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Emissions and temperature benefits: The role of wind power in China

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ABSTRACT

Background: As a non-fossil technology, wind power has an enormous advantage over coal because of its role in climate change mitigation. Therefore, it is important to investigate how substituting wind power for coal-fired electricity will affect emission reductions, changes in radiative forcing and rising temperatures, particularly in the context of emission limits.
Methods: We developed an integrated methodology that includes two parts: an energy-economy-environmental (3E) integrated model and an emission-temperature response model. The former is used to simulate the dynamic relationships between economic output, wind energy and greenhouse gas (GHG) emissions; the latter is used to evaluate changes in radiative forcing and warming.
Results: Under the present development projection, wind energy cannot serve as a major force in curbing emissions, even under the strictest space-restraining scenario. China's temperature contribution to global warming will be up to 21.76% if warming is limited to 2 degrees. With the wind-for-coal power substitution, the corresponding contribution to global radiative forcing increase and temperature rise will decrease by up to 10% and 6.57%, respectively.
Conclusions: Substituting wind power for coal-fired electricity has positive effects on emission reductions and warming control. However, wind energy alone is insufficient for climate change mitigation. It forms an important component of the renewable energy portfolio used to combat global warming.

1. Introduction

The latest studies reveal that the current atmospheric CO_2 concentration has exceeded the 400 ppmv threshold (WMO, 2015). If this trend continues, the global average surface temperature will have increased by 4 degrees by the end of this century (relative to pre-industrial levels). This warming is predicted to cause the extinction of one-sixth of the planet's species (Onozuka and Hagihara, 2015; Urban, 2015). Most climatologists agree that limiting global temperature rise to 2 °C is necessary to avoid climatic catastrophe. Achieving this goal will require a 41–72% reduction in emissions in 2050 from 2010 levels, and near-zero emissions in 2100. The realization of these reduction targets depends on the development of non-fossil technologies, particularly wind power. The share of non-fossil fuel energy in 2050 and 2100 should be increased to 60% and 90%, respectively (Jacobson and Archer, 2012; IPCC, 2014).

China will need to adjust its energy structure, promote industrial upgrading and develop non-fossil energy technologies to peak its emissions in 2030 and increase the amount of non-fossil fuels in its total primary energy demand (TPED) to 20%. It will obviously be challenging to double the amount of non-fossil energy in less than 15 years, given that the current share of non-fossil energy in TPEC is just 11%, and this goal is likely to be unattainable without the rapid penetration and use of renewables such as wind power (Sun et al., 2015). In fact, as an energy source with near-zero emissions, wind power is widely regarded as a crucial substitute for conventional fuels. This is particularly true for China, which simultaneously faces a high increase in energy demand and the need for significant emission reductions. It is advantageous for China to develop wind energy for many reasons.

First, China is rich in wind resources, which provides a solid foundation for development of wind power technology. Recent statistics show that China's total wind energy potential is over 3000 GW, of which 86.7% is 70 m offshore and the rest is 100-m onshore wind. Even with current technology, developable wind energy resources are as high as 2000 GW. The present ‘surveyor's pole’ price of wind power is 0.51–0.54 yuan per kilowatt hour (yuan/kW h), which is approximately 0.25 yuan/kW h more expensive than coal-generated power. However, improvements in wind power technology will drive the price of wind power to equal that of coal-fired power by 2020, even without taking into account the negative externalities of coal (ERI, 2011).

Second, China is capable of developing wind energy on a large-scale. After nearly 30 years of development, the wind energy market in China has reached a near-mature stage. Despite some disadvantages due to the nationalization of key components,

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onshore wind energy technology and grid dispatching, China has the advantage of a sound policy support system that shapes R&D and manufacturing bases, as well as complete industrial chains. These factors make China the largest wind energy market in the world now and in the future. In fact, wind power has become the largest renewable power supplier, in addition to hydropower and nuclear energy, with its consumption share in TPEC reaching around 0.5% in 2014 (BP, 2015).

Finally, deployment of wind energy provides important environmental benefits. Wind power is actually not a zero-emission technology from the perspective of life cycle emissions. However, wind power has GHG emissions per kW h as low as 8–20 g, which is just 2.2% of the emissions generated by coal (Dones et al., 2005). Emissions resulting from electricity generation have serious negative externalities. For instance, each terawatt hour (TW h) of power generation causes an average of 24.5 deaths, 225 serious illnesses and 13,288 minor illnesses (Markandya and Wilkinson, 2007; Wiser, 2012). As a consequence, the GHGs reduction potential of wind power has enormous environmental benefits (Vautard et al., 2014; Xue et al., 2015).

Despite a slight decline in recent years, the share of coal in the TPED was still 70.6% in 2012, and coal dominates the energy supply market (NBS, 2013). Thus, it is feasible to reduce the externalities associated with coal emissions by developing wind energy and promoting the transition from coal to wind power. In fact, the environmental benefits of wind energy deployment are apparent. The amount of wind power generation exceeded 100 TW h in 2012 alone, signifying energy savings of 3.29 million tons of standard coal and an 8.43 million ton reduction in CO_2 emissions.

An investigation of the benefits to emissions and warming associated with wind-for-coal substitution must address the tension between economic development, investment in energy technologies and emission reductions. This is especially important because China has committed to peak its emissions by 2030 and increase the share of non-fossil fuel energy in its TPED to 20%. An accelerated transition from coal to wind power will not only contribute to peaking emissions ahead of time, but will also allow more time for the development of other renewable technologies (Barthelmie and Pryor, 2014). Additionally, emission reductions from wind-for-coal substitution can help control temperatures, which will in turn lower the death rate from the warming effect (Li et al., 2014; Ma et al., 2015).

To date, few studies have examined the long-term potential of substituting wind power for coal-fired electricity and its contribution to emission reductions, from the perspectives of full spectrum and life cycle emissions. Research is also lacking on the beneficial effect of emission constraints on China's radiative forcing and temperature rise. Xue et al. (2015) discussed the prominent performance of wind energy penetration in cutting down GHG emissions and fine particles (such as PM10), affirming the environmental benefits that arise from wind energy development. Cardell and Anderson (2015) argue that wind power alone may not be sufficient to reach the US EPA's emission reduction goals, despite its considerable effects on emission reduction. Gutiérrez-Martín et al. (2013) analyzed the impacts of the intermittent nature of wind energy on emission reductions in Spain; they conclude that intermittency of wind power lowers its potential for emission reductions. Inhaber (2011) also reached this conclusion. Barthelmie and Pryor (2014) investigated the effects of wind power deployment on the time necessary to reach the 2 °C temperature threshold under various representative carbon pathways (RCPs). They found that a moderate wind power development plan would delay crossing the 2 °C temperature threshold by 1–6 years.

Considering full spectrum and life cycle emissions, we aim to explore the long-term emission reduction potential of wind energy penetration in this study. In particular, we assess and analyze the environmental benefits arising from substitution of wind power for coal-fired electricity under given emission-control conditions. Specifically, we study the evolution of the wind energy penetration's contribution to reductions, explore the role of wind energy development in controlling global warming and assess the radiative forcing and temperature benefits that result from wind-for-coal electricity substitution. To fulfill these tasks, we innovatively combine an energy-economy-environmental integrated model with a simple slab ocean model and propose a new integrated assessment methodology framework.

2. Methodology

2.1. Data sources

Macroeconomic and energy data are the most important inputs for our model (Duan et al., 2013). Gross domestic product (GDP), consumption, investment and capital storage data comes from the China Statistical Yearbook-2011 (NBS, 2012). The total energy consumption in 2010 is from the China Energy Statistical Yearbook-2011 and the annual report of Chinese power regulation-2011 (SERC, 2012; NBS, 2013). The coal price refers to the plate price of coal in Shanxi Province and the prices of oil and natural gas are set based on the price of international crude oil and domestic residential gas, respectively. The cost distribution interval is very wide for non-fossil fuels because of the differences between plant locations, installment capacity scales and technical levels. For example, the prices of hydropower and nuclear power are now very close to the prices of fossil fuels; the electricity generation cost for onshore wind power can be up to 1.5 times that of conventional energy; and the cost of offshore power is even greater, reaching 4–7 times higher than that of fossil fuels (Gerlagh and van der Zwaan, 2003; CNREC, 2014).

Obtaining life cycle GHG emission inventories is essential to estimate dynamic GHG emission levels and investigate the effect of electricity replacement on emissions trajectories. Generally speaking, the life-cycle (LC) GHG emissions for one unit of coal-fired power are the highest among the fossil fuels, ranging from 800 to 1000 gCO_{2eq} (grams of CO_2 equivalent). This is in contrast to the lowest per-unit LC fossil fuel emissions from gas-fired electricity, which range from 360 to 575 gCO_{2eq} (Dones et al., 2005; Weisser, 2007). We note that non-fossil fuel technologies may not be zero-emission from a life-cycle perspective. For example, GHG emissions per unit of hydropower are approximately 22.84 gCO_{2eq}, while the emissions for one unit of offshore wind power are 20.23 gCO_{2eq}. The per-unit GHG emissions from solar energy may be the highest among the renewables, ranging from 26 to 217 gCO_{2eq} (Dones et al., 2004; Amponsah et al., 2014). We summarize the LC emission information in Fig. 1.

2.2. 3E integrated model: CE3METL

The methodology of this paper is divided into two parts: an energy-economy-environmental (3E) integrated model (the CE3METL model), and the emission-warming climate response model. The former is used to simulate dynamic GHG emissions and wind power penetration pathways in the presence of carbon control; the latter converts emissions to atmospheric GHG concentrations and evaluates the warming effect associated with wind-for-coal electricity substitution.

CE3METL is a tech-driven endogenous economic growth model with a logistic technical diffusion mechanism (Duan et al., 2013). These characteristic enable the model to consider multiple energy