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Key factors affecting long-term penetration of global onshore wind energy integrating top-down and bottom-up approaches

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ABSTRACT

We quantified key factors affecting the penetration of global onshore wind energy by 2050. We analyzed a large set of scenarios by combining a wind resource model and a computable general equilibrium (CGE) model. Five factors, including onshore wind resource potential, investment cost, balancing cost, transmission cost and climate change mitigation policy, were considered to generate 96 scenarios and regression analysis was used to assess relevance among the factors. We found that the strongest factors were resource potential and climate target, followed by wind power technology investment cost. Other factors, such as balancing and transmission costs, had relatively smaller impacts. World total onshore wind power in 2050 increases by 13.2 and 15.5 (41% and 49% of 2005 total power generation, respectively) EJ/year if wind potential rises from low to medium and high levels, respectively. Furthermore, 5.9, 17.8, and 24.3 EJ/year of additional wind power could be generated under climate targets of 650, 550 and 450 ppm $CO_{2\text{-eq}}$, respectively. Moreover, reducing wind power technology investment cost would increase global wind power by another 9.2 EJ/year. The methodology can be extended to assess other mitigation technologies if the related data is available.

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1. Introduction

Climate change is one of the most serious challenges facing the human race in this century. There is increasingly reliable evidence that climate change is caused by anthropogenic greenhouse gas (GHG) emissions, especially from fossil energy combustion [21]. To mitigate climate change, the deployment of technologies that are more energy efficient and/or that can provide energy with lower carbon emissions is crucial. Renewable energy (RE), one of the most important low-carbon options, encompasses a wide range of energy sources and technologies, including solar power and heat, wind power, geothermal energy, bioenergy, hydroelectric power, and ocean-based energy. Life-cycle assessment of RE production indicates that GHG emissions in RE are generally much lower than those caused by fossil fuels [32].

Wind power is a RE with huge resource availability and a large deployment rate, and is thus one of the most promising GHG mitigation technologies. Assessments suggest that the resource potential of wind power is large, although uncertain, with a practical potential range of 70–450 EJ/year and the technical potential for as much as 5700 EJ/year [5,15,27,31,41], which could supply a significant proportion of all world energy needs. Studies also show that for regions with limited resource base for onshore wind, offshore wind could provide a key source of renewable energy [11]. Furthermore, the resource potential of all RE exceeds the current energy demand by at least one order of magnitude; thus, global and regional technical potential are unlikely to limit RE deployment [5].

Existing studies, performed using integrated assessment models, indicate that wind energy for power generation is one of the most important options to mitigate climate change [29] [2]. showed that the top five key carbon reduction technologies are carbon capture and storage (CCS), solar, wind, biomass power generation, and biofuels, and that wind power generation accounts for 10% of the total emission reduction in 2050 in a 450 ppm (parts per million) scenario. Ref. [23] argued that to meet the European goal of reducing GHG emissions by 80% by 2050, wind energy will become the most important renewable technology, reaching a similar deployment level as nuclear energy. Another review of 162 recent medium-to long-term scenarios by Ref. [24] showed that annual growth rates of wind and solar energy over the 2010-50 period would be nearly 10% and the share of wind in global

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electricity generation in 2050 would be ~15% in 440-ppm scenarios. Ref. [28] further assessed the role of renewable energy in climate stabilization and found that wind energy would be competitive even without a climate policy.

Despite its rich resource potential and importance in mitigating climate change, however, future deployment of RE may be affected by various factors, such as competition with alternative sources of energy and technology, high direct economic costs, regional heterogeneity of resources, systems-integration constraints [28] and climate policy issues, such as a carbon tax [17]. Further assessment of RE penetration needs to take these aspects into account, comprehensively. However, how these factors affect RE penetration is not quantified by resource assessment studies or by integrated assessment studies.

Given this context, in this study, we aimed to identify key factors affecting the future penetration of onshore wind power on a global scale. Five factors are considered, including resource potential, integration cost, investment cost, and transmission cost of wind and climate policy target. All factors can change the competitiveness and, thus, the penetration of wind energy.

For this purpose, we used a technology-rich computable general equilibrium (CGE) model combined with a wind resource model. CGE models are a top-down type of integrated assessment model. Compared with bottom-up-type models, the CGE model has the advantage of assessing climate change mitigation policies, taking into consideration the interaction between whole economic sectors and agents. Additionally, we established nearly 100 scenarios that considered combined effects of the above factors looking forward, to reduce the uncertainty. We chose 2050 instead of a shorter term (e.g., 2020) as the target year given this timeframe is long enough to obtain significant penetration of wind power and assess the impact of climate policies such as carbon tax. On the other hand, a longer timeframe (e.g. 2100) was avoided in order to give room for discussion on policy implications of the factors analyzed.

The paper is structured as follows: Section 2 presents the methodology of how scenarios are set by combining a resource model with a CGE model. Results from the scenario analysis are presented in Section 3 and discussed in Section 4. Conclusions are explained in Section 5.

2. Methodology

This study combines a resource model and Asian-pacific Integrated Model (AIM)/CGE model (Fig. 1). The resource model estimates three levels of wind resource availability and unit cost of supply. The wind supply data are then fed into the AIM/CGE model, in which wind power competes with other power generation technologies, to estimate the penetration of wind power up to 2050. In total, 96 scenarios were generated in the CGE model combining different combinations of these factors (Table 3).

2.1. Global resource model

The resource assessment of onshore wind power is based on a geographic information system (GIS) database with high spatial resolution (0.5 arc-minute or ~1 km at the equator) [16,35]. The resource model computes the average annual energy potential and the corresponding supply costs for each grid cell, and aggregates results in 17 world regions. The model's equations incorporate four groups of parameters: land use, technical, economical, and spatial parameters.

Wind energy technical potential

$$Q_{Wind\_onshore} = A_G * r_{LC} * \rho_{Capac} * T_{FullLoad} * \eta_{Av} * \eta_{Array} * \eta_{Correct} * (1 - L_{Transm} * D_{Transm}) \tag{1}$$

Capacity

$$\mathrm{P_{Wind}} = \mathrm{A_G} * \mathrm{r_{LC}} * \rho_{Capac} \tag{2}$$

UnitCost

$$\mathrm{UnitCost_{w.transm.}} = \frac{\left[(\mathrm{C_{Cap}} * \mathrm{CRF} + \mathrm{C_{OM}}) + (\mathrm{C_{Transm}} * \mathrm{CRF} * \mathrm{D_{Transm}})\right] * \mathrm{P}}{\mathrm{Q}} \tag{3}$$

Q: Energy potential [MWh/yr]
A_G: Grid cell area [m^2]
r_{LC}: Land suitability factor (for a given land cover type) [-]
ρ_{Capac}: Density of capacity of wind turbine [MW/m^2]
$T_{FullLoad}$: Equivalent operation hours of wind turbine at full load capacity [h/yr]
η_{Av}: Availability factor of wind turbine [-]
η_{Array}: Efficiency of wind turbine array (wind farm) [-]
$\eta_{Correct}$: Power correction factor [-]
L_{Transm}: Electricity transmission losses [MW/MW/km]
D_{Transm}: Distance of electricity transmission line (closest urban area) [km]
P: Total capacity [MW]
C_{Cap}: Capital cost of technology [USD/MW]
CRF: Capital recovery factor (or annuity factor) [-]
C_{OM}: Fixed operation and maintenance cost [USD/MW]
C_{Transm} Capital cost of electricity transmission [USD/MW/km]

Operation hours at full load are calculated based on wind speed using a Rayleigh distribution function and a wind power curve. Average annual wind speed data originate from monthly average wind data at 50 m height above ground [36], and are converted to speed at hub height (80/90/100 m) using a wind shear exponential function [35]. The Rayleigh distribution function approximates the fraction of time (i.e. frequency) that a wind speed occurs at a given average wind speed, while the power curve converts these wind speeds into turbine's power output. Wind power curve considers a representative 2 MW wind turbine that operates from a cut-in wind speed of 3 m/s and a cut-out wind speed of 25 m/s, and a maximum power output at 12 m/s [40]. Land use parameters include land suitability factor and density of capacity. Land suitability factor represent the availability of land for installing wind farms, resulting from a high or low degree of competition with other land uses. Values assumed are within the range observed in the literature [15,41]. Density of capacity indicates the number of wind turbines per area and, thus, the installed capacity, depending on the spacing among turbines to avoid wind speed losses. Wind farms are restricted in wetlands, urban areas, snow- and ice-covered areas, and protected areas. Additionally, locations over 2000 m above sea

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