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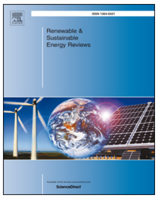

A decision-making model for the analysis of offshore wind farm projects under climate uncertainties: A case study of South Korea

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ABSTRACT

Wind power supplies clean energy, but it is vulnerable to climate change. As the impacts of climate change increase, economic assessment methods of wind power projects are required to capture climate uncertainties. The study proposes a decision-making model to analyze the economic feasibility of offshore wind farm projects considering the impacts of climate change using real options analysis (ROA). The model can consider project volatility using the wind speed projected from climate scenarios that affect wind power production. A case study of an offshore wind farm in South Korea was conducted to confirm the validity of the proposed model. The case study proved that the managerial flexibility provided by the proposed real options effectively reduces risks and increases the long-term profitability of offshore wind farm projects.

1. Introduction

Wind power produces renewable electricity using wind resources [1]. Wind resources are abundant and evenly distributed in nature, and they are not depleted, unlike oil and coal [2]. Wind power is the first renewable energy source to have achieved grid parity [3]. Wind power facilities with generation capacity of 433 GW (gigawatts) were installed by 2015, accounting for 3.7% of the world's electricity consumption [4]. Globally, US$ 109.6 billion was invested in newly installed wind power in 2015, accounting for 38.3% of the total investment in renewable energy in 2015 [4]. Wind power is divided into onshore and offshore wind power based on the location of the facility. The capacity of offshore wind power facilities installed in 2015 was approximately double the capacity of those installed in 2014 [4]. The construction cost of offshore wind power, which was high compared to that of onshore wind power, has been drastically lowered because of the development of new technology [5].

Renewable energy sources, such as offshore winds, are generally associated with high uncertainty. As climate uncertainty increases, it becomes increasingly difficult to predict the amount of wind power production. In order to assess the economic feasibility of wind power project, it is very important to estimate the production amount. The discounted cash flow (DCF) method has been used as a major tool to understand the economic feasibility of energy projects. However, in this method, it is difficult to reflect the managerial flexibility that can be exercised considering the uncertainties in the business environment [6]. This study aimed to develop a model that can analyze the economic feasibility of offshore wind farm projects considering future climate change impacts. Because the impacts of climate change have increased worldwide, this study should not rely on past climate information [7]. The proposed model uses climate scenarios to quantify climate uncertainties and estimate the profit from a given investment. Using the proposed model, investors can decide whether they want to expand their investment, continue at the same level, or abandon it depending on the specific climate situation using ROA. Decision makers can establish the most appropriate strategy for an offshore wind farm project considering climate change using the proposed model. The remainder of this paper is organized as follows. Section 2 presents a review of past related studies on the impacts of climate change on wind power projects, methodologies for investment decisions, and ROA. Section 3 presents the proposed model methodology, while Section 4 shows how the model was validated through a case study of a 99.2 MW offshore wind farm in South Korea. Section 5 discusses the results of the case study and derives the implications. Finally, Section 6 summarizes the research and presents conclusions, including the contributions of this study.

2. Literature review

Wind power production is heavily influenced by climate factors [8].

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An increase in the uncertainty associated with the supply of wind resources makes it difficult to predict wind power production. Depending on the region, climate change causes changes in annual wind volume and affects wind quality [9]. Based on the climate scenarios, climate change alters wind density and speed [10]. Wind power production is mainly determined by wind speed [11]. Fluctuations in wind speed make it difficult to determine the investment feasibility of projects.

Efforts have been made to accurately estimate the feasibility of wind farms in different regions of the world. Satir et al. [12] proposed a methodology to determine the feasibility of a wind energy project in Turkey based on the historical data of the Aegean Sea. Barroso and Iniesta [13] estimated the annual electricity production of a wind power project in Germany using the past monthly data of wind speed. Pryor and Barthelmie [14] claimed that wind energy would be a sustainable source of renewable energy even with climate change in Northern Europe. Using three years of wind speed data, Shoaib et al. [15] showed that a wind farm in Baburband, Pakistan, was economically feasible at 80-m mast height.

Recently, climate scenarios have been used for studies on the economic analysis of wind power projects. Davy et al. [10] predicted wind resources by estimating future wind speeds in Europe to analyze the economics of wind energy projects under regional climate scenarios. Koletsis et al. [11] estimated the potential production of offshore wind power in the Mediterranean Sea and the Black Sea using regional climate scenarios. Ruffato-Ferreira et al. [16] found that the use of wind speed information from climate scenarios facilitated the prediction of wind power production in a Brazilian case study.

In general, economic analysis for investment decisions in the wind power business is performed using a traditional economic analysis method called DCF, which is represented by the net present value (NPV) and the internal rate of return (IRR) [17]. This method is the most widely used economic analysis tool for various investment projects but not for projects with high volatility and uncertainty [6]. In particular, the traditional methods are inappropriate for evaluating renewable energy projects that are highly affected by climate uncertainty [18]. ROA, which can consider climate uncertainty, can be a better tool for the feasibility analysis of renewable energy investments [19,20]. Martinez-Cesena and Mutale [21] argued that the uncertainty of wind power projects could be assessed using ROA.

This study provides a decision-making model using ROA. Option values are calculated by a binomial lattice approach. Two option pricing approaches are widely employed: (1) the Black–Scholes approach and (2) the binomial lattice approach. The Black–Scholes approach analyzes the option values using a partial differential equation with the assumption of European options that are only exercised at the proposed time of the project period [22]. However, the ROA in infrastructure projects has mostly the American options that can be excised at any time during the project period. The binomial lattice approach is mostly used for real options pricing, as it allows easy calculation and visual interpretation, applicability of any type of option, and decision-making at any time during the project period [23]. The binomial lattice approach assumes that an underlying asset rises or falls and can be applicable under various cases, so it can be applied to both European and American options [24]. The case study of an offshore wind farm project has the American option. Thus, it is also reasonable to use the binomial lattice approach for the ROA of the case study.

ROA has been used for understanding the economic feasibility of a single wind power project. Loncar et al. [3] applied a compound option model to a wind power project in Serbia. Abadie and Chamorro [25] developed an ROA model for investment in a wind farm in the UK considering future electricity markets. Lee [26] proved the effectiveness of the ROA in the case of a Taiwan-based wind power project using the Black–Scholes option pricing model. Considering wind power generation costs, government subsidies, and volatility in power production, Reuter et al. [27] presented an ROA model for wind power investment with hydro-pumping storage in Germany and Norway. Kim et al. [28] proposed a compound options model to evaluate a wind power project considering the optimal investment time under uncertain energy markets in South Korea.

The effects of wind energy policies were studied to promote the investment in wind power projects. Venetsanos et al. [29] developed an ROA framework for supporting investment decisions in wind energy projects after the deregulation of the Greek electricity market. Yang et al. [30] proposed a Clean Development Mechanism policy based on the ROA of wind power projects in China. Boomsma et al. [31] used ROA to suggest a government subsidy policy in Norway for encouraging wind power projects. Kitzing et al. [32] developed an ROA model to determine the size and timing of a wind power project considering different support policies in Denmark.

Previous studies have widened the application of ROA to wind power projects. However, there is a lack of applicable methodologies that consider the impacts of climate change on wind power projects. Thus, this study proposes an ROA model applicable to wind power projects. In order to minimize the impacts of climate change, this study applies real options to wind farm projects using future climate scenarios.

3. Methods

3.1. Decision-making model for offshore wind farms

The cost of constructing an onshore wind power plant is lower than that of an offshore plant, but onshore plants have the disadvantages of noise generation and unstable wind direction and speed [33]. Offshore wind power plants generate more stable wind power than onshore wind power plants, but their installation costs are high and connecting such plants to the electricity grid is expensive [33]. To lower cost, economies of scale with offshore wind power must be achieved. Thus, it would be desirable to have, for example, an expansion option so that the project could be expanded later if the business environment is positive. This study proposes a decision-making model for investment in offshore wind farm projects using real options. With this model, investors can retain and exercise such options to avoid risks arising from uncertainties in long-term projects and preserve or enhance the project value [34]. The model proposed herein comprises three steps: 1) analyzing the impacts of climate change on offshore wind power projects, 2) forecasting wind energy production based on climate scenarios, and 3) calculating the option value and determining investment strategies (Fig. 1). A detailed description of each step is given in the next section.

3.2. Impacts of climate change on energy production

Climate scenarios are often used to assess the economic feasibility of projects that consider the impacts of climate factors [20]. This study uses the Representative Concentration Pathways (RCPs) climate scenarios published by the Intergovernmental Panel on Climate Change (IPCC) in 2014 [35]. The RCP scenarios simulate the degree of climate change in the future based on the changes in CO_2 emissions and comprise four different scenarios (RCP8.5/6.0/4.5/2.6). RCP2.6 is a climate change scenario that remains at pre-industrial global warming levels, RCP8.5 is a climate scenario that would occur if no efforts are made to reduce greenhouse emissions, and RCP4.5 and RCP6.0 are intermediate climate scenarios [35]. Future wind power production is estimated using time-series wind speed data simulated using both RCP2.6 and RCP8.5. The impact of climate change is the highest under RCP8.5 and the lowest under RCP2.6.

Offshore wind power projects that use wind resources to produce energy are vulnerable to climate change impacts. Wind speed is the most important climate uncertainty factor that determines wind power production [3]. The amount of wind power production P_{wind} is determined using Eq. (1) [11,17]: