Applied Energy 142 (2015) 33–43

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Optimal subsidy estimation method using system dynamics and the real option model: Photovoltaic technology case

Chanwoong Jeon [a], Jeongjin Lee [b], Juneseuk Shin [c,*]

[a] Graduate School of Management of Technology, Sungkyunkwan University, 2066, Seobu-Ro, Jangan-gu, Suwon, Gyeonggi-do 440-746, Republic of Korea
[b] School of Computer Science & Engineering, Soongsil University, 369 Sangdo-Ro, Dongjak-Gu, Seoul 156-743, Republic of Korea
[c] Department of Systems Management Engineering, Sungkyunkwan University, 2066, Seobu-Ro, Jangan-gu, Suwon, Gyeonggi-do 440-746, Republic of Korea

HIGHLIGHTS

- We propose a method of estimating optimal financial subsidy and public R&D investment.
- System dynamics is used to analyze a complex system of energy subsidies.
- Appropriate real option valuation models are matched and used to estimate optimal subsidies.
- Our approach can reduce the total Korean photovoltaic subsidy by $US 359.5 million.

ARTICLE INFO

Article history:
Received 21 May 2014
Received in revised form 20 November 2014
Accepted 27 December 2014
Available online 12 January 2015

Keywords:
Optimization
Subsidy
System dynamics
Real option
Photovoltaic

ABSTRACT

In this paper, we propose a method of optimizing financial subsidies and public research and development investments for renewable energy technologies, rather than optimizing financial subsidy alone. By combining system dynamics with real option models, we capture dynamic complex interactions among investors, consumers, and policymakers, as well as future uncertainties of key energy, economic, and environmental factors. Our method thereby makes subsidy optimization more accurate and flexible. To evaluate our model, we apply it to the Korean photovoltaic subsidy and determine that the government can achieve the photovoltaic diffusion target, even if it reduces the total subsidy by $US 359.5 million. The optimal approach is to increase research and development funding by $US 310.4 million while reducing the financial subsidy by $US 669.9 million. Our method helps policymakers optimize their subsidy allocation and therefore reduces subsidy inefficiencies.

1. Introduction

Public subsidies have been primary policy instruments for spurring adoption and progress of renewable energy technologies. Global renewable energy subsidies have been steadily increasing; in 2011, they reached US $88 billion [1]. Since 2000, renewable energy technologies have received higher subsidies for electricity generated than fossil fuels or nuclear energy [2]. Through these generous subsidies, several countries, including Germany, the United States, China, and Japan, have increased electricity production from renewable technologies [3,4].

There are several reasons why renewable energy technologies have been subsidy-driven. Given the risk of environmental degradation and energy insecurity, unsustainable technologies must be replaced [5]. However, renewable energy technologies require more than a decade to attain grid parity [6]. Moreover, an individual firm does not expect positive externalities from a learning-by-doing approach, which therefore constrains investments in renewable technologies [5]. Thus, a market failure will occur with investments below the socially optimal level [7]. Finally, lock-in effects and incentives to continue exploiting the existing energy infrastructure hinder efforts to replace legacy energy technologies [8]. Without some policy rents, such as subsidies, renewable energy technologies must be developed and adopted far slower than is socially needed.

For renewable energy technologies, a large proportion of subsidies has been provided through a feed-in tariff (FIT), production tax credit (PTC), and research and development (R&D) funding [2]. Several studies have examined the effects of these subsidies on the diffusion of renewable energy technologies and determined that FIT is more efficient and effective than alternative policies [9–12]. However, the adoption of renewable energy technologies

* Corresponding author. Tel.: +82 31 290 7607; fax: +82 31 290 7610.
E-mail addresses: newstain@hanmail.net (C. Jeon), leejeongjin@ssu.ac.kr (J. Lee), jsshin@skku.edu (J. Shin).

http://dx.doi.org/10.1016/j.apenergy.2014.12.067
0306-2619/

could not reach the given target when the financial subsidy alone was implemented. This implies that financial subsidies should be used together with R&D funding [13]. At a minimum, subsidy optimization should consider both the financial subsidy and R&D funding.

In response to tight national budgets and broad impacts of global low economic growth, many countries, including Germany and Italy, have significantly reduced FIT rates for renewable energy technologies [3]. In addition, public R&D investments in solar power, wind, biomass, and biofuels have decreased in most developed countries, including the United States, Germany, and Japan [3]. Under severe budget constraints, many governments are seeking new ways to meet increasing policy targets of development and deployment of renewable energy technologies and to maximize the benefits of these technologies, including reduction of greenhouse gas emissions, enhanced energy security, and economic growth [14–16]. Nevertheless, governments intend to optimize energy subsidies at any given moment.

Among subsidy estimation methods, the discounted cash flow (DCF) method is widely used. It is appropriate for short-term estimation with certainty; however, it is not appropriate for long-term estimation with severe uncertainties [17]. Instead, researchers suggest optimization approaches, including the real option model [17], consumer choice model with the learning-by-doing effect [7], and the consumer choice model with the option valuation model [18]. These approaches have the advantage of reflecting various factors and their uncertainties; nevertheless, these models cannot consider their interactions. Additionally, the appropriate option model varies with the type of investment, which implies that the most appropriate option model exists for each subsidy type [19,20].

To address these issues, we propose a new method to determine the optimal amount of financial subsidy and R&D funding for renewable energy technologies. System dynamics (SD) enables this method to reflect various factors as well as their interactions. Further, we match the most appropriate real option model to each type of subsidy and thereby increase the optimization accuracy. By leveraging the advantages of both methods, our approach can improve the optimal subsidy estimation for renewable energy technologies. As an example, we estimate the optimal financial subsidy and R&D funding for Korean photovoltaic (PV) technology.

2. Literature review: renewable energy subsidy optimization

Given the policy target, the appropriate level of subsidy is determined in practice by using DCF. DCF estimates and sums all expected future cash flows to set the amount of subsidy regardless of different subsidy design and implementation options [21,22]. DCF is suitable for short-term subsidy estimation with little uncertainty; however, it is not appropriate for strategic investment, such as renewable energy subsidies affected by severe uncertainties [23]. A wide array of uncertainties exist, including advancing competitive energy technologies, constricting budget reductions, stronger environmental regulations, infrastructure accidents, and others. Moreover, various other factors amplify uncertainties and make DCF inappropriate; these include subsidies, generation costs, and environmental regulations, which interact in complicated ways. Researchers conclude that other methods are better than DCF in terms of robustness and accuracy [24,25].

The real option approach is a recommended alternative. It can reflect various factors and their uncertainties in estimation; therefore, it is more effective than DCF [26]. Davis and Owens [17] estimate the renewable electric R&D expenditure from both the real option and DCF perspective; they demonstrate that the real option is more effective than DCF. Using real option models, researchers have attempted to estimate financial subsidies, including FIT [27], and R&D investments [28,29]. Further, recent studies have evaluated the overall technology investment, including subsidy and infrastructure investments [30,31]. Considering various market and policy uncertainties, these studies avoid the over- and underestimation of subsidies by DCF and therefore improve the accuracy of estimation.

Recently, under conditions of global low economic growth and fiscal burdens, the necessity of subsidy optimization has been increasing for many governments, which warrants more advanced approaches [14–16]. Some researchers have used a consumer choice model to forecast future PV demands and estimate the minimal subsidy for achieving the policy adoption of targets [7]. This optimization approach has the advantage of considering uncertainties in consumer demand and PV technology development, as well as of maximizing the overall social value conferred, including consumer, investor, and policymaker benefits and costs.

Other researchers have suggested optimization models to include important but hard-to-measure factors, including different investor attitudes toward market risk [32,33], different subsidy designs [34], and network effects [18]. Using option valuation models, these studies account for different exposures and attitudes of investors, consumers, and policymakers to market, technology, and policy risks. Accordingly, they make optimization more realizable.

Despite their contributions, previous studies do not consider interactions among multiple stakeholders, which influence factors and uncertainties. For instance, PV module manufacturers decide investment levels for plants, which affect PV pricing and consumer adoption. Our SD model provides a means of analyzing their interactions as well as circular causalities; it therefore traces dynamic changes of key variables and their effects on subsidies. Our model can make dynamic subsidy optimization more reliable and identify time-varying effects of key variables on subsidies as well as other variables. Moreover, subsidy planning can become more accurate and flexible.

In addition, there has been no effort toward multi-subsidy optimization. For example, many previous studies have improved ways of optimizing FIT; however, they do not try to optimize more than two types of subsidies together. Financial subsidies and R&D funding can create a synergy for facilitating consumer adoption. Thus, the optimal subsidy for either one is not optimal but sub-optimal. Our model provides a way of optimizing two types of subsidies together; it therefore can be a first step toward multi-subsidy optimization. Finally, there has been little effort at identifying the most appropriate subsidy optimization model for a specific subsidy policy with different objectives, benefits, and uncertainties. Our model strives to match an appropriate model to a specific subsidy.

3. Methodology

3.1. Research framework

As noted above, renewable energy technology subsidy optimization must consider: (1) complex interactions among various factors, (2) dynamic uncertainties and their influences, and (3) appropriateness of an optimization model for a specific subsidy. Most deterministic valuation and optimization methods, including DCF and the consumer choice model, can partially meet the third requirement but cannot meet the others. The real option approach was proven to be appropriate for the second requirement; it can also provide various subsidies with well-matched optimization models. SD was initially developed to address the dynamics of complex systems characterized by uncertainties and sophisticated interactions; it therefore satisfies the first and second requirements. By combining SD with appropriate real option models, we