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# Decomposing driving factors for wind curtailment under economic new normal in China

Changgui Dong[a,b], Ye Qi[c,d,*], Wenjuan Dong[d], Xi Lu[e,f], Tianle Liu[c], Shuai Qian[c]

[a] School of Public Administration and Policy, Renmin University of China, Beijing 100872, China
[b] National Academy of Development and Strategy, Renmin University of China, Beijing 100872, China
[c] School of Public Policy and Management, Tsinghua University, Beijing 100084, China
[d] Brookings-Tsinghua Center for Public Policy, Tsinghua University, Beijing 100084, China
[e] School of Environment, State Key Joint Laboratory of Environment Simulation and Pollution Control, Tsinghua University, Beijing 100084, China
[f] State Environmental Protection Key Laboratory of Sources and Control of Air Pollution Complex, Beijing 100084, China

## HIGHLIGHTS

- China's wind curtailment resurged since 2015 following a temporary relief.
- The recent resurge is tightly linked with the economic deceleration.
- Electricity demand deceleration pushed up wind curtailment.
- Our decomposition results present a valid proof to the conclusions above.

## ARTICLE INFO

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## ABSTRACT

China's energy transition, from a coal-dominated system to one with the world largest deployment of wind power, is facing major challenge as China entered the economic "New Normal" in recent years. A key phenomenon is serious wind curtailment, where potential clean wind power is abandoned and the associated environmental and climate benefits could not be fulfilled. Multiple causes have been identified to explain the serious wind curtailment in China; but few studies provide explanations for the patterns of wind curtailment and quantify the relative contributions of the underlying factors. We develop a flexible analytical framework and adapted the logarithmic mean Divisia index method to quantify the contributions of key factors in the change of wind curtailment rate. While the early stage of wind curtailment was constrained by limited transmission capacity, recent wind curtailment is primarily driven by the deceleration of the overall economic growth, which resulted in a slowdown of electricity demand and low willingness-to-accept imported power across provinces. The current economic transition has induced an oversupply of power in general and wind power in particular, especially in wind rich provinces. This seems to be hindering further energy transition. With greater political will and better policy design, the oversupply of power could be an opportunity to speed up substitution of coal with wind and to expedite the de-carbonization of the economy.

## 1. Introduction

Renewable energy is the catalyst of energy transition and a key policy to address climate change [1–5]. Former US president has even called renewable energy an irreversible trend [6]. However, due to the intermittency of renewable energy output, current grid systems require adaptations, ranging from transmission construction to market re-design, in order to integrate renewable energy [7–10]. Insufficient adaptations could result in wind power curtailment: i.e. the abandonment of electricity generation of effective wind power capacity or simply preventing wind turbines from generating power when they are able to [11]. As the share of wind and solar energy increases in the electricity mix, the curtailment of various renewable energy has become an important policy issue, posing tangible threats to clean energy transition and climate change mitigation [12,13,14].

International experience indicates that wind curtailment rate typically ranged from 1 to 3% of potential wind generation [14]. Denmark, with a wind penetration rate of over 40% in 2014, saw essentially zero

* Corresponding author at: Tsinghua University, Haidian District, Beijing 100084, China.
*E-mail address:* qi@tsinghua.edu.cn (Y. Qi).

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curtailment [13]. Similarly, Germany and the United Kingdom seldom experienced a wind curtailment rate above 4% before 2015 [15]. On the other hand, back in 2009, Italy and Texas in the US witnessed wind curtailment rates as high as 9.7% and 17.1% respectively. Nevertheless, these rates dropped to less than 1% a few years later, due to the expansion of transmission networks [13,15,16].

China, despite having nearly twice as much wind capacity installed, generated less electricity from wind power than the US in 2015 [17]. In 2016, China has curtailed 49.7 TW h of wind power, with a national average curtailment rate of 17.1% [18]. This amount of wind power being curtailed is equivalent to more than half of the annual electricity generation by the Three Georges Dam. If being able to replace existing coal power generation in China and assuming an emission factor of 94.6 metric tons $CO_2$/TJ [19,20], the curtailed wind power in 2016 corresponds to a lost opportunity of reducing China's $CO_2$ emission by about 17 million metric tons, which is the total emission of $CO_2$ equivalents of Slovenia in 2015 [21]. Though Texas has previously seen similar wind curtailment rate, its actual wind curtailment amount was roughly 3 TW h [13], a scale much smaller than that of China. Comparably, the province with the most serious wind curtailment in China, Gansu, experienced a wind curtailment rate as high as 43% in 2016, while discarding 10.4 TW h of potential wind power. In this perspective, wind curtailment in China appears to be historically one of the most significant challenges that the industry has faced in integrating wind.

Many causes have been identified to explain the scale and scope of wind curtailment in China, reflecting the complexity of the phenomenon: (*i*) inflexible coal generation fleet or grid inflexibility [17,22–27]; (*ii*) grid operation and pricing norms favoring coal [17,28–30]; (*iii*) lack of transmission capacity or mismatch between transmission and wind capacity development [17,24,25,27,31–34]; (*iv*) overcapacity of electricity generation [31,33,35,36]; and (*v*) slowing down in growth of electricity demand [22,24,33]. Although all factors seem relevant, they target different aspects of the problem – including technical, policy, and economic causes – without coming up with a consistent analytical framework. Furthermore, most studies are descriptive in nature, and therefore lack quantitative analysis on the impact of each factor and discussion of their relative importance. This paper fills in the research gap by quantitatively disentangling various factors that impact wind curtailment that is flexible and easy to extend to other technology and other regions with similar problems.

Various wind integration studies used simulation techniques to gauge the effects of multiple constraints on wind penetration and curtailment. For example, Waite and Modi [37] simulated the effect of adding 10–37.5 GW of wind capacity to the New York State Grid, and found that demand, baseload generation, and transmission constraints could have a significant impact on wind power curtailment. Shu et al. [25] developed a production simulation model to analyze the effect of enhancing regulation capability, grid interconnection, and load size on alleviating wind curtailment in China. Jorgenson et al. [38], de Jong et al. [39], Miranda et al. [40], and Zhang et al. [41] conducted similar studies. However, these simulation studies share a common problem – they seek to propose technical and ideal solutions to wind curtailment without sufficiently assessing the underlying reasons that cause wind curtailment first. As such, this study collects extensive wind curtailment data in China and leverages empirical methods to understand the fundamental reasons behind its wind curtailment problem.

Disentangling and quantifying the effect of each factor on the wind curtailment problem is essential to proposing useful and informative policy alternatives. First, the impacts of two or more factors can be intertwined. Taking Gansu Province as an example, its 43% wind curtailment rate can be attributed to either the lack of transmission capacity or the lack of power-importing demand from other regions. If the real problem is the latter, building more transmission capacity could be waste of money and time. Furthermore, the driving factor behind wind curtailment at different development stages may vary. Thus, it is necessary to analyze the relative contribution of all factors over time. Lastly, each province may have its own reasons for wind curtailment, and solving the provincial-level wind curtailment problem requires regionally specific answers.

Figuring out the underlying reasons for China's wind curtailment is critical not only from the energy and financial perspectives, and but also from an environmental perspective. Considering the negative externalities of 50 TW h of coal power that could be avoided annually [42], understanding and solving China's wind curtailment problem should not only act as a critical step toward low-carbon energy system in China but also have broad global implications on mitigating climate change [43]. China's energy transition, from a coal-dominated system to one with the world largest deployment of wind power, has been in part driven by demand from the rapid economic growth [3,44]. Currently, wind curtailment appears to be spreading quickly, in parallel with China's economic deceleration, a phenomenon better known as the economic "New Normal". The "New Normal" has been considered as "a crucial rebalancing, one in which the country diversifies its economy, embraces a more sustainable level of growth, and distributes the benefits more evenly [45, p.1]," or simply summarized as "slower but high-quality growth" [46]. As such, the "New Normal" has significant and direct implications on wind curtailment from a demand perspective. Under the Paris Agreement, China has committed to increase the share of non-fossil fuels in primary energy consumption to around 20% and peak its carbon dioxide emission by 2030 or even earlier years [47,48]. Since both China's energy and economic systems are in a state of unprecedented transition, how it evolves should have global implications [43].

Our work makes several contributions to the existing literature. First, we develop a flexible analytical framework for decomposing driving factors of wind curtailment in China, and it can be easily adapted to study other regions and to include more factors. Through this framework, we quantify the relative contributions of various factors to wind curtailment, which is the first such effort in the literature to our knowledge. Second, we identify two phases of serious wind curtailment in China and the different driving factors behind them. Especially for the second and most recent wind curtailment, electricity demand deceleration was the major factor that increased wind curtailment. Third, we highlight that building more transmission capacity to transport wind power may not be an effective solution to China's wind curtailment problem, as wind-rich and power-exporting provinces could run into a problem of low willingness-to-accept in power-import provinces.

In the following sections, we begin with a review of China's wind curtailment development since 2010. Section 2 highlights the two waves of wind curtailment, as indicated by the fast increase of wind curtailment rates. We then propose a five-factor, definition-based analytic framework to explain the changes in wind curtailment rate in Section 3, and further adapt the logarithmic mean Divisia index (LMDI) method to disentangle the contribution of each factor to the wind curtailment problem from 2011 to 2016. Section 4 presents decomposition results at both the national level and provincial level, and further explains our results with corroborating macro-level evidence. Section 5 links our analytical results to proposed wind curtailment solutions in the literature, discusses their potential roles, and concludes our findings.

## 2. Wind curtailment: Time trend and spatial pattern

Wind curtailment started to become a policy concern in China as early as 2010, when China surpassed the US and became the top wind energy developer in the world. In 2016, wind capacity amounted to roughly 150 GW in China (9% of all capacity), and wind power accounted for 4% of total electricity generation at the national level, with the highest provincial-level share at 12%. Due to the energy structure in China, most wind intermittency is balanced by coal-fired power.

The amount of wind power curtailed in 2010 was around 4 TW h