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 four 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 legacy government production planning—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. This study tailors a unit commitment optimization, a common power systems engineering model with significant technical detail, to incorporate findings from qualitative interviews (2014-2016) of key grid and government stakeholders in three cases in northern China in order to examine underlying causes of curtailment and potential impacts of reforms. Results demonstrate why the Chinese government's preferred policy choice—medium-term bilateral contracts—will likely fall short of addressing curtailment, and highlights interactive effects of conflicts relating to inter-jurisdictional trading not previously discussed in the literature.

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1 Introduction

Over the last decade, China has undergone the world's largest electricity infrastructure expansion program, 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 four 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. China's stated goals are to enhance efficiency and address renewable energy integration challenges, which potentially entails large changes to the institutional setting, and is an interesting case of the co-evolution of technological development and political economy.

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 average production costs—depend significantly on the details and interactions of the new institutions, not simply that markets are engaged.[1] For example, using three metrics of restructuring in a panel regression study—privatization, independent regulation, and competition—benefits of privatization were only found when coupled with establishing independent regulators (Zhang et al., 2008).

Using a methodological approach that iterates between engineering models and qualitative interviews,

[1]For an excellent review of the effects of electricity sector reforms in developing countries see Zhang et al. (2008); 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).

this paper examines underlying causes of wind curtailment in China and analyzes the probable impacts of current reform policy on renewable energy integration. 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 results demonstrate why the preferred policy approach in China—the creation of medium-term bilateral contract markets at the provincial level to gradually replace the planned quota allocation—will likely fall short of addressing curtailment. These suggest that larger regions for power markets, encompassing multiple provincial jurisdictions, and reflecting short-run marginal costs not average costs of production, will be necessary to achieve substantial renewable energy gains. 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 Literatures

2.1 Renewable Energy Integration: Engineering and Political Economy Challenges

Delivering electricity is fundamentally different than supplying any other commodity, as dictated by physics and relatively stable economic drivers: electricity supply and demand must be balanced instantaneously within a small margin to maintain quality of power demanded by modern machines; it cannot cost-effectively be stored on a large-scale (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 hours and shorter intervals. Specific electricity generation technologies also introduce various constraints on the system, complicating coordination. For conventional fossil-fuel powered generators, output cannot be arbitrarily set: there exist minimum outputs below which combustion becomes unstable (for typical coal plants, these can range from 40-60%); changing output (or, ramping) is limited by additional thermodynamic factors; and turning on (off) generators can require lengthy startup (shutdown) sequences from several hours up to days (Bozzuto, 2009; Kumar et al., 2012). Intermittent renewable energy presents different complexities: its output is both variable (i.e., less controllable) and uncertain (i.e., difficult to predict hours to days in advance). 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 relate to the flexibility of system operation practices: how frequent are scheduling decisions for conventional units; how much in advance of real-time are decisions on individual outputs of generators determined (i.e., balancing); and what types and how much fast response "reserve" (backup) generation are necessary in case of large forecast errors (Xie et al., 2011; Holttinen et al., 2011). The cost and ability to provide flexibility also depends on the generation mix; hence, each of the above should consider the impacts and requirements for long-term investment decisions, as generators can have 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, entailing: transfers of economic rents from politically-connected incumbents to new entrants; increased coordination demands on complicated and entrenched governing bureaucracies; and several cost allocation questions related to renewable energy subsidies, additional grid investments, and system balancing Davidson et al. (2016). Successful examples of high wind penetration 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, mandatory dispatch rules with stiff penalties for failing to integrate available renewable energy are seen by the renewable energy industry as essential EWEA (2014).

Renewable energy in many countries competes in various forms of "restructured" electricity markets, which have been reformed from the government-run electric utilities or private monopoly franchises that predominated prior to the 1990s. There are multiple segments of the electricity supply chain, and similar to other infrastructure industries, some are natural monopolies in which it is not socially beneficial to encourage direct competition (Newberry, 2002). The generation segment, which consists of multiple interconnected electric power plants that supply electricity to the grid, is a key activity that was recognized early on to lack a natural monopoly and hence could be open to competition (Joskow and Schmalensee, 1983). One of the basic goals of this and other market creation initiatives is to improve system performance on metrics of efficiency, productivity and total output. However, other motivations may exist: 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 overburdened public finances in addressing electricity shortages. It has also been noted that exogenous macroeconomic events such as financial crises as well as "structural adjustments" encouraged by international development organizations may precipitate electricity sector reforms (Williams and Ghanadan, 2006).

Based on the first three decades of international experiences, a blueprint or "textbook model" of restructuring has been discussed in the regulatory economics literature, which includes how and which markets to create as well as relevant institutions to oversee their functioning (Hunt, 2002; Joskow, 2008). Because of electricity's fundamental characteristic of the need to instantaneously balance supply and demand, this leads to a "spot market" with a market-clearing marginal price for power evaluated on hourly or shorter time scales and fine geographic granularity (Schweppe et al., 1988).

There is significant debate about the ability of current electricity markets (focused predominantly on U.S. and EU systems) to accommodate large quantities of intermittent renewable energy (Ahlstrom et al., 2015; Pollitt and Anaya, 2016; Neuhoff et al., 2016). Renewable energy sources have close to zero marginal cost because of the lack of fuel costs and the bulk of costs, such as investment, are constant regardless of production, whereas electricity markets when created were typically thought of in terms of fuel-consuming generators (Ahlstrom et al., 2015). Nevertheless, a spot market can accommodate renewable energy by addressing many of the above system flexibility issues, if it is well-designed, e.g., no restrictive price caps and floors, prices determined on short (e.g., intra-hourly) intervals and over small geographic distances, and co-optimized 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 security concerns such as network stability. Additionally, variability in prices such as sudden drop-offs in renewable energy leading to price spikes provide 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 would tend 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 transmission allocation across market borders might be enhanced with more variable flows from renewable energy (Neuhoff et al., 2016). Distributed renewable energy generation (i.e., connected on low-voltage networks typically beyond the visibility of current price formation) will present a new set of challenges (Pollitt and Anaya, 2016).

There is little indication that various systems will converge on the same design. The complex nature and ordering of creating new market-supporting institutions (e.g., separating conflicts of interest between operation and market transactions, and regulatory bodies) 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 due to vested interests and weak economic and regulatory institutions. Countries without a strong tradition of independent regulatory agencies or robust financial systems, as well as those with substantial government involvement and intervention in the sector, may also face challenges carrying out the standard prescription (Jamasb, 2006).

Once established, increasing trade between neighboring markets has well-recognized theoretical implications for reducing costs and addressing integration issues of renewable energy, such as 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), which are dominated by panel regressions with institution dummies (e.g., Steiner, 2000). 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, Zhang et al. (2008) uses a single country-wide number derived from market concentration of top firms to represent how competitive a country's electricity system is. 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 inter-regional trading arrangements potentially have much bigger impacts on efficiency, such as the expansion of centralized PJM market into a service territory previously using bilateral contracting mechanisms, which led to an estimated greater than $160 million annual savings in a portion of the mid-western U.S. (Mansur and White, 2012).

Furthermore, studying the effects of different interventions on renewable energy integration outcomes is relatively new, and complicated by the variability and different operational challenges outlined above. Quantitative simulations incorporating greater technical detail can address the challenges of attribution on cost metrics as well as the specifics of renewable energy. Typically, the models are similar to those used in practice by power system operators, sufficiently simplified to aid analysis, which fundamentally assume a cost-minimization paradigm (Stoft, 2002). These models have been applied in Europe to understanding the impacts on cost and integration outcomes of fundamental market design choices such as the detail with which networks should be considered when evaluating prices (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 role in the sector, including both setting price and quantity. 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 purposes of granting this discretion was initially to encourage self-sufficiency in the planned economy, and later to experiment with different forms of markets during the post-1980s economic reform period (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). Electric power shares many of these features: provinces were given the ability to invest in their own generation plants in the 1980s and to lead the process of setting annual generation and consumption plans (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 strong 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. This is reflected internationally, as well, in vertically-integrated electric utilities and other network industries that are subject to price regulation, and is a major issue to be tackled through restructuring (Newberry, 2002). 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 being created (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 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 slowly reducing the amount of planned electricity sales sold to the grid by generators at the government-set price, and moving all commercial and industrial electricity demand to medium-term bilateral contracts (monthly to annually) by 2020, with prices determined directly with electricity generators (NEA, 2016c). Residential and other small consumers are being targeted through separate retail electricity reforms, where newly formed retail companies contract on their behalf similar to the large bilateral contracts. The reforms also call for prioritizing hydropower, solar and wind in annual planning processes, and increasing inter-provincial trade (NDRC and NEA, 2015).

The strong preference for medium-term contracts between large conventional generators and commercial and industrial users is driven in part by a history of using this approach of "growing out of the plan" in other sectors and products, particularly during the waves of corporatization and privatization in the 1990s, which saw gradual raising of market transactions in lieu of eliminating price controls (Naughton, 1995). Bilateral contract experiments are now widespread.

The Inner Mongolia Grid Company began contracts in 2010, setting aside a specified percentage of projected electricity demand for bilateral contracts and multilateral exchanges (North China SERC, 2010). Gansu province began bilateral contracts in 2009 (SCEO, 2015), and many other provinces have experiments (BJX.com.cn, 2015). The guidelines for contracting are determined mostly on a province-by-province basis.[2]

Wind and solar energy capacity has increased over 100 times in the last decade (2007-2016), joining a system primarily dominated by coal and hydropower (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 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

[2] 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).

[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", in contrast to a coal plant, which reduces fuel consumption (hence, costs) when lowering output.

(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: from transmission bottlenecks and an inflexible fossil generation mix, poor siting of wind generation, to protectionist policies supporting coal generation (Zhao et al., 2012; Kahrl et al., 2013). 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 State Council (2015)—call for market mechanisms. Various provinces have experimented with renewable energy participation in electricity markets, though still on a limited scale and primarily medium-term bilateral contracts or multilateral exchanges (IMAR SASAC, 2011; Gansu Electricity Exchange, 2016). Additionally, other highly non-traditional experiments are also underway: the Northeast Grid has a "peaking ancillary services" market that allows coal plants across four provinces to bid an opportunity cost for producing below their administratively-determined minimum output in an effort to free up integration space for wind NEA (2014b). 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

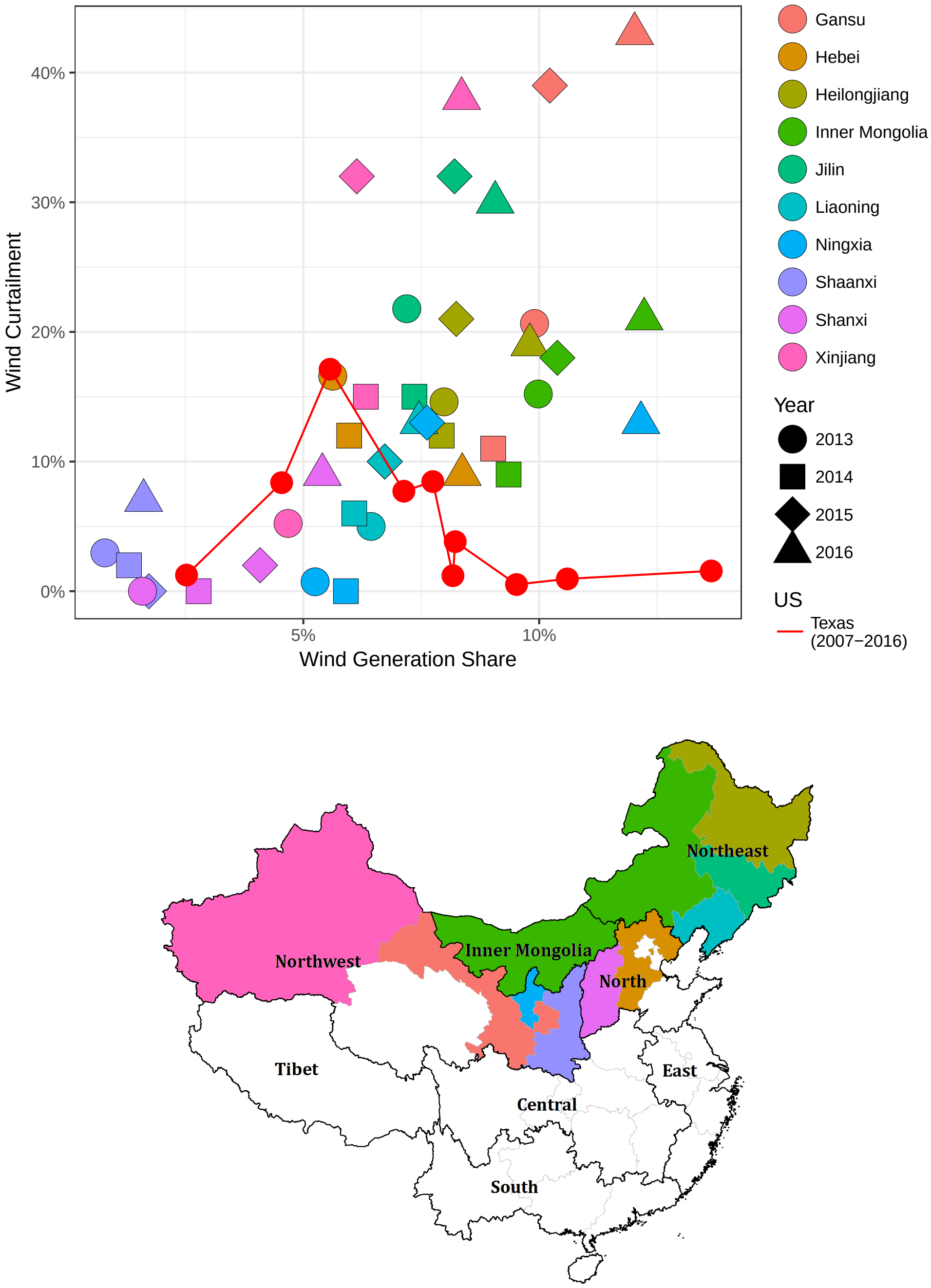


Figure 1: Wind curtailment in major wind provinces of China, 2013-2016, and Texas (*top*). Source: NEA, Wiser and Bolinger, 2017. Note: actual data is from the ERCOT grid region whose borders differ slightly from the state of Texas.
Grid regions of China (*bottom*). Inner Mongolia is split between the 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.

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.

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 chapter, 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 motivate an iterative multi-methods approach that combines a commonly-used quantitative engineering-economic model with a qualitative multiple case study of electricity system operations 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 in the context of the above case studies, and based on cross-case comparison of underlying processes, some scoping conditions are proposed. 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. Ongoing work involves refining quantitative constraints based on these insights and testing these models on out-of-sample regions to strengthen causal arguments.

Beyond simply the concept of triangulation, where biases in multiple methods are reduced through complementary use of different methods, this iterative approach is similar to a "nested analysis" which seeks to combine different methods "simultaneously" (Lieberman, 2005, p. 436). It is distinguished from a nested analysis in at least two dimensions: 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, which historically is just in northern China, 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

[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).

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

Semi-structured interviews were conducted in Chinese over multiple visits in 2015-2016 with respondents from grid companies, local and central governments, and generation plants (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.

For each case, qualitative data is analyzed with a process tracing lens, examining causal processes along the chain (e.g., system operation and market experiments) from independent to dependent variables **?**. Specifically, this paper uses a process tracing framework to:

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.

Question guides were tailored for each organization, to address:

1. What does the rule-making process for electricity systems operations look like? How does it convert goals of policy-makers into operational regulations?
2. Who has discretion to implement these rules and what accountability processes are in place?
3. What conflicts, if any, arise in implementing rules from different authorities, and how are these resolved?
4. How do outcomes compare to the original intent of the regulation?

3.3 Quantitative Grid Model

Electric power systems operation, due to complex network interactions, 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. Schematically, the model minimizes production costs by choosing appropriate values of production variables subject to (s.t.) various constraints:

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

s.t. Supply/demand balance

Network losses

Minimum/maximum outputs

Ramp limits

Minimum up/down times

District heating requirements

Hydropower storage

Reserve requirements

$\boldsymbol{x}$: 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-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. Four key assumptions of this model are 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 we should examine *to what extent these hold*, or in the case where we know they do

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

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., deployed wind capacity). Here, the basic issues will be low statistical power given limited sub-annual data availability, technically infeasible or highly uneconomic production schedules, and non-linear interactions among institutions and with un-modeled technical constraints. Infeasible schedules could arise when extrapolating from a treatment effect (e.g., the coal quota on wind curtailment) beyond the support for a given set of covariates: for example, there may be network and technology-specific features which prevent coal generation going below certain thresholds. Interaction terms (e.g., of inflexible power supply and deployed wind) will also be inadequate as proxies to capture relevant technical constraints, because they are overly coarse in the time dimension and still diminish the importance of threshold effects.

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. Of course, considering such a massive number of variables would typically lead to concerns of overfitting in estimation techniques, but in an optimization framework they are addressed by heavily constraining physical and economic criteria—362k constraints in the basic formulation used for this study (see Figure 2).

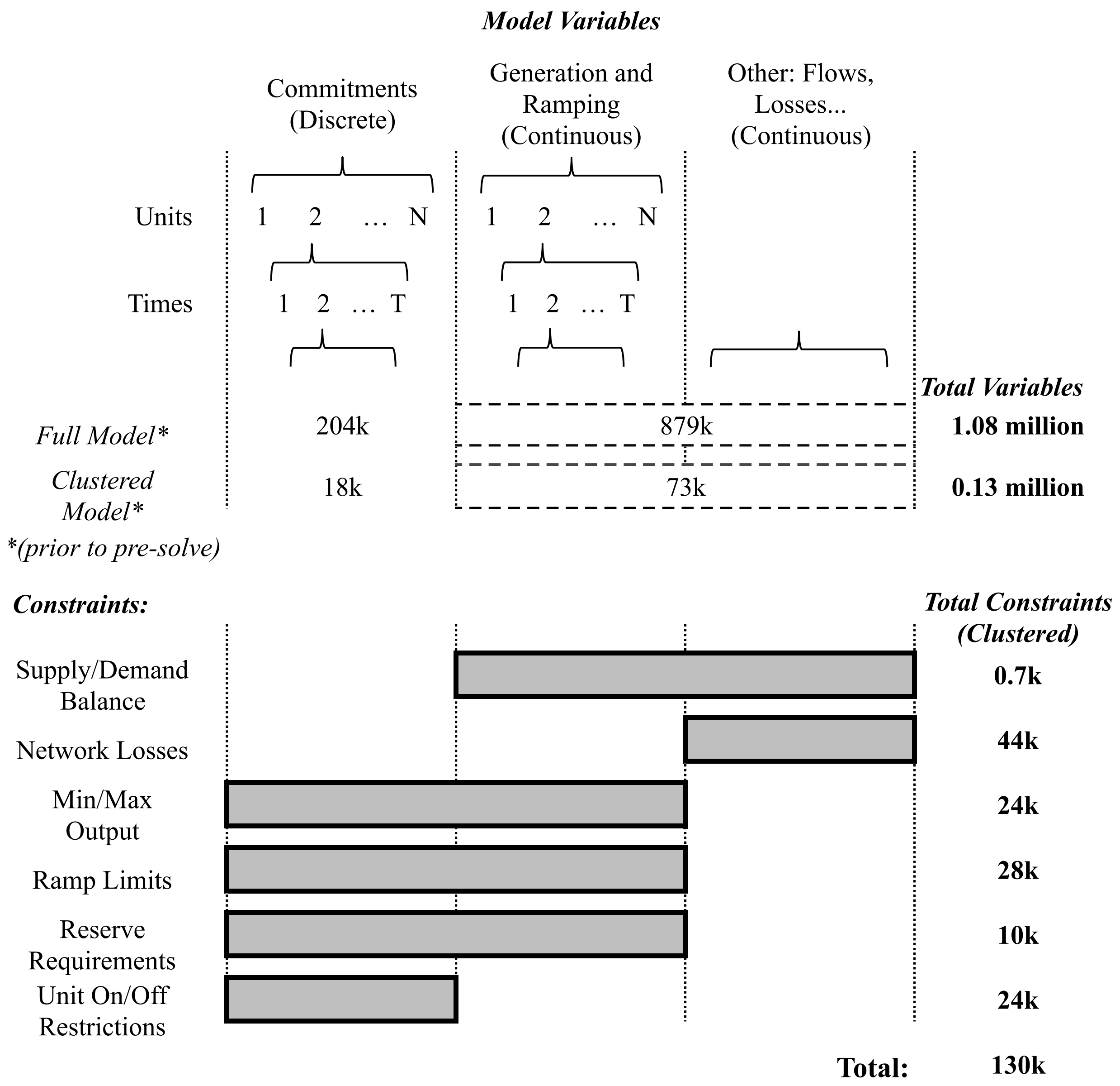


Figure 2: Structure of variables and constraints in quantitative UC model. Blocks under constraints indicate which variables are included in equation systems.

4 China's Grid Operations Institutions

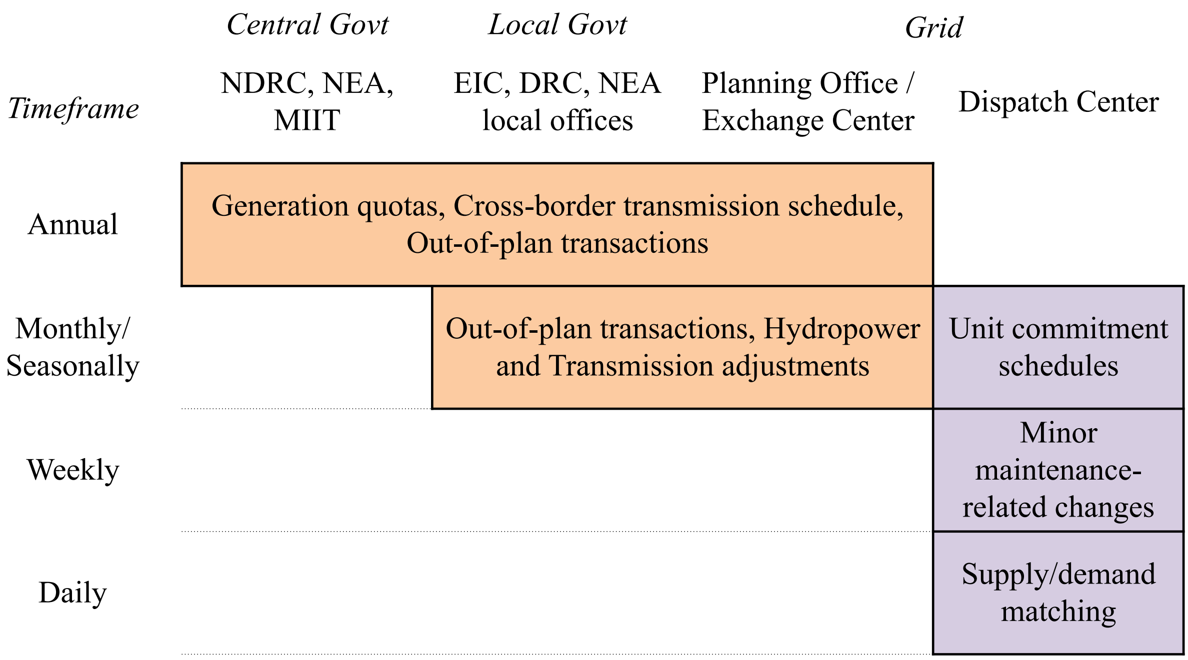
4.1 Overview of Dispatch Planning

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. Out-of-plan transactions such as bilateral contracts frequently take place at an annual level, and are effectively added to the planned amounts for the purposes of grid coordination. This is further broken down into seasonal and monthly decision points, where adjustments to the plan and additional out-of-plan exchanges 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 planning 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 (*jingjihe xinxihua weiyuanhui* | 经济和信息化委员会) or Industry and Information Commissions (*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.

Replacing portions of the annual plan with medium-term contracts (monthly, seasonally, or annually)



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.

has been piloted in all three cases. Shorter-term contracts have not been a primary focus (see Figure 3). Facing large generator overcapacity and struggling local energy-intensive industry, Gansu in the Northwest grid has for several years organized exchange markets—both bilateral and multilateral—that allow coal-fired electricity to be sold at below-benchmark rates. Since 2015, renewable energy also began to participate, though many wind farm respondents expressed doubts that exchanges led to additional generation, but rather were methods for local governments to allow users to get around paying the full central tariff. Western Inner Mongolia (WIM) has also allocated a portion to contracts, which due to high thresholds for consumers to participate, also effectively supports energy-intensive industry.

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, 2014a). This structure has been confirmed by multiple grid operators 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. There are numerous reported examples of violations (SERC, 2011; NEA, 2016b). While there are policies such as *sangong* to follow, grid companies face no specific penalty for failing to comply, unlike generators which can be fined for not meeting their production contracts.

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 section 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) 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 virtually all other products.

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

	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

for the case of electricity there are multiple pathways to explain this outcome. In the next section, I describe these conflicts in greater detail and how they can be modeled quantitatively.

4.4 Quantitative Modeling of Institutional Conflicts

Based on these qualitative data into dispatch planning practices, I isolate three political 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 transfers 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 (35).	Implemented as reduction in interconnection capacity and restricted flow directions between provinces, in (8).	Must have adequate reserves available within province, according to (32)-(33)

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. Complete analysis would include a two-stage model that modeled uncertain realizations of wind and load forecasts, and performed statistical analysis on actual costs (Constantinescu et al., 2011). However, China's day-ahead plans (both generation and transmission decisions) are seen by dispatch operators as constraints to be met, rather than scheduling guidelines that can be superseded by changes in real-time. Hence, this model 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 should be conducted.

Zonal demand and supply Intra-provincial constraints are relevant, and 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, this wind would not face any transmission constraints until it tries to cross provincial borders, and hence model results would tend to underestimate the engineering 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 (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 30%, 19% and 13% in Jilin, Heilongjiang and Liaoning provinces in 2016 (NEA, 2017b). In our formulation, the NE grid is considered to be isolated from neighboring grids, based on its limited external interconnections: only 21.5 TWh, or 5% of total generation, was exported to North Grid in 2014 (NECG, 2015).

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 different scenarios of wind production keeping all other inputs (e.g., demand) constant. To test the impact of the identified institutional features, a full factorial setup of all combinations of turning on and off the three

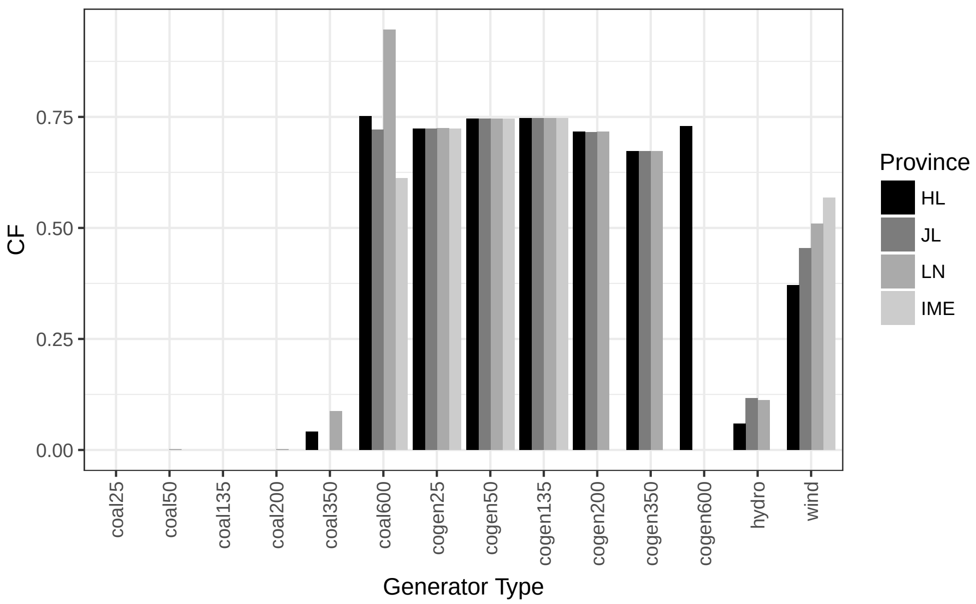


Figure 4: Capacity factors of generation types by province

political conflicts was performed (8 models in total).

5.1 Reference Model 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 1% (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 Effects of Political Conflicts

The results of layering on political conflicts 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

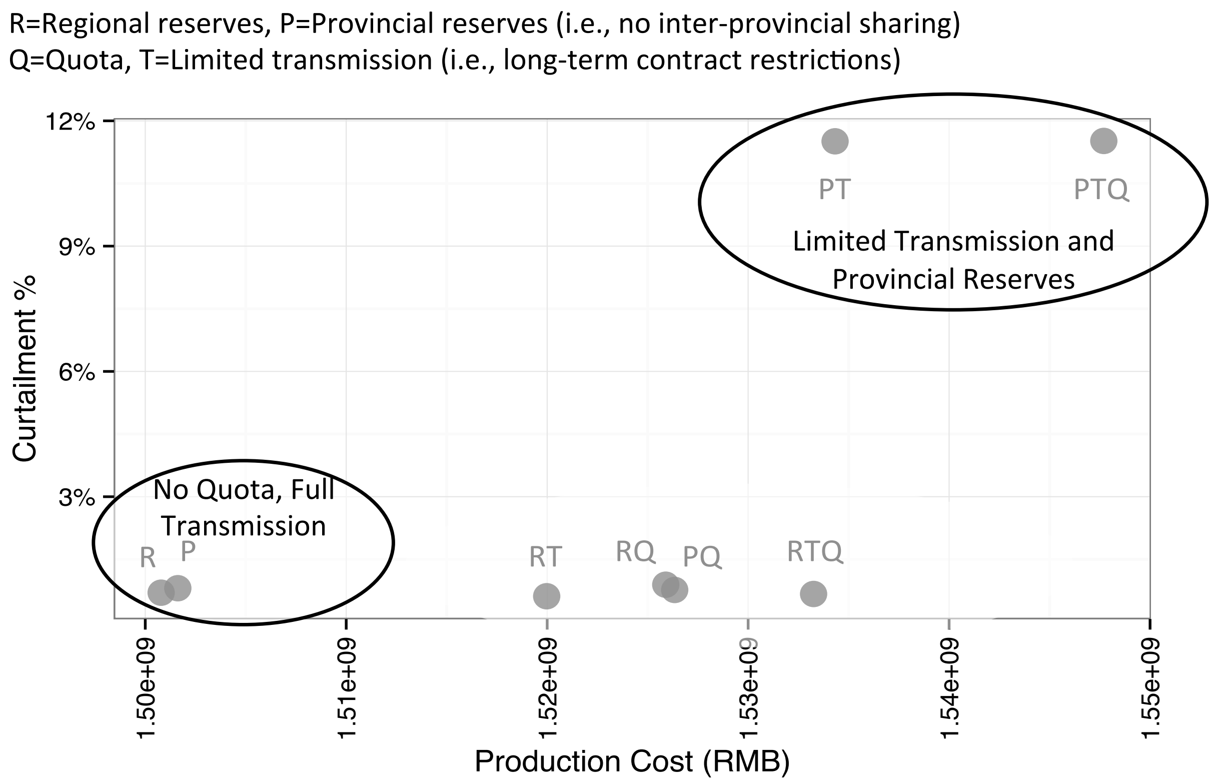


Figure 5: Model results for all combinations of political conflicts

expected. Curtailment is most affected, however, by the interaction of the constraints on limited transmission 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.

The clustered model formulation allows us to run efficiently a large number of scenarios, e.g. to test the effect of varying institutional parameters over a wider range, both as sensitivities as well as to identify implications of policy changes. We show this in Figure 6 for the case of modifying the quota. In it, we change uniformly for each province the ratio of the quota 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.

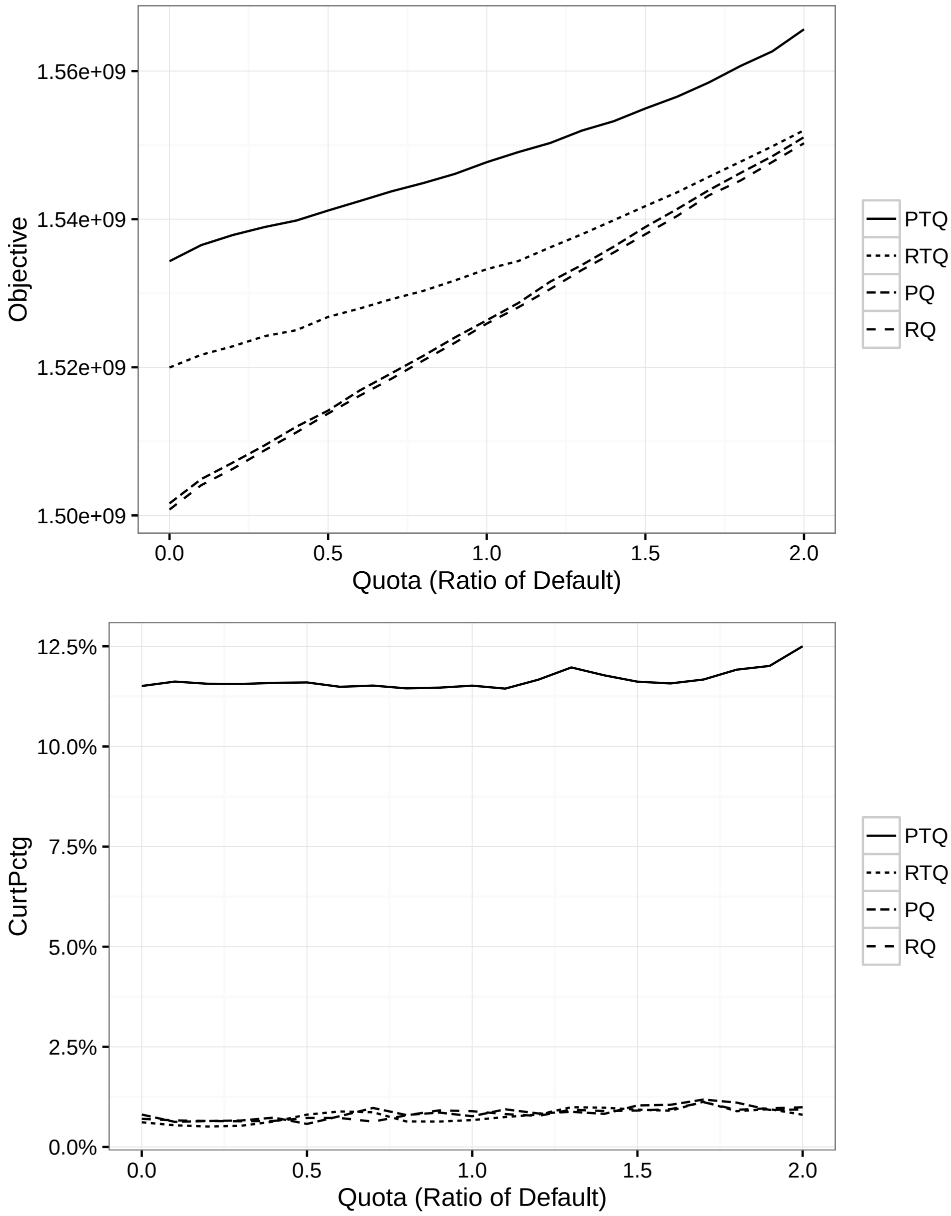


Figure 6: Objective (*top*) and wind curtailment (*bottom*) as a function of quota relative to default values. R=Regional reserves, P=Provincial reserves, T=Limited transmission, Q=Quota.

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 the world's worst renewable energy curtailment problem. 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 the 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 exceptions currently being explored that deserve further study are the Northeast "peaking ancillary services" market where coal plants bid to open up space for wind, and the (currently small) bidding of excess hydropower from Yunnan to Guangdong (NEA, 2014b; Wang, 2017).

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.

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 substantially more complicated: 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.

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/potential benefits of reducing the quota through increased bilateral contracts. They have also helped refine continuing case study work, where the process of a specific market mechanism (e.g., bilateral contracts) will be followed from inception to outcome within a single province of a case region.

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, linear 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 of NE grid in 2011 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. 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 (2017). 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

$$\min \quad \sum_{p\in P}\sum_{k\in K}\sum_{t\in T}\left(p_k^{su}\boldsymbol{v}_{p,k,t}^{up} + p_k^{var}\boldsymbol{y}_{p,k,t}\right) \tag{2}$$

$$s.t.$$

Supply/Demand Balance

$$\sum_{k\in K}\boldsymbol{y}_{p,k,t} - \sum_{p'\neq p}\left[\boldsymbol{f}_{p,p',t} + \boldsymbol{l}_{p,p',t}/2\right] = d_{p,t}\ ,\ \forall p \in P \tag{3}$$

$$\boldsymbol{f}_{p,p',t} = -\boldsymbol{f}_{p',p,t} \tag{4}$$

$$\boldsymbol{f}_{p,p',t} = \boldsymbol{f}^{+}_{p,p',t} - \boldsymbol{f}^{-}_{p,p',t} \tag{5}$$

$$\sum_{s}\boldsymbol{j}_{p,p',t,s} = \boldsymbol{f}^{+}_{p,p',t} + \boldsymbol{f}^{-}_{p,p',t} \tag{6}$$

$$\forall t \in T,\ p, p' \in P \tag{7}$$

Transmission Losses

$$\boldsymbol{f}_{p,p',t} + \boldsymbol{l}_{p,p',t}/2 \leq \overline{F}_{p,p'} \tag{8}$$

$$\boldsymbol{l}_{p,p',t} = \mu_{p,p'}\sum_{s}\alpha_{p,p',s}\boldsymbol{j}_{p,p',t,s} \tag{9}$$

$$\alpha_{p,p',s} = (2s-1)\,\Delta f_{p,p'}\ , \tag{10}$$

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

$$\Delta f_{p,p'} = \overline{F}_{p,p'}/S \tag{11}$$

$$\boldsymbol{l}_{p,p',t}, \boldsymbol{f}^{+}_{p,p',t}, \boldsymbol{f}^{-}_{p,p',t}, \boldsymbol{j}_{p,p',t,s} \geq 0 \tag{12}$$

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

Minimum/Maximum Outputs

$$\underline{P}_k\boldsymbol{u}_{p,k,t} \leq \boldsymbol{y}_{p,k,t} \leq \overline{P}_k\boldsymbol{u}_{p,k,t}\ ,\ \forall p \in P, k \in G_{thermal} \tag{13}$$

$$0 \leq \boldsymbol{y}_{p,k,t} \leq W_{p,k,t}\ ,\ \forall p \in P, k \in G_{wind} \tag{14}$$

Ramp Limits

$$\boldsymbol{w}_{p,k,t} = \boldsymbol{y}_{p,k,t} - \underline{P}_k \boldsymbol{u}_{p,k,t} \tag{15}$$

$$\boldsymbol{w}_{p,k,t} - \boldsymbol{w}_{p,k,t-1} \leq \boldsymbol{u}_{p,k,t} RU_k + \boldsymbol{v}^{up}_{p,k,t} \underline{P}_k \tag{16}$$

$$\boldsymbol{w}_{p,k,t-1} - \boldsymbol{w}_{p,k,t} \leq \boldsymbol{u}_{p,k,t} RD_k + \boldsymbol{v}^{dn}_{p,k,t} \underline{P}_k \tag{17}$$

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

Minimum Up/Down Times

$$\boldsymbol{u}_{p,k,t} \leq |G_{p,k}| \tag{18}$$

$$\boldsymbol{u}_{p,k,t} \geq \sum_{t'=t-MU_k}^{t} \boldsymbol{v}^{up}_{p,k,t'} \tag{19}$$

$$|G_{p,k}| - \boldsymbol{u}_{p,k,t} \geq \sum_{t'=t-MD_k}^{t} \boldsymbol{v}^{dn}_{p,k,t'} \tag{20}$$

$$\boldsymbol{u}_{p,k,t} - \boldsymbol{u}_{p,k,t-1} = \boldsymbol{v}^{up}_{p,k,t} - \boldsymbol{v}^{dn}_{p,k,t} \tag{21}$$

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

District Heating Requirements

$$\underline{P}_k \leq \boldsymbol{y}_{p,k,t} \leq \overline{P}_k \ , \ \forall p \in P, k \in G_{CHP} \tag{22}$$

Hydropower Storage

$$\boldsymbol{h}_{p,k,t} - \boldsymbol{h}_{p,k,t-1} = H_{p,k} - \boldsymbol{y}_{p,k,t} \tag{23}$$

$$\boldsymbol{h}_{p,k,t} = HL_{p,k,t}\ ,\ t \in \{1, |T|\} \tag{24}$$

$$\boldsymbol{h}_{p,k,t} \geq \underline{HL}_{p,k} \tag{25}$$

$$\boldsymbol{h}_{p,k,t} \leq \overline{HL}_{p,k} \tag{26}$$

$$\boldsymbol{h}_{p,k,t} \geq 0 \tag{27}$$

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

Reserve Requirements

$$\boldsymbol{r}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}\overline{P}_k - \boldsymbol{y}_{p,k,t} \tag{28}$$

$$\boldsymbol{s}_{p,k,t} \leq \boldsymbol{y}_{p,k,t} - \boldsymbol{u}_{p,k,t}\underline{P}_k \tag{29}$$

$$\boldsymbol{r}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}RU_k \tag{30}$$

$$\boldsymbol{s}_{p,k,t} \leq \boldsymbol{u}_{p,k,t}RD_k \tag{31}$$

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

$$\sum_{k \in G_{res}} \boldsymbol{r}_{p,k,t} \geq \overline{RES}_{p,t} \tag{32}$$

$$\sum_{k \in G_{res}} \boldsymbol{s}_{p,k,t} \geq \underline{RES}_{p,t} \tag{33}$$

$$\forall t \in T, p \in P \tag{34}$$

Minimum Generation Quotas

$$\sum_{t \in T} \boldsymbol{y}_{p,k,t} \geq Q_{p,k} \cdot |T| \cdot |G_{p,k}| \cdot \overline{P}_g,\ \forall p \in P, k \in G_{quota} \tag{35}$$

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.

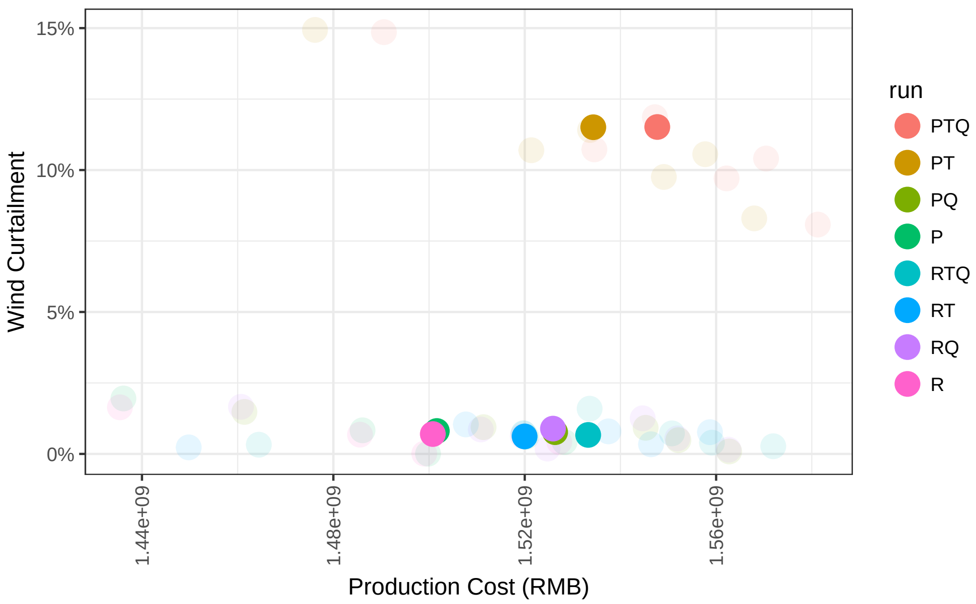

Figure 7: All wind scenario model results for NE. Solid points are averages, as shown in Figure 5. R=Regional reserves, P=Provincial reserves, T=Limited transmission, Q=Quota.

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).

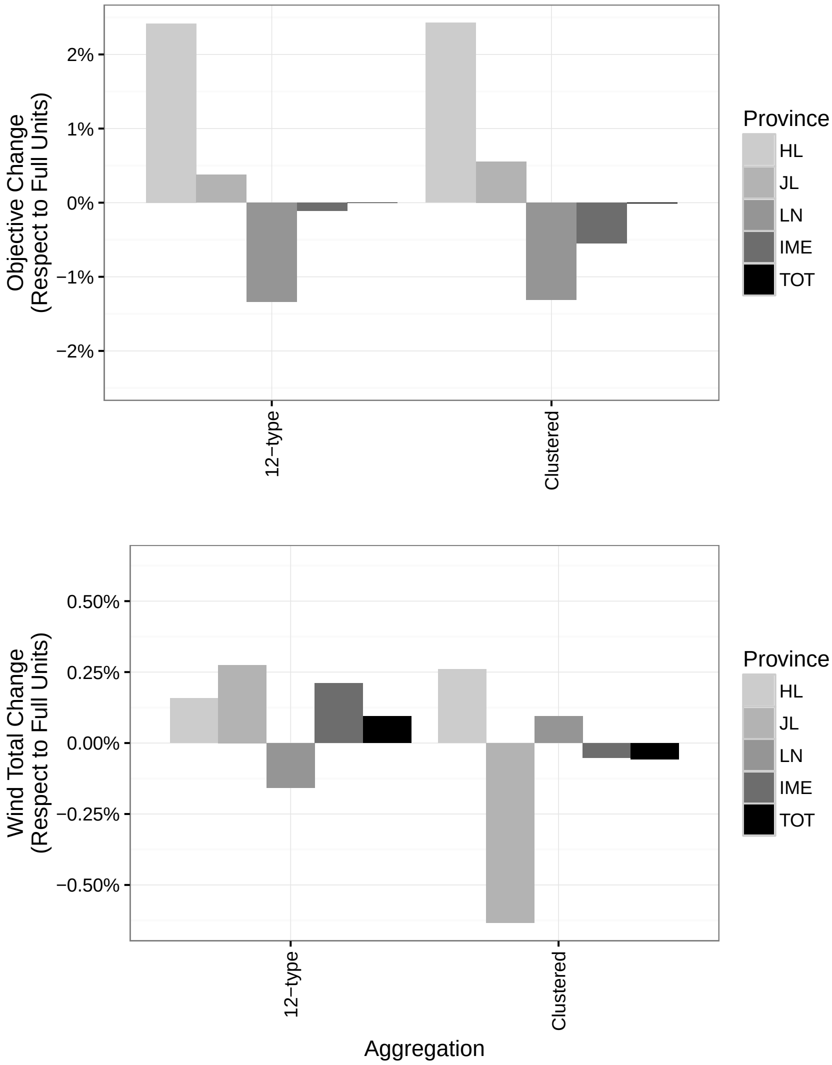

Figure 8: Aggregation errors of objective and wind totals by province for aggregated-binary (12-type) and aggregated-integer (Clustered), reference case.