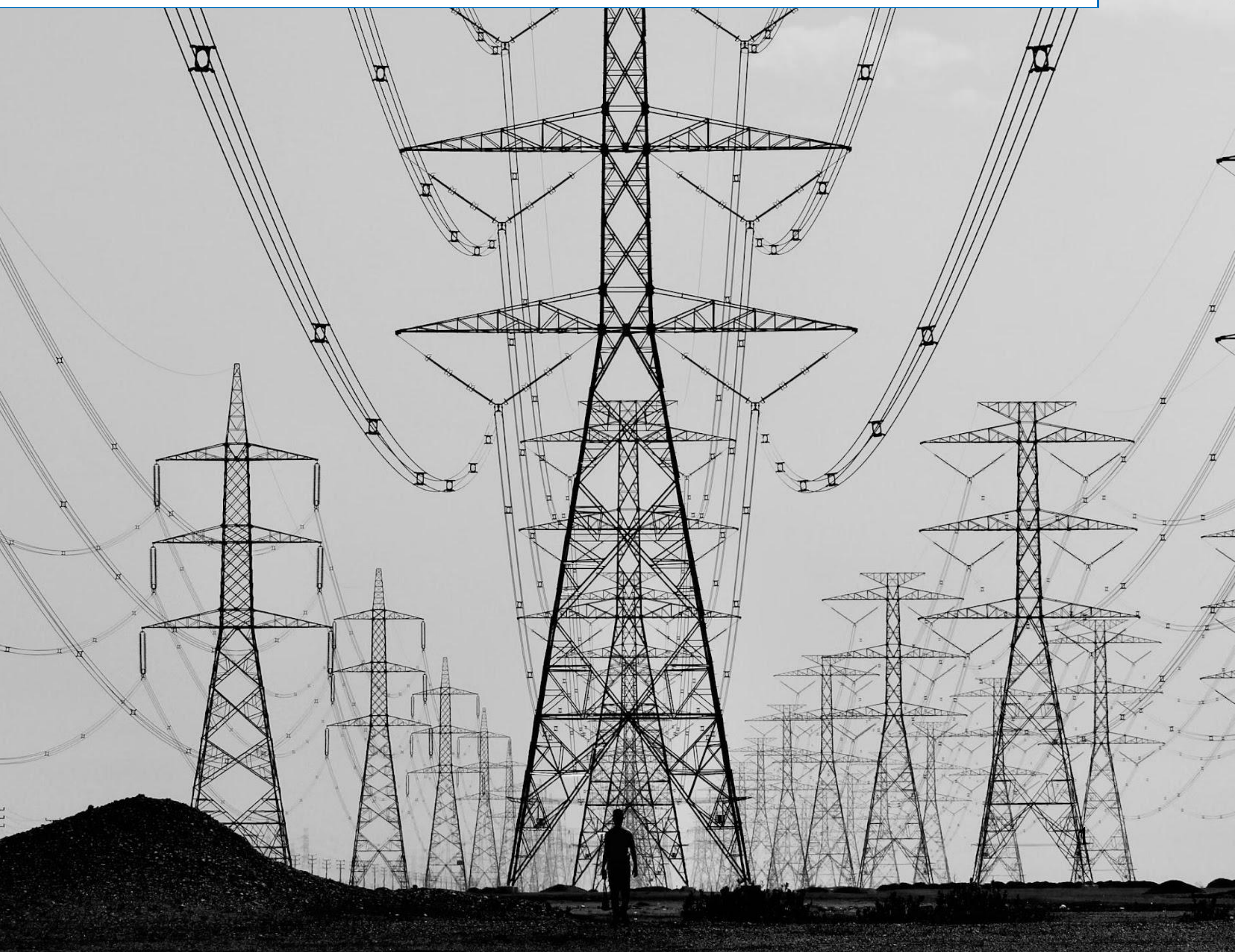
Northeast China Grid Winter Resource Adequacy Report

September 2023



Report Team

University of California, San Diego

Michael Davidson

Fikri Kucuksayacigil

Ming Wei

Boyu Yao

Regulatory Assistance Project

Max Dupuy

Chi Gao

North China Electric Power University

Jiahai Yuan

Jian Zhang

Kai Zhang

About the Project

This report was produced by the Electricity Market Tracker project, an initiative to generate independent analytical capabilities to respond to the myriad debates over power market designs occurring in provinces throughout China. Through collection of market and grid data, development of modeling simulation tools, and analysis of international experiences, the project aims to address policy-relevant research questions and disseminate results to a wide range of stakeholders.

To learn more about Electricity Market Tracker, please visit: www.emtracker.org

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Executive Summary

Purpose of this Project

This document offers case study examples of two types of routine public reports that are common internationally and are important in supporting a reliable new energy system, particularly in a marketized power system context.

1) Post-crisis analysis reports: in the aftermath of a large-scale blackout or other system crisis, it is very valuable to have an officially commissioned and published analysis of root causes along with a discussion of needed reforms. We provide a case study example that looks back at China's late 2021 power crisis as it unfolded in the Northeast Grid (NEG).

2) Forward-looking seasonal resource adequacy outlook reports: Published seasonal outlooks can help manage near-term risks and boost confidence in reliability of the new energy system. Our case study example provides a resource adequacy outlook for two months in Winter 2022/2023 using data available as of October 2022.

In February 2023, the National Energy Administration (NEA) released a document titled "Notification on Refining Analysis on Power System Operation and Enhancing Management of Power System Operation Risks". This is the first policy document that mandates the standardized operation mode analysis at a system level, aimed at avoiding systemic risks. This marks a substantial step forward in enhancing the reliability of the power system and predicting power system risks. Specifically, this document requires power grid companies to conduct three system operation mode analyses each year, including the annual forward-looking operation analysis, the winter seasonal forward-looking analysis, and the summer seasonal forward-looking analysis. In addition, it also requires a summary of the previous year's system operation situation and an analysis of "power safety incidents within the scope of dispatch and control." This report aims to provide a starting point for further discussion. In line with the requirements put forward by NEA in this document, we use the Northeast China Grid (NEG) as an example to illustrate some methods of such system analysis. Additionally, the report delves into an analysis of the power outage incidents in the Northeast in 2021 and puts forward some policy recommendations for reference.

Key Findings

<u>2021 Post-Crisis Analysis</u>

- Resources would have been adequate to maintain system reliability in the face of extreme weather conditions if there had been no policy-related system rigidities or large administrative export requirements.

- However, the combination of extreme weather, large administrative export requirements, and policy rigidities led to significant load shedding episodes.

Winter 2022 / 2023 Modeling Results

- Modeling simulations indicate that generation resources will be adequate to maintain system reliability in the face of extreme weather conditions, assuming no policy rigidities or export priority requirements.
- However, when considering policy rigidities, including incomplete market opening leading to coal capacity going offline, there remain risks of significant episodes of system "tightness" and blackouts.

Policy Implications

1. Inflexible administrative on-grid prices and incomplete market mechanisms should be reformed. We recommend:
    a. Implementation of regional unified spot markets, starting with a feasible and perhaps simplified design. This will rationalize incentives to generators and other power resources, guiding economic dispatch for the unified region.
    b. Liberalization (elimination) of the administered benchmark coal-fired electricity price and easing of spot market price controls. The spot market should replace the benchmark coal price as the compensation mechanisms for thermal generators.
    c. Implementation of transparent backward- and forward-looking resource adequacy analysis by energy agencies, as described in this report.
2. Finally, we offer two concluding thoughts based on international experience:
    a. Constructing more coal-fired power plants is unlikely to be the least-cost answer to support a reliable new energy power system.
    b. Instead, it is essential to continue developing policy and market rules that unlock the benefits of demand response and energy savings investments. These can help achieve a reliable system at a reasonable cost and provide a more economic complement to emergency "orderly use" policies.

1 Introduction

This document offers case study examples of two types of routine public reports that are common internationally and are important to support a reliable new energy system, particularly in a marketized power system context.

1) *Post-crisis analysis reports:* In the aftermath of a large-scale blackout or other system crisis, it is very valuable to have an officially commissioned published analysis of root causes along with discussion of needed policy and market rule reforms. This can help policymakers, market participants, and end-users understand the policy implications and rationally evaluate typical post-crisis controversies, such as the impact of variable renewable generation on reliability. We provide a case study example that looks back at China's late 2021 power crisis as it unfolded in the Northeast Grid (NEG).

2) *Forward-looking seasonal resource adequacy outlook reports*: Published seasonal outlooks can help manage near-term risks and boost confidence in reliability and in the new energy system. Our case study example provides a resource adequacy outlook for two months in Winter 2022/2023 using data available as of October 2022.

We draw on evolving international discussions about best practices for these analyses. Our NEG case study analyses fall short of the best international examples, however, in one important respect: publicly available data for NEG (and other grid regions in China) are sparse relative to the marketized parts of the U.S. and E.U. power systems. In addition, full resource adequacy reports of this type typically require large teams and official support. In these respects, our case studies should be regarded as indicative of the types of reports that should be developed in more detail by officially-designated institutions with sufficient resources.

Fall 2021 Post-crisis – Background

This section provides a brief overview of the Fall 2021 crisis in the NE. Investigating the root causes of the power crisis offers invaluable insights into reliability risks that could cause recurring power crises in the future. In other countries, post-crisis investigative reports are often commissioned by policymakers and written by entities such as regional system operators (RTOs/ISOs) or state-level public utility commissions in the US context, who have unconstrained access to system operations data and system operator personnels' testimonies. For example, here is a list of public reports accounting for some of the most well-known power outages in recent years: 2021 Texas power crisis [1], 2020 California power crisis [2], 2019 Britain power crisis [3] [4], and the 2016 South Australia power crisis [5].

These post-crisis analysis reports provide entry-points for future research, where more granular description and analysis on factors contributing to the crisis can be developed, often through modeling exercises. In this report, qualitative descriptions of the 2021 blackout in the NE inspire the design of scenarios, in which potential contributing factors are closely examined to assess their impact on NEG's resource adequacy. A similar process could happen on a societal scale: upon the release of these reports by authoritative sources, derivative research projects conducted by analysts, research institutes, and observers will further the initiative.

In the fall of 2021, China experienced a widespread electricity crisis, revealing the challenges of ensuring safety and reliability during China's power sector transformation. Blackouts, electricity rationing, and orderly power consumption reductions were called into action in around 20 provinces across China beginning in September 2021. The power crisis in the Northeast—consisting of Heilongjiang (HL), Jilin (JL), Liaoning (LN), and the Eastern portions of Inner Mongolia (IME)—was most severe. Residents in northeastern China experienced unprecedented unannounced power cuts, as the electricity crisis that initially hit factories spread to homes, transportation, water supply, and other essential social power consumption.

In NEG, Liaoning is the largest demand center and a net importer from the other provinces, and Inner Mongolia East has a large generation surplus (Figure 1). The NEG region is also a net exporter to the neighboring North China Grid, which includes Beijing, Hebei, Henan, Shandong, Shanxi, and Tianjin.

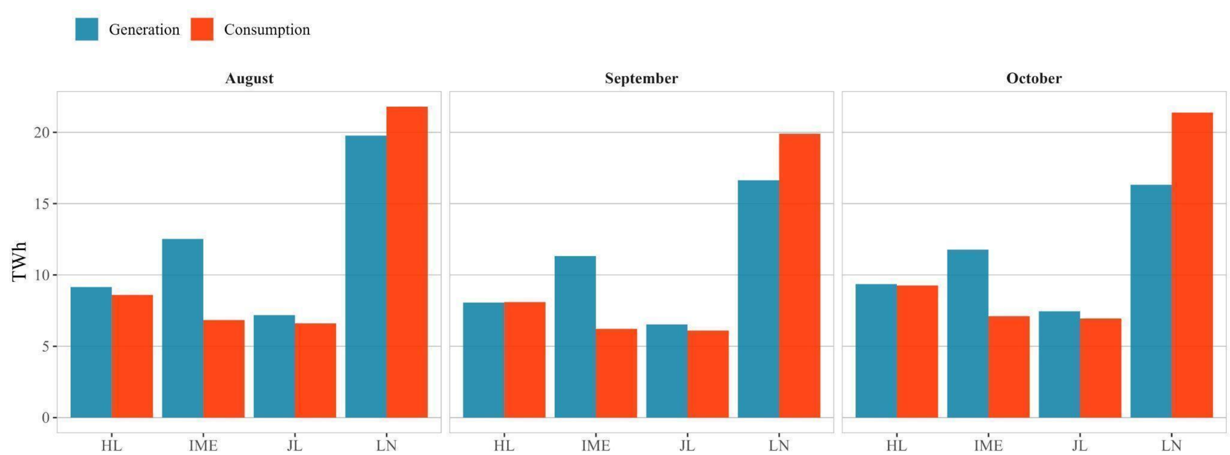

Figure 1. NE region electricity generation and consumption during power shortage events of Fall 2021 [6] [7]

The following section provides a brief account of what happened during the 2021 NEG power crisis, with an emphasis on Liaoning, the largest province of NEG in terms of power demand. Through retrospective analysis, several potential factors, as attributed by many sources ranging from official outlets to media comments, were evaluated to gauge how they have (and have not) contributed to the crisis. Though other provinces in NEG have slightly different system conditions, many common pitfalls in Liaoning's power system can be observed in other provinces as well, making Liaoning an appropriate case to study.

Overview of Fall 2021 Blackout

In the first eight months of 2021, driven by rapid economic recovery, electricity demand in Liaoning surged, growing 9.5% from the same period last year and hitting an all-time high. Starting on September 10, 2021, the net power imported by Liaoning province decreased significantly, putting pressure on local power supply, which could not meet the industrial load. From September 23 to 25, the power supply crunch further increased to a serious level. Utilizing the authority granted by the "Orderly Power Consumption Management Measures", Liaoning initiated three rounds of level II (10-20% load gap) orderly power consumption measures. These measures encompass a range of administrative, economic, and technical strategies aimed at reducing electricity demand of energy-intensive industrial customers in the case of insufficient power supply to ensure grid stability while meeting social needs to the extent possible [8]. During some peak periods, even with the implementation of maximum peak-shifting measures of 4,169 MW in Liaoning, there were still power outages in NEG. The severe power outages resulted in the system frequency dropping below 49.8 Hz, a level that could damage certain electrical equipment and trigger both frequency instability and even a total grid collapse. According to the "Regulations on Power Grid Dispatch Management", the Northeast Power Grid Dispatch Department issued instructions to implement "emergency load shedding" [9]. Unlike the more controlled orderly power consumption, emergency load shedding is the last resort to secure system stability and has a significant impact on industrial, residential, and commercial customers. In response to the thermal power shortage, on October 6, 2021, Inner Mongolia East Power Grid issued an "Orderly Power Consumption Plan" and because of high capacity adequacy and low demand in IME, the region avoided significant power cuts.

Context for the NEG Power Crisis – Prominent Public Narratives

The national crisis prompted vigorous discussion amongst experts and stakeholders, garnering substantial media attention. In this section, we evaluate some key narratives that emerged in those discussions, which helped to motivate the modeling scenarios we will explore in the following section.

Wind power output behavior

Much like other instances of severe power outages that gained global media attention, the NEG's blackouts have been attributed to low renewable energy availability. Admittedly, due to annual weather patterns, the months of July to September are indeed the weak wind period in NEG, with monthly power generation falling to about half of the strong wind period. A government source announced that after a cold front passed through in September, wind power output decreased. However, it should be noted that more than 60% of the load shedding occurred before the worsened weather conditions. What's more, wind plays only a small role in Liaoning's power supply, with a share of less than 9% of total power generation in 2021.

Economic recovery and power demand surge

A strong economic recovery resulted in the mounting electricity demand. In 2021, China's economic recovery from the Covid-19 pandemic was speedy, with its GDP growing 8.1% from the last year [10]. In the Northeast, economic growth recovered, albeit at a slower pace of 5.8% over the previous year [11]. In 2021, Liaoning's electricity demand grew 6.3%, the second-highest growth rate since 2012 [12].

Rising coal prices and constrained supply

Coal prices rose throughout the year. During the months of July, August and September 2021, coal prices surged due to coal mine incidents, safety inspections, safety supervision, environmental inspections, and production restrictions linked to the National Games hosted in Shaanxi [13]. The coal market has been liberalized since the 1990s, however policymakers continue to exert control over coal supply via numerous administrative tools. Policy concerns such as avoiding highly visible coal mine accidents, addressing overcapacity and managing coal sector profits are some key factors motivating supply interventions by the central government [14]. In late 2020, compounded with the changes in international trade of coal, these restrictions led to an unexpectedly high thermal coal price and low coal inventories in many power plants throughout 2021. In response to the coal supply shortage and power crisis, NDRC and NEA sought relief by increasing the domestic coal supply.

Effects of on-grid coal power price mechanism

Low electricity prices relative to the rising costs of coal led to serious loss for power generation companies and low enthusiasm to guarantee power generation. According to statistics from the Qinhuangdao port in September 2021, the price of 5500 kcal thermal coal reached a two-decade high of more than 2000 yuan/ton, up from only 600-630 yuan per ton a year prior [15]. Historically, benchmark on-grid coal-fired electricity prices were set administratively, with occasional adjustments to account for changes in fuel prices [16]. Since the new round of power sector reforms began in 2015, coal-fired power plants have expanded their participation in medium-to-long term (MLT) markets. However, market prices were typically still anchored around the administrative on-grid price. Starting in 2020, on-grid prices were allowed to float within a band (from -15% up to 10% above the on-grid price) and in the wake of the 2021 power crisis, the range was further expanded to allow the market to play a more significant role in determining the electricity price [17]. However, this constrained pricing flexibility was still not enough for coal generators to pass on the increased fuel costs to consumers.

For example, in Liaoning, prior to October 2021, the wholesale price for coal electricity was capped at 0.4124 yuan (benchmark price of 0.3749 yuan/kWh * 110%) [18]. Assuming a typical coal plant operating at a coal use of 305.5 grams of standard coal per kilowatt-hour [19], equivalent to 388.8 grams of Q5500 thermal coal, and 2000 yuan/ton coal price, the approximate fuel cost for this coal-fired unit alone would reach 0.78 yuan/kWh. This would result in a 0.37 yuan/kWh loss for the typical plant, even before accounting for other non-fuel costs. Coal prices went far beyond the tipping point where coal-fired generators could not recoup their operational costs of power production. In response, some coal-fired power plants reduced their output or went offline [20] [21].

Contractual obligations for inter-regional exports

The Northeast grid has long-term contractual obligations to export power to North China Grid (NCG). Two cross-regional transmission lines connect NEG and NCG with a total transmission capacity of about 5 GW. While China is a world leader in the construction of ultra-high-voltage transmission lines, the flexible operation of these lines is still a developing aspect. Scheduled flows over these lines are extremely rigid and are often determined months ahead of the actual dispatch. During the crisis in the Northeast, the region was still exporting contracted amounts to nearby provinces such as Shandong and Hebei, which were facing less severe shortages [14][22]. Thus, while conditions were tight in NCG, those provinces were able to shed load from industrial and commercial customers without resulting in residential power rationing.

The review of these potential factors paved the way for the modeling exercises, where a combination of these factors are evaluated in the simulated NEG to see their potential impact on the power system.

Immediate measures taken to resolve the crisis

Constrained by the current coal-dominant energy mix in the short term, for Liaoning, managing the coal supply is still a critical component of electricity reliability. In response to the impending power crunch, in late-September 2021, the Liaoning Province Department of Industry and Information Technology and State Grid Liaoning Electric Power Company suspended the operations of magnesium companies, releasing around 2,000 MW of electricity demand from the power grid. Meanwhile, 18 coal-fired power plants with a total of 6,150 MW of coal-fired power generation capacity were required to reduce their maintenance outages [23].

Furthermore, China's central economic planner, the National Development and Reform Commission (NDRC), was making efforts to ensure the nation's power supply through better electricity pricing mechanisms and improved energy structure [24].

After September 27, 2021, the orderly power consumption in Liaoning was further strengthened, and widespread power outages were eliminated. The NDRC and the National Energy Administration also sought relief for thermal generators by increasing the domestic coal supply. The stock of coal-fired power plants in Liaoning gradually increased from 1.89 million tons in late-September 2021 to 2.36 million tons by early October, and the power load gap narrowed from more than 5,000 MW at the end of September to about 2,000 MW in early October [23]. Heilongjiang and Jilin experienced a similar situation and as a consequence, power rationing and blackouts occurred there as well.

2 Methodology

This study employs a Unit Commitment and Economic Dispatch (UCED) model to examine the generation, transmission, and consumption of power in NEG, as well as their transmission to NCG through ultra-high voltage lines. The objective of the study is to evaluate resource adequacy in NEG under various scenarios for December 2022 and February 2023. The model inputs consist of data selected from 4 weeks in each month, for a total of 8 weeks, running individually with repeating boundary conditions.

Load, Generation and Transmission

The power load in NEG is composed of two components: regional power demand and the obligation to export to NCG. The demand in NEG zones is simulated based on the NDRC typical power demand curves for provincial power grids in the year of 2018 [7], and the demand for following years are projected out with an annual growth rate of 5%. The export power obligation is derived from the adjusted monthly cross-regional electricity transmission data, which is obtained by aligning raw data with a typical segmented export profile [25]. This profile effectively captures the characteristics of importing provinces' demands. In the event of unfulfilled demand during simulation, the model will produce non-served energy (NSE) at a considerably higher cost, which is defined as the NSE Penalty in this study.

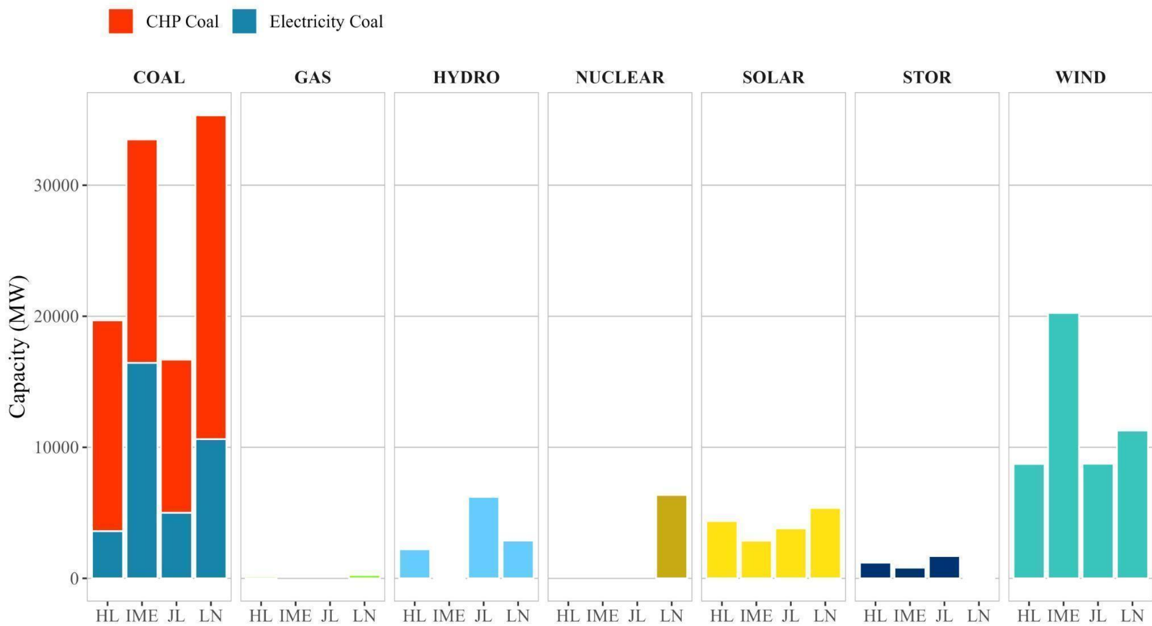

Figure 2. Installed capacity in NEG

Generator information includes a unit-level classification of coal-fired generators, differentiating between Combined Heat and Power (CHP) units and electricity-only units. Heilongjiang and Liaoning provinces also have a small fleet of gas-fired generators. Renewable energy profiles are based on typical hourly profiles in key renewable producing regions in each province simulated by Renewables Ninja [26]. Figure 2 summarizes the installed capacity in NEG. In winter months, when CHP units are producing heat at maximum capacity, their corresponding maximum output for electricity will decrease to around 70% of their rated capacity [27] [28] [29] (As shown in Appendix Table A.6).

Transmission path capacities between each province are considered in aggregate, and transmission losses are calculated between each pair of provinces based on line lengths and voltages between each zone (see Appendix for detailed information)

Scenarios

The Baseline scenario simulates normal operations, including the use of renewable energy profiles from 2020, standard coal prices based on the annual long-term contract price in 2020, and common operation of coal-fired units. This scenario assumes resources are dispatched according to the merit order that is often achieved through an efficient spot market. There are no interprovincial barriers to transmission beyond the physical line capacity within NEG, and all regional resources are treated equally during dispatch decisions. Arguably, the Baseline scenario is different from the reality, but provides valuable insights into how the grid is operated in the idealized situation where the short-run system cost is minimized. Other scenarios explore the effects of various existing policies and dispatch rules currently in use in NEG.

Table 1. Simulated scenarios and key parameters

Scenarios	Demand	Coal-Fired Capacity	Coal Prices	Renewable Profiles	NSE Penalty in NCG
Extreme Weather	+ 15%	-	-	Low availability	-
High Fuel Price and Derated Capacity	-	Derated	High	-	-
Prioritized Export	-	-	-	-	High
Combined	+15%	Derated	High	Low availability	High

Scenarios are listed in Table 1, where "-" indicates Baseline input. Demand **"+ 15%"** refers to a 15% increase in energy demand across all zones, taking into account data from Chinese historical records during extreme weather conditions [30]. **"Derated"** coal-fired capacity denotes the reduction in total coal generator capacity from electricity-only coal generators. It signifies a decrease of approximately 11% in NEG (20% in Liaoning [31], 10% in both Heilongjiang and Jilin, 0% in IME). This derating percentage was established following an evaluation of the actual unexpected reduction in available coal generating capacity during the 2021 power crisis in NEG, which was primarily attributed to inflexible pricing mechanisms. **"High"** coal prices are calculated based on the highest fuel prices observed in October 2021. **"Low availability"** renewable profiles refer to the lowest average renewable energy profiles over the past 10 years for relevant months. **"High"** NSE penalty in NCG means that the NSE cost in NCG is twice as high compared to NEG, which mimics a prioritization to meet export demand to NCG, whereas local demands are deemed secondary. All CHP units are guaranteed to stay committed in all scenarios.

3 Results

Modeling simulations are conducted for December 2022 (peak winter month) and February 2023. The primary difference between the two months is that December 2022 had higher overall energy demand. The Lunar New Year holiday reduces energy use over January/February, depending on the year.

Table 2. Operational costs by scenario in Winter 2022/2023 (US$M). Exchange rate: 1 USD= 7.00 RMB

	Baseline		Extreme Weather		Combined	
	December 2022	February 2023	Decembe r2022	February 2023	Decembe r2022	February 2023
Variable Cost	1,589	1,597	2,181	2,211	3,379	3,228
Start Cost	**3.25**	10.8	1.9	9.3	0.5	7.7

The Baseline scenario has the lowest variable costs and the highest start costs, indicating efficient coal-fired generation with more frequent unit start-ups and shut-downs (Table 2). In the Extreme Weather scenario, increased demand and limited availability of renewable energy result in higher coal-fired generation and reduced unit start-ups and shut-downs. In the Combined Scenario, resource inadequacy results in minimized start-ups and shut-downs and high power generation from coal-fired plants, reflected in the highest variable costs and lowest start costs in both months.

December 2022

In the Baseline scenario, all NEG zones maintain resource adequacy and fulfill export obligations to NCG. The main power sources in the region are coal-fired power and wind power, and coal units reduce their output when wind generation is sufficient (Figure 3). Inner Mongolia East is primarily responsible for supplying power to Heilongjiang and Liaoning provinces, due to its abundant capacity. Additionally, Jilin also supplies power to Heilongjiang and Liaoning during periods of high wind generation. Energy storage is charged at night when wind is abundant and discharged during peak hours to relieve stress on the system.

In the Extreme Weather scenario, where the system is stressed with high demand and low renewable availability but has well-functioning markets, NEG is still able to maintain its resource adequacy while fulfilling its export obligations to NCG for most of the time. However, it experiences periods of NSE during peak hours when renewable energy is extremely limited (Figure 4), and concurrently, it also upholds a relatively high export obligation to NCG during peak hours. The output of coal power has increased across all provinces, with coal power units reducing start-up and shut-down times to maintain higher output and complement the reduction in renewable energy. The decrease in wind and the increase in demand also result in reduced amplitude and frequency of storage unit charging/discharging.

Usually, coal units stably serve as base-load units and rarely shutdown. Existing coal unit capacity can accommodate wind power well under various wind availability scenarios assuming well-functioning markets.

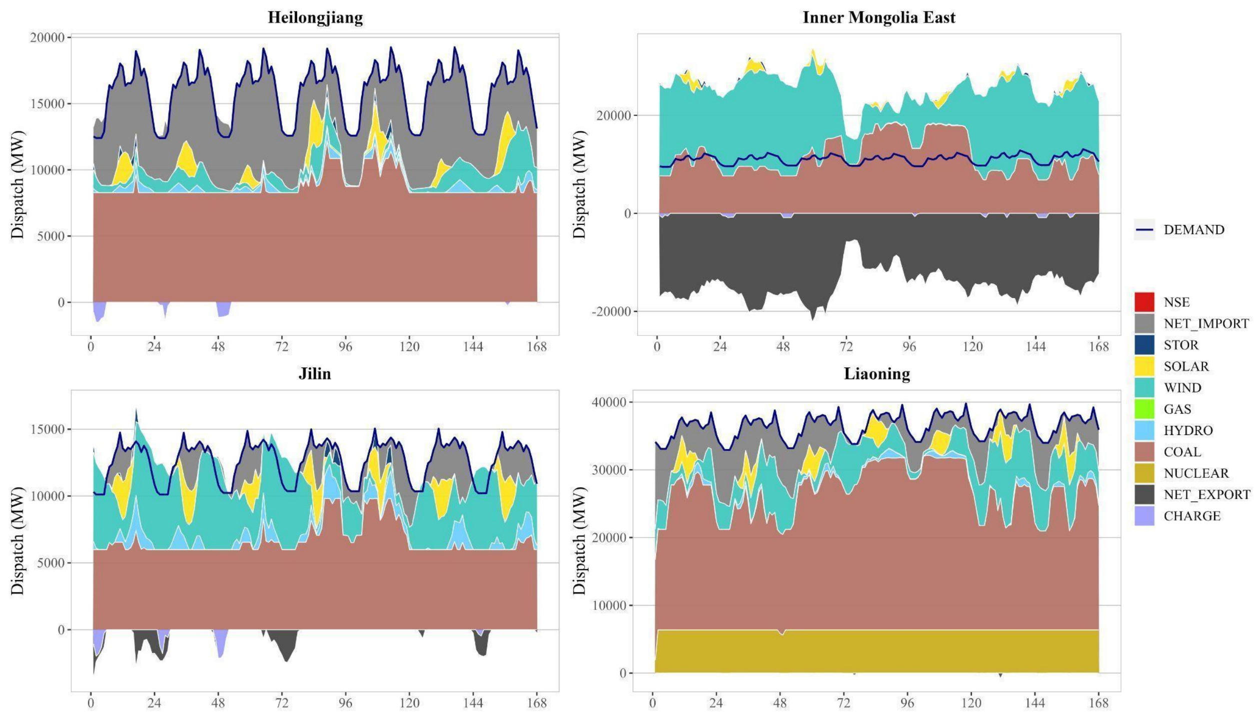

Figure 3. Dispatch results in peak week of December 2022 (Baseline)

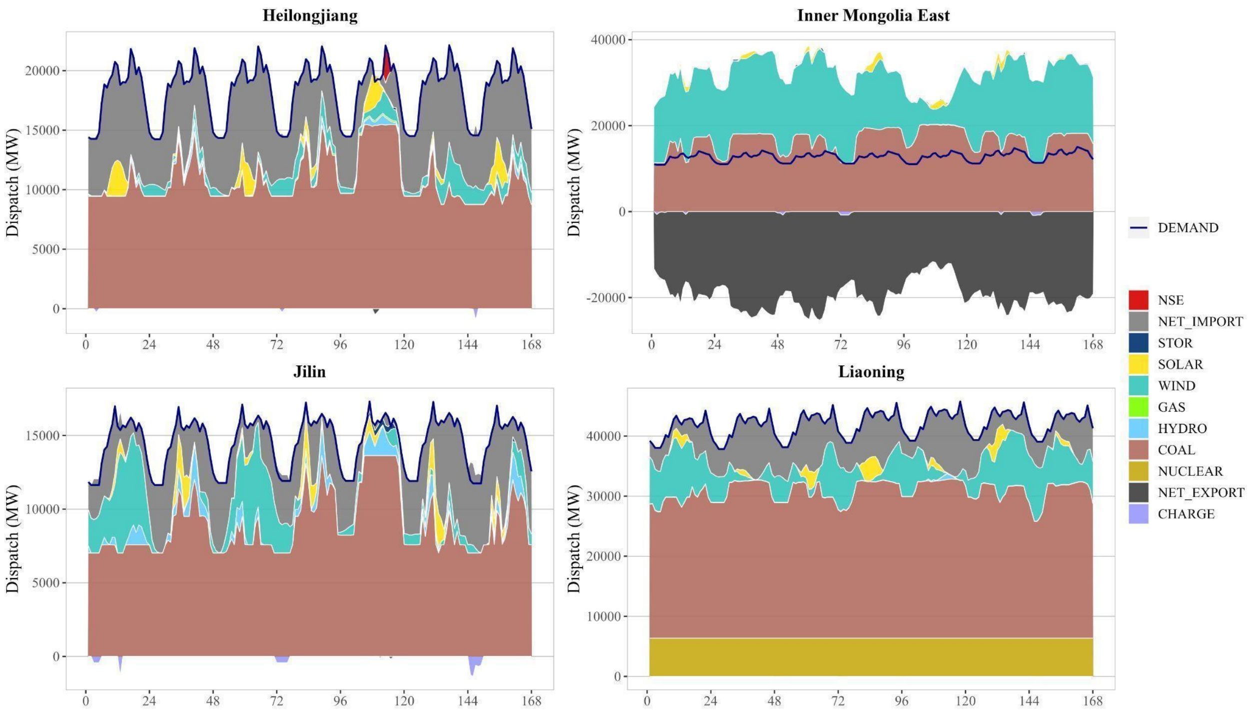

Figure 4. Dispatch results in peak week of December 2022 (Extreme Weather)

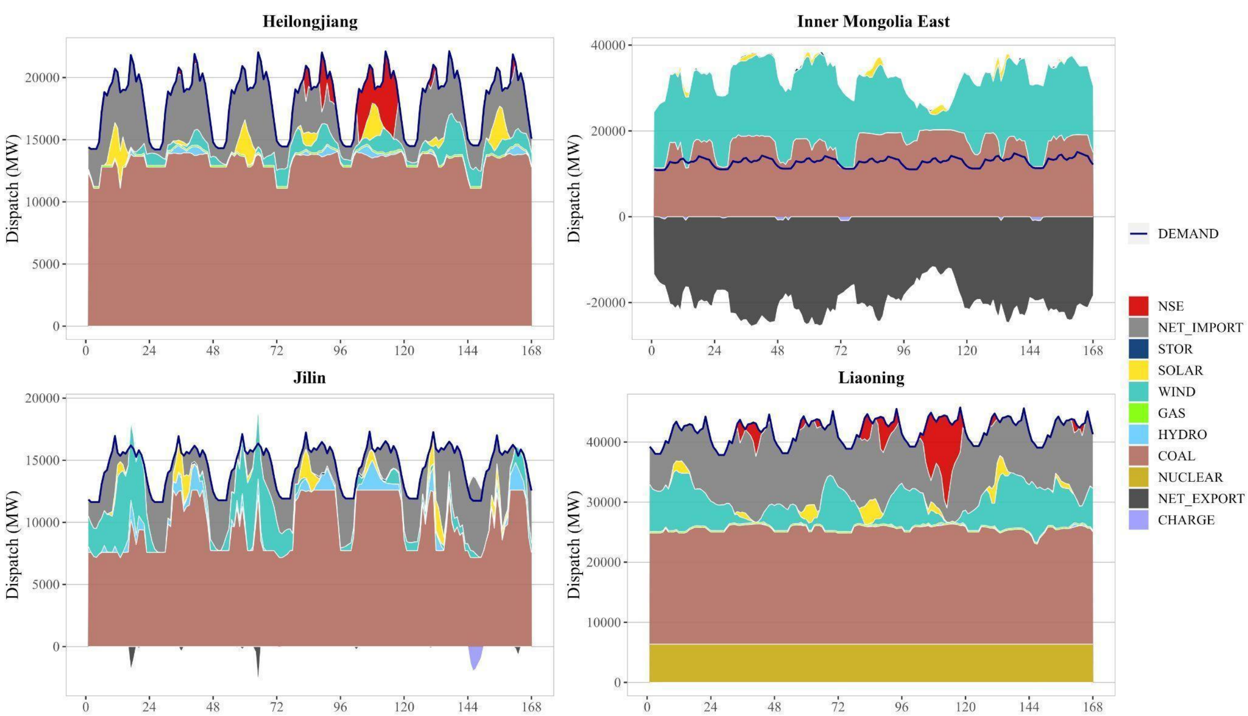

Figure 5. Dispatch results in peak week of December 2022 (Combined Scenario)

In the Combined Scenario, NEG is unable to maintain its resource adequacy nor fulfill its export obligations to NCG. The region experiences significant NSE, even during off-peak hours at night when wind availability is limited and coal-fired capacity is reduced (Figure 5). Reducing CHP units' electricity capacity dramatically compresses the NEG's capacity and undermines its adequacy and peak-shaving flexibility during low wind and high load hours.

In the NEG during the four weeks of December, the renewable shares are 34% in the Baseline scenario, 23% in the Extreme Weather scenario, and also 23% in the Combined scenario. The reduction in renewable share observed in the Extreme Weather scenario can be attributed to the limited availability of solar and wind resources under the constraints of extreme weather events. The Combined Scenario demonstrates a slight increase in renewable share relative to the Extreme Weather scenario, primarily due to the decrease in coal's contribution to generation.

Average utilization rate of transmission paths in Baseline was 44% while the Combined Scenario results in 39% (Figure 6). This decrease is due to energy availability constraints, causing a trend towards self-sufficiency in all zones after meeting NCG export obligations. Export paths from Inner Mongolia East and Jilin are increased while other paths are reduced. The lack of support from Jilin to Heilongjiang results in decreased usage of the Jilin-Heilongjiang path and increased NSE in Heilongjiang.

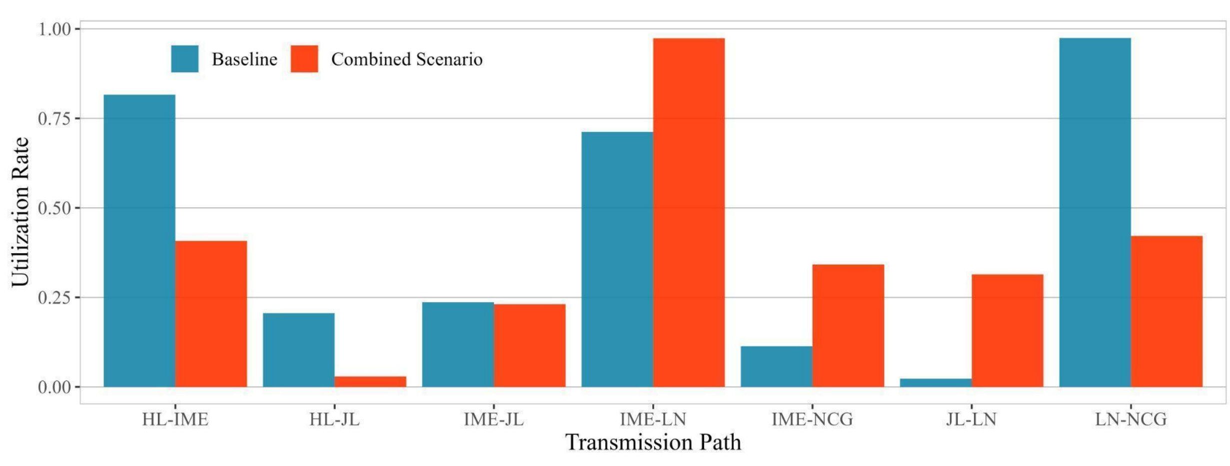

Figure 6. Transmission path utilization rate in December 2022

High Derating Sensitivity Analysis

Historical data indicates that during this period, 6150 MW of coal generator capacity in Liaoning province was unavailable [31]. Based on documented observations and estimates, the derated coal generator capacity in Liaoning province may have peaked at 20-30% of total capacity. The effects were comparatively milder in other provinces in NEG due to lower power demands.

Averaging across all provinces within the NEG, we arrived at an average derate of approximately 11% across the entire NEG as our main scenario. In a high derating sensitivity, we extended Liaoning's 20% derating across the entire NE region (excluding Heilongjiang due to its limited electricity-only generators). The objective was to explore the potential repercussions of additional derating of coal power units on the system, particularly on NSE.

We then assessed the impact of these different derating scenarios on costs and NSE for December 2022. When comparing the 20% derating scenario to the 11% scenario under the same demand across the NE region, the former has fewer startups and shutdowns, thus lowering the start cost. This is because under tremendous demand pressure, most available units are already committed.

Table 3 presents the findings related to NSE: for an additional 9% derating, the system would suffer from an increase of NSE by about 7000 MW in the worst-case scenario. This would escalate the max instantaneous NSE from 22.4% to 34% of the total demand at that instant. The average NSE increased more than twofold, rising from 2.4% of total demand to 8.4%.

Table 3. Non-served energy in December 2022 under different derate capacity

	NEG Max. NSE (MW)	NEG Max. NSE (% of Demand)	NEG Avg. NSE (MW)	NEG Avg. NSE (% of Demand)
11% Derate	21,553	22.4	2,124	2.4
20% Derate	28,428	34.0	6,498	8.4

The findings from our sensitivity analysis highlight the impact of further derating. To the extent that deratings are largely caused by ineffective pricing mechanisms, these findings also underscore the crucial role of effective market mechanisms in the NEG's ability to reliably meet demand.

February 2023

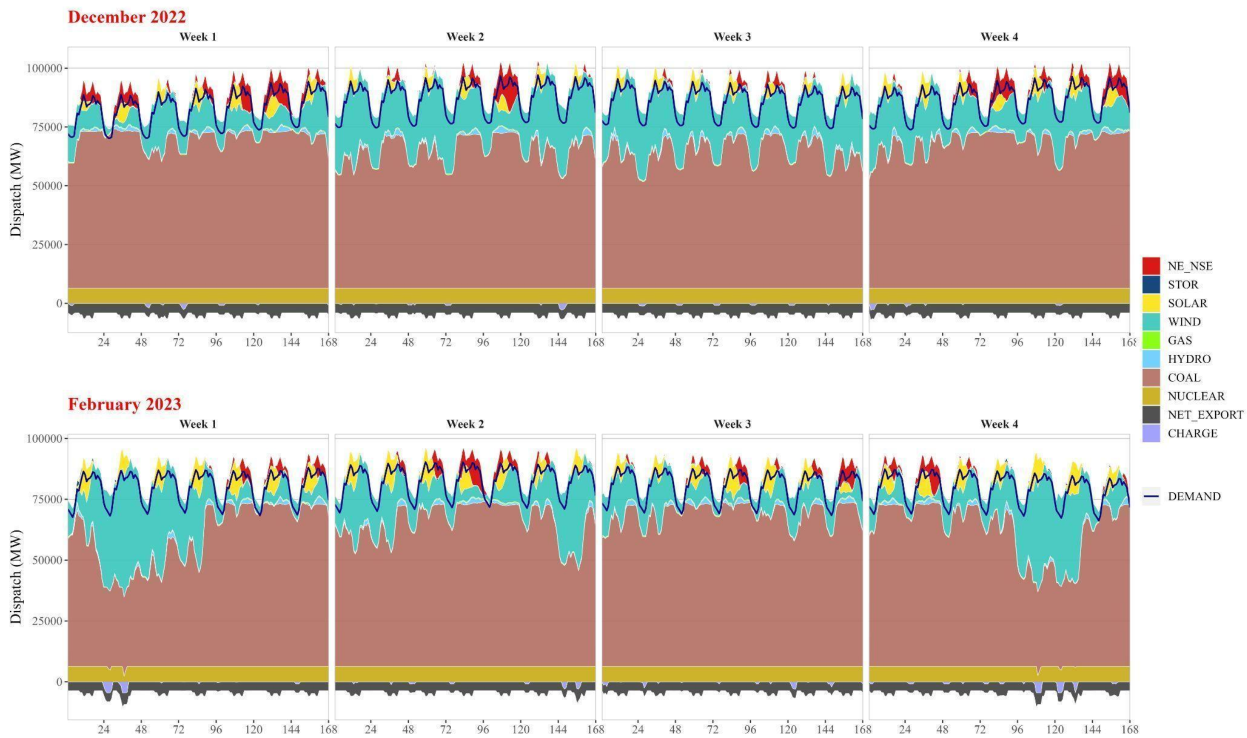

Figure 7. NEG regional monthly dispatch (Combined Scenario)

The results of the February 2023 simulation are consistent with the findings from December 2022 (Figure 7), though the system was less stressed in February 2023 compared to December 2022. The decline in average and maximum power demand led to a decrease in NSE and path utilization in extreme conditions, allowing provinces to better meet demands with their own resources (Tables 4 and 5). As shown in Table 5, the highest demand month (December 2022) sees less utilization of energy storage, because there is insufficient generation capacity available to charge and make available for peak-hour power demands. Nevertheless, without generator derating and other factors, it is expected that the growth of energy storage in NE will positively contribute to improving resource adequacy.

Table 4. Demand in NEG and NCG

Modeling Periods	NEG Max. Demand (MW)	NEG Avg. Demand (MW)	NCG Max. Demand (MW)	NCG Avg. Demand (MW)
December 2022	84,239	74,436	5,590	4,032
February 2023	78,383	70,146	5,072	3,659

Table 5. Non-served energy, transmission utilization, and energy storage in Combined Scenario

Modeling Periods	NEG Max. NSE (% of Demand)	NEG Avg. NSE (% of Demand)	Avg. Path Utilization (%)	Total Storage Charged (MWh)
December 2022	**22.4**	2.4	38.9	82,496
February 2023	**17.6**	1.6	34.4	165,780

Even though Liaoning is usually a net power importer, it plays a significant role in exporting power to NCG that are generated by Liaoning and neighboring provinces (Figure 8). The net transmission flow decreases overall in the Combined Scenario as all provinces need more capacity locally: provinces with surplus capacity provide less support, while other provinces with limited capacity, such as Liaoning, must still fulfill significant export tasks due to export contracts, further exacerbating the power crunch.

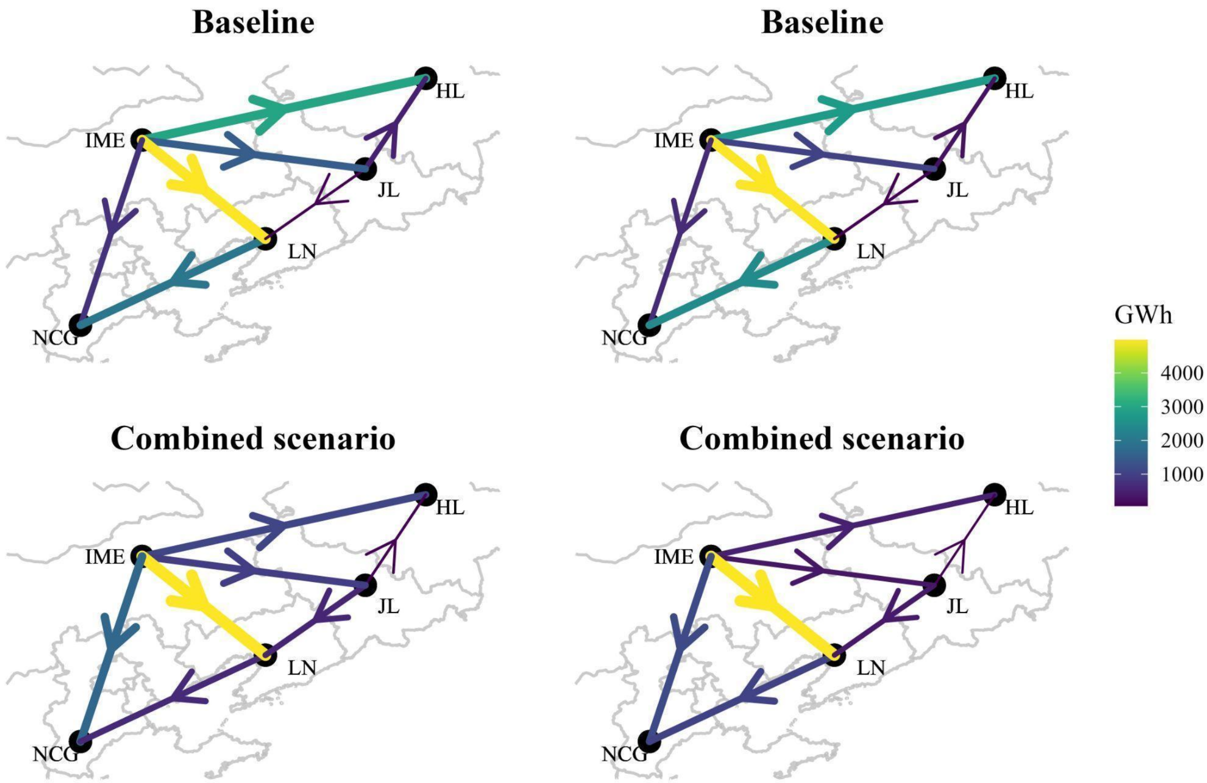

Figure 8. Transmission net flow (December 2022, left; February 2023, right)

According to the results of December 2022 and February 2023, Inner Mongolia East is the main exporter to other zones, with Jilin assisting in export when its wind power resources are sufficient, thereby helping Heilongjiang and Liaoning meet their power demand. Under the most extreme conditions (Combined scenario), a large amount of NSE is observed in Heilongjiang and Liaoning. The results of the model also indicate that in all scenarios, renewable energy curtailment is minimal, which aligns with the actual situation of 2-3% during these periods of high demand.

Wind power output in NEG is correlated with the occurrence of NSE due to its high share in the generation mix. This impact is observed during both peak and off-peak hours, when wind power availability is severely constrained, a considerable amount of non-served energy is generated. While this does not mean wind power output reduction caused more NSE, it does demonstrate that system adequacy is more susceptible to variation in renewable energy generation when thermal plants' performance are severely constrained by suboptimal market arrangements.

AC lines within the region connecting Inner Mongolia East with Jilin and Heilongjiang improve resource adequacy and wind power balancing. New AC lines under construction (Balin-Naiman-Fuxin 500 kV with 1000 MW transmission capacity) will also help to alleviate some congestion and advance RE integration.

Energy storage could play a role in mitigating resource adequacy challenges, though with some caveats. In some NEG zones where high NSE occurs, storage units account for only a small portion of generation profile. For instance, Liaoning has only 16 MW battery storage even though this zone suffers from severe resource inadequacy in the Combined Scenario. On the other hand, some NEG zones with high NSE potential have non-negligible amounts of storage capacity, but these units are not operated often due to severe resource inadequacy of generators to charge. For instance, Heilongjiang has 1200 MW pumped hydro, but it is not dispatched in Combined Scenario even during NSE periods. Since these storage units would not be able to recharge over extended periods of system stress, they provide less support to the grid. We also observe that storage units withhold a significant portion of their capacities to provide operating reserves, a necessary backup source to avoid unexpected blackouts.

4 Policy Recommendations

The results from the analyses presented in this paper suggest policy reforms are needed to support power system reliability at reasonable cost while achieving emissions reduction goals. In this section, we discuss some existing problems in policy, compensation mechanisms, and planning practices and offer some practical recommendations.

Markets and prices

The 2021 power crisis in the Northeast was not caused by a lack of firm power generation capacity; rather, one of the main contributors to this crisis was the administered coal on-grid electricity price mechanism, which hampered the system's ability to adjust for high fuel coal prices. Coal prices increased significantly over the course of 2021, yet the on-grid coal-fired electricity price was not sufficiently flexible to reflect this price surge, and markets were predominantly medium- or long-term (MLT) contracts of monthly or longer. As a result, coal-fired power plants found themselves losing money for each additional kWh of electricity generated, causing significant withholding of coal generation capacity [32]. While this may have made a positive short-term contribution to emission-reduction goals, it was not an efficient or sustainable way to do so. More broadly, the implications of these rigidities go beyond coal power withholding. Failure to rectify them will stymie the ability of the power system to integrate higher shares of variable renewable generation in coming years.

We recommend expediting the implementation of a unified regional Northeast spot market. A unified regional spot market lies at the foundation of rationalizing compensation to resources. Having a unified regional spot market without overly-restrictive price limits (but subject to careful monitoring and market power regulation) would encourage available dispatchable resources to operate during times of system need (in response to higher market prices and on short time intervals) and yield to variable renewable generation during times of high solar or wind output. There are now spot market pilots across the country underway with many distinct rules. We recommend leapfrogging provincial-level spot market implementation and move directly to a unified regional spot market for each region. The existing northeast region ancillary services market mechanism may provide an initial basis from which to build a practical regional spot market. The priority should be to create a time-varying wholesale spot price that reflects system conditions and offers reasonable compensation to resources [33].

Under a working unified regional spot market, there is no need for an administered benchmark coal-fired electricity price as a compensation mechanism for thermal generators. In the wake of the 2021 power crisis, NDRC widened the allowed band around the on-grid price for market transactions. Specifically, the lower limit had previously been set at 15% below the benchmark and the upper limit at 10% above the benchmark. These limits were widened to 20% on both sides (high-energy-consuming enterprises are not subject to the 20% price cap) to help address the conflict between benchmark electricity price and fuel coal price [17]. While this is a positive step forward, markets are still too restrictive.

First, the new band could still discourage generation during future episodes of high coal prices. In other words, it can undermine compensation for firm capacity to be available when needed. Second, when coal prices are lower, it tends to encourage coal generators to look for ways to increase their output above efficient levels, leading to excess system costs and emissions. Third, if dispatch centers make efforts to ensure MLT contracted hours are met at the end of each month, it tends to undermine hour-by-hour flexibility that is much needed with high levels of wind and solar generation. Like many other sectors in the Chinese economy, the electricity sector is growing “out of the plan”. In the past, the benchmark price played a role in promoting electrification and stabilizing electricity prices. However, the 2021 power crisis shows that the administered on-grid coal price mechanism is not compatible with a new energy system.

It is time to liberalize the administered aspects of the benchmark price and let the spot market take a larger role in thermal resource compensation. As in other countries, thermal generators could still seek to lock in MLT contracts on a competitive basis (through financial contracts, such as contracts-for-difference), but the MLT price should not be administered or restricted by bands—and the spot market should be the main price signal driving thermal generator incentives.

Planning processes

Forward-looking analysis investigates the security of the electricity system ahead of a seasonal period (typically, winter and summer) by looking at where system adequacy is at risk. It is an important and evolving part of the power system planning processes globally. Even with seasonal resource adequacy assessments, systems may still suffer from episodic reliability problems, but it is clear that improved forward-looking analysis can help support the reliability and safety of electricity systems, particularly in more open, marketized systems with growing shares of renewable energy. How to refine these processes is a hot topic in the US and EU [34] [35]. In addition, forward-looking scenarios can provide a useful reference point to evaluate crises and periods of tightness after the fact. Once a resource adequacy vulnerability is identified, policymakers can then make risk-informed decisions to address the gap.

Some notable examples include the Seasonal Outlooks conducted by ENTSO-E in the EU and Seasonal Reliability Assessments conducted by various regional reliability organizations under the supervision of NERC and FERC at the federal level in the US [36][37][38]. Improved forecasting of weather extremes, and of weather effects on demand and supply, are under development. In regions of China with significant district heating provided by CHP plants, the interactions with the heating system should be incorporated.

Additional policy perspectives

Finally, we offer three additional observations based on international experience and our understanding of current conditions in the Northeast and China as a whole, which would be worth analyzing in future work.

First, instead of solely focusing on having enough thermal generation capacity to meet peak load, the emphasis should be on optimizing the use of a wide range of resources. The software (dispatch practices, official regulation, market rules, business models, and incentive structures) of the power system is just as important as the hardware (generators, transmission and distribution lines) in ensuring reliability.

Second, constructing additional coal-fired power plants is unlikely to be the least-cost answer to support a reliable, new energy power system. The market and planning mechanisms that we recommend above are likely to identify better solutions than new coal power capacity to support a power grid with increasing amounts of renewables. They are also likely to reject “establishing coal plants first before tearing them down” as uneconomic. This is certainly true around the world, due to several factors that are also present in China, even though the details vary. These factors include the decline in cost of wind, solar, and storage resources and the ongoing availability of low-cost demand-response and energy savings options [39]. A power system with high levels of flexibility can maximize the use of inexpensive variable renewable resources while optimizing the role of other resources in supporting roles. Our analysis in this paper does not address the long-term trajectory for coal capacity in NEG or for China overall. However, some recent modeling efforts have indicated that China's existing thermal fleets can support 80% non-fossil generation mix without the need to further expand its coal fleet [40]. In the long term, new "clean firm" power resources may be needed for future electricity mixes with even higher penetrations. In several grids, including the Northeast examined here, there are plans to construct large amounts of battery and pumped hydro energy storage which can partially offset the need for coal for reliability purposes. Additional transmission lines are also under construction and will help alleviate resource adequacy challenges if operated efficiently.

Third, it is important to continue developing policy and market rules to unlock the benefits of demand response and energy savings. To incentivize holistic development of more flexible resources to serve a new energy system, system planners could engage additional demand side resources, including energy savings. In the Northeast, due to the large amount of existing coal capacity, much of the interest in increasing system flexibility has been focused on retrofitting existing coal-fired power plants [41]. While these plants can partially supply much needed flexibility at a scale of hours and days, more granular flexibility that will adjust power output within seconds will require the participation of a variety of fast-responding resources such as demand response, energy storage, and possibly gas-fired capacity [42]. The market needs to be designed to allow more diversified participants (including those representing demand-side resources) to participate in spot electricity markets. These resources can provide valuable system flexibility services and help integrate growing shares of renewable energy and should be rewarded fully and fairly for doing so. These resources can provide better and lower-cost alternatives to emergency "orderly use" policies with large societal costs.

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Appendix

Input data

Data Sources

The data utilized in this study were obtained solely from public sources, specifically the Global Energy Monitor (GEM), WIND Financial Terminal (WIND), Renewables Ninja (RN), PowerGenome (PG), as well as news articles and reports (NR). Further details regarding the sources of data can be found in Table A.1.

Table A.1 Data sources for generators information

Generator Type	Capacity	Performance	Capacity factors	Heat Rate	Start cost	Fuel prices
Coal	GEM	NR	1	GEM	PG	WIND
Gas	GEM	NR	1	PG	PG	WIND
Wind	WIND	1	RN	0	0	0
Solar	WIND	1	RN	0	0	0
Hydro	WIND	PG	WIND	0	0	0
Nuclear	NR	NR	1	-	PG	0
Storage	NR	1	1	0	0	0

Demand

Simulated power demand for NE and NE to NCG export obligations are shown in Figure A.1.

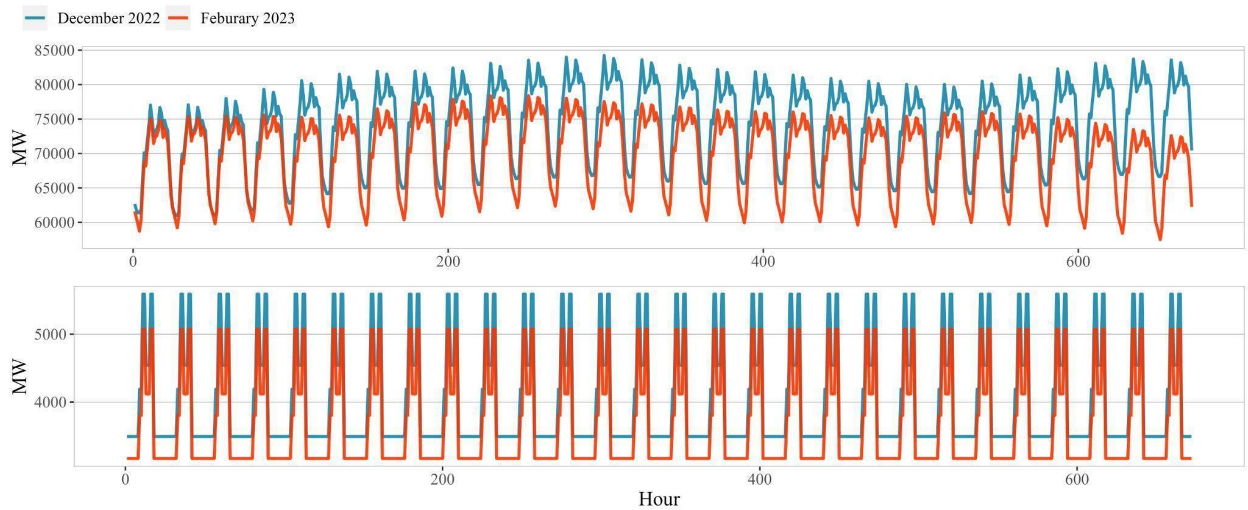

Figure A.1 Demand for Winter 2022 / 2023 (NE, top; NE to NCG export obligation, bottom)

Fuel prices

We show fuel prices in Table A.2. Coal prices in Baseline is calculated based on Qinhuangdao Q5500 annual long-term contract price + transportation cost to each zone (assume 0.33 RMB/(ton*km)). Coal prices in High Fuel Price/Derating Capacity refers to the monthly long-term coal prices + transportation cost calculated from:

Monthly long-term contract coal price (weekly index) = 1/3 * ((CCI index + CCTD index + CECI index) at last Tuesday)

Table A.2 Coal prices ($/MMBTu)

Provinces	Baseline Coal Price	High Coal Price
Heilongjiang	5.82	9.27
Inner Mongolia East	4.74	8.19
Jilin	5.38	8.84
Liaoning	4.52	7.98

Gas prices in all scenarios refer to Natural Gas Benchmark Price published by the State Council, as shown in Table A.3.

Table A.3 Gas prices ($/MMBTu)

Provinces	Benchmark Gas Price
Heilongjiang	6.56
Inner Mongolia East	4.88
Jilin	6.56
Liaoning	7.36

Transmission topology, path capacities, and line losses

Transmission lines aggregated in paths and their voltages are illustrated in Figure A.2. The maximum transmission capacity for each transmission path is shown in Table A.4. Line losses incurred during transmission are calculated under parallel lines (R = 1 / sum_k(1/r_k) , r_k = resistance over line k, where r_k is indicated in terms of %) based on the specific losses in Table A.5.

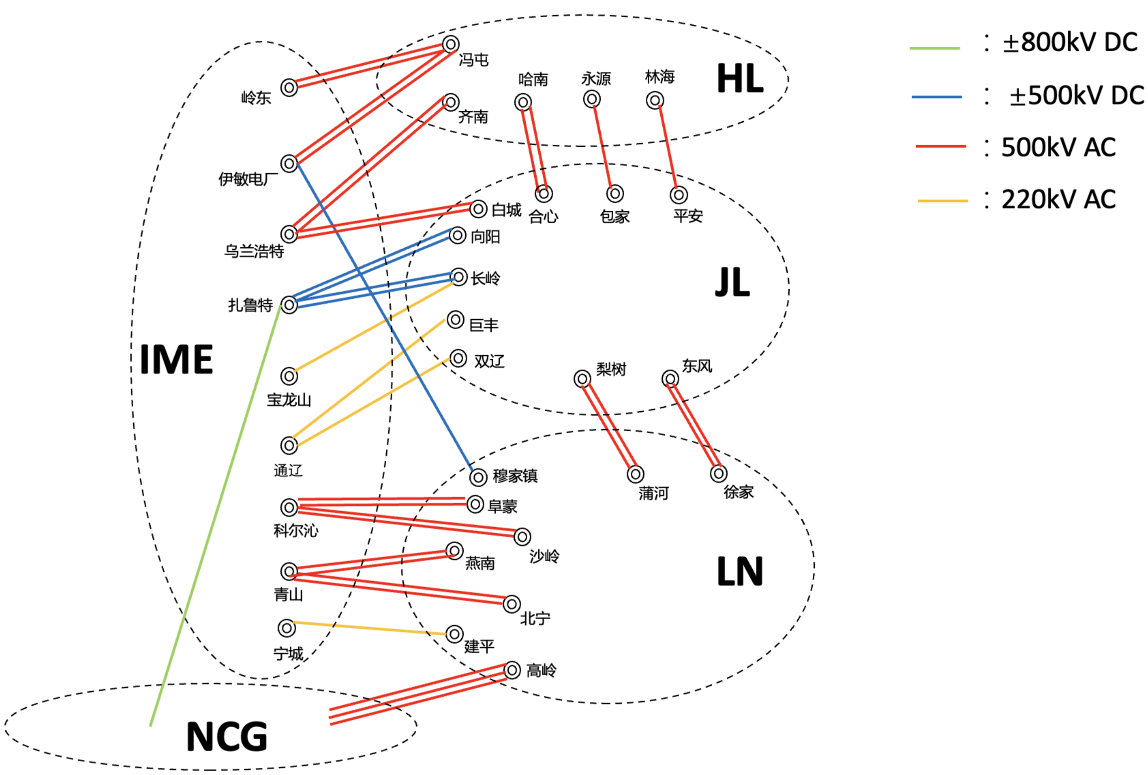

Figure A.2 NEG interprovincial transmission network

Table A.4 Transmission path capacities

Path	Aggregated Capacity (MW)	Path	Aggregated Capacity (MW)
HL-IME	5400	HL-JL	3600
IME-JL	9360	IME-LN	10400
JL-LN	3600	IME-NCG	10000
LN-NCG	3000		

Table A.5 Transmission losses

Transmission Line	Losses (per 100 miles)	Transmission Line	Losses (per 100 miles)
±800 kV DC	0.31%	±500 kV DC	0.45%
500 kV AC	1.30%	200 kV AC	4.20%

Capacity allocation for heat operations

About two-thirds of all coal-fired installed capacities in NE are from CHP units, which provide 70% of NE's heat load in winter. When the units produce heat at its maximum, the corresponding maximum output for electricity will decrease as shown in Table A.6.

Table A.6 Maximum power output for electricity from CHP units

Rated Capacity (MW)	Reduced Capacity (MW)	Number of CHP units
0 - 150	No change	120
200	155	39
300	241	30
330	279	61
600	410	9
800	No change	2

1000	No change	2

NSE Cost

Unmet demand incurs $9,000/MWh for all zones and NCG in Baseline scenario. Prioritized Export reduces this number to $4,500/MWh for NE zones.

Model

Computational setting

Our model is a mixed-integer linear programming model. We use the barrier method to find a relaxed solution in the starting node of the branch & bound tree. The MIP optimality gap is 0.5% and the time limit is 26 hours (more than enough because one scenario run only takes 3 - 4 minutes). We use Julia as a programming language, JuMP as a mathematical optimization interface, and Gurobi as optimization engine.

We solve each week independently from the next week. We enforce repeating boundary conditions at the beginning and ending of each week. Solving the model for each week independently remarkably reduces the computation time relative to simulating a whole month at one time.

Resource classification

Thermal resources (subject to unit commitment operations) include CHP coal, electricity-only coal, nuclear, and combined cycle natural gas units. Storage units are batteries and hydroelectric pumped hydro. All hydro units are reservoir hydro. Non-dispatchable renewable resources are solar (solar photovoltaic) and wind (onshore wind). Dispatchable renewable resources include only reservoir hydro units.

Thermal resources are represented at unit level. All other resources have aggregated capacities.

Decision variables, constraints, and objective function

Hourly decision variables include commitment, start-up and shut-down status for thermal units, dispatch, charge of storage units, state of charge of storage units, zonal NSE amount, flow on transmission lines, and up and down operating reserves. Commitment, start-up, shut-down variables are integer variables. We do not have generation resources in NCG.

Constraints include weather-dependent limitation on dispatch from solar and wind resources, minimum power requirement for committed thermal resources, ramp-up/down limitations for thermal resources, state of charge of storage units limited by energy capacities, charge and discharge operations for storage units considered with two-way efficiency factors (we fix state of charge of storage units at an equal level), commitment operations for thermal units, minimum up/down time periods for thermal resources, power flow on lines limited by power capacities considered with transmission loss, demand-balance constraints (transmission loss in exporting and importing zones are equally distributed), up and down reserve contributions from resources, and up and down reserve requirements for each NE zone at each hour. We make sure that flow on transmission lines connecting NE to NCG is one-directional (only from NE to NCG)

Objective function is the sum of variable, start-up, and NSE costs. Variable cost includes variable operation and maintenance cost and fuel cost. Start-up cost is incurred when a thermal resource starts operating. It includes start-up cost per MW and cost of fuel burned during start-up operations. NSE cost refers to the cost of unmet demand in the form of blackout. We assume that fuel prices stay constant during a month.

Operating reserves

Up reserve contribution from thermal resources is less than committed capacity, remaining of committed capacity after excluding dispatch amount, and ramp-up capacity. Down reserve contribution from thermal resources is less than committed capacity, minimum power requirement, and ramp-down capacity.

Up reserve contribution from dispatchable renewable resources is limited by their capacity and remaining capacity after excluding dispatch amount. Down reserve contribution from these resources is limited by their capacity and dispatch amount.

Up reserve contribution from reservoir hydro is limited by their capacity, remaining capacity after excluding dispatch amount, remaining energy capacity considering minimum water level requirement, and ramp-up capacity. Down reserve contribution from these resources is limited by ramp-down capacity and dispatch amount.

Storage units contribute to up and down reserve while charging and discharging. Details of this modeling can be found at code repository.

For each zone, the up-reserve requirement consists of 5% of demand plus 10% of dispatch from renewable energy resources, and includes a contingency (the largest thermal unit or AC transmission line capacity, might be defined as N-1 contingency). We ignore operating reserves for NCG because NE only needs to meet NCG demand. Down reserve requirement is the same as up requirement, except that there is no contingency and non-dispatchable resources can contribute to down reserve.

Reservoir hydro modeling

We model reservoir hydro units as both storage and generators. It can store water in its reservoir and control the generation amount. The amount of stored water is controlled by the inflow and generation amounts. The amount of stored water is bounded above by the energy capacity of the reservoir and below by minimum allowed water level. We fix the level of water at half of energy capacity for the both ends of a week.

Hydro inflow refers to historical hourly generation data divided by capacity (similar to capacity factor of non-dispatchable resources). Capacity and historical generation data are obtained from the WIND Financial Terminal, and generation is assumed to remain constant throughout the month.

Scenarios

Extreme Weather models a 15% increase in power demand across all zones, and uses the lowest average renewable energy profiles over the past 10 years for relevant months. High Fuel Price and Derated Capacity simulates the conditions of the 2021 Northeast Blackout, with extreme fuel prices observed in October 2021 and an overall 11% reduction in total coal generator capacity from electricity-only coal generators. We derate coal generator capacities for each zone separately (10% of Heilongjiang and Jilin, 20% of Liaoning and none from IME), starting from the least efficient units (the highest heat rate) until the assigned ratio% of total coal capacity is reached. Prioritized Export prioritizes power export to NCG by implementing a higher NSE penalty in NCG compared to NE, as stipulated by their long-term power transmission contract. Combined combines Extreme Weather, High Fuel Price and Derated Capacity, and Prioritized Export.