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Economic analysis of a residential PV system from the timing perspective: A real option model

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ABSTRACT

This paper proposes a new model for determining optimal investment time for residential photovoltaic (PV) power systems. The model explicitly incorporates the cost uncertainty of the PV system and a resident's option to defer investment, using a real option model. The paper provides theoretical analysis as well as case studies. Using the real option model, we show that the optimal investment threshold decreases in case of volatility increase, mean-drift decrease and benefit decrease. A sensitivity analysis using different PV sizes illustrates that the optimal waiting time for substantial PV diffusion to smaller PV systems is longer than that of larger systems. The paper also investigates the expected investment times in the United States, Germany, Japan, and Korea and shows that all countries except Germany need to wait to invest. Moreover, a comparison study to the net present value (NPV) method demonstrates that PV system investment can be additionally delayed by 5.76–11.01 years.

1. Introduction

Recently there has been a surge in the deployment of photovoltaic (PV) systems, and this trend is expected to accelerate with the continuing decline in PV module cost [1]. A report by the National Renewable Energy Laboratory (NREL) shows that the rooftop PV in California could generate up to 74% of the electricity demand provided by their utilities in 2013 [2]. Even Washington State which has the lowest PV potential in the United States (US) might be able to generate 27% of their demand [2]. Also, for sustainability, society and the government should take steps to tap renewable energies such as solar, wind, and bio-mass. The United Nations Framework Convention on Climate Change (UNFCCC) agreement in Paris compelled many nations to adopt renewable energy technologies. Governments adopt different policies such as Renewable energy Portfolio Standard (RPS), Feed-in-Tariff (FIT), subsidies, and tax credits to promote PV adoption.

However, some studies show that the PV diffusion is slow because of the cost, particularly for residential PV systems. NREL analyzed the US photovoltaic price by breaking down the component cost [3]. At the residential level, the PV cost is a barrier to proliferation of PV systems. Another study analyzed the cost-effectiveness of PV over different consumer market segments and concluded that cost-effectiveness is the major obstacle to expansion, especially for residential segment with small size PVs [4]. Besides, the empirical research in Ref. [5] shows that the cost of residential PV systems in the US is almost twice of the cost in Germany. Therefore, in this paper, we evaluate the economic feasibility of the residential PV system investment.

In the economic analysis, one of the main challenges is the uncertainty of the cost of a residential PV system. Lawrence Berkeley National Laboratory (LBNL) reports high variation in the cost of PV system [6]. The economic feasibility of PV has been investigated by using the levelized cost of electricity (LCOE) in Refs. [7–9]. However, these studies did not explicitly include uncertainty in their model or perform sensitivity analysis of the uncertain factor. Furthermore, the economic literature has shown that the uncertainty can change decision making, especially when the investor has the option to invest later [10]. Here, note that PV investment is optional to a resident who already uses electricity from an existing grid. Thus, this paper investigates how uncertainty and this option can affect the investment decision for a residential PV system. For theoretical and empirical analyses, we apply a real option valuation (ROV) method to incorporate cost uncertainty and the option to delay. We then compare it with the traditional net present value (NPV) method which is widely used in economic analysis and does

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not include the resident's option. In addition, the proposed model estimates the optimal time to invest, which is not easy to obtain using the NPV method.

In order to design appropriate policies and manage investment, a policy-maker, an investor, or a resident may want to know when PV adoption could become substantially active or when it would be good to invest, rather than whether the current condition is good or not. Using our real option model to consider uncertainty and the resident's option, we show that it could take −0.28–45.83 years depending on the country. Interestingly, our results show that the NPV method indicates that in most countries, now is a good time to invest in a residential PV system. Furthermore, the gap between the two methods' investment timings does not seem to be small, which is ranging from 5.76 to 11.01 years. This warns that the NPV method may underestimate the economic value of a residential PV system and thus lead to PV adoption earlier than optimal. Likewise, throughout our real option model study, we investigate how the expected time to substantial PV diffusion might change depending on the countries, PV size, and characteristics of uncertainty such as volatility and mean-drift.

This paper is structured as follows. Section 2 reviews literature of the economic analysis of PV investment and the real option theory. Section 3 develops a novel real option model for residential PV system investment. Section 4 quantifies the characteristics of uncertainty using the data of different sizes of PVs and different countries. from the section further uses the proposed model to conduct simulation and analyses examine how investment decisions change due to uncertainty, option and other important environments. Also, for each scenario, we provide the expected time to substantial PV diffusion. Section 5 discusses the limitations of our model and analyses and suggests further research directions. Section 6 summarizes the major results and provides managerial implications.

2. Literature and methodology

Several studies on the economic valuation of renewable energy are reviewed in Ref. [7]. Most of these studies do not explicitly consider uncertainty, while some of them conduct sensitivity analyses of important input parameters. As pointed out in Ref. [11], the cost of a PV system shows significant variation, with the standard deviations of 5%–8% which could be due to the wide range of labor rates, installer productivity and so on. The cost of PV system components fluctuates over time as well. Moreover, from Ref. [12], the LCOE metrics widely used in the PV industry can be misleading and should be applied with caution. In this respect, several papers have studied the uncertainty in LCOE. They estimated the LCOE using a probabilistic distribution instead of just a single number for a parameter [13,14].

However, when the investor has the option to invest now or later, this uncertainty can affect the investor's decision making. This is the case for the investment in residential PV systems too; a resident may opt for a PV system, but does not necessarily have to invest right now, and can wait until the PV system becomes cheaper. Because losing the option to wait exposes the resident to the potential loss of money [15,16], it is common in financial economics not to invest until the net profits compensates the loss of the "value of waiting" [17]. In contrast, a traditional investment evaluation method, such as the NPV method, does not capture the loss of the value of waiting. Therefore, many scholars have proposed the so-called real option valuation model to quantify the decision flexibility under uncertainty ([18–21]). The economic analysis literature has shown that ROV is more appropriate for model valuation of a project under uncertainty [18,21,22]. Also, the existence of opportunity costs has been shown to influence decision-making behavior [10]. For this reason, some recent works [23–28] in the energy area have suggested the use of this new approach, ROV. Nevertheless, a real option model for residential PV system investment is yet to gain attention.

Another advantage of the real option model is its ability to capture the optimal investment timing. Conventional investment decision making methods do not focus on the optimal time to invest, but rather focus on whether or not the project is economically feasible at the time of decision making. While existing methods try to decide between yes and no, the ROV method estimates the optimal time to invest. For example, suppose that a resident considering a PV system investment first estimates the benefits and costs and then calculates the NPV, discounting the future cash flows. Under the traditional NPV method, the resident would give up the project if the NPV of the project is less than 0. In contrast, under the ROV method, the resident can determine the time to invest and will compute the investment values for every future time before choosing the most profitable time. Thus, the real option method, while considering the resident's behavior, helps in estimating the optimal time to invest.

Some recent studies have adopted the ROV method for renewable energy projects. For example, the ROV method was applied to a mini-hydro power plant project in Ref. [26], and it showed that the project value given by the real option method was higher than that given by the NPV method [29]. A similar real option analysis of another mini-hydro power in Ref. [30] showed the necessity of using the ROV method. In Ref. [31], a real option analysis of hydrogen storage for a wind park in Germany, while considering decision flexibility, finds that the storage is unprofitable if it is used for electrical energy. In Refs. [32,33], when the investor's option and uncertainty are embedded in the evaluation of renewable wind energy investment, the volatility of uncertainty, risk-free rate, and time-to-maturity are shown to influence the investment decision in Taiwan. In Ref. [34], a real option model is applied to estimate the implicitly embedded values of a regulation for several countries. The paper provides a comparative study regarding the public incentives for wind power energy in Finland, Denmark, and Portugal within the regulatory framework, and shows that the implicit option values for the countries could be different. However, some critiques of previous real options research in energy system have recommended more practical and physical assumptions to reflect reality [35]. Thus, more recent paper have attempted to cover more complicated options in the evaluation of renewable energy projects [36]. The model incorporates stepwise investment, such as invest, expand, repower, contract, and abandon, and applies Monte Carlo simulation. Moreover, by utilizing the advantage of a real option model incorporating the decision flexibility of an investor, a study [37] developed a model for R&D public financing on renewable energy and to estimate an appropriate grant level that compensates the loss of decision flexibility from the company's perspective, which cannot be developed with a traditional NPV.

However, only a few papers have discussed the application to a PV system, as mentioned in Ref. [38]. In particular, the economic analysis of residential PV systems, the focus of this paper, has been rarely studied. In Ref. [39], a real option model is developed to show how an investor can evaluate feed-in-tariff (FIT) in the presence of uncertain fossil fuel prices. Another study [40] focusing on the policy for PV power systems and their real option model shows that under the current level of subsidy, the government might encounter a loss, unlike an investor, and this could lead to an unbalance of interest. The study also points out that the real option model is more efficient than a traditional method. A case study in Ref. [38] provides some implications of a real option model from the timing perspective. For example, when carbon emission is considered in China, the optimal investment timing could become