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Long-term renewable energy technology valuation using system dynamics and Monte Carlo simulation: Photovoltaic technology case

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ABSTRACT

A new long-term technology valuation method for renewable energy technologies that combines system dynamics with Monte Carlo simulation is proposed. Existing valuation methods using surveys or cash flows are suitable for technologies characterized by short lifecycles and little uncertainty, but are not appropriate for renewable energy technologies affected by various uncertainties over the long term. A variety of macro- and micro-factors interact in sophisticated ways, create uncertainty, and make valuation difficult. System dynamics provides a good method of structuring these complex interactions. Monte Carlo simulation can consider long-term uncertainties in valuation. Using the advantages of both methods, our method can improve not only the long-term reliability of probabilistic technology valuation but also R&D decisions and investments on both the private and public sides. Korean photovoltaic power generation, a representative renewable technology, is used as an example.

1. Introduction

Driven by climate change and fossil fuel depletion, an international consensus was made on the necessity of global energy transition from fossil fuels to renewable energy sources. Over the last several decades, this agreement has been made more explicit through a series of international treaties including the United Nations Framework Convention on Climate Change (1992), the Kyoto Protocol (2005), the Copenhagen Accord (2009), and the Cancun Agreements (2010). In particular, countries which depend heavily on foreign fossil fuels have shown positive attitudes toward renewable energy.

Of the various renewable energy sources, solar PV (photovoltaic) energy has been a center of focus. The PV market size was 16.8 GW in 2010, occupying 8% of the overall renewable energy market. Since 1997, its growth rate has been the fastest, reaching 45% between 2003 and 2009 [1]. However, against expectations, its diffusion has been limited due to high costs. The PV market cannot grow without national incentive policies. As the world economy heads into a low growth phase, the PV market has been struggling due to reduced national incentives. Doubts have been cast on the possibility of making PV costs comparable to other electricity generating technologies. That is why many companies and governments are interested in efficiency, cost, and valuation of PV.

Among several renewable energy valuation methods, the CVM (contingent valuation method) and DCF (discounted cash flow) have been widely used. CVM has been applied mainly to public energy resources using WTP (willingness-to-pay) [2,3]. People are asked through a survey how much money they would be willing to pay for new energy resources, and the WTP is converted into a monetary value. Focusing on the economic value, DCF estimates and sums up all expected future cash flows to judge whether this energy project or technology is profitable or not. Both are suitable for short term valuation with little uncertainty, but are not appropriate for renewable energy technologies affected by severe uncertainties over the long term. Moreover, various factors including corporate R&D investment, government policy, and international regulation interact in sophisticated ways, create severe uncertainty, and make the above-mentioned methods inappropriate.

As an alternative, the real option method has been suggested. Davis and Owens (2003) applied both real option and DCF to renewable energy technologies. They concluded that DCF is bad at valuing renewable energy technologies without considering various uncertainties such as oil price volatility [4]. Researchers have tried to develop improved real option methods, including the binomial lattice model [5] and the dynamic programming model [6,7]. The real option methods reflect various factors and their uncertainties in valuation, but cannot consider their interactions.

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Despite the limitations of these methods, there has been little effort to suggest a new long-term valuation method for renewable energy technologies.

Tackling this issue, we present a new probabilistic valuation method for renewable energy technologies over the long-term. SD (system dynamics) enables us to reflect various factors, uncertainties, and their interactions in valuation. Monte Carlo simulation overcomes the limitations of deterministic DCF, and makes probabilistic valuation possible with due regard to the volatility of relevant factors. Taking advantage of both methods, our method can improve valuation accuracy. As an illustrative example, we make a valuation of Korea's PV technology.

2. Industrial background

The PV industry value chain starts from polysilicon production through the production of wafers, ingots, cells, and modules, to overall system integration. Wafers and ingots are made of polysilicon. Cells are made from bulk materials that are cut into wafers through processes like those used for semiconductors, and then are electrically connected and encapsulated as a module. A PV system is made up of modules and other electrical components. Modules are the basic units of cost and efficiency, representing about 55% of total PV system cost [8]. The PV module cost is the highest.

Driven by governmental support that reduces the cost burden, the global PV market has grown rapidly since the late 1990s. Germany and Italy boosted this growth, occupying more than 80% of the overall demand by 2009. In the late 2000s, the US, China, and Japan entered the PV market, accelerating its growth. The global PV market is expected to grow by more than 18% annually over the next five years, and to reach up to 77 GW by 2016 [1]. Put simply, the PV market has been, and will be, a fast growing market.

Obviously, government policy has been a key driver in accelerating PV investment and market growth. There are three types of policies, comprising FIT (feed-in tariff), RPS (renewable portfolio standard), and subsidy. Under FIT, government pays a cost-based price for renewable electricity. RPS forces suppliers to deliver a fixed portion of their electricity to consumers from renewable energy sources. Or, government can simply directly give companies subsidies to pay for their PV system installation.

A number of studies have investigated the effectiveness and efficiency of these policies. Some studies have supported FIT based on the fast diffusion of PV systems in Germany and Italy [9–11]. Taking a step further, recent studies have proposed an effective method of implementing FIT called the optimum pricing scheme [12]. Recently, researchers have paid more attention to subsidies. Dusonchet and Telaretti (2010) studied Belgian PV system subsidies [13]. Talavera et al. (2010) analyzed the economics of subsidies using the internal rate of return and sensitivity analysis [14]. Chiung-Wen Hsu (2012) compared FIT with subsidies in terms of economic benefits [15]. Commonly, they suggested country-specific optimal policies, implying that there is no single best policy for several countries. In other words, renewable energy policy should be customized to country-specific characteristics which include technological capability, the government's financial conditions, and others [16].

Driven by government policies, many companies have made huge PV investments, and have been expanding PV production capacity to create competitive advantage by achieving economy of scale. They expected that the PV price would decline rapidly as production capacity increased. However, the price has not fallen as expected, creating some doubts about the policies that have been implemented. Slowing global economic growth amplifies doubts, and forces some governments to change renewable energy policies. European countries have kept the FIT, but reduced it by more than 10% due to increasing fiscal burden. Many countries under severe budget constraints have made a shift from FIT to RPS. To facilitate PV diffusion, some countries introduce FIT in part, while maintaining RPS.

Overall, the PV industry faces two risks. The primary risk comes from the PV cost per unit of electricity, which is higher than that of other fossil fuel technologies. The relatively high cost results in reduced PV adoption. Lower levels of adoption will lead to less PV investment, which will delay PV technology advances as well as cost reduction. Once this vicious cycle is in place, many private companies might withdraw from the PV industry. In addition, policy incentives for renewable energies, such as FIT and direct subsidies, will be further reduced in some countries, encouraging private companies to enter the cycle. Without considering these risks, governments and private companies might have large PV investment losses. Thus, considering key factors and risks including cost, R&D investment, and policy, they should evaluate PV technology more accurately to make better R&D investment decisions.

3. Methodology

3.1. Research framework

Long-term renewable energy technology valuation must consider 1) circular causalities among various internal and external variables, 2) long-term dynamic uncertainties and their influences, and 3) probabilistic valuation. However, as noted above, deterministic valuation methods including DCF and CVM cannot meet any of these requirements. Real option methods cannot meet the first requirement. SD was developed to analyze the dynamics of complex systems characterized by circular causality and severe uncertainty, and thus is the most appropriate method to meet the first and second requirements. Monte Carlo simulation is a widely-used method for investigating uncertainties in a probabilistic way, therefore satisfying the second and third requirements. Thus, combining SD with Monte Carlo simulation, we can develop a long-term technology valuation method to meet the three key requirements.

Hagenson (1990) suggests that a combination of SD and Monte Carlo simulation could be a useful tool for recognizing potential risks, but did not quantify the risks [17]. Taking a step further, Dhawan (2005) conducted a series of controlled experiments to test the effects of deterministic SD, SD with sensitivity analysis, and probabilistic SD [18]. Probabilistic SD models represent the true behavior of a complex system better than the other two techniques. In particular, SD with Monte Carlo simulation has been tested in some previous studies, providing some evidence of usefulness in investigating uncertainties [19,20]. Using SD as a basis model, SD with Monte Carlo simulation is the most appropriate method to analyze the dynamic uncertainties of a complex system.

Our method has three modules comprising 1) a basic technology valuation model with internal factors, 2) a model of the causal relationships between external factors, and 3) an integrated probabilistic valuation model. Note that the PV cost per unit of electricity is important to companies. Thus, our method values a technology by the actual costs incurred in creating a PV module. The cost can be reduced both by learning effects and technological innovation. The two-factor learning curve is appropriate for reflecting the influence of these internal factors. SD can represent various external factors and casual relationships. In this way, we can reflect complex interactions among the internal and external variables in technology valuation. However, the method is deterministic. Monte Carlo simulation makes valuation probabilistic, effectively dealing with long-term uncertainties. Objectives, key processes, and methods are as shown in Table 1.