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A two-stage data envelopment analysis model for efficiency assessments of 39 state's wind power in the United States

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ABSTRACT

The average global surface temperature increased by 0.85 °C since 1850 because of irrepressible increase of the concentration of greenhouse gases (GHG). Electricity generation is the primary source of GHG emissions in the United States. Hence, renewable energy sources, which produce a negligible amount of GHG emissions, have gained enormous attention, especially in the electricity generation sector over the past decade. Wind power is the second largest renewable energy source to generate electricity in the United States. Therefore, in this study, a two-stage Data Envelopment Analysis (DEA) is developed to quantitatively evaluate the relative efficiencies of the 39 state's wind power performances for the electricity generation. Both input- and output-oriented CCR (Charnes, Cooper, and Rhodes (1978)) and BCC (Banker, Charnes, and Cooper (1984)) models are applied to pre-determined four input and six output variables. The sensitivity analysis is conducted to test the robustness of the DEA models. Tobit regression models are conducted by using the DEA results for the second stage analysis. The DEA results indicate that more than half of the states operate wind power efficiently. Tobit regression indicates that early installed wind power was more expensive and less productive relative the currently installed wind power. Findings of this study shed some light on the current efficiency assessments of the states and the future of wind energy for both energy practitioners and policy makers.

1. Introduction

Global warming is defined as the average temperature increase in Earth's surface, air, and oceans, and it was first recognized by Fourier [1]. Arrhenius [2] developed the earliest model to investigate the relationship between the temperature of the ground and carbon dioxide concentration. However, global warming's perceived effects on human beings became more detectable and measurable within the last five decades. The average global surface temperature increased by 0.85 ± 0.20 °C (1.53 ± 0.36 °F) since 1850 [3]. Moreover, 2014, 2015 and 2016 were the three warmest years in a row since modern record-keeping began in 1880 [4], because of irrepressible increase of the concentration of greenhouse gases (GHG). According to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC), even if the level of the concentration of the GHG will be kept constant, the global average surface warming would be about 0.2 °C for a decade [5]. According to the scenario projections in this report, the ecosystem will face severe problems all over the world, when the warming increases by 2 °C. For example, approximately 25% of the plant and animal species will be in danger of extinction; crop productivity will decrease leading to food scarcity in many regions of the world; millions of people will have health problems because of increase in malnutrition [5]. In addition, climate change also results in significant rising of sea levels; this will lead islands in Asia, Africa, and the Caribbean to become vulnerable to storms surge, inundation, and erosion, and some of them will vanish [5]. Also, by 2020, climate change will cause between 75 and 250 millions of people to have fresh water problems in Africa [5]. Shortly, climate change would cause many severe problems if the global warming is not restrained.

Not surprisingly, global warming and climate change became the most critical environmental and political issue between countries. A total of 192 countries have signed the Kyoto Protocol which delimits the production of GHG emissions to fight global warming and climate change. More recently, 197 United Nations Framework Convention on Climate Change (UNFCCC) members have signed, and 129 of them ratified the Paris Agreement, which aims to reduce the global average temperature to pre-industrial levels [6]. Therefore, renewable energy sources, which produce a negligible amount of GHG emissions, have gained enormous attention, especially in the electricity sector over the past decade.

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There are five main sources of GHG emissions in the United States: electricity production 30%, transportation 26%, industry 21%, commercial and residential 12%, and agriculture 9% [7]. These values are consistent with the worldwide data of IPCC 2014, where the electricity production contributes most to the total of GHG emissions [3]. According to the U.S. Energy Information Administration (EIA) data [8], in 2015, 67% of electricity was generated by burning of fossil fuels (coal 33%, natural gas 33%, and petroleum 1%) which are the primary sources of GHG emissions for the electricity production. Nuclear power plants produced the twenty percent of total electricity generation, and only 13% of electricity in the United States (U.S.), was generated by renewable energy sources. Renewable energy is produced and replenished by natural resources such as sunlight, wind, tides, and rain. There are five primary sources of renewable energy: hydropower, wind power, biomass, geothermal, and solar. Fig. 1 depicts the main sources of GHG emissions and as well as the contribution of each energy source for electricity generation in the U.S.

As seen in Fig. 1, wind power is the second largest renewable and sustainable energy source that generates electricity by converting the kinetic energy of air flow through wind turbines via a wind generator. Wind power has gained enormous interest for electricity generation during the last decade in the U.S. because of various reasons: the falling cost of wind energy, the rising awareness of environmental issues, and the new supportive policies and incentives. In 2005, the cumulative installed wind power capacity was about 8.99 GW, and in 2010, it was about 40.28 GW [10]. During 2015, 8.60 GW new wind power capacity was added in the U.S., and the cumulative installed wind power capacity reached 74.47 GW [9]. Thus, 4.7% of electricity demand is provided by wind energy by the end of 2015 [9]. Another 1.73 GW was added, and the U.S. installed wind capacity was 75.72 GW by the end of third quarter of 2016 [10]. Fig. 2 illustrates trends of both newly installed wind capacity and cumulative installed wind capacity in the U.S. from 2000 to the third quarter of 2016 [10]. As pointed out before, wind power has enormous environmental benefits as well. In 2015, 74.47 GW installed wind power generated almost 191 million megawatt-hours (MW h) electricity which avoided 132 million metric tons of carbon dioxide, and 73 billion gallons of water consumption [10]. Besides environmental benefits, wind power has significant contributions to the U.S. economy as well. During 2015, wind industry created more than 15,000 direct jobs, and the wind industry employed 88,000 people by the end of 2015 [10]. In 2015, $14.7 billion was invested in the wind energy projects, and the cumulative wind projects paid $222 million annually to local landowners for land leases [10].

In 2016, the Department of Energy released a report: "Wind Vision: A New Era for Wind Power in the United States." According to this report, 10% of U.S. electricity demand will be provided by wind power by 2020, 20% by 2030 and 35% by 2050 [11]. The Wind Vision Report emphasizes the importance of wind power for the U. S. as a whole, and as well as for each individual state. This study focuses on the 39 states who have utility-scale wind project(s). Fig. 3 illustrates the cumulative installed wind power capacity of each state of the U.S. which was ended up with 75.72 GW by the end of third quarter of 2016 [10]. Almost 25% of the wind power of the U.S. have been installed in Texas (TX, 18,531 MW). Iowa (IA) and California (CA) follow Texas with the cumulative installed wind power capacities of 6365 MW and 5662 MW respectively. On the other hand, the lowest installed wind power capacities belong to New Jersey (NJ) 9 MW, and Delaware (DE) 2 MW. The 11 states (Alabama (AL), Arkansas (AR), Connecticut (CT), Florida (FL), Georgia (GA), Kentucky (KY), Louisiana (LA), Mississippi (MS), North Carolina (NC), South Carolina (SC), Virginia (VA)) do not have any utility-scale wind power.

There are twelve U.S. states: Colorado (CO), Idaho (ID), Iowa (IA), Kansas (KS), Maine (ME), Minnesota (MN), North Dakota (ND), Oklahoma (OK), Oregon (OR), and South Dakota (SD), Vermont (VT), and Texas (TX), where the wind power share was 10 percent or more for the 12 month period between July 2015 and July 2016 of all in-state electricity generation [12]. During the same time period, almost 36% of Iowa's, 28% of Kansas's, 27% of South Dakota's in-state electricity demand was generated by wind power. These individual contributions are critical to support the Department of Energy's Wind Vision Program, and at the same time, they are also essential to meet with state's Renewable Portfolio Standards (RPS). RPS have been mandated by 29 states across the U.S. and District of Columbia (DC), which require certain targets for a proportion of in-state electricity production will be provided by the renewable energy sources by a certain target year. According to the RPS, Hawaii (HI) targeted that the renewable energy sources will provide 100% of electricity production by 2045, Vermont (VT) targeted 75% by 2032, and California (CA) targeted 50% by 2030 [13]. Thus, wind power will have a vital role for each state to meet their RPS requirements.

In this study, linear programming problems are modeled to quantitatively evaluate the relative efficiencies of the 39 states' wind power performances for electricity generation by using

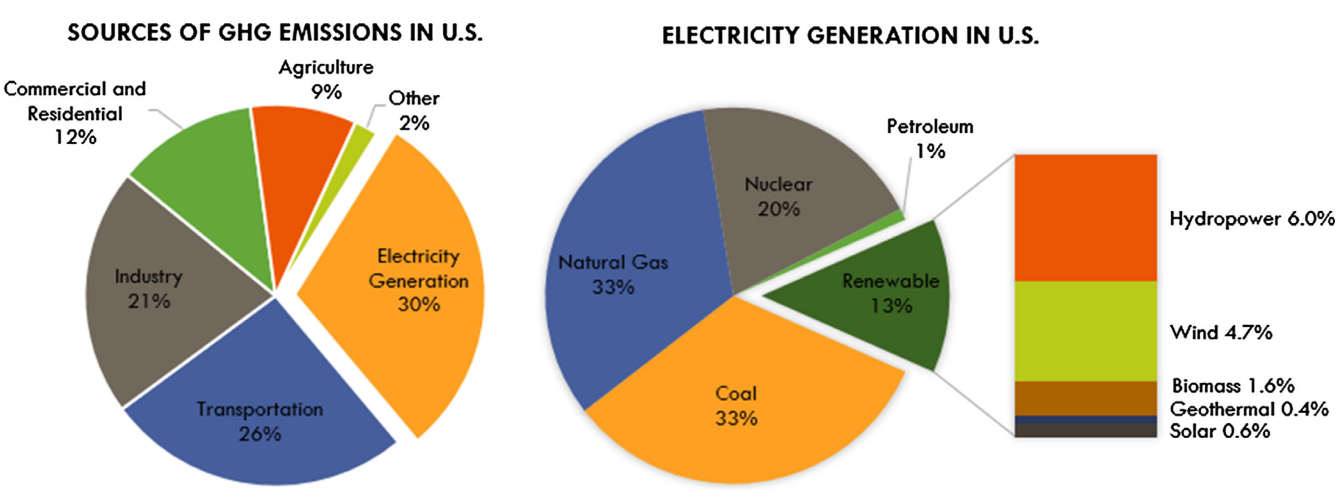

Fig. 1. Sources of Greenhouse Gas Emissions and Electricity Generation. *Source:* EIA [8]