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Assessment of the productive efficiency of large wind farms in the United States: An application of two-stage data envelopment analysis

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ABSTRACT

Wind power is one of the most promising renewable energy sources that has gained enormous attention, especially in the electricity generation sector over the past decade in the United States. In this study Data Envelopment Analysis (DEA) is implemented to quantitatively evaluate the relative efficiencies of the 236 large utility-scale wind farms. Input- and output-oriented CCR (Charnes, Cooper, and Rhodes) and BCC (Banker, Charnes, and Cooper) models are applied to pre-determined three input and three output variables. The sensitivity analysis is conducted for the robustness of DEA by introducing seven new models with the various combinations of input and output variables of the original model. Tobit regression models are developed for the second stage of the analysis to investigate the effects of specifications of the wind turbine technologies. DEA results indicate that two-thirds of the wind farms are operated efficiently. On average, 70% of the wind farms have a considerable potential for further improvement in operational productivity by expanding these wind farm projects, 24% of them should reduce their operational size to increase their productivity level, and 6% of them are operating wind power at the most productive scale size. Nonparametric statistical tests show that the most efficient wind farms are located in Oklahoma because of the relatively high wind speed resources. Tobit regression model indicates the selection of the brand of the wind turbine has a significant contribution to the productive efficiency of the wind farms. The results of this study shed some light on the current efficiency assessments of the 236 large utility-scale wind farms in the United States and the future of wind energy for both energy practitioners and policy makers.

1. Introduction

The National Oceanic and Atmospheric Administration (NOAA) reports that the average global surface temperature increased by 0.94 ± 0.15 °C (1.69 ± 0.27 °F) because of irrepressible increase of the concentration of greenhouse gases (GHG) [1]. Additionally, the last three years (2014, 2015 and 2016) were the three warmest years in a row since modern record-keeping began in 1880 [1]. The Intergovernmental Panel on Climate Change (IPCC, 2014) reports that the ecosystem will face severe problems such as endangered of animal and plant species, food scarcity, malnutrition, floods and freshwater problems if the global warming is not restrained [2]. Hence, global warming and climate change became one of the most critical environmental and political issues between the countries in the 21st century. Kyoto Protocol, which delimits the production of GHG emissions to fight global warming and climate change, has been signed by a total of 192 countries. However, it was not an unmitigated success because of two reasons: first, only 38 countries have binding targets for the first commitment period (2008–2012), and 37 countries for the second commitment period (2012–2020) which is also known as the Doha Amendment. Second, India, PR China, and the United States, who are producing more than the half of the global GHG emissions, have no binding targets for both of these commitment periods. As a result of negotiations of the Doha Amendment, a total of 197 countries have signed, and 152 of them ratified the Paris Agreement, which aims to reduce the global average temperature to the pre-industrial levels [3]. Therefore, renewable energy sources which produce a negligible amount of GHG emissions, have gained enormous attention in the electricity generation sector for each country all over the world.

As shown in Fig. 1, there are five main sources of GHG emissions in the United States: electricity generation, transportation, industry, commercial and residential, and agriculture where the electricity generation contributes most to the total of GHG emissions [4]. In 2016, 65% of electricity was generated by burning of fossil fuels (natural gas 34%, coal 30%, and petroleum 1%) which are the primary sources of GHG emissions for the electricity production. Nuclear power plants produced the 20% of the total output, and only 15% of electricity was generated by renewable energy sources which are produced and

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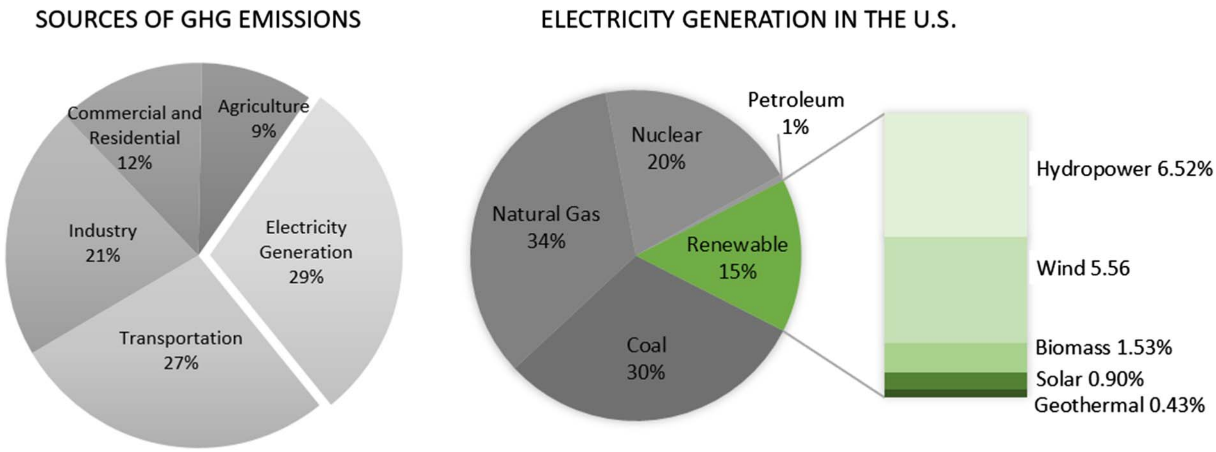

Fig. 1. Primary sources of greenhouse gas emissions and electricity generation.
(Data Source: EPA [4], EIA [5]).

replenished by natural resources such as sunlight, wind, tides, and rain [5]. There are five primary sources of renewable energy: hydropower, wind power, biomass, solar and geothermal. Fig. 1 depicts the main sources of GHG emissions on the left, and the contribution of each energy source for the electricity generation on the right, in the United States. Wind power is the second largest renewable energy source for the electricity generation in the United States. It has gained enormous interest during the last decade by declining levelized cost of wind energy and supporting policies and incentives.

Fig. 2 illustrates the exponential growth (statistically significant) of newly installed wind capacity, cumulative installed wind capacity, and net generation of wind power in the United States from 2000 to the end of 2016 [5,6]. In 2000, the nameplate generating capacity for wind energy was only 2.54 GW, it increased to 8.99 GW in 2005, and, it was about 40.28 GW by the end of 2010 [6]. During 2016, 7.70 GW new wind power capacity was added, and the cumulative installed wind power capacity reached 82.17 GW [6]. Thus, 5.56% of electricity demand was provided by wind energy in 2016 [5].Fig. 2 also depicts the reactions of the energy market to the Production Tax Credit (PTC). The first lapse of PTC came in December 1999, and then it had expired and extended three times which caused booms (1999, 2001, 2003, and 2012), and busts (2000, 2002, 2004, and 2013) for the investment in the wind industry.

As pointed out before, wind power has enormous environmental benefits as well. In 2016, 82.17 GW installed wind power generated 226,821 GW h electricity which avoided 160 million metric tons of carbon dioxide and 88 billion gallons of water consumption [7]. Besides the environmental benefits, wind power has significant contributions to the United States economy as well. There are more than 1000 utility-scale wind farms and 500 wind-related manufacturing facilities spread across the United States. During 2016, wind industry created more than 15,000 direct jobs, and the wind industry employed 102,500 people by the end of 2016 [6]. Besides, $14.1 billion was invested in new wind energy projects, and the cumulative wind projects paid more than $245 million annually to local landowners for land leases [6].

In 2015, the U.S. Department of Energy released a technical report which evaluates the economic, environmental, and social benefits of the future of wind industry in the United States. The Wind Vision report targets that wind power will provide 10% of U.S. electricity demand by 2020, 20% by 2030 and 35% by 2050 [8]. Other key targets of this report can be listed as follow [8]:

- the cumulative installed wind power capacity will be about 404 GW,
- the wind industry will create more than 600,000 direct and indirect wind-related jobs across the nationwide,
- 12.3 giga-tons carbon dioxide emissions and 250,000 metric tons of

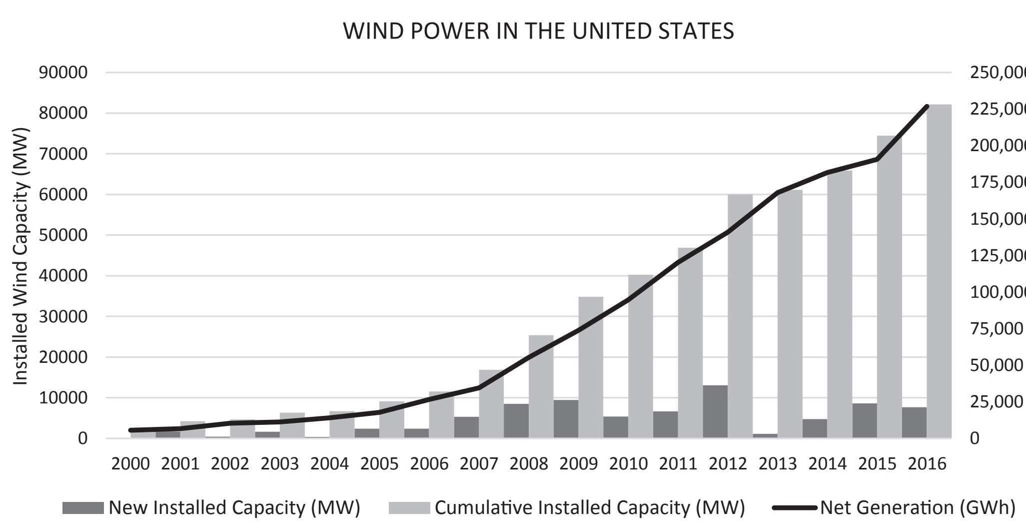

Fig. 2. Wind power in the United States from 2000 to 2016.
(Data Source: EIA [5], AWEA [6]).