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Optimizing capacity investment on renewable energy source supply chain

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ABSTRACT

In China, power producers sell renewable energy to consumers through the power market, and have formed a multi-echelon renewable energy source power supply chain (RESPSC). This paper studies decisions on capacity investment for power producers facing a location problem in this dual-echelon RESPSC. We assume that demand and supply are uncertain, while the grid-connected power price is fixed. The problem can be modeled as a Stackelberg game from the perspective of RESPSC. We also analyze the impact of intermittence on profit distribution and risk sharing. From a comparison between centralized vs decentralized capacity investment decisions, we find that site candidates with higher market value should be given priority to invest under centralized decisions, while candidates with lower equivalent cost should be invested in first under conditions of a decentralized decision. The results suggest that RESPSC can be coordinated only if the profit share of the producer is zero, since the revenue share of the vendor decreases as investment increases. Meanwhile, because the intermittent supply of renewable energy affects the cost incurred by producers and the price given by vendors, respectively, power producers and vendors will evaluate the sites in different ways to maximize their own benefits. If disagreements regarding site quality arise between producers and vendors, RESPSC will no longer be effective under decentralized decisions.

1. Introduction

In the 21st century, ensuring energy safety and environmental protection have become global problems. Renewable energy plays an important role in relieving the tension between energy supply and demand. Governments in many countries have formulated series of policies, such as subsidies and fixed power prices, to stimulate the sustainable development of renewable energy. In China, renewable energy is also growing at rapid speeds. According a report by Chinese Wind Energy Association, since 2005, the scale of the wind power industry has doubled every year. Although China has become a global leader in wind power and solar power, problems still exist in relation to the policy of fixed power prices, which limits the application of renewable energy (Ehrenmann & Yves, 2011). The power generated by renewable energy source is still little in China because it is difficult for energy to be supplied through a grid to achieve high efficiency in operation (Wang, Yin, & Li, 2010). Therefore, the capacity of renewable energy power plants needs to be planned carefully to balance the profit of members in the supply chain.

Pricing mechanisms and related policies, such as price intervention, have focused on closing the gap between the cost of renewable energy vs. fossil energy (Martinot, 2010). However, renewable energy is characterized by the property of intermittence because of limitations pertaining to weather conditions (Chao, 2011). The duration of power generation is not only limited, but unstable and uncontrollable (Ma & Zhao, 2015). Based on a study of the relationship between intermittence and the price of wind power, Ketterer (2014) concludes that wind power decreases the power price but also makes it flexible. The present paper introduces the property of intermittence of renewable energy sources to the power capacity investment model, and analyzes the impact of intermittence on renewable energy power cost and market price under various transaction models. We also study the optimization of capacity decisions in relation to renewable energy sources.

1.1. Related literature

Current literature on renewable energy sources reveals that the generation of renewable energy reduces spot power prices in the

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environment of a perfect competitive power market because the replacement of traditional fossil power with renewable energy reduces expensive fuel costs (Sensfub, Ragwitz, & Genoese, 2008; Woo, Horowitz, Moore, & Pacheco, 2011). However, the property of intermittence raises the variance of spot power prices at the same time (Chao, 2011; Milstein & Tishler, 2011). The cost structure of renewable energy also significantly differs from that of regular energy. For renewable energy, capital cost dominates total cost because no fuel input is needed. The marginal cost is also so low that can be ignored. Therefore, variability in the production cost of renewable energy power is very low (Arthur, 2015). The economic efficiency of renewable energy development is decided by the capital cost and capacity coefficient (Nishio & Asano, 2006). Cory and Schwabe (2009) also point out that the cost of renewable energy power varies in different geographical areas. Chang-Chien and Yin (2009) calculate the cost of wind power in different environments and find that the installation cost and power generation capacity coefficient significantly affects the power cost. Their study also indicates that focused research and operation experience reduces installation cost. In large-scale development period, if power suppliers are allowed to make decisions on capacity and production according to power market demand signals by themselves, the grid connecting cost can be reduced (Hiroux & Saguan, 2010; Klessmann, Nabe, & Burges, 2008). Olsina, Röscher, Larisson, and Garcés (2007) conclude that if each wind farm is kept independent, the law of diminishing marginal profit is tenable.

Power capacity has been studied widely in the power industry, but few studies focus on renewable energy power capacity. Tishler, Milstein, and Chi-Keung (2008) evaluate a situation in which price fluctuation is allowed, while Cory and Schwabe (2009) argues that the property of randomness and lack of schedulability is similar to that of regular power demand. Cory models renewable energy as negative demand. Miah, Ahmed, and Chowdhury (2012) introduce the concept of permeability (the ratio of renewable energy in the power market), treating initial and final permeability as exogenous parameters and discussing how to increase renewable energy's permeability at the lowest cost using dynamic programming. All of the above studies assume that renewable energy's output is stable, and thus fail to consider its intermittence. Compared to regular energy, the cost and metric value of renewable energy differ. Therefore, a traditional power capacity model is not suitable for renewable energy power capacity planning (Munoz, Oschmann, & Tabara, 2007).

In general, for countries in which marketing reform for the power industry is still ongoing, there is neither a well-established daytime power market nor a set of market regulations for spot power prices. Power is usually traded through bilateral transactions (Trainer, 2010). In a perfect competitive market, power's real-time balance between supply and demand relies on the adjustment of real-time fluctuations in the power price. When a market mechanism is introduced to elevate competition in the power market, the market structure must be designed carefully (Ma & Zhao, 2015). Whatever the structure of the market, renewable energy is characterized by a lack of schedulability (Green, 2008; Henriot, 2015). Although it is technically possible to store renewable energy in batteries for later use, the current energy storage technology is rarely cost effective. Therefore, the techniques of power transmission and storage also limit the application of renewable energy (Hu, Gilvan, Souza, & Wang, 2015; Erol-Kantarci and Mouftah, 2015). This is why a balance between renewable energy power generation and power demand is necessary (Reichelstein & Sahoo, 2015). Nowadays, power producers usually invest multiple sites to minimize the risk of power shortage which is caused by the uncertainty in supply. Thus it leads to a multi-site production networks tendency. Furthermore, to solve the problem of uncertainty, a collaborative supply chain can be formed as a possible way to improve supply chain performance (Chong & Zhou, 2014).

A large literature studies the collaborative supply chain in uncertain scenario. Angerhofer and Angelides (2006) model the constituents of a collaborative supply chain and find the appropriate performance measures in a decision support environment. Their results pinpoint areas where the supply chain can be improved and hence manage the chain's performance. In today's unstable business environment, companies should collaborate to achieve mutual goals and competitive advantage. Defining relationship commitment and collaboration in supply chains (from social exchange theory point of view) is the basis of the research. The aim is to examine the influence of relationship commitment on collaboration in supply chains (Kac, Gorenak, & Potočan, 2015). However, most of the research focuses on the industrial and agricultural supply chain. The output of industrial supply chain is more controllable compared with RESPSC. Since the product is usually storable, uncertainty can be summarized as a problem of uncertain time of delivery. Other researchers study the collaborative capacity investment with uncertainty. Ojala and Hallikas (2006) address the problems of investment decisions of the network companies by discussing how some important factors like openness, trust, power, and dependence affect the financial decisions of subcontractor in a network environment. Risks are mainly related to the increased responsibilities for suppliers and reliability of information when enterprises handle their partnership relationships. Meisel (2012) provides modeling and decision support methods for supplier selection and supplier development in dynamic markets. Supplier development comprises the selection and scheduling of development projects in the course of time. Development projects are joint activities of a buying company and a supplier that require spending resources (investments). The successful realization of this project improves the production capacity of the supplier and reduces the procurement cost. In a single-vendor single-buyer supply chain with centralized coordination in the presence of an uncertain investment opportunity, Marchi, Ries, Zanoni, and Glock (2016) present a joint economic lot size model that allows investments financed cooperatively by the members of the supply chain. In particular, they assume that the vendor has an option to invest on promoting production rate. The outcome of these attempts is uncertain and follows an investment success probability. They find that if the vendor and the buyer share the investment and the outcome uncertainty, the benefits of both parties increase. Liu, Zeng, and Zhao (2014) apply option pricing and model cooperative investment decisions under uncertainty using the Black–Scholes (BS) model. They also compare their results with the net present value (NPV) approach. Their results show several institutional characteristics such as size, financial power and IT capability affect how institutions make cooperative decisions in community source development. Different from industrial supply chain, RESPSC is affected by natural conditions. In industrial and agricultural supply chain, practitioners balance the demand and supply of the supply chain by different combinations of products. However, such method is not able to work in RESPSC. The long-term investment cycle and the property of intermittence caused by the natural conditions limit the efficiency of production scheduling in RESPSC. In this paper, we try to deal with uncertainty using multi-site capacity investment, which is efficient for RESPSC.

1.2. Contributions

As discussed above, extant literature does not study renewable energy power from the perspective of the supply chain. In comparison, our study supports policy makers in two respects. First, our