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The institutional logic of wind energy integration: What can China learn from the United States to reduce wind curtailment?

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ABSTRACT

To date, China has the world's largest wind power generation capacity, followed by the United States. Yet, China's utilization of this installed capacity trails that of the United States by a huge gap. This paper seeks to explain this gap by focusing on the role of institutions. First, it analyzes the institutions that either facilitate or impede wind integration in the two countries. Next, it synthesizes these institutions into coherent institutional logics for China and the United States. Then, it corroborates the institutional analysis with empirical evidence from China and the United States. Finally, it compares the two countries and summarizes what China can learn from the United States to reduce wind curtailment. Overall, this paper finds that China's dominant institutional logic of wind integration is state centrism and it is complemented by partial decentralization and liberalization – a system that is more conducive to capacity addition than capacity utilization. By contrast, the United States' dominant institutional logic of wind integration is market competition but a competing logic also exists which is regulatory interventionism – a system that aligns capacity addition and utilization better but engenders greater policy uncertainty. Because the two countries have distinct institutional logics that generate different root causes for wind curtailment, this paper argues that simply transplanting solutions from the United States to China will not work. What China can learn from the United States is to make incremental improvements to address the frictions between its dominant and complementary institutional logics.

1. Introduction

Wind energy is renewable energy. It is generated by converting the kinetic energy in natural winds into electrical energy. Physically, wind-generated electricity is identical to that generated by coal-fired power plants and natural gas turbines. Yet because wind energy is abundant, renewable, and zero-emission, it is an important component in the greening and decarbonization of modern electricity systems. To generate electricity from wind energy, first wind turbines need to be installed, then the turbines need to run and inject electrical energy into the power grid. Sometimes the installed wind generation capacity is not utilized to its full potential, i.e. grid-connected wind generators are not allowed to produce what is enabled by the wind conditions. This situation is commonly referred to as "wind curtailment" [1,2].

Curtailment happens in all electric systems with wind power. "Curtailment level" is a measure of the severity of curtailment. Mathematically, it is defined as the ratio between the curtailed wind power and the total available wind power. The optimal level of curtailment varies by specific applications. Absolute zero curtailment is difficult to attain and imposes significant system balancing costs. Severe curtailment is also problematic as it impairs the financial viability of wind power projects. Generally, curtailment at or below 5% is considered

Abbreviations: GW, Gigawatt; MW, Megawatt; TWh, Terawatt-hour; REL, Renewable Energy Law; SOE, State-owned Enterprise; SGCC, State Grid Corporation of China; NDRC, National Development and Reform Commission; NEA, National Energy Administration; SASAC, State Assets Supervision and Administration Commission; MOF, Ministry of Finance; FPA, Federal Power Act; IOU, Investor-owned Utility; OPEC, Organization of Petroleum Exporting Countries; PURPA, Public Utilities Regulatory Policy Act; QF, Qualifying Facility; FERC, Federal Energy Regulatory Commission; EPA, Energy Policy Act; PPA, Power Purchase Agreement; PTC, Production Tax Credit; ITC, Investment Tax Credit; RPS, Renewable Portfolio Standard; BPA, Bonneville Power Administration; UHV, Ultra-high Voltage; RCO, Renewable Consumption Obligation; OATT, Open Access Transmission Tariff; REC, Renewable Energy Certificate.

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desirable in most applications [1,3,4]. Curtailment higher than 5% is commonly associated with capacity underutilization and system inefficiency. Therefore, from a policy perspective, there is an imperative to contain wind curtailment within a certain level.

Wind energy plays a significant role in the energy transition of China and the United States [5,6]. Both are large, continental nations with great wind resource endowments [7]. Both also have large power grids spanning multiple subnational jurisdictions, a (historical) reliance on coal as the major power source, and dual regulation by the central (federal) and provincial (state) governments [8]. As Fig. 1 shows, the two countries have similar trends in the scale of wind power development. As of 2019, China has the largest wind generation capacity in the world – at 210 GW including both onshore and offshore installations [9]. The United States ranked second with 104 GW of installed capacity [9]. In terms of actual generation, wind energy makes up 5.2% of China's total electricity production and 6.6% of that in the United States in 2018, so the two countries also have a similar share of electricity from wind energy.

Despite the similarities, a huge gap exists between China and the United States in the capacity utilization of installed wind turbines. The United States utilizes installed capacity more effectively and has only moderate levels of wind curtailment. As Fig. 2 shows, typical curtailment levels in the United States range from 1 to 4% and vary by wholesale power market region. Texas once had high curtailment, up to 17% during the years of rapid capacity expansion, but this problem was resolved after the state quickly built out transmission lines and redesigned its power market [1]. Curtailment in other regions is quite low and has stayed below 5%.

By contrast, China's wind power industry has struggled with overcapacity and underutilization over the past decade. As Fig. 3 shows, annual nationwide wind curtailment levels stayed above 5% until 2019. The most severe curtailment has occurred in the windy northern provinces where capacity deployment has been rapid. For instance, in 2016, Gansu, Xinjiang, Jilin, and Inner Mongolia curtailed up to 43, 38, 30, and 21% of wind power generation. The situation started to be alleviated in 2017 after the central government launched a multi-pronged initiative to combat renewable energy curtailment [12,13]. Nationwide wind curtailment level fell consecutively from 2017 to 2019, but this aggregate figure masked regional variations. For instance, Xinjiang and Gansu still curtailed up to 14 and 8% of wind power generation in 2019.

China's rapid wind power development is astonishing. Its ability to deploy a massive amount of political, financial, and human capital in a short time is even more so [15]. Ironically, this seems at odds with the country's inability to effectively utilize already installed capacity. Given the aforementioned similarities between China and the United States, why is there a big difference in their wind curtailment levels? Moreover, what can China learn from the United States to reduce wind curtailment?

The above questions present an opportunity for a comparative study on China and the United States. Indeed, recognizing the social, political, and cultural embeddedness of energy governance is a prerequisite for prescribing pragmatic energy policies [16–21]. On the subject of wind energy integration ("wind integration" hereafter), such embeddedness is more visible when comparing two countries than focusing on one. Numerous studies have tried to explain China's wind curtailment. They have identified a multitude of contributing factors as listed in Table 1. Yet, these studies have drawn conclusions by focusing on China alone and have not explicitly considered China's unique social, political, and cultural context [15]. Meanwhile, one way to demonstrate the embeddedness is by analyzing a country's institutional logic of wind integration, and wind curtailment is the candidate issue through which this logic can be accessed [22–25]. Institutional logic is a concept from new institutionalism and it has been used to construct systematic and coherent accounts of the institutions in clean energy transition [19,21,26–28]. A key analytical task is to endogenize the institutional factors that either facilitate or impede wind integration – a task to which a comparative study is better suited than a single-country analysis [27].

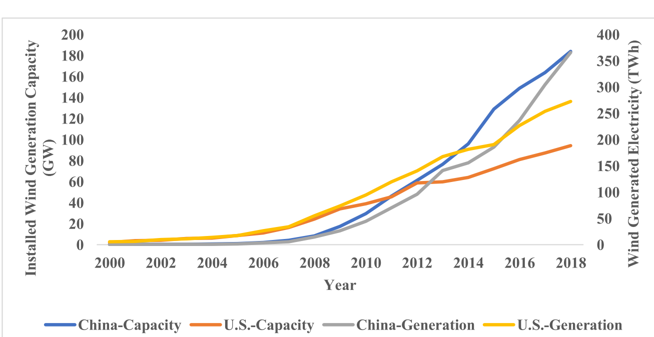

Fig. 1. Wind power development in China and the United States (data from Ref. [10,11]).

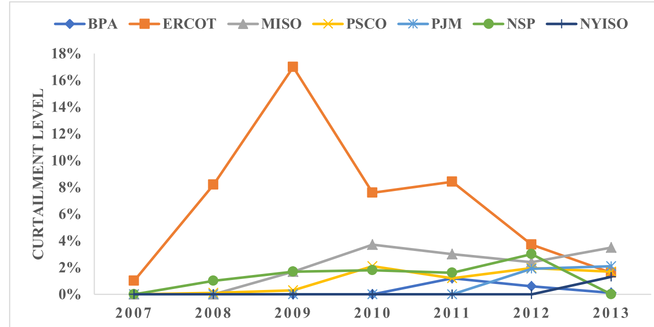

Fig. 2. Wind power curtailment in the United States (data from Ref. [1]).

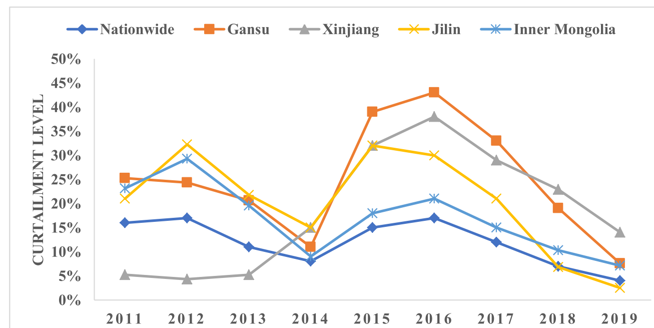

Fig. 3. Wind power curtailment in China (data from Ref. [14]).

Table 1
Factors contributing to China's wind curtailment.

Category	Factors	Studies
Technological	Bad wind power forecast	[19,29,30]
	System inflexibility	[19,29–39]
	Insufficient transmission capacity	[19,25,30–32,35,36,38,39]
	Generation overcapacity	[25,31,32,36,38–40]
Economic	Over-subsidization	[19,24,41,42]
	Inefficient generation dispatch	[29–32,34,37,39,43]
	Lack of market competition	[25,29–32,37,43]
	Lack of demand-pull mechanisms	[24,37,39,43,44]
Institutional	Lack of integrated planning	[24,29,30,32,35,38,39,42,44]
	Dispute over integration costs allocation	[24,30,32,37,42–44]
	Grid/Market fragmentation	[29,31,32,37,38,43,45]
	Insufficient legal protection	[32,39,44,46]

Furthermore, a study that compares China and the United States carries great empirical significance in the field of wind energy research. As the two countries together added more than half of the world's new wind generation capacity from 2017 to 2019 [9], they make the two largest laboratories from which lessons can be drawn for the rest of the world.

Therefore, this paper conducts an institutional analysis of wind integration in China and the United States. It connects both the factors that promote wind power capacity addition and those that cause wind curtailment to the institutional logic of wind integration in the two countries. By comparison, this paper seeks to find what China can learn from the United States to reduce wind curtailment.

The rest of this paper is structured as follows. Section 2 introduces the theories and method of this paper. Sections 3 and 4 analyze the institutional logic of wind integration in China and the United States, respectively. Sections 5 and 6 discuss the practical measures taken to reduce wind curtailment in China and the United States, respectively. Section 7 compares the findings on the two countries and derives this paper's conclusion.

2. Theory and method

"Institutions" is a cross-disciplinary concept. Generally defined, institutions are the formal and informal rules that shape societal expectations and constrain human activities [47,48]. Institutions exist at various levels of society and they play important roles [49]. They determine the performance of economic systems [47,48,50], constrain or drive social change [51–53], and coevolve with the ideas embedded in the cognitive patterns and normative preferences of society [54,55]. Institutional theories are gaining traction in the study of clean energy transition because they help connect microlevel economic activities with macrolevel politics, governance, and culture [23,28,56].

New institutionalism is not a unified body of thought as there are different schools that originate from different disciplines. The field can be divided into four schools with crossovers in between [55,57]. They are historical institutionalism, rational choice institutionalism, sociological institutionalism, and discursive institutionalism, all of which have found increasing application in the organizational field of clean energy [22,23,28,56]. This paper draws insights from all four schools of new institutionalism. Table 2 briefly introduces each school and explains how it informs the analysis in this paper.

Table 2
The four schools of new institutionalism and their insights.

Schools of New Institutionalism	Description	Insight
Historical	Historical institutionalism sees the polity and political economy as the principle factors that structure collective behavior and generate distinctive outcomes. It emphasizes that institutions are historically determined and institutional changes are often path-dependent and incremental (though sometimes abrupt when arriving at critical junctures) [55,57].	Historical institutionalism is best at recognizing the political economy of utility regulation, the historical and structural factors in determining economic outcomes, and the power asymmetries in the agenda setting, design, and implementation of energy sector reforms.
Rational Choice	Rational choice institutionalism emphasizes the collective action dilemma in social and political processes. It sees individuals' goal-oriented, strategic pursuit of self-interest as the main driving force and postulates clear preferences and instrumental behavior on the individual. It also sees institutional change as a gradual and intentional process to define property rights, reduce uncertainty and transaction costs, and achieve higher collective benefits [55,57,58].	Rational choice institutionalism offers a cleaner and more operational framework for theorizing regulations and modeling regulatory reforms (e.g. game theoretical models), both highly relevant to electricity marketization and decarbonization where new contractual relations, property rights, and market structures are being established.
Sociological	Sociological institutionalism sees the institutional forms and procedures of modern organizations as culture-specific practices. It argues that individuals act by the normative and cognitive rules prescribed by institutions to achieve social acceptance. It also argues that institutional change is driven by the need to enhance the social legitimacy and cultural appropriateness of the organizational field and its participants [55,57].	Sociological institutionalism helps identify more underlying motives for both individual behavior and institutional change from the repertoires of values and culture, and this corresponds to the aspects of renewable energy that cannot be explained by utility maximization or power struggle.
Discursive	Discursive institutionalism seeks to explain the dynamics of institutional change by studying how ideas and discourses influence individuals' preferences, strategies, and normative orientations, and vice versa. It sees institutions as structures and constructs of meaning that are created, maintained, communicated, and changed by agents with different ideational and discursive abilities [54,55].	Discursive institutionalism complements the first three by explicitly laying out the ideational and discursive elements that endogenize path dependence, instrumental rationality, and cultural framing. This helps decipher the dynamic, interactive processes of idea deliberation and discourse communication that surround the different facets of renewable energy – a subsistence resource (as with all energy supply), a burgeoning industry (in competition with fossil fuels), a new profession (more intensive in technology and human capital), and a new consumer identity (i.e. the decarbonization, digitization, and democratization of energy).

After drawing insights from the four schools of new institutionalism, this paper uses the "institutional logics" perspective to the findings. A most frequently cited definition of institutional logics is "the socially constructed, historical patterns of material practices, assumptions, values, beliefs, and rules by which individuals produce and reproduce their material subsistence, organize time and space, and provide meaning to their social reality" [59]. Simply put, institutional logics are the organizing principles of institutions that are identified at different levels of analysis [27]. The concept has been used across social science disciplines, building up to a metatheoretical framework for understanding the interrelationships among institutions, individuals, and organizations in social systems [60,61]. In any organization field there is often one dominant institutional logic and several complementary or competing logics that work to entrench or alter the dominant logic [27,28,62]. Compared to other institutional analysis frameworks such as the Multi-level Perspective by Geels [63,64] and the Institutional Analysis and Development framework by Ostrom and the Bloomington School [65,66], the institutional logics perspective is less structurally deterministic, can accommodate institutional pluralism better, and offers a more flexible interpretation of state-market relationship that is historically contingent and internal to politics and ideologies [27]. These attributes are particularly useful for a China-U.S. comparative study.

Overall, this paper seeks to capture and compare the institutional logic of wind integration in China and the United States, and from that to find the lessons that China can learn from the United States to reduce wind curtailment. It carries out a three-step analysis that is summarized in Fig. 4. First, this paper surveys the existing literature for institutional factors that either facilitate or impede wind integration in the two countries. In the review, it pays particular attention to the analytical insights from the four schools of new institutionalism. Second, this paper synthesizes the institutional factors into institutional logics of wind integration in China and United States, respectively. In this process, this paper uses primarily abductive and inductive analysis which is common in institutional logics studies [67]. It also constructs a coherent, dominant logic for each country and acknowledges any complementary or competing logics when they cannot be ruled out. Lastly, this paper employs a simple "method of difference" to derive the conclusions. The "method of difference" is a rudimentary method used in comparative social science studies [68]. Simply put, it seeks crucial differences between similar cases to explain the difference in a particular outcome [69]. By setting up China and the United States as having similar geography, wind resource endowments, grid infrastructure, (quasi-) federalist governance, and growth in wind generation capacity, this paper seeks to find an explanation for the two countries' differing wind curtailment levels in their respective institutional logics of wind integration. From there, it reflects on the lessons that China can learn from the United States to reduce wind curtailment.

3. An institutional analysis of wind integration in China

This section analyzes China's institutional logic of wind integration which is summarized in Fig. 5. Square bubbles at the top contain the synthesized dominant and complementary institutional logics. Ovals in the middle contain the intermediate outcomes with regard to incentives for wind power capacity addition and capacity utilization. Ovals at the bottom contain the final outcomes with regard to capacity deployment and curtailment. Sections 3.1 and 3.2 detail the analysis.

3.1. The institutions that facilitate or impede wind integration in China

China's present-day energy governance has cultural roots from the country's imperial era [18]. The system is highly centralized with hierarchical bureaucracies and low tolerance for alternative centers of power. Moral order and social conformity are prioritized, and laws and regulations are meant less for the protection of civil rights and more for the preservation of social order and the regime [21]. The official policy process is more about communication than coordination, with policy deliberation at the top and implementation at subnational levels. Accountability is controlled *ex ante* by persuasion and exhortation and *ex post* by nomenklatura reward and punishment [70]. Consensus among key players is important in decision-making, and it is achieved through both formal participatory processes and informal personal networks (i.e. "guanxi") [18]. Policy discourses usually emerge from the top and are passed down through slogans, campaigns, and mass mobilization [71]. Important natural resources, including energy, are monopolized and controlled by the state and offered to the public at affordable prices [18].

The governance of wind integration in China fits the above description well. Indeed, state activism and centralized policymaking are more than visible in China's wind power development. As a single-party authoritarian government, China's party-state needs to respond swiftly and effectively to salient issues of society. Given the imperative to curb severe air pollution, enhance energy security, promote indigenous technological innovation, and avert an economic downturn [72], the mass deployment of wind power becomes a strategy to reinforce the legitimacy of the party-state [15,68,73]. With centralized policymaking authority, the Chinese central government is able to set and implement aggressive wind power development targets with certainty and effectiveness [24,74]. In 2005, the National People's Congress passed the REL which established the legitimacy, the mandatory grid interconnection and purchase requirement, subsidized feed-in tariffs, and cost-sharing and financing mechanisms for wind power [75]. Since then, annual and five-year plans have continuously prescribed ambitious quantitative development targets. Administrative fiats and technical guidelines have been issued to implement these plans [46]. These economic and legal institutions constitute a top-down, state-led approach to wind integration where the central government controls agenda setting, policymaking, pricing of key resources, financing, and the administrative and legal apparatus to push its agenda down to local governments and SOEs [24]. Under this view, China's wind power growth has been associated with the "developmental state" model [76,77] and ideology-driven state capitalism and corporatism [78–80].

A more nuanced view, while still acknowledging the center role of the state, sees different degrees of decentralization, liberalization, and pluralization. Under this view, China's wind power development has been associated with local experimentation and policy learning [81], industry lobbying [82] and strategic investments [82,83], and strong subsidies coupled with industry agglomeration effect [41,84]. The fundamental institution of China's economic governance is "regionally decentralized authoritarianism" [85]. Since the beginning of China's market-oriented reform, the central government has delegated more authority so that provinces and municipalities can make and pursue their own economic initiatives [72]. In wind power development, political devolution has created a quasi-federalist regime under which localities bargain for resources and flexibility from the central government, bear the burden of experimentation, innovation, and potential failure, and propagate their experience to other localities when they succeed [29,81]. State ownership also plays a significant role. SOEs control more than 80% of China's wind power market [83]. Among China's ten largest wind power developers, eight are central SOEs and they make up 67% of the China's total installed wind generation capacity by the end of 2018 [86]. SOEs' investment in wind power is driven by politics and profits. On one hand, SOEs have the statutory obligation to carry out the Chinese Communist Party's grand plan for China's technological and ecological modernization [87], and an important part of this obligation is to diversify China's energy supply and develop indigenous clean energy technologies [24,72]. On the other hand, SOEs can take higher financial risks than private firms and they are willing to trade short-term profitability for long-term strategic assets. This is because SOEs have superior access to capital and policy information and do not face the same budget constraints as private companies do [88,89]. For instance, central SOEs continued to scale up their wind generation capacity in the northern provinces despite rampant curtailment in the region because they wanted to capture the good resource sites and they were confident that the central government would resolve the curtailment problem soon [83].

The state's objective to deploy wind energy could not have been

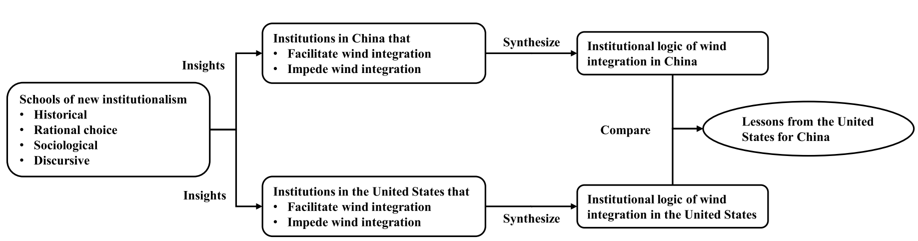

Fig. 4. Analytical process for comparing wind integration in China and the United States.

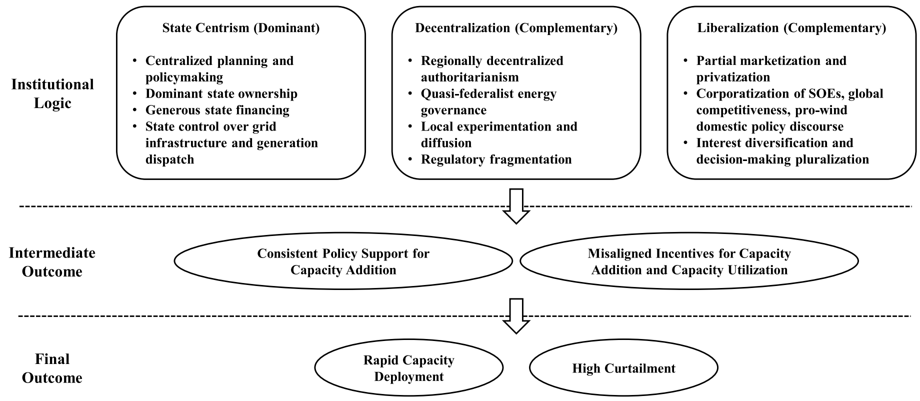

Fig. 5. Institutional logic of wind integration in China.

achieved without the help of market mechanisms. Compared to conventional generation technologies like coal and hydroelectric, new technologies like wind and solar grow in a more market-friendly environment where there are less direct administrative intervention, lower market concentration, and more private participation [90]. Chinese wind and solar power equipment manufacturers – both public and private – have gained global recognition and some brands even acquired a dominant position in the field [91]. Chinese power generation corporations have listed their renewable energy subsidiaries on overseas stock markets to raise capital [92]. Moreover, wind power producers have been vocal supporters of China's electricity marketization and reform as they expect to gain from open access to the grid, market-based generation scheduling and dispatch, and the integration of provincial markets [25,29,38,43,45].

Apart from the support by the state and the market, China's wind integration faces several institutional obstacles. One is the allocation of "integration costs". Because wind power is intermittent, it adds cost to the prevailing regime which was built upon baseload generation technologies [93]. The allocation these costs – primarily cost of transmission expansion and system balancing – is a subject of great contention in China [24,68]. As stipulated by the REL, this cost is shouldered by all electricity consumers through an add-on to the retail price [46]. In practice, collection of this money has not always been successful, leading to depletion of the national renewable energy development fund and causing severe delays in the allocation of subsidies [32,44].

More pertinent to wind curtailment are the misaligned incentives for capacity addition and capacity utilization. Compared to building wind farms, actually absorbing wind power into the grid requires more profound changes to the institutions that govern resource planning, pricing, and generation dispatch, and this causes rent and power redistribution that provokes strong resistance from incumbents [74]. China's state apparatus has been described as "fragmented authoritarianism" which refers to the jurisdictional gaps and overlaps between government agencies and the information asymmetries between different levels of government [94]. China's energy bureaucracy has gone through multiple rounds of decentralization and recentralization in the past, and this has created a multitude of state and state-related actors [95]. Consequently, energy policymaking becomes a field of intense bargaining and power grabbing, and an incentive structure that motivates all actors is difficult to design [24].

The key actors in China's wind power industry include central government agencies, provincial governments, power generation companies, power grid companies, and wind power equipment manufacturers [74]. Fig. 6 shows their command relationships and major roles. The upper half contains government entities who are responsible for planning and regulating the industry. The lower contains business entities who are directly involved in the investment and operation of wind farms.

Fig. 7 shows the specific motivations for each actor to support either capacity addition or capacity utilization. This paper assumes the NDRC and NEA to be neutral, meaning they strive to balance capacity addition and capacity utilization. Actors on the left have an overall interest in capacity addition. Actors on the right have an overall interest in capacity utilization. Actors in the middle can go either way, depending on the relative strength of different motivations. Clearly, the actors' incentives do not align. Therefore, collective action is needed to reduce China's wind curtailment, and it requires aligning the interests of the key actors in the industry [24,29,38,68]. However, such collective action is difficult to achieve due to many actors having veto power [74,96], the significant information asymmetries [96], and the lack of coordination mechanisms [97]. Moreover, the decentralization, liberalization, and pluralization that facilitated the central government's initiative for capacity expansion also created bureaucratic bickering [97], local protectionism [98], regulatory capture [82], and policy discord [38]. These issues exacerbated the collective action problem, expanded the gap between capacity addition and capacity utilization, and eventually led to high levels of curtailment.

Finally, there is a legal aspect in China's wind curtailment. China's judicial system functions as a complementary, not a competing, instrument of governance [21]. In energy regulation, laws play a more symbolic than substantive role. China does not have an overarching energy statute. The REL was enacted to provide a broad policy framework for renewable energy integration [46]. For long the legal efficacy of the REL has been questioned [99]. Despite being explicitly prohibited, delayed interconnection, rampant curtailment, and default on subsidy payment have occurred frequently without real legal ramifications [7,100]. No party, to date, has ever sought remedies for wind curtailment through formal litigation.

3.2. The institutional logic of wind integration in China

Synthesizing Section 3.1, this paper finds that China's dominant institutional logic of wind integration is "state centrism" which includes centralized planning and policymaking, dominant state ownership, generous state financing, and state control over grid infrastructure and generation dispatch. Historically and culturally, this dominant institutional logic is rooted in the ideal that the state is authoritative and benevolent, and it shall directly control important natural resources and make them broadly available to its citizens. Structurally, this dominant institutional logic builds upon China's ubiquitous governing machine, i.e. the party-state, and its embeddedness in the administrative, legislative, judicial, and business arenas. Instrumentally, this dominant institutional logic is reified in the aggressive development targets, implementation plans, and favorable pricing and dispatch policies. Overall, this state-centric logic aligns perfectly with China's dominant institutional logic of the whole electricity industry since the post-war era

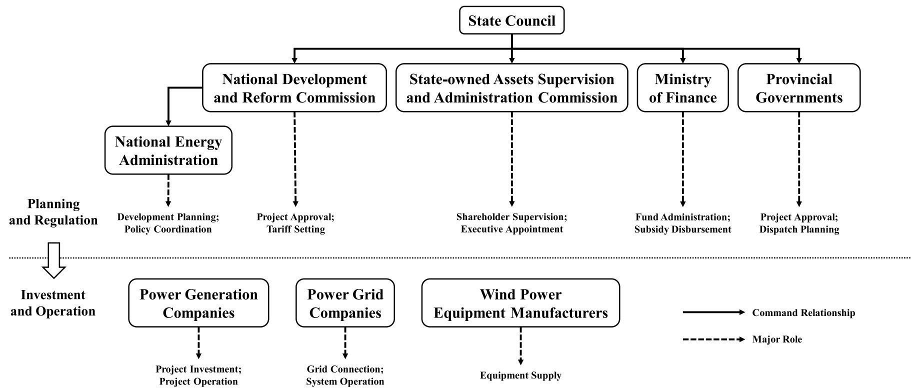

Fig. 6. Key actors in China's wind power industry.

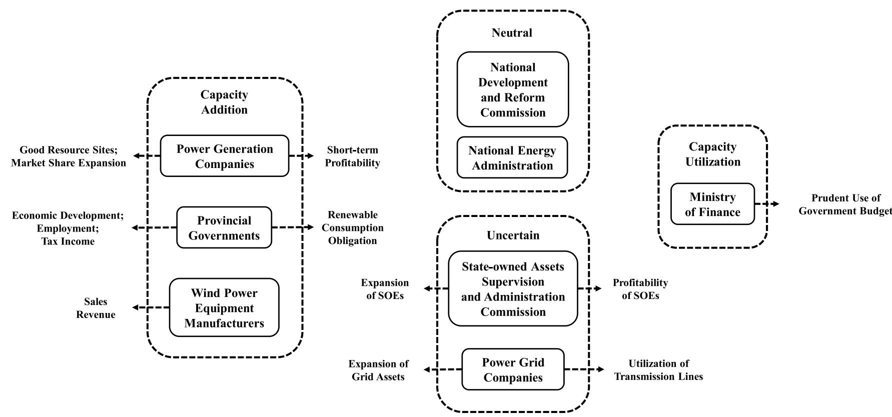

Fig. 7. Key actors' motivations towards wind power capacity addition and utilization.

– to maintain state control of critical infrastructure and to supply electricity in a way that meets the imperatives of the time (e.g. universal, affordable, reliable, clean, etc.) [101,102].

Besides state centrism, this paper also finds that China has two complementary institutional logics of wind integration: decentralization and liberalization. Both are fueled by China's deliberate, decade-long effort to introduce market mechanisms and increase regulatory flexibility into the energy sector. Decentralization coupled with China's quasi-federalist energy governance formed the institutional foundation for provincial experimentation and diffusion of wind power capacity addition. Liberalization, corporatization of SOEs, and partial privatization together not only lifted China's wind industry to global competitiveness but also created a domestic political climate that enabled the pro-wind policy discourse to self-sustain. Meanwhile, however, decentralization and liberalization led to interest diversification and regulatory fragmentation, both impeded the collective action needed to improve the utilization of installed capacity. This combined with the geographical distribution of China's wind resource and the intermittency of wind power eventually created China's wind curtailment problem.

4. An institutional analysis of wind integration in the United States

This section analyzes the United States' institutional logic of wind integration which is summarized in Fig. 8. Square bubbles at the top contain the synthesized dominant and complementary institutional logics. Ovals in the middle contain the intermediate outcomes with regard to incentives for wind power capacity addition and capacity utilization. Ovals at the bottom contain the final outcomes with regard to capacity deployment and curtailment. Sections 4.1 and 4.2 detail the analysis.

4.1. The institutions that facilitate or impede wind integration in the United States

The analysis begins by tracing the history of electricity regulation in the United States. Government regulation of public utilities started in the late 19th century when individual states began to regulate railroads, telephones, and gas and electric power companies on the basis that these businesses are "affected with a public interest". Federal regulation of electricity began in 1920 with the passage of the FPA and was expanded in 1935 to include all interstate electricity transmission and wholesale power sales [103]. In general, post-war economic governance in the United States shifted away from *laissez-faire* market capitalism and towards state-centric Keynesianism [101]. The latter advocated for a bigger role for the government in maintaining macroeconomic stability and accomplishing social goals. In the electricity industry, this era was marked by the propagation of vertically-integrated IOUs operating under the "regulatory compact" [104], the establishment of statutory authorities charged with operating and marketing federal hydropower, and the emergence of municipal and rural electric cooperatives as a localized alternative to the first two. The overarching socio-economic orientation of the time – the welfare state – was ingrained into the conception of electricity as a universal and affordable service that propels continuous growth and prosperity [101].

The intellectual foundation of early electricity regulation in the United States was two-fold. One was Samuel Insull's business model that the vertically-integrated electric utility is a natural monopoly, and thus best managed under cost-of-service regulation to prevent duplicative waste and monopolistic pricing [105]. The other was the New Deal mentality that the government has an active role to play in encouraging

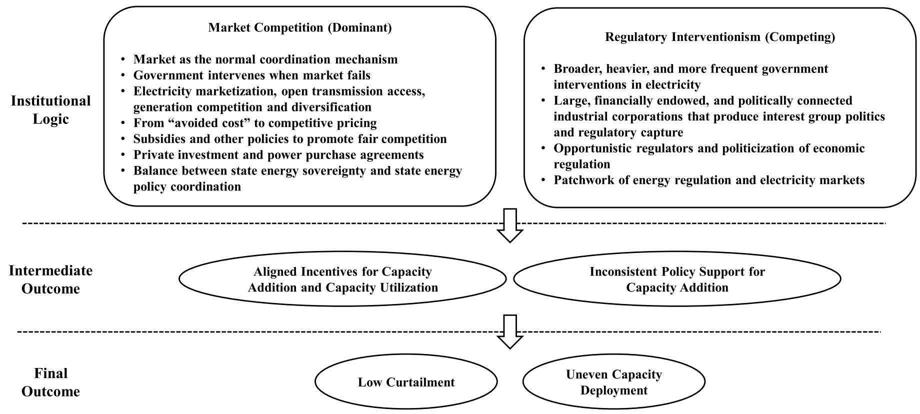

Fig. 8. Institutional logic of wind integration in the United States.

economic growth by making electricity universally available and affordable [103]. This intellectual foundation remained solid until the 1970s when the OPEC oil embargo threatened the country's energy supply and systemic stagnation put Keynesianism under heavy criticism. There was a growing belief that excessive government intervention was to blame for the underperformance of the economy [106]. In the electricity industry, consumer dissatisfaction surged as utilities kept raising prices to cover cost-ineffective power plant investments [107].

Consequently, in the 1980s a socio-economic re-orientation towards neoliberalism occurred in the United States, which emphasized the role of market competition, private property, and minimal government intervention in delivering efficient outcomes [101]. Ethically, neoliberalism was to promote individual free choice, civil liberty, and human dignity, and to resist imposed collective action [108]. The following decade saw broader economic reforms that promoted market competition, private investment, deregulation, and foreign trade. As part of the neoliberal transition, the electricity industry was reformed to diversify generation technology, open up transmission access, adopt market-based generation dispatch and electricity exchange, and establish sector-specific independent regulation. Technological advancement also contributed to the reform. Combined-cycle gas turbines emerged as a small-scale, cleaner, and more flexible competing generation technology to the large-scale, capital-intensive, baseload thermal power plants (including coal-fired and nuclear) that were suffering cost overruns and increasing environmental oversight. Power electronics and cybernetics enabled power system control over greater geographical areas, which in turn expanded the market for electricity transactions [101].

It was against this background that renewables like wind power rose in the United States. In 1978, Congress passed the PURPA to establish the legal basis for third-party, commercial generation facilities and open the door for non-discriminatory transmission access and wholesale competition [103]. PURPA sought to increase U.S. energy independence and lower energy prices by expanding domestic energy production and promoting competition in power generation. It created a new category of generators – the QFs – that included units that are 80-MW or smaller in capacity and use co-generation or renewable energy [109]. Under PURPA, electric utilities were required to purchase electricity from QFs at a rate equal to the "avoided cost".[1] The siting, interconnection, and rates of QFs remain subject to state regulation. Meanwhile, the FERC was given the authority to regulate power transmission networks as "common carriers" which contributed to the later formation of competitive wholesale electricity markets [103].

Wind power became a poster child of the U.S. electricity reform because it was a major beneficiary of deregulation and marketization. In 1992, Congress passed the EPA which legally required all electric utilities to at least functionally separate their generation and transmission businesses and to provide equitable transmission service to external users. To implement this statute, the FERC issued a series of orders that prescribed the design of the U.S. present-day wholesale electricity markets [109]. Under this design, wind power can bid into the centralized spot markets and, given its near-zero marginal cost, it is easily prioritized in generation dispatch. Also, adjustments were made to the prevailing regulatory paradigm (the one built upon conventional power plants) to accommodate wind power better. These include updating grid interconnection protocols, improving transmission service and information sharing, coordinating transmission planning and integration cost allocation, improving reserves management, lowering price floors in spot markets, expanding grid balancing areas, and refining PPAs [1,2,93,109,110].

Additionally, measures are taken to account for the positive environmental externalities of wind power. For instance, there are federal and state policies that support wind integration from both the supply and demand sides. Federal financial incentives include the PTC, the ITC, U.S. Treasury cash grants, Department of Energy loans, and accelerated and bonus depreciation. They reduce the capital costs for wind power projects (in the case of ITC) and enable them to bid lower prices in spot markets (in the case of PTC). Many states also offer financial incentives, but a more powerful tool is the RPS. RPS takes several forms, the most popular of which requires in-state electric utilities to source a minimum percentage of electricity from renewable resources. In other words, this type of RPS ties the utilities' performance directly to actual wind power generation thus provides a stronger safeguard against curtailment.

The above measures all contributed to the cost competitiveness of wind power, which in turn promoted wind integration in the United States. To a large extent, the rise of wind power relied on the post-war conception of electricity by deriving its legitimacy mainly from being a cost-effective alternative to conventional power sources [103,111]. Regardless of the interplays between the government and the industry and the complex rationales for regulation and deregulation, the idea that electricity shall be a universally and cheaply available product remains unchanged [103,112]. After the deregulation and marketization reform, efforts to promote renewable energy are joined by environmentalists and others concerned about climate change. Yet, as other attributes are attached to the main character of electricity, they play only a supplemental role in shaping the underlying regulatory regime [101,103,113]. Thus, the institutional change associated with renewables integration in the United States has been characterized as "layering" instead of "transformation" [53,113]. Essentially, when the factors (e.g. energy crisis, technological advancement, global warming) driving the institutional change are considered exogenous and the direction of change is

[1] Roughly defined, "avoided cost" equals the fixed plus marginal costs those utilities would otherwise incur if the electricity is sourced from their own generators.

considered towards establishing property rights (e.g. RPS), lowering transaction costs (e.g. open transmission access and information sharing), and enforcing new rules and contracts (e.g. PPA), a coherent rational choice explanation for the U.S. wind integration is obtained [114].

However, rational choice does not tell the whole story. The political dimension of wind integration is at least equally important [115]. Compared to Denmark, Germany, and China, energy policymaking in the United States is subject to heavier lobbying and interest group politics [68]. From the PURPA of 1978, which granted grid access to QFs, to the EPA of 1992, which created the PTC for renewables, then to the numerous state-level electricity reform bills that established RPSs, renewable energy succeeded in attaching itself to major energy legislation that was motivated by crises. Yet, this is not only because those crises demanded a rational response but also because they created an opportunity for nascent technologies to find allies and gain acquiescence from their powerful enemies who were paying more attention to other issues that were more immediately important to them (e.g. vehicle fuel-efficiency standards, domestic oil production, compensation for stranded investment, etc.) [113]. As low-carbon energy technologies matured, they faced fiercer and determined push back from threatened incumbents. Thus, interest group politics created policy volatility, which in turn led to boom-bust cycles in wind power annual installations [68, 116].

Contention over wind power generally revolves around government subsidies, integration costs allocation, land acquisition, and ecological and community impacts [117,118]. Politics, in general, can work either for or against wind power development depending on a state's particular circumstances [119]. Texas, for instance, has the largest wind generation capacity among all states. This achievement is often attributed to the state's resource endowment (e.g. massive acreage of land suitable for wind-farm development) and favorable economic conditions (e.g. competitive electricity markets and high electricity price). Meanwhile, the political environment also plays an important role. In Texas, the power of electricity policymaking is concentrated in the hands of a few elite stakeholders (e.g. electric utilities, the Electricity Reliability Council of Texas, and the Public Utility Commission of Texas) who are able to control the political discourse (e.g. emphasizing the economic benefits of wind power and disassociating wind power with climate activism) and induce cooperation using public policy (e.g. administrative fiats and financial subsidies) [120,121]. Minnesota, by contrast, has only modest wind power development despite a comparable wind-power profile, a head-start in wind generation technology, stronger public support for climate action, and more aggressive renewable energy targets [120]. This is because Minnesota has more inclusive, bottom-up energy governance that is not as effective in producing swift collective action [121]. Interestingly, the same institutions that slow down the wind power policy in Minnesota also make the policy harder to be reversed once it is established [113].

Finally, the political institution of federalism plays a role in wind integration. Electricity regulation in the United States was established on the principle of "dual federalism". In an effort to fill the "Attleboro gap" [122], the 1920 FPA (as amended in 1935) divided federal and state jurisdictions by whether or not an electricity transaction is interstate. This tradition was preserved in all subsequent amendments of the FPA, though over the years the courts have adopted a more encompassing interpretation of what qualifies as interstate electricity transaction [122]. This allowed the FERC to assert broader and more coercive authority over both transmission and wholesale generation markets. Meanwhile, intrastate electricity commerce remains under state jurisdiction. Distribution, retail, and generators that do not sell into federal wholesale markets are overseen by state commissions and subject to state laws [109]. QFs are categorically put under state regulation, and PPAs are enforced by state commissions and courts. There are also entities subject to neither federal nor state regulation. Some are federal power marketing agencies, such as the BPA, that carry their own statutory authorities and obligations. Others are municipal power districts and rural electric cooperatives that are regulated by either local governments or elected boards [8].

The divide between federal and state jurisdictions created some obstacles to wind integration. For instance, the siting and financing of transmission lines is a major challenge. New transmission lines are often needed to connect remote wind farms and wheel the power to the users, sometimes crossing state borders. These projects face legal and political hurdles that straddle federal and state jurisdictions. Issues over land use, environmental impact, and cost allocation often arise, and lines that cross multiple states require significantly more coordination [123]. For these reasons, transmission expansion frequently lags increasing wind generation capacity, and it is the primary cause of wind curtailment in the United States [1,3].

The gaps between the FERC, state commissions, and unregulated entities also creates some coordination problems that are demonstrated in two well-known cases of wind curtailment. One case is in the Pacific Northwest where the BPA curtails wind power to manage springtime hydropower oversupply. Parties brought suit to the FERC. Confined by its statutory authority, the FERC demanded a remedy that to some observers fell short of compensating the wind farms on a non-discriminatory basis [124,125]. The other case was when Portland General Electric Company denied PáTu Wind Farm's request for dynamic scheduling.[2] Even though dynamic scheduling is a transmission matter, the FERC ruled that Portland General did not violate the anti-discrimination requirement because its contract with PáTu was for retail generation, not wholesale transmission. The D.C. Circuit Court of Appeals upheld the FERC's decision, concurring that PáTu's case should be resolved as a contract dispute and left to the Oregon Commission to decide.

4.2. The institutional logic of wind integration in the United States

Synthesizing Section 4.1, this paper argues that the dominant logic is market competition because wind power rode the waves of two major energy reforms (PURPA of 1978 and EPA of 1992) and it was legitimized mainly by consumers' spontaneous pursuit of low-cost alternatives to domestic nuclear and coal-fired power and foreign oil. In other words, it is the market logic and the merits of competition that justified the majority of wind integration in the United States. Intellectually, this dominant institutional logic draws on the neoliberal ideal of economic regulation under which the market is the normal coordination mechanism and the government intervenes only when the market fails to deliver desired economic or social outcomes (e.g. environmental externalities, market power mitigation, "just and reasonable" rates). Structurally, this dominant institutional logic is built on private ownership (return on private wind power investment), electricity restructuring and wholesale competition (open transmission access and economic dispatch), legal protection of contracts (enforcement of PPAs), and dual federalism (balance between state sovereignty in energy supply and synergistic efficiency from coordinated state energy policies). Instrumentally, this dominant institutional logic consistently follows the economic rationale that the benefit of wind integration should justify its cost (from "avoided cost" to competitive pricing) and that regulations should level the field between new and incumbent players (improving transmission operation and market design, fairly allocating integration cost, and using subsidies and demand-pull policies to correct externalities). Overall, this market logic forces better alignment between wind power capacity addition and utilization, which keeps curtailment at a minimum level [126].

The above said, there is also a competing institutional logic of wind integration in the United States and that is regulatory interventionism.

[2] For details on the D.C. Circuit case, see *Portland Gen. Elec. Co. v. Fed. Energy Regulatory Comm'n,* 854 F.3d 692 (D.C. Cir. 2017).

Despite the appeal and prospect of the market logic, electricity regulation still involves broader, heavier, and more frequent government interventions than the average economic sector in the United States. On one side, there are large, financially endowed, and politically connected industrial corporations who can capture regulators and influence policies. On the other side, there are regulatory agencies who are in theory insulated from politics but in practice prone to act opportunistically and use regulations to advance political agendas (e.g. rent redistribution between producers and consumers or between different consumer classes). Essentially, the U.S. electricity regulation is a typical story of how a product of "public interest" is provided in the political economy of the regulatory state [103]. Wind power, as with all other forms of electricity, is not exempt from this highly politicized environment and its interest group battles. Also, the progression and retrenchment in electricity reform across states have created the patchwork of state and regional electricity markets each of which has different design and priorities. The resulting coordination difficulty has been an obstacle to transmission expansion and developing long-term plans for wind power development.

5. Measures taken to reduce wind curtailment in China

China's most severe wind curtailment occurred in 2016. The issue received substantial attention in the media, raised public concern, and was finally brought to the attention of the State Council. The same year, China launched a multi-pronged policy program to curb wind curtailment which consisted of technological retrofit, transmission buildout, and performance targets. This section discusses each of these policy measures and their preliminary effects.

5.1. Technological retrofit

Technological retrofit refers to the decoupling of heat and power production capacity in coal-fired power plants. It improves coal plants' downward regulation capacity and allows them to operate more flexibly [33]. This in turn helps to reduce wind curtailment by lowering the system minimum generation level under oversupply situations. In China's northeastern provinces, more than 70% of coal-fired power plants are cogeneration plants whose flexibility is limited during the heating season [127]. This decreases the level of reserve generation capacity in the power system. Meanwhile, winter and spring typically have stronger winds and thus higher wind power output. The combination of high baseload generation, reserves depletion, and high wind power output created severe curtailment in the region.

In mid-2016, the NEA issued the plan to retrofit coal-fired power plants. Two rounds of pilot programs were rolled out, followed by nationwide expansion. Overall, the plan was to retrofit 215 GW of coal plants in the northern provinces by the end of 2020. The NEA also issued two supplemental measures. The first was to offer additional production quota to coal plants which act as backup generation for intermittent renewables when called upon. The second was to establish the Northeast Electric Power Ancillary Services Market. Both measures remunerated coal plants with higher flexibility and lower minimum-output levels. According to the SGCC: 12 coal plants in the northeastern region completed retrofit by mid-2018, creating an additional 4.2 GW output space for wind power; nationwide, 30 GW of coal plants completed retrofit by the end of 2018.

5.2. Transmission buildout

The mass buildout of UHV transmission lines was part of the SGCC's grand plan to build a "strong national smart grid" [128]. Despite that the physical viability and economic merit of the plan were still being debated, the SGCC managed to push it onto the central government's agenda [96]. Being the largest SOE in China's power sector, the SGCC's strong political sway was clearly a major factor. Another important factor was the instrumental value of UHV lines in improving renewables integration. By June 2019, 19 UHV transmission lines had been completed and 4 were under construction. Also, there were 15 transmission lines (some of which are UHV lines) dedicated to serving wind and solar, providing an additional 3.7 GW transmission capacity. By the end of 2018, totally 5430 km of transmission lines had been deployed across China, providing transmission access to 506 utility-scale wind and solar projects.

The newly deployed transmission lines enabled bulk electricity transfers across regions. They became the backbone of China's inter-regional electricity trading. According to the SGCC, long-term cross-provincial renewable electricity trading totaled 71.8 TWh in 2018, a 46% increase from 2017; cross-regional renewable electricity spot trading totaled 7 TWh in 2018, a 21% increase from 2017. The expansion of transmission infrastructure also enabled regional-level coordination in balancing and dispatch operations. The breaking of provincial boundaries in managing peaking generators and operating reserves increased the grid's capability to accommodate intermittent generation and thus reduced security-related wind curtailment. Towards this end, the northwestern power grid conducted an exemplary stress test where the entire Qinghai province ran completely on clean and renewable generators for 7 consecutive days in 2017 and 9 consecutive days in 2018 by drawing on grid services from other provinces within the region.

5.3. Performance targets

The most extensive measure to curb wind curtailment in China is through performance targets which are carried out by a series of central government decrees. One is the "guaranteed minimum utilization hours". Realizing that the grid could not practically "take all renewables as available" as stipulated by the REL, in 2016 the NDRC issued a policy that prescribes the minimum annual utilization hours that need to be fulfilled [129]. For wind power, this varies between 1800 and 2000 h, depending on the local wind condition and is to protect the bottom-line financial viability of wind power projects. This policy fits well into China's electricity regulation because generation dispatch in China is guided by an annual planning process where utilization hours are allocated to individual power plants [114]. It offers renewable generators a quantitative certainty that was not available in the vague stipulations of the REL. Enforcement of this policy is by information disclosure and by the threat to halt approval for future projects. Starting 2017, the NEA publishes annual reports on the performance of provinces in complying with the minimum utilization hours requirement. Violators are put under "close monitoring" and can potentially forfeit the authority to approve new projects or even be forced to halt undergoing constructions. Given that local governments and state-owned generation companies in China are inclined to overinvest, this policy curbs their activities more effectively than market disciplines in China's state-dominated power sector.

Another measure is the RCO. In 2019, the NDRC and NEA jointly issued the RCO policy that stipulates the minimum percentage of electricity to be sourced from renewables in each province [130]. Unlike in the U.S. where RPSs are enacted by state legislatures, provincial RCO targets in China are determined by the central government and updated annually. Provincial governments are the first line of accountability, as they are required to develop detailed implementation plans which are to be submitted to the central government for approval. The implementation plan divides the provincial target into obligations for individual power distribution companies. Consumption of renewable electricity is credited and can be traded among regulated entities. Non-compliance will face penalties that are to be devised by provincial governments considering local circumstances. Overall, the ROC provides a strong demand-pull mechanism that acts against incentives to curtail wind power. It is under pilot run from 2018 to 2020 and will begin formal enforcement in 2021.

6. Measures taken to reduce wind curtailment in the United States

Regulators in the United States have taken various measures to reduce wind curtailment. These can be categorized into the following issue areas: grid interconnection, transmission service, wholesale market design, and power purchase agreements.

6.1. Grid interconnection

The FERC has promulgated a series of orders to standardize grid interconnection services. These include measures to prevent discrimination, reduce interconnection time and cost, and prescribe technical standards, all of which contribute to the reduction of wind curtailment. For instance, Order 888 requires all public utilities that have interstate transmission facilities to have OATTs that contain minimum terms and conditions of non-discriminatory service. Prior to this order, wind generators faced delays, reluctance, and discriminatory treatment when requesting grid interconnection from utilities. Order 2003 prescribes standard procedures and a standard agreement for the interconnection of generators larger than 20 MW. It helps to reduce interconnection time and cost. Building on Order 2003, Order 661 specifically accommodates the design and operational characteristics of wind generators.

6.2. Transmission service

The FERC has promulgated a series of orders to improve transmission service, reduce undue discrimination, and encourage coordinated transmission planning, all of which contribute to the reduction of wind curtailment. For instance, Order 890 requires transmission utilities to participate in "coordinated, open and transparent transmission planning" on a local and regional level. It helps to relax the transmission constraint on the growth of intermittent generators. Order 1000 builds on Order 890 to improve regional-wide transmission planning and cost allocation. It helps to connect policy-driven renewable energy projects and reduce their economic burden in paying for transmission upgrades and grid expansion.

6.3. Wholesale market design

Competitive wholesale markets cover about two-thirds of electricity consumers in the United States [109]. Because the FERC has jurisdiction over wholesale market design, it can reduce wind curtailment by changing wholesale market rules. For instance, the Dispatchable Intermittent Resource Protocol is a set of wholesale electricity market rules that facilitate wind generators to participate in real-time security-constrained economic dispatch as conventional generators do. The protocol utilizes more frequent wind forecasts, allows wind generators to bid into and be priced in real-time markets, and manages most curtailment events through price signals. It enables wind generators to be curtailed voluntarily, economically, and through automation. This way of curtailment is both more economically efficient and beneficial for overall grid operation with high penetration of intermittent renewables [131].

6.4. Power purchase agreement

PPAs for wind power needs to address certain issues not generally applicable to fossil-fuel power plants. These include minimum output obligations considering the intermittency and seasonal variability of wind power, the ownership and transfer of RECs, and must-take obligations on part of the buyer. For instance, utilities may agree to take wind power whenever it is available. They may agree to a "take or pay" obligation under which they either buy the agreed amount of electricity or pay for damages associated with failure to accept. These damages may include loss of wholesale revenues, PTCs, and RECs. A fail-to-take by the buyer is one type of wind curtailment, and PPAs usually define the compensation for such curtailment. Other contingencies also cause curtailment but may not be factored in PPAs. When disputes cannot be resolved under contract terms or through negotiation, parties can seek adjudication by state commissions or go through formal litigation.

7. Comparison and conclusion

China and the United States have many similarities in wind power development. The two countries are comparable in wind resource endowments, landscapes for developing wind power projects, grid infrastructure, central-local government structure, and growth in wind generation capacity. They also face similar hurdles in connecting wind farms to the grid, improving transmission services, allocating integrating costs, and coordinating policies between government agencies. Then, why does China have much higher levels of wind curtailment than the United States. The answer to this question lies in the institutional logic of wind integration in each country.

Wind integration in the United States follows primarily the logic of market competition because wind power is a major beneficiary of the electricity regulatory reform and it takes a growing share in the U.S. electricity portfolio by being a cost-effective alternative to nuclear and coal-fired power. The market discipline also imposes rigorous requirements on the financial aspect of wind power projects, aligning the incentives for capacity addition and capacity utilization, effectively preventing high levels of curtailment. Meanwhile, wind power is not exempt from the political economy of energy regulation in the United States. Lobbying and interest group politics have caused significant policy volatility at both federal and state levels. The politicization of electricity regulation has resulted in disparate market conditions across states and regions which, together with dual federalism, creates challenges for the long-term development of wind power in the United States.

Wind integration in China follows primarily the logic of state-centric development which encompasses centralized planning and policymaking, dominant state ownership, generous state financing, and state control over critical infrastructure and market transactions. This aligns well with China's party-state governance over its "strategic industries" and creates the main driving force for wind power capacity deployment. Recent progress towards regulatory decentralization and market liberalization complements the central government's effort at driving capacity growth by encouraging local experimentation and policy learning and developing China's wind power industry into both a significant domestic stakeholder and a leading global player. However, decentralization and liberalization also lead to interest diversification and regulatory fragmentation, both of which impede the collective action needed to improve the utilization of installed capacity. This, combined with the geographical distribution of China's wind resource and the technical attributes of wind power, creates China's wind curtailment problem.

By comparison, China and the United States have very different institutional logics of wind integration which generate different root causes for wind curtailment. Therefore, simply transplanting solutions from one country to another will not work. What China can learn from the United States is to make incremental improvements along its dominant institutional logic while addressing the frictions created by its complementary institutional logics. The United States has one dominant and one competing institutional logic, and it is working on both fronts – by perfecting the market conditions and by mobilizing political support for wind power. As Section 6 mentions, the FERC has been moving consistently towards integrating the U.S. power markets and making them more friendly to renewables, but it has also respected its statutory limitations and delegated authority to power market operators and grid balancing agencies.

Like the United States, China can utilize its party-state apparatus to solve some of the collective action problems that prevents effective capacity utilization. For instance, the central government can tie wind power capacity utilization to provincial administrator performance evaluation, or it can encourage a key actor to lead the coalition and provide economic and political benefits in return. As Section 5 mentions, China's NEA played into the political economy of wind integration by resorting to the motivations of key stakeholders (e.g. providing incentives to retrofit coal plants and acquiescing with SGCC's ambition for expansion). These state-led programs are already showing effects on reducing China's wind curtailment.

Author contribution

Feng Song: conceptualization, methodology, supervision, writing – original draft. Zichao Yu: conceptualization, formal analysis, writing – original draft, writing – review & editing, visualization, project administration. Weiting Zhuang: resources, investigation, writing – original draft. Ao Lu: resources.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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