical practice. Instead, the *relative* changes under different institutions (treatments) are used to build up contributions toward efficiency losses and other societal outcomes, with the remaining unexplained portions left for further qualitative analysis and/or modeling improvements. Given this structure, the *key model assumptions* are laid out in Table 3, and what should be examined is *to what extent these hold*, or in the case where they do not hold, *to what extent they change based on the individual treatments*.

It is instructive to contrast with statistical estimation techniques commonly used in political analyses and cross-country restructuring studies. A statistical approach to understand drivers for wind curtailment might use a panel regression at the unit of the province with covariates for various institutions and power system data (e.g., coal capacity, exports, etc.). This presents issues of estimation (e.g., low statistical power given limited sub-annual data availability) as well as identification (e.g., interactions among institutions and un-modeled technical constraints). The system has many thresholds and discrete effects that are difficult to capture: for example, there may be network and technology-specific features which prevent coal generation from going below certain levels or attaining certain intermediate values (e.g., discontinuous changes associated with turning on/off units). In this case, moving beyond the support of a given set of covariates to estimate a treatment effect may result in infeasible production schedules that, in practice, could not occur. Introducing more complex interaction terms (e.g., percentage of inflexible power supply and deployed wind) will be insufficient to address this, because they are nevertheless too coarse in the time dimension.

The UC model dramatically enhances the time resolution with respect to statistical models, creating an optimization problem with on the order of a million variables. Considering such a massive number of variables in a statistical estimation would lead to concerns of overfitting. However, this interpretation does not extend to an optimization framework, where these degrees of freedom are heavily constrained by physical and economic criteria—roughly 360,000 constraints in the basic formulation used for this study (see Figure 2).

4 China's Grid Institutions

4.1 Overview of Planning and Dispatch Operations

Concentrating on important decision points in annual and sub-annual electricity system operations, case study interviews indicate a power system in transition between traditional government-led production planning processes and decentralized actors responding to market forces. Local and central governments, grid companies, and generation companies engage in a highly structured annual planning process, similar to prototypical planning processes, which determines expected production totals for the year, confirmed by respondents in all cases. This is further broken down into seasonal and monthly decision points, where adjustments to the plan take place. Finally, sub-monthly adjustments are conducted almost exclusively within the grid company, and in most cases (with the exception of WIM) are restricted to maintenance scheduling and daily balancing functions. These short-term decisions typically do not adjust coal plant commitment decisions or inter-provincial transmission flows (see Figure 3).

The number of actors and diversity of interests have increased relative to pre-reform production plan-

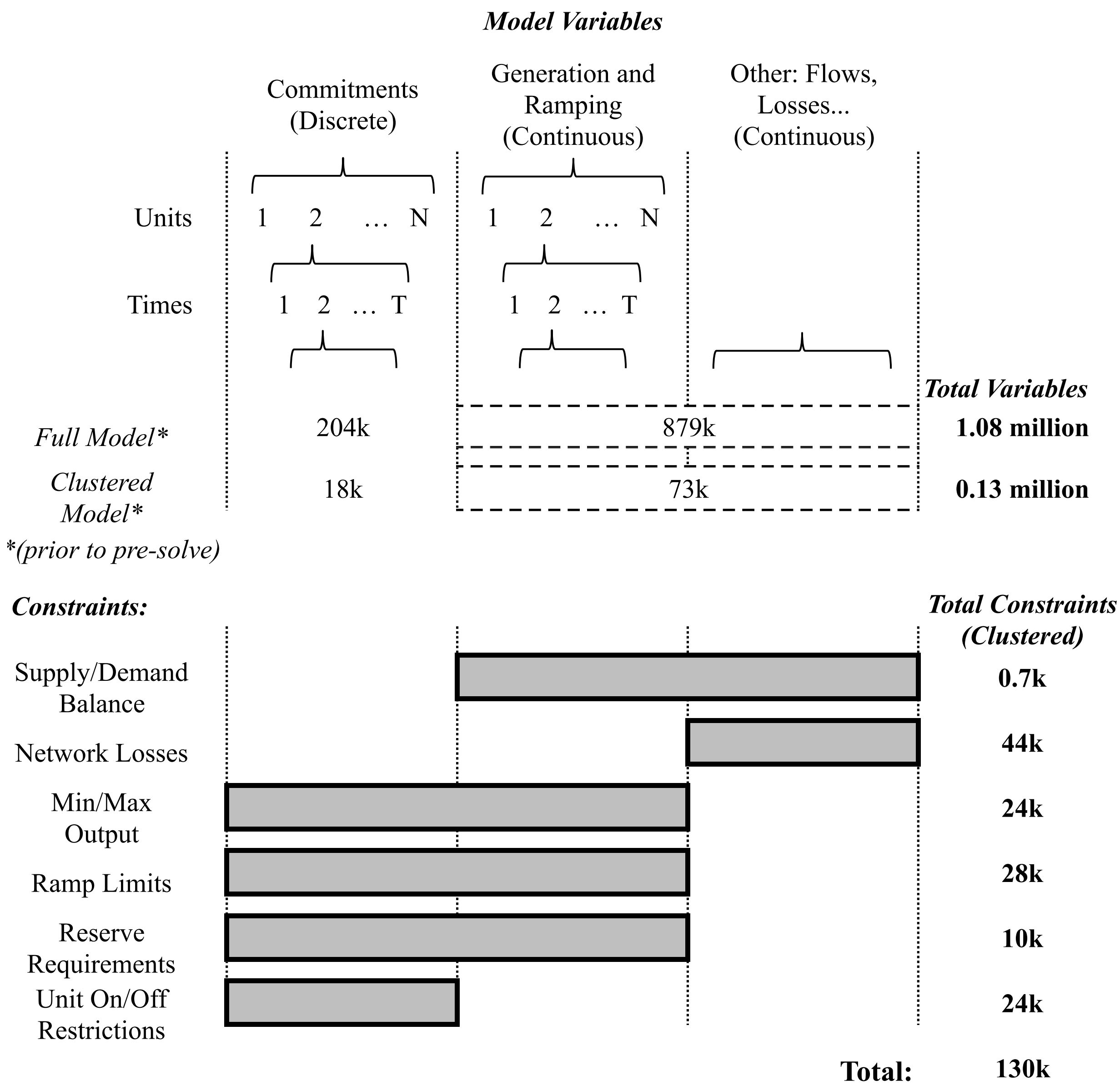
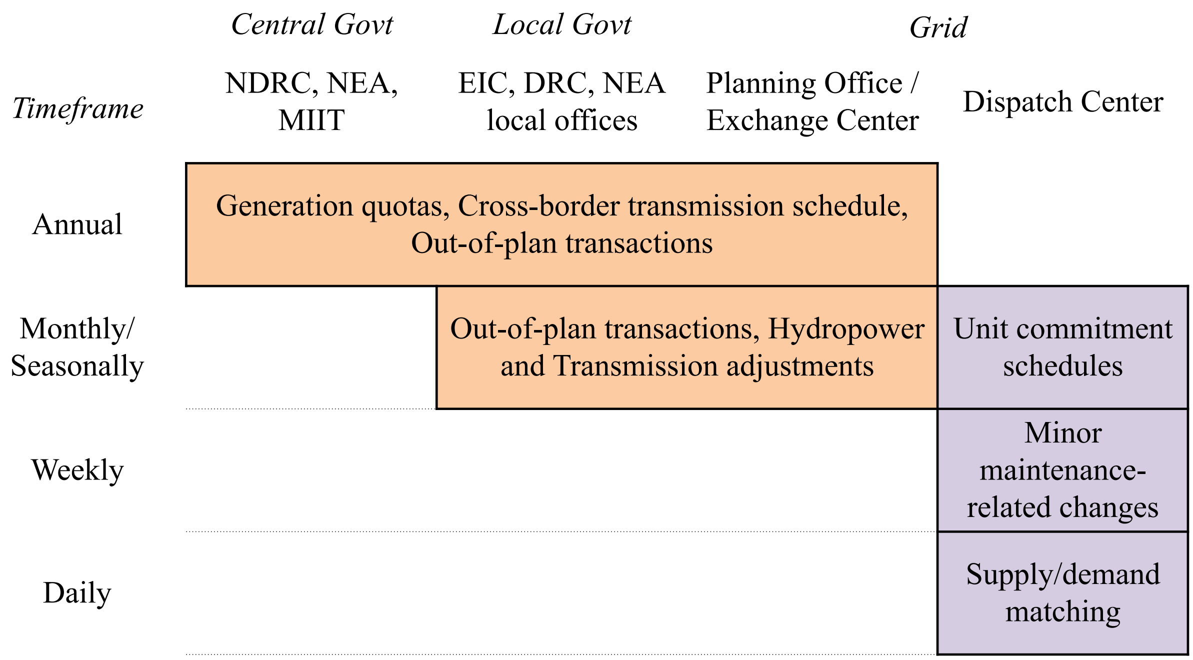


Figure 2: Structure of variables and constraints in quantitative UC model. Blocks under constraints indicate which variables are included in equation systems.



NDRC: National Development and Reform Commission
NEA: National Energy Administration
MIIT: Ministry of Industry and Information Technology
EIC: Economic and Information Commission (MIIT local bureau)
DRC: Development and Reform Commission (NDRC local bureau)
WIM: Western Inner Mongolia

Figure 3: Overview of dispatch planning process. Orange areas indicate focus of recent market reforms.

ning processes, which numerous respondents confirmed are resolved through negotiations at multiple stages. The provincial planning process is governed by local bureaus of the Ministry of Industry and Information Technology (*gongyehe xinxihuabu* | 工业和信息化部), which are referred to as either Economic and Information Commissions (EIC | *jingjihe xinxihua weiyuanhui* | 经济和信息化委员会) or Industry and Information Commissions (IIC | *gongyehe xinxihua weiyuanhui* | 工业和信息化委员会). These take the lead and make the final decision on annual plans. Inter-provincial trade that occurs within a single grid region is negotiated between relevant parties prior to this stage and typically sets boundary conditions for the provincial plan, though there maybe an iterative process based on concerns surfaced within provinces.

The central government observes this process, and of the local branches of central ministries, central priorities appear to be most represented in the National Energy Administration (NEA) local offices. They have the nominal authority to enforce certain central regulations (e.g., permitting approval procedures), though regulators in two regions confirmed that the power of the local NEA office is heavily constrained. They do not have the *de facto* power to approve or reject plans; rather, in the rare case they raise objections, this serves the purpose of prompting further negotiation with the local government.

By contrast, cross-regional trade amounts are essentially decided centrally in Beijing, based on national strategies such as large-scale plans for energy transfer from west to east and to substitute polluting coal-fired generation in load centers (NEA, 2014). This structure has been confirmed by multiple grid operator respondents and by other researchers (Kahrl and Wang, 2014). Once trade totals are decided (typically annually and adjusted monthly), there are various methods at the local level of allocating to generation firms, including bid-based markets such as between generators in Ningxia and load in Shandong via the Ning-Dong ultra-high voltage (UHV) line; allocation mechanisms such as Northeast Grid-North Grid electricity exchanges in which NE wind generators bid quantity into a centralized exchange at a fixed price; and through the typical provincial planning processes. Central directions following the 2015 reform document indicate preferences to handle both cross-provincial and cross-regional through bilateral negotiation and possibly auctioning, for the purposes of creating long-term, fixed-price contracts (NDRC, 2015).

4.2 Grid Company Roles

In determining which generator gets dispatched when and by how much, the grid company is more than an agent implementing the wishes of government officials. In the annual planning process, the provincial government takes the lead role, but the grid company can put limits in terms of how much generation it says it requires from various units for technical reasons. At seasonal and monthly intervals, this situation is reversed: the grid company's planning office (*jihuabu* | 计划部) and exchange center (*jiaoyi zhongxin* | 交易中心) have authority to allocate annual totals to months and clear various contracts, respectively, while the provincial government may influence the scope of these contracts. In all cases new exchange centers were recently established in line with reforms, though the notion of "relative independence" was challenged by many, elaborated further below.

On monthly and shorter intervals, the grid company's dispatch control center (*diaodu kongzhi zhongxin* | 调度控制中心) has almost complete autonomy in determining the commitments of units and output schedules. These should nominally meet the monthly plan totals, but all grid company respondents confirmed that there is flexibility in this process as long as annual totals are basically met. By contrast, monthly contracts must be met at the end of the month, reducing the flexibility of the dispatch control center to reallocate generation throughout the year.

Grid company discretion throughout this process is enhanced when annual plans cannot be met precisely, for example, when demand growth fell much below expectations in recent years or when dealing with uncontrollable resources such as wind, solar and hydropower. The set of basic principles guiding grid company actions is known as "transparent, fair and just" (*gongkai gongping gongzheng* | 公开公平公正) dispatch, abbreviated as *sangong* (三公) (SERC, 2003). Under this requirement, if demand is less than expected, then the relative shares of each generator in total production should be unchanged. In practice, this may be difficult to achieve, especially with multiple additional exchanges occurring throughout the year, and it could conceivably be used as a method of discrimination to give more production to preferred generators, though complaints of this among respondents were rare. Grid companies face no specific penalty for failing to comply with *sangong*, though there are numerous reported examples of violations (SERC, 2011; NEA, 2016b).

The grid company's interests do not completely align with the local or central governments. First, local grid company revenues come from the difference between the selling and buying price of electricity (for provincial grids). Hence, local grid companies will seek to reduce the price at which it buys electricity. Hydropower is generally the least expensive energy, subject to long-term, fixed-price contracts. Coal and renewable energy under the annual plan have the same price for grid companies, with the renewable energy subsidy paid by the central government, though the two are very different from government perspectives of employment and tax revenues.

Second, regional and national grid companies gain revenue from cross-provincial transmission tariffs. Hence, these grids should seek to expand and increase usage of cross-border transmission networks. By contrast, protectionist governments will aim to restrict imports and increase exports through the annual planning processes. Crucially, these make grid companies not independent parties to dispatch and network expansion, particularly of long-distance, high-voltage lines which receive the highest administratively-determined usage fees. Current plans to change grid compensation according to the 2015 reforms are to move from this "difference"-based approach to a "cost-plus" approach, wherein the grid company is simply paid back its costs plus a reasonable rate of return. Respondents noted that this would cause large changes in the above incentives, though no significant changes have been implemented yet in the regions studied.

In terms of market operation, mitigating any potential conflicts was the purpose of creating "relatively independent" exchange centers outside the grid company, though in practice, there appears to be little independence. They may take over the same people that were overseeing contracts previously under the planning office; and their offices may be co-located in the grid company. The reshuffling has resulted in very little change to operational practice.

Furthermore, counter-intuitively, if independence of the exchange center were achieved, this may make it more difficult to create short-term markets. There is considerable ambiguity, if a spot market (e.g. day-ahead or hourly) were established, who would operate it. International experiences indicate that to capture a reasonable level of network detail, some sophisticated models such as in Sec 3.3 would be required. This capability and relevant data currently only exist in the dispatch center. However, if the exchange is to handle all market transactions and were made fully autonomous, then it would require not only to have the model capability, but also to have access to a significant amount of data from the grid company, which it may not be willing to provide.

4.3 Inter-Provincial Trade Barriers

The primary economic unit in electricity planning is the province. Import and export totals between provinces are thus typically planned annually, negotiated between governments on the basis of supply and demand conditions. Because demand growth has not kept up with oversupply of generation capacity over the last 5+ years across the country, this is an extended negotiation process. For example, while Gansu used to have an advantage in being able to export its wind to other provinces, its neighbors have since developed their own renewable energy infrastructure, limiting the appetite and urgency to accommodate Gansu's excess supply. The grid company is evaluated on how closely electricity exchanged between provinces matches these plans. Official documentation shows that the provincial exchange verification process began as early as 1995 (CEAEC, 2003).

On a daily basis, cross-provincial flows are determined by these contracts and sets of prescribed profiles. For intra-regional flows, there is some flexibility in these profiles—e.g., ±10%—which Gansu has used successfully to integrate more wind. To make adjustments for the next day or current day's schedule, the provincial grid dispatch operator phones the regional grid, which acts as intermediary with the neighboring provincial grid company.

Cross-regional electricity trade is coordinated by the national dispatch center primarily through annual contracts, largely driven by demand requirements in the receiving regions. Negotiation processes for these are significantly more complex—involving local government offices, governors, all relevant local grids, the national grid and some central agencies—and thus considerably less flexible. For example, Northwest and Central grids share the *DeBao* (德宝线) ultra-high-voltage line that has a northern flow during wet summer months and switches southward during the dry season. In 2014, due to greater than predicted rainfall the Sichuan government had to petition the central government to extend the northern transfer an additional three weeks. A similar situation on a line to nearby Hubei in Central Grid was unable to be resolved, resulting in some early season curtailment of hydropower. These kinds of cross-regional adjustments have never happened to the author's knowledge in response to availability of non-dispatchable renewable energies like wind. Cross-regional transmission from WIM and NE to North Grid (which includes the Beijing region and surrounding provinces) functions similarly: the daily export profile is fixed based on the load, and total amounts on an annual basis are decided by North Grid and central officials.

To illustrate the role of grid operations and electricity sector institutions in creating barriers to trade, here I describe two types of barriers—"short-term" and "long-term"—and compare to the consequence of a typical barrier (import tariff) for a standard product, an automobile (see Table 4). Long-term barriers typically result from protectionist measures to support local industry in order to enhance local tax revenue, employment, industrial growth potential, and investment indicators. With an import tariff, this is a simple remittance. With electricity restrictions, it may be price-based, which can influence how much and where the marginal generator is located; it can also be quantity-based, which may require a complex allocation mechanism. Short-term barriers may be protectionist, but they may also be bureaucratic in nature: separate dispatch organizations may be unable to coordinate on the required time intervals to trade. Electricity systems also include different types of products known as "ancillary services", such as reserve generation (backup), which is the unused capacity of generators able to respond within seconds or minutes of system condition changes. There is no analogue to automobiles and many other products.

When compared to the automobile example, trade barriers in electricity system operations involve a

	Electricity	**Automobiles**
“Long-Term”	**Restriction:** Annual electricity import limit, import fee **Consequence**: *Limit*: Allocation to monthly plans, and conversion to restrictions in actual transmission flows for individual hours of day. *Fee*: Shifting price and location of marginal generator.	**Restriction:** Import tariff **Consequence:** Remit to government at time of purchase or on regular basis
“Short-Term”	**Restriction**: Limited ability to change transmission flows over short periods (e.g., daily to sub-hourly) **Consequence**: Provincial grids must handle internally short-time period imbalances. Limited trade in reserve generation.	N/A

Table 4: Illustrative barriers to trade for electricity and automobiles

wider range of actors and some may be the result of bureaucratic structures interacting with technical complexity, rather than intentional restrictions. This has important implications for research that takes interest alignment as the fundamental lever for successful reforms (e.g., Lema and Ruby, 2007). For example, one could misattribute a particular outcome such as low inter-provincial electricity trade as primarily the result of interest politics, which may be perfectly reasonable in the case of other traded goods, while for the case of electricity and other infrastructure goods there are multiple pathways to explain this outcome.

4.4 Market Experiments

Replacing portions of the planned electricity quota with medium-term contracts (monthly, seasonally, or annually) through bilateral or multi-lateral exchanges is the dominant form of market experiment in China, and has been piloted in all three regions. Shorter-term contracts or spot markets have not been a primary focus (see Figure 3). For example, facing large generator overcapacity and struggling local energy-intensive industry, Gansu in the Northwest grid began bilateral contracts in 2009, which allowed coal-fired electricity to be sold at below-benchmark rates (SCEO, 2015). In fact, it was so eager to avoid the central government-set tariffs that it began these markets without explicit approval and was ordered to temporarily stop (SCEO, 2015). Grid revenues remain unchanged under the arrangement, as the grid tariff is fixed according to the plan prices and “cost-plus” reforms are still in their infancy.

Contracts on monthly to annual timeframes integrate relatively seamlessly with existing dispatch institutions in the grid company and the newly created exchange centers. They can be tabulated alongside the quota, settled using the same system as the benchmark tariff (with the exchange center as clearinghouse), and incorporated in an analogous fashion into the monthly commitment scheduling process. Institutionally, they require relatively minor incremental changes, and the grid company (through the exchange center) still controls settlement. This alignment of legacy institutions and provincial government interests in lowering tariffs for large consumers explains why these types of contracts dominate.

In these electricity market pilots, local governments intervene in multiple ways that distort quantity and price. The EIC/IICs can determine market entry conditions, the total size of the market, price ranges (or even directly control the price), and the process of clearing bids.[5] These can be used to advantage consumers over generators, or even specific consumers, such as the case of WIM where industries compete on price differences relative to the government-set tariffs rather than on absolute price, thus preserving the aluminum industry's preferential rates. The Gansu IIC has even nullified exchanges whose outcomes they did not like, because they too heavily favored one market actor. Maintaining multiple levers of control even after directly giving up electricity quota planning, government officials and regulators appear to be motivated by desires to maintain control, reducing frictions with market introduction, in addition to protecting favored industries.

Since 2015, renewable energy began to participate in several exchanges, either through contracts with consumers similar to those described above, or through inter-regional "excess wind exchanges" that essentially allocate more transmission space for export at reduced price. Faced with high curtailment, wind farms have piled on in large numbers. Still, participation is uneven within and between grid regions: e.g., in the Northeast region, Heilongjiang and E. Inner Mongolia have been more frequently oversubscribed than other provinces. Many wind farm respondents expressed concerns that exchanges did not lead to completely additional generation—that is, they cannot easily confirm what would have been curtailed in the absence of signing these contracts. This is a fundamental difference between conventional energy and intermittent renewable energy, since the latter cannot be scheduled to be committed and dispatched a month in advance. Instead, the respondents admit that these renewable energy markets may be methods for local governments to partially allow users to avoid paying the full central tariff for electricity that would already be integrated.

[5] For example, Gansu's announcement of 2017 contracting only cites high-level central reform documents encouraging market contracts, and has numerous province-specific market design details such as participation thresholds (Gansu DRC, 2016).

4.5 Quantitative Modeling of Institutional Conflicts

Based on these qualitative data into dispatch planning practices, I isolate three conflicts caused by institutional design that likely have impacts on outcomes of interest (production cost and wind curtailment) and that are modelable within the proposed framework: the generation quota (Q), the limited transmission between provinces (T), and the limited ability to share reserves between provinces (P). These, and their model implementation, are summarized in Table 5 and detailed in the Appendix.

Quota (Q)	**Limited Transmission (T)**	**Provincial Reserves (P)**
Minimum generation allowance to coal-fired generators.	Planned total transfers between provinces.	Provinces cannot share reserve generation.
Implemented as minimum constraint on total generation for each type of generator, according to (44).	Implemented as reduction in interconnection capacity and restricted flow directions between provinces, in (10).	Must have adequate reserves available within province, according to (40)-(41)

Table 5: Three key political conflicts of grid operation modeled in this study. Equation references are in Appendix A.

The quantitative dispatch model rests on at least the four assumptions outlined in Table 3, which I explored through the qualitative interviews. Greater confidence in the model results will result from evidence that these hold or that the extent to which they do not hold does not depend on the three institutional treatments above. Findings for each of these is described in turn here.

Welfare maximization Current practice in China does not incorporate a short-term optimization that strictly dispatches generators according to least marginal cost. There are various directives such as mandatory dispatch of renewables and energy-efficient dispatch that would influence this, but they appear to implemented (if only partially) on a longer-term basis. Hence, it cannot be argued that the quantitative model is an accurate representation of the actual decision-making situation faced by Chinese grid operators. On an intra-day basis, some limited form of optimization may be implemented to minimize deviations with the day-ahead schedule (e.g., Yang and Tang, 2011).

But, some of the political conflicts modeled here—e.g., generation quotas and market transactions, and inter-provincial transmission contracts—are clearly seen and implemented as constraints. For example, the grid company does not compensate generators for failing to meet their contracts—it simply must meet them. Compensation for curtailment or failure to meet quotas would, on the other hand, need to be added to the objective function. In alignment with the model structure, reserves are implemented as constraints in practice, hence co-optimized by dispatch.

Single optimizing agent Dispatch is indeed centralized in Chinese systems, as opposed to complete self-scheduling, as in the UK, or partial self-scheduling, as in many other power markets. Furthermore, since there is no short-term bidding, the effects of market power do not enter dispatch. One additional consideration has to do with potential conflicts of interest: favoritism in dispatch was not noted by any wind generators as a serious issue, in contrast to reported widespread favoritism in the 1990s (Bai and Qian, 2010). Hence, the single provincial dispatch optimizing agent case appears to be supported. The counterfactual of regional dispatch is also reasonable, given that some plants are already dispatched by the regional operator.

Perfect information The model presented solves simultaneously an entire week's commitments and dispatch, assuming perfect knowledge of demand and wind. This is not an accurate description of reality since forecast errors of both can be substantial. Extensions of this work use a two-stage model with uncertain realizations of wind to uncover greater nuance in China's scheduling practices (Davidson and Pérez-Arriaga, 2018). The model presented here is arguably *no worse* than what China does in practice. The modeled institutions do not directly implicate changes in how forecasts are utilized, so I argue they are not co-dependent. However, if day-ahead decisions on transmission inter-ties were to be more flexible—such as is the case in Northwest, the subject of future modeling scenarios—then a full uncertainty analysis is needed.

Zonal demand and supply Intra-provincial constraints are ignored, which is possibly the greatest limitation of this analysis. For example, wind power concentrated in certain areas (e.g., Baicheng in Jilin province, as noted by some respondents) may be unable to export to the rest of the province. These constraints were not considered due to difficulty in obtaining sub-provincial network detail. In the model, integrating this wind would not face any transmission constraints until changes to inter-provincial flows would be required, and hence model results would tend to underestimate the technical causes of curtailment. These further impact reserve requirements, because generators behind a congested line cannot provide some reserves to the rest of the province. Quotas and inter-provincial transmission are less affected by this.

5 Model Results

I demonstrate these formulations on the Northeast China Grid (NE) using historical data from 2011 winters (capacities at the end of 2010) from an authoritative source for plant-specific information produced by the country's main electricity trade association (CEC, 2011). The NE grid is recognized for its high degree of technical inflexibility from the large penetration of coal-fired combined heat and power plants, relative lack of flexible generation such as hydropower and natural gas, and overcapacity in thermal generation (Zhao et al., 2012). Overcapacity would tend to increase the relative importance of quotas as more thermal generators must be accommodated, and collectively these indicate signs of coupled political and technical constraints modelable within this framework. Among other outward signs of operational difficulties, the NE has consistently high amounts of wind curtailment, reaching 20%, 15% and 10% in Jilin, Heilongjiang and Liaoning provinces in 2011, rising to 30%, 19% and 13%, respectively, in 2016 (State Grid, 2012; NEA, 2017b). The year 2011 was also chosen to simplify the analysis to just the NE grid, as its external connections to other grid regions were very limited and can be ignored: only 3% of total generation was exported (to North China Grid) in 2011 (State Grid, 2012).

The experimental setup consists of running the unit commitment model over a one-week horizon (168 hour time-steps) in the winter season when wind curtailment is highest, and averaging results over six different scenarios of wind production keeping all other inputs (e.g., demand) constant. The impact of the identified institutional features is tested through a full factorial setup of all combinations of turning on and off the three political conflicts (8 models in total), as well as a number of sensitivities.

5.1 Reference Results

The reference model, in the absence of political conflicts, results in high capacity factors from must-run cogeneration units, wind, and high-efficiency coal (coal600). All other generators are relatively unused, and production from low-efficiency non-cogeneration units are basically zero (see Figure 4). This is consistent with a system with sufficient technical flexibility to accommodate wind, with wind curtailment less than 2% (see Figure 5). Additional validation of the clustered model with respect to the traditional binary commitment variable model ("full model") was performed, and errors introduced by this simplification were small: objectives are within 0.02% and wind totals within 0.14% (see Appendix for more details).

5.2 Disaggregating Institutional Effects

The results of layering on institutions are shown in Figure 5, plotted as a function of the two outcomes of interest: wind curtailment percentage and total production cost. The reference case without any of the institutional constraints is in the bottom-left (R) which is essentially the same result as the case of adding only provincial reserve and technical constraints (P). This shows that even in a baseline case, there is some limited wind curtailment due to technical constraints alone. As constraints are added, costs increase, as expected. Curtailment is most affected, however, by the interaction of the constraints on limited transmis-

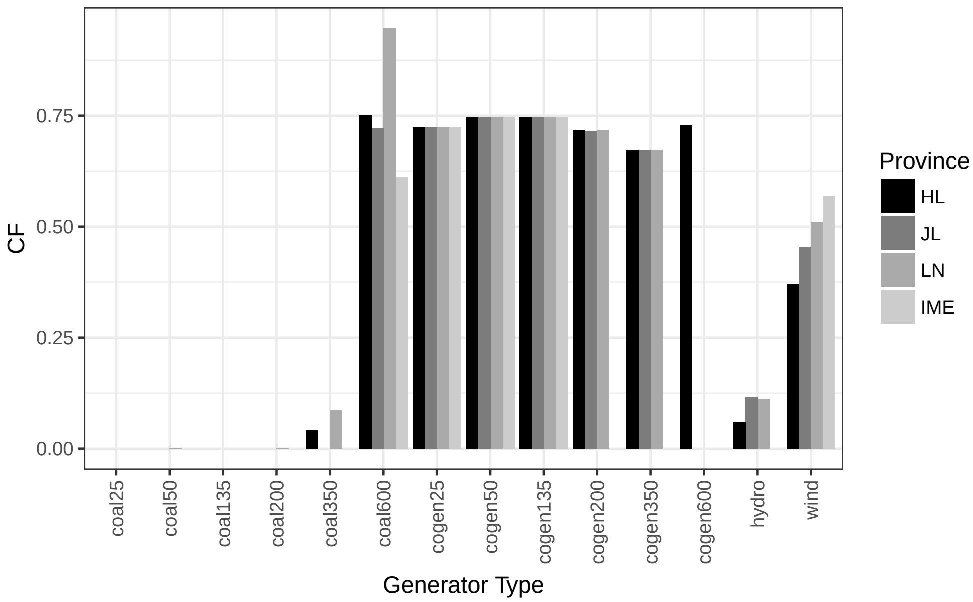


Figure 4: Capacity factors of generation types by province

sion and on requiring provinces balance reserves themselves (no reserve sharing). Without either of these, wind curtailment falls dramatically. Put another way, the quota alone does not explain wind integration outcomes. Individual wind scenario results show large variances in terms of costs, but relatively consistent wind curtailment rates, as shown in Appendix B, Figure 7.

Using the computationally-efficient clustered model formulation, a large range of institutional parameter sensitivities is run: see Figure 6 for the case of modifying the quota. Here, the ratio of the quota in each province is changed uniformly with respect to the default quotas, i.e. a ratio of 1.0 is the default, and 0.0 is the absence of a quota.

As the quota increases, the effect of limited transmission on the objective decreases, causing convergence of RTQ, PQ and RQ. The interaction of transmission and within-province reserves is robust, however, to changes in quota: the effect on wind curtailment is essentially flat for all quota values.

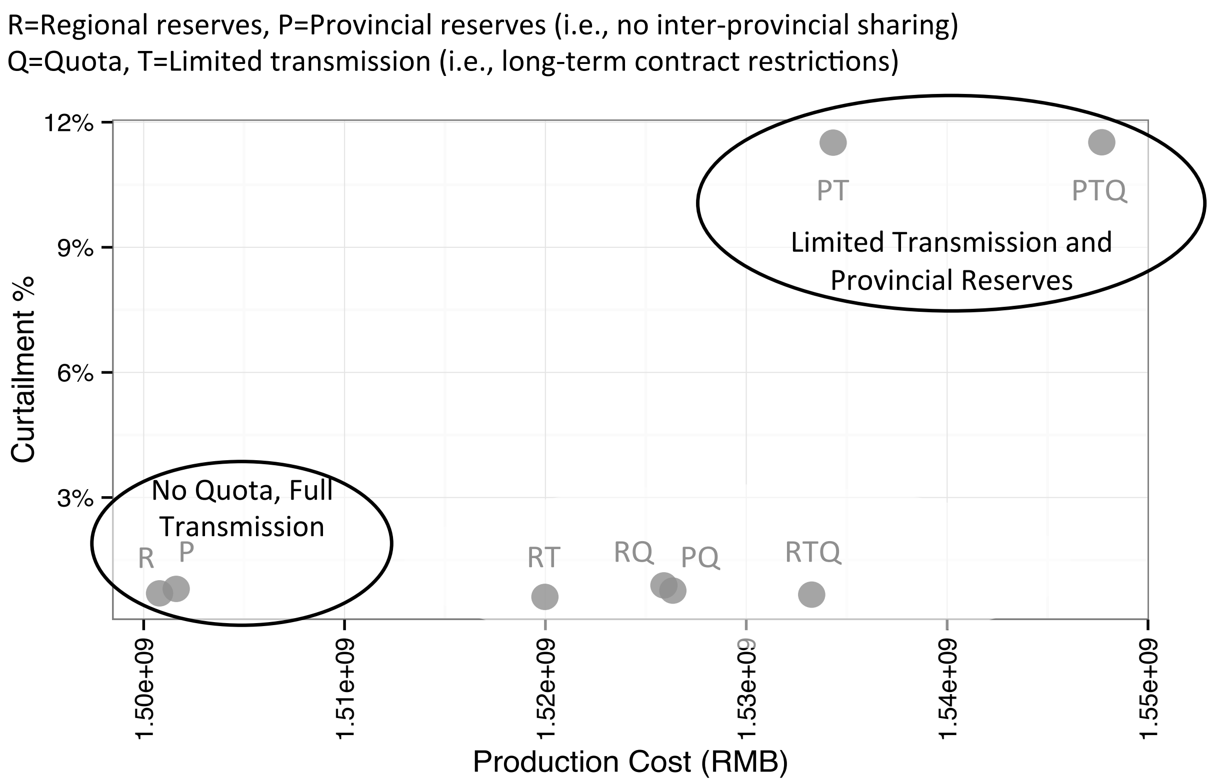


Figure 5: Model results for all combinations of political conflicts

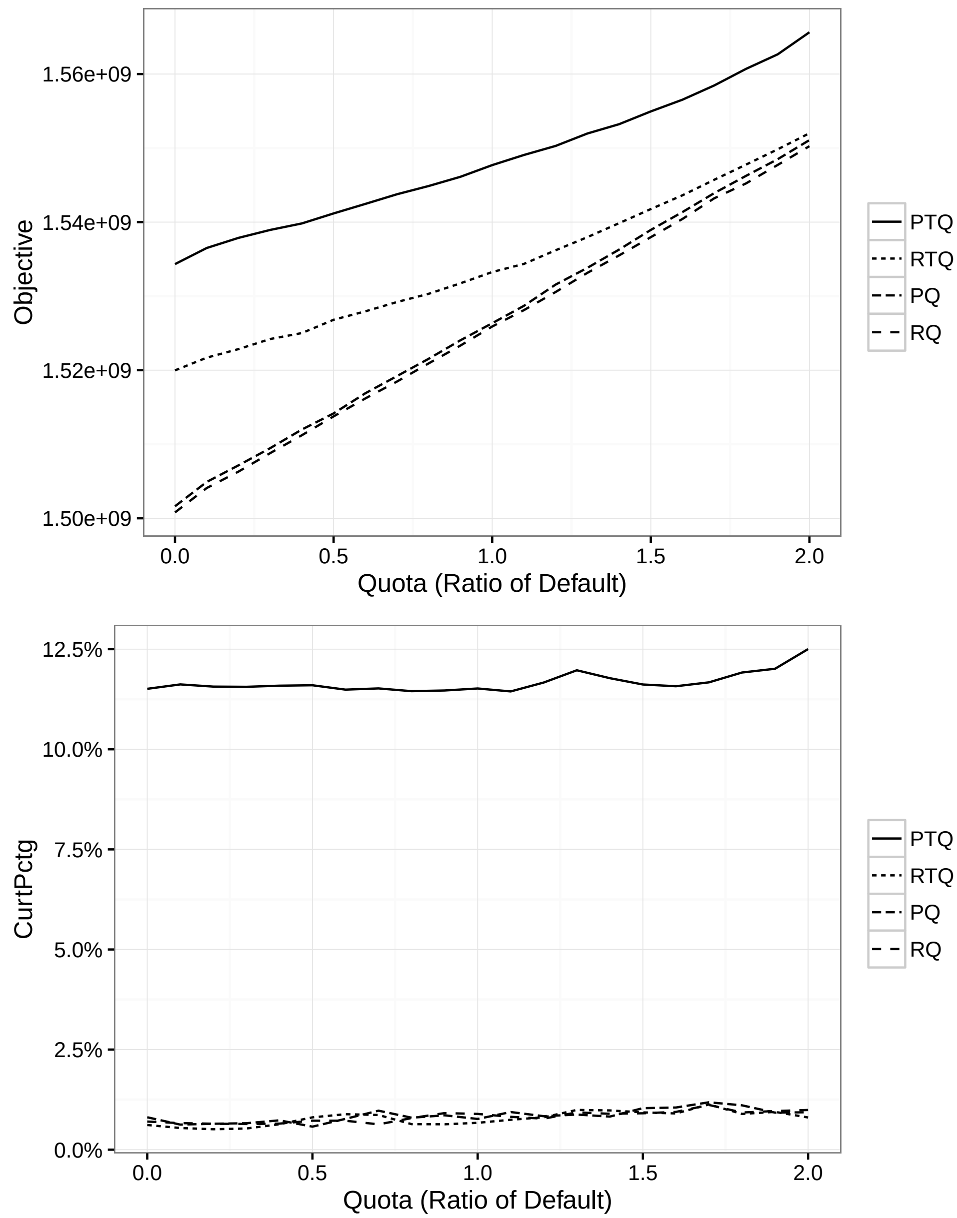


Figure 6: Objective (*top*) and wind curtailment (*bottom*) as a function of quota relative to default values. R=Regional reserves, P=Provincial reserves, T=Limited transmission, Q=Quota.

6 Discussion

6.1 Implications for China's Electricity Policy Reforms

China's latest round of electricity reforms, inaugurated in 2015, reiterate central government intentions to address inefficiencies in the "planned" sector by moving to more market mechanisms, including addressing renewable energy curtailment. Nevertheless, proposed approaches differ from international lessons, and because of local government autonomies over market design and operation, there is still considerable uncertainty over how much and how fast institutional change is to be expected. Because of complexities in system operation restricting the ability of actors to pursue interests, this study advances a combined quantitative-qualitative approach that can address traditional questions of the benefits of market restructuring as well as its much more difficult to assess impacts on renewable energy outcomes.

A quintessential feature of operations in China is the quota system, which allocates on an annual basis planned generation to conventional generators (i.e., non-renewable). Key emphasis in reform documents has been placed on moving away from the quota toward market-driven contracts as observed in China's approach to liberalization in other sectors. Modeling results indicate this would reduce overall costs, but have limited impacts on wind integration without changing other institutions. In particular, keeping other institutions the same, reducing quotas by implementing medium-term bilateral contracts—assuming contracted coal plants have lower marginal costs than quota-dependent plants—would shift production around among coal plants more than from coal to renewable energy. Additionally, there are indications that contracts lead to greater inflexibility in dispatch than traditional planning processes, potentially problematic for system operation and renewable energy.

Model results confirm the crucial role of inter-provincial trading in addressing wind energy integration challenges. By contrast, virtually all proposed generation markets to date are in the context of provincial pilots; hence, they do not alter the current plan-based cross-provincial trading schemes. This study shows the limitations of this approach and the need to look at institutions causing cross-provincial trade barriers in order to achieve stated renewable energy goals. Some of these institutions, such as sharing reserves, are less likely the result of intentional protectionist trade measures as opposed to coordination challenges and desires by both grids and governments for autonomy. Additionally, numerous technical constraints modeled here limit the extent to which politicians can direct benefits and costs of production, analogous to the distributive politics of provision of access.

The focus on intra-provincial markets derives from strong interest alignment of both central and local governments in reducing planned electricity allocations: the center sees benefits of enhanced efficiency, and the provinces see reductions in electricity price for local industries. Secondarily, even if interests were realigned to promote inter-provincial trade through annual plans, this still may not capture all benefits of electricity trading in the absence of other less visible institutions, such as coordinated reserve generator sharing and dispatch coordination. In one of many idiosyncratic issues with the electricity system, technical issues such as these may require institutional changes that appear to be less significant or extend beyond simply aligning interests.

More fundamentally, these cases caution against the universality of the "market" concept. As has been noted for other sectors, Chinese market planners may have different efficiency goals—e.g., making incumbents stronger rather than inviting disruptive new entry (Steinfeld, 2004). In fact, markets may be engaged as a way to achieve a state objective other than efficiency, where administrative processes have been inadequate. While the security of property rights has been reinterpreted in analysis of China's local economic reforms to include informal connections, the rapid scale-up of electricity market has been greased partially by local government predation on insecure property rights, such as the case of excess wind contracts.

Establishing trading arrangements among relatively autonomous jurisdictions is notoriously difficult, but there are many international examples from which to learn. The US model of fully-integrated sub-national jurisdictions into ISOs has demonstrated significant economic gains but requires states to give up the greatest amount of autonomy. The EU model of separating external and internal transactions is more politically palatable to participating nations but at some cost, particularly in terms of flexibility to accommodate renewable energy. China's provinces are likely closer to the EU member states in terms of the degree of political and regulatory autonomy they enjoy from their neighbors, hence the history of EU electricity markets should be instructive for Chinese policy-makers.

In the absence of improved inter-provincial trading, China's road to addressing renewable energy curtailment becomes more difficult: as the quota is not the primary political factor driving wind integration challenges, new iterations—such as the successor to "energy-efficient dispatch", known as "green dispatch" —will need to address short-term dispatch priorities, rather than continuing to focus on annual plan-based allocation, to be effective. However, as current reforms focusing just on bilateral contracts can reduce total costs, providing large benefits to local industrial interests, addressing renewable energy curtailment will likely need to raise in importance for local governments as well to obtain more difficult reforms to system operation.

China's challenge in increasing efficiency and flexibility while preserving institutional legacies is mirrored in the restructuring difficulties of other developing countries. India's power sector is predominantly locked into 25+ year contracts that are regulated differently depending on whether they are intra- or inter-state, resulting in only a small fraction of short-term transactions (Kumar and Chatterjee, 2012; CERC, 2017). The Southern African Power Pool, consisting of 12 countries, has inefficiencies resulting from preserving various longer-term contracting methods over the flexibility of short-term exchanges (Rose et al., 2016).

6.2 Methodological Notes

6.2.1 Iterative Methodology

This paper demonstrates an approach to combine qualitative case fieldwork with a quantitative model to represent complex technical and institutional processes. The results show the benefits of basing quantitative models on qualitative insights in order to understand interacting institutions. There is a strong case for qualitative→quantitative reasoning in the traditional triangulation sense of identifying the subset of causes that are supported by multiple streams of evidence.

The converse logic, quantitative→qualitative reasoning, also held in this case, albeit more indirectly. The model-building process and case interviews were concurrent over the course of the study (2013-2016): between field visits new features were added to the quantitative model, and these results sharpened question guides in subsequent interviews. I will particularly note this with regard to processes underlying reserve sharing and to the role and benefits of reducing the quota through increased medium-term contracts.

There are several limitations to this type of approach. Most notably, iteration will only work on modelable institutional constraints, which must by definition have a quantitative nature and be amenable to the chosen modeling framework. For optimization models such as presented here, this should take the form of adjusting variables, constraints or decision-making objectives. For regression models, options are more limited: typically, additive controls on proposed covariates or interaction terms. In particular, this model does not address the interests and relative strengths of actors during the quota-setting process; specific coordination processes such as between provincial dispatch institutions; more complex motivations of grid companies, especially at different jurisdictions; and effects of strategic behavior and political connections of generation companies. There are also significant time and resource requirements to develop and test an appropriate model, and conduct iteration over multiple field visits, which should be considered before embarking on this type of analysis.

Assumptions underlying the quantitative model, often untested in comparative analyses on restructuring, have also been highlighted, in an analogous way to assumptions for causal inference using regression techniques. I have found that some assumptions—e.g., single optimizing agent—are well-supported, and others—e.g., welfare maximization and perfect information–-are reasonably unrelated to the institutional treatments. The choice of provincial zones of demand and supply (neglecting intra-provincial congestion) could be problematic, particularly for the role of reserve calculations, requiring further study.

6.2.2 Generalizing Implications of Quantitative Results

An important finding for the modeled case was the role of the interaction of different institutions on outcomes of interest, in particular wind integration. Relieving or removing some of the negotiation processes among diverging interests (e.g., long-term barriers to trade arising from protectionist policies) can lead to improved outcomes for some metrics, even without relieving some of the bureaucratic constraints. Conversely, improving flexibility by removing bureaucratic constraints—in particular, sharing reserves across provinces—can lead to better outcomes even while maintaining interest-driven negotiations.

Because of manifold differences in provincial electric systems, these implications should be appropriately scoped. Here, case work can help to highlight similarities and differences in crucial processes. For example, across the cases studied, there is broad convergence on the assignment of authorities, responsibilities and bargaining game structures, even across different grid companies. Some differences were apparent: respondents in the WIM grid noted, because it is limited to a single province there is closer alignment with the local government. The grid company also has more authority such as the ability to create commitment schedules primarily on the weekly level as opposed to monthly. One hypothesis for future study is that the former provides the local government (principal) with more confidence to grant autonomy to the grid (agent).

Another key difference is along the dimension of relative importance of cross-regional exports: the NW and WIM have very large export capacities, and their exports align with central government goals of large energy transfers. The modeled NE case does not consider this higher level of national strategy.

6.3 Future Work

Additional modeling opportunities include using the quantitative grid operation model to evaluate additional tests of hypotheses such as the effect of different forms of bilateral contracts, which may also provide direction for future small-N inquiries, e.g., by looking at other cases with low wind penetration but significant bilateral contracts. Expanding the grid operation model to multiple regions, including out-of-sample cases, can help strengthen causal interpretations from the quantitative model. This is not trivial, as each new region requires data collection and parameterization, but it is often easier than adding an entirely new set of field visits. The case work also highlights the complex set of grid company incentives in dispatch, which were not modeled here beyond fulfilling government-mandated quotas. Future modeling efforts could examine these, as well as how they might change under proposed changes to grid company compensation rules.

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Appendix A: Clustered Unit Commitment Model

The standard unit commitment problem seeks to minimize operational costs of meeting a given electricity demand, whose objective consists of variable generation costs and the startup (commitment) costs of thermal generators. In the classic formulation (Ostrowski et al., 2012), this results in a mixed-integer linear program (MILP) of minimizing a linear objective subject to linear constraints and variables that are either continuous or discrete as in (1). It is implemented in this study in GAMS and solved numerically using ILOG CPLEX 12.6.2. Each scenario is run using up to 24 parallel threads on a dual-socket 12-core 2.5 GHz Intel Xeon machine with 128 GB RAM. The mixed integer optimality tolerance is set to 10^{-3} and the resource limit (time at which to terminate the algorithm if unable to converge) to 240 minutes.

The model and data inputs are outlined below and described in detail in Davidson and Pérez-Arriaga (2018). Generator constraints on production and commitment include minimum and maximum outputs, maximum ramp rates, and minimum startup and shutdown times, based on generic values as a function of unit size. The network is simplified to one node per province and inter-provincial transmission constraints to Kirchhoff's first law, neglecting complex power flows. Hence, intra-provincial network congestion is ignored. Between provinces, some standard assumptions on capacities and losses as a function of voltage and distance are used (PJM, 2010). This formulation uses a piece-wise linear loss function, an adequate approximation for the general loss formulation which involves sinusoids (Fitiwi et al., 2016). Reserve constraints are enforced at either provincial or regional level (depending on the institutional constraints) to respond to unpredicted changes in demand or supply. Data on generator sizes, transmission networks, and wind and demand profiles are as in Davidson and Pérez-Arriaga (2017).

Combined heat and power (CHP) for district heating is widespread in northern China, where much residential heating in urban areas as well as process steam for industrial applications are provided by centralized cogeneration facilities (Zhao et al., 2012). These primarily coal-fired cogeneration units have different operational constraints than conventional coal units, co-dependent on heat and electricity output, and have higher minimum and lower maximum limits, verified from interviews to be reasonable. After fixing minimum outputs of these must-run units, the fraction that are committed must also be specified. The ranges offered in previous studies demonstrate some data concerns (Zhao et al., 2012, 2013). Hence, for this study, cogeneration units from each province are made must-run roughly equally across sizes in order to achieve around a 80% commitment rate. Sensitivities around this threshold have been shown to not influence the main results qualitatively (Davidson and Pérez-Arriaga, 2017).

Improving computational performance of unit commitment models is a major area of research. Here, a multi-nodal clustering approach based on the single-node formulation is employed, where multiple binary commitment variables of similar units are combined into integer variables over the combined cluster of generators (Palmintier and Webster, 2014). This results in some loss of precision, but significantly improves solution times and the ability to capture long-term coupling constraints such as the production quota. The validation presented in Appendix B demonstrates that errors are minimal for this system. Coal units are clustered according to the closest of six different sizes frequently found in China and observed during cross-checking: 25, 50, 135, 200, 350 and 600 MW. Combined with the CHP and electricity-only distinction, this leads to 12 coal clusters per province. Wind and hydropower are each a single cluster per province. The NE grid has some hydropower facilities, which are considered as a flexible resource over the model horizon, with inflows given by historic ranges and fixed initial and final states, and minimum and maximum reservoir levels.

Due to additional institutions governing China's electricity sector operations, this formulation does not represent the decision-making situation faced by grid operators. As a result of strong provincial autonomy in dispatch, *long-term inflexibilities* associated with inter-provincial transmission contracts and *short-term inflexibilities* due to coordination challenges between distinct operators in charge of balancing operations ($<$ 1 hour). The former are based on average transmission using annual exchange data (State Grid, 2012). The latter are imposed through separate reserve requirements at the provincial level.

The quota is represented as a minimum amount of generation over the course of the time period that must be met collectively by each generator cluster. These are not published, and hence must be inferred from annual average capacity factors, collected from 2012 due to data unavailability in the modeled year of 2011 (CEC, 2011).

Nomenclature

Sets:

$k \in G$: clustered generator types

$t \in T$: time periods

$p \in P$: provincial nodes

$G_p \subset G$: generators in province p

$G_{p,k} \subset G_p$: generators of cluster type k in province p

$G_{wind} \subset G$: wind generators

$G_{hydro} \subset G$: hydro generators

$G_{res} \subset G$: generators providing reserves

$G_{thermal} \subset G$: thermal generators

$G_{CHP} \subset G_{thermal}$: combined heat and power generators

$G_{quota} \subset G_{thermal}$: thermal generators with quotas

Decision Variables:

$\boldsymbol{y}_{p,k,t} \geq 0$: production of cluster k in p at time t

$\boldsymbol{w}_{p,k,t}$: auxiliary ramping variable, cluster k in p at time t

$(\boldsymbol{u}_{p,k,t}, \boldsymbol{v}^{up}_{p,k,t}, \boldsymbol{v}^{dn}_{p,k,t}) \in (\mathbb{Z}_{\geq 0})^3$: commitment variables in clustered formulation

$\boldsymbol{r}_{p,k,t}, \boldsymbol{s}_{p,k,t} \geq 0$: up and down reserve capabilities in clustered formulation

$\boldsymbol{f}_{p,p',t}$: flow from p to p' at time t

$\boldsymbol{f}^+_{p,p',t}, \boldsymbol{f}^-_{p,p',t}$: positive and negative components of $\boldsymbol{f}_{p,p',t}$

$\boldsymbol{l}_{p,p',t}$: transmission losses due to flow $\boldsymbol{f}_{p,p',t}$

$\boldsymbol{j}_{p,p',t,s}$: sth piece-wise segment of the flow $\boldsymbol{f}_{p,p',t}$

$\boldsymbol{h}_{p,k,t}$: hydro reservoir level of hydro generator cluster k in p, in units of generation

Parameters:

$d_{p,t}$: demand at p at time t

p^{var}_k: variable cost of generator type k

p^{su}_k: startup cost of generator type k

$\underline{P}_k, \overline{P}_k$: minimum and maximum outputs of generator k

$\overline{F}_{p,p'}$: transmission flow limit from p to p'

$\mu_{p,p'}$: quadratic resistive loss coefficient of path p to p'

$W_{p,k,t}$: available wind power of generator type k in province p at time t

RD_k, RU_k: down and up ramp rate limits of generator type k

MD_k, MU_k: minimum down and up times of generator type k

$\underline{RES}_t, \overline{RES}_t$: down and up regional reserve requirements at time t

$\underline{RES}_{p,t}, \overline{RES}_{p,t}$: down and up provincial reserve requirements in p at time t

$H_{p,k}$: mean hydro inflow of cluster k in p over a timestep

$HL_{p,k,t}$, $t = \{1, |T|\}$: initial and final levels of hydropower cluster k in p

$Q_{p,k}$: minimum generation quota at p for generator cluster k

Model

$$\min \qquad \textstyle\sum_{p\in P}\sum_{k\in K}\sum_{t\in T}\left(p_k^{su}\boldsymbol{v}_{p,k,t}^{up}+p_k^{var}\boldsymbol{y}_{p,k,t}\right) \tag{3}$$

$$s.t.$$

$$\tag{4}$$

Supply/Demand Balance

$$\sum_{k\in K}\boldsymbol{y}_{p,k,t}-\sum_{p'\neq p}\left[\boldsymbol{f}_{p,p',t}+\boldsymbol{l}_{p,p',t}/2\right] = d_{p,t}\ ,\ \forall p\in P \tag{5}$$

$$\boldsymbol{f}_{p,p',t} = -\boldsymbol{f}_{p',p,t} \tag{6}$$

$$\boldsymbol{f}_{p,p',t} = \boldsymbol{f}^{+}_{p,p',t}-\boldsymbol{f}^{-}_{p,p',t} \tag{7}$$

$$\sum_{s}\boldsymbol{j}_{p,p',t,s} = \boldsymbol{f}^{+}_{p,p',t}+\boldsymbol{f}^{-}_{p,p',t} \tag{8}$$

$$\forall t\in T,\ p,p'\in P \tag{9}$$

Transmission Losses

$$\boldsymbol{f}_{p,p',t}+\boldsymbol{l}_{p,p',t}/2 \leq \overline{F}_{p,p'} \tag{10}$$

$$\boldsymbol{l}_{p,p',t} = \mu_{p,p'}\sum_{s}\alpha_{p,p',s}\boldsymbol{j}_{p,p',t,s} \tag{11}$$

$$\alpha_{p,p',s} = (2s-1)\,\Delta f_{p,p'}\ , \tag{12}$$

$$\forall s=1..S$$

$$\Delta f_{p,p'} = \overline{F}_{p,p'}/S \tag{13}$$

$$\boldsymbol{l}_{p,p',t},\boldsymbol{f}^{+}_{p,p',t},\boldsymbol{f}^{-}_{p,p',t},\boldsymbol{j}_{p,p',t,s} \geq 0 \tag{14}$$

$$\forall t\in T,\ p,p'\in P$$

$$\tag{15}$$

Minimum/Maximum Outputs

$$\underline{P}_k \boldsymbol{u}_{p,k,t} \leq \quad \boldsymbol{y}_{p,k,t} \quad \leq \overline{P}_k \boldsymbol{u}_{p,k,t} \ , \ \forall p \in P, k \in G_{thermal} \tag{16}$$

$$0 \leq \quad \boldsymbol{y}_{p,k,t} \quad \leq W_{p,k,t} \ , \ \forall p \in P, k \in G_{wind} \tag{17}$$

$$\tag{18}$$

Ramp Limits

$$\boldsymbol{w}_{p,k,t} = \boldsymbol{y}_{p,k,t} - \underline{P}_k \boldsymbol{u}_{p,k,t} \tag{19}$$

$$\boldsymbol{w}_{p,k,t} - \boldsymbol{w}_{p,k,t-1} \leq \boldsymbol{u}_{p,k,t} RU_k + \boldsymbol{v}^{up}_{p,k,t} \underline{P}_k \tag{20}$$

$$\boldsymbol{w}_{p,k,t-1} - \boldsymbol{w}_{p,k,t} \leq \boldsymbol{u}_{p,k,t} RD_k + \boldsymbol{v}^{dn}_{p,k,t} \underline{P}_k \tag{21}$$

$$\forall p \in P, k \in K, t \in T$$

$$\tag{22}$$

Minimum Up/Down Times

$$\boldsymbol{u}_{p,k,t} \leq |G_{p,k}| \tag{23}$$

$$\boldsymbol{u}_{p,k,t} \geq \sum_{t'=t-MU_k}^{t} \boldsymbol{v}^{up}_{p,k,t'} \tag{24}$$

$$|G_{p,k}| - \boldsymbol{u}_{p,k,t} \geq \sum_{t'=t-MD_k}^{t} \boldsymbol{v}^{dn}_{p,k,t'} \tag{25}$$

$$\boldsymbol{u}_{p,k,t} - \boldsymbol{u}_{p,k,t-1} = \boldsymbol{v}^{up}_{p,k,t} - \boldsymbol{v}^{dn}_{p,k,t} \tag{26}$$

$$\forall p \in P, k \in K, t \in T$$

$$\tag{27}$$

District Heating Requirements

$$\underline{P}_k \leq \quad \boldsymbol{y}_{p,k,t} \quad \leq \overline{P}_k \ , \ \forall p \in P, k \in G_{CHP} \tag{28}$$

$$(29)$$

Hydropower Storage

$$\boldsymbol{h}_{p,k,t} - \boldsymbol{h}_{p,k,t-1} = H_{p,k} - \boldsymbol{y}_{p,k,t} \tag{30}$$

$$\boldsymbol{h}_{p,k,t} = HL_{p,k,t} \text{ , } t \in \{1, |T|\} \tag{31}$$

$$\boldsymbol{h}_{p,k,t} \geq \underline{HL}_{p,k} \tag{32}$$

$$\boldsymbol{h}_{p,k,t} \leq \overline{HL}_{p,k} \tag{33}$$

$$\boldsymbol{h}_{p,k,t} \geq 0 \tag{34}$$

$$\forall p \in P, k \in G_{hydro}, t \in T$$

$$(35)$$

Reserve Requirements

$$\boldsymbol{r}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}\overline{P}_k - \boldsymbol{y}_{p,k,t} \tag{36}$$

$$\boldsymbol{s}_{p,k,t} \leq \boldsymbol{y}_{p,k,t} - \boldsymbol{u}_{p,k,t}\underline{P}_k \tag{37}$$

$$\boldsymbol{r}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}RU_k \tag{38}$$

$$\boldsymbol{s}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}RD_k \tag{39}$$

$$\forall p \in P, k \in G_{res}, t \in T$$

$$\sum_{k \in G_{res}} \boldsymbol{r}_{p,k,t} \geq \overline{RES}_{p,t} \tag{40}$$

$$\sum_{k \in G_{res}} \boldsymbol{s}_{p,k,t} \geq \underline{RES}_{p,t} \tag{41}$$

$$\forall t \in T, p \in P \tag{42}$$

$$(43)$$

Minimum Generation Quotas

$$\sum_{t \in T} \boldsymbol{y}_{p,k,t} \quad \geq \quad Q_{p,k} \cdot |T| \cdot |G_{p,k}| \cdot \overline{P}_g, \ \forall p \in P, k \in G_{quota} \tag{44}$$

Quota Implementation

The generation quota is the outcome of annual negotiations specifying a minimum amount of generation over the course of the year. This creates a large coupling constraint, which would be intractable if directly implemented in a unit commitment over this time horizon. Instead, the quota is implemented as an aggregate constraint over the clustered generators—similar units made identical with a combined integer commitment variable. The benefit of this is not all units need be committed during the model horizon in order to meet their annual quota. The assumption is that because clustered units are similar cost, then the result of an aggregate constraint on production over a shorter time horizon should not differ from constraining each individual generator over the year, with the possible exception of commitment costs. A week was chosen as the model horizon because it is a reasonable unit for commitment schedules in practice, and in order to capture demand variability.

Appendix B: Additional Results

Individual Wind Scenarios

In the main text, results are averaged over all 6 wind scenarios taken from the modeled winter season. Each of these individual scenarios are shown in Figure 7, with solid points indicating averages from Figure 5. Total production costs can vary dramatically depending on wind availability (more wind → less coal production → lower fuel costs), and as expected, curtailment does increase under higher wind production (i.e., lower production cost). Importantly, the results of wind curtailment differences as a function of institutional configurations are stable across different wind scenarios.

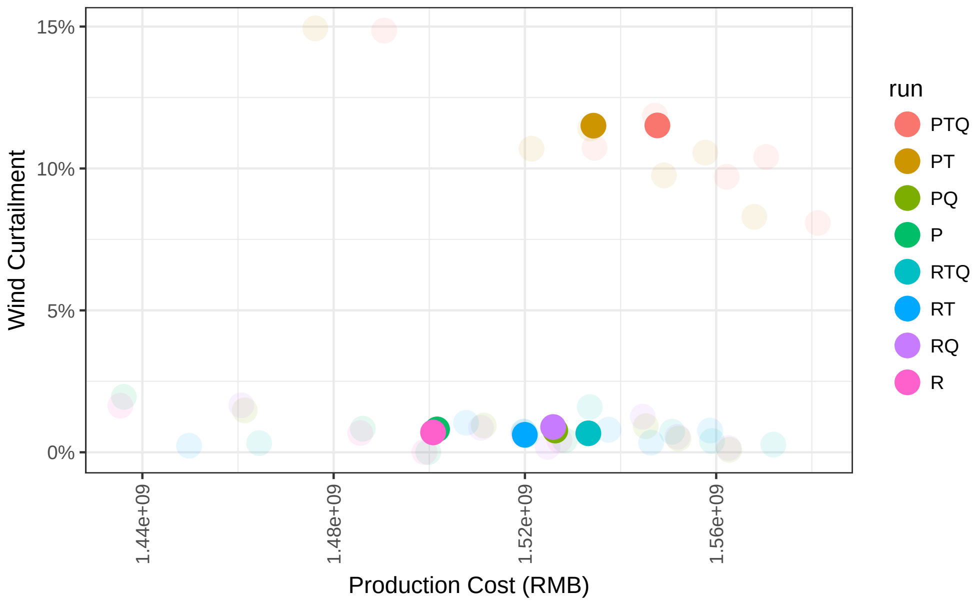

Figure 7: All wind scenario model results for NE. Solid points are averages, as shown in Figure 5. R=Regional reserves, P=Provincial reserves, T=Limited transmission, Q=Quota.

Clustering Validation

The clustering algorithm consists of two distinct steps, each of which can introduce errors with respect to the full model of binary commitment variables and generator-specific data: making similar units identical (e.g., the 12 coal unit types), and converting individual binary commitments variables of similar generators into a single integer variable. For this system in the reference case (without political conflicts), each of these two sequential simplification steps has only a limited impact on the two outcomes of interest: objective and wind total. Comparing the aggregated binary (12-type) and aggregated integer (Clustered) formulations, the errors introduced with respect to using the full set of units: objectives are within 0.02%, and wind totals within 0.14% (see Figure 8). These errors are magnified at the individual provincial node in the objective, ranging from $-1.4\% \sim +2.4\%$ for the 12-type and $-2.1\% \sim +3.1\%$ for the clustered formulations. Wind totals at the province are within $\pm 0.75\%$. Collectively, these demonstrate that clustering can be used on this simple network with the given set of generator parameters (in particular, heat rates are assigned in all formulations based on the aggregated generator type, not on unobserved individual heat rates).

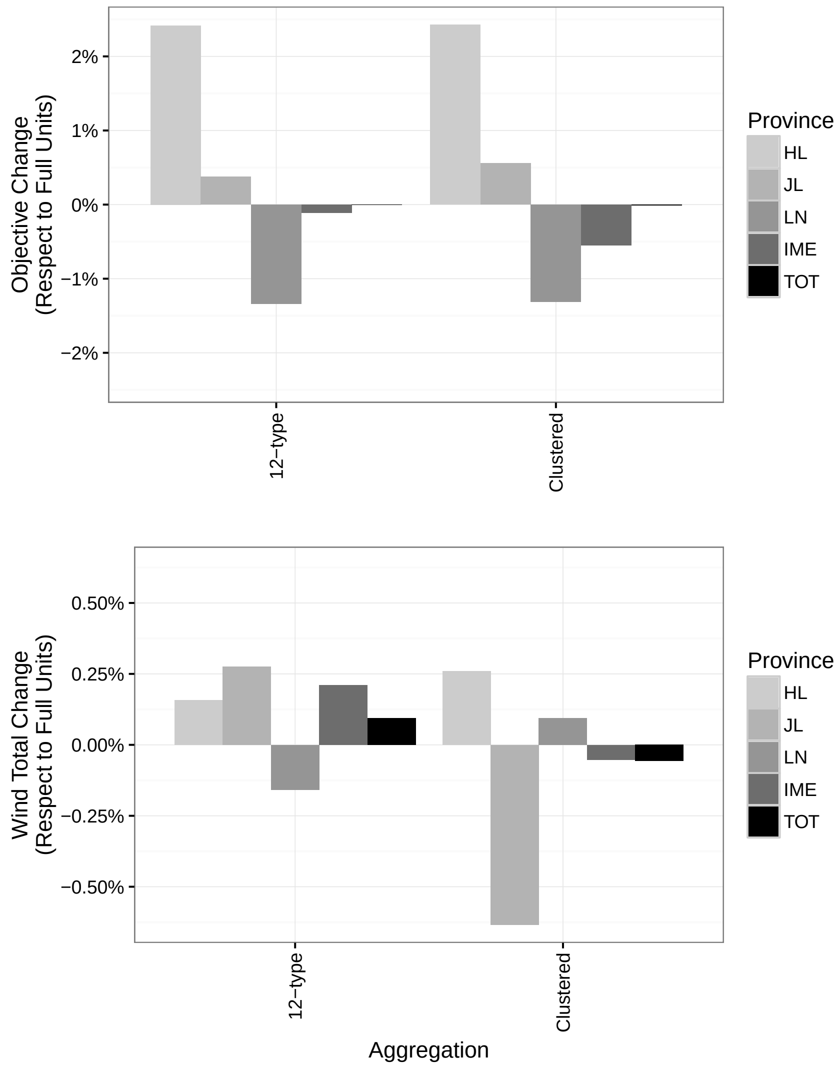

Figure 8: Aggregation errors of objective and wind totals by province for aggregated-binary (12-type) and aggregated-integer (Clustered), reference case.